Future scenarios of the electricity system and Power Purchase Agreements（PPAs）

– Assessment of future electricity market price drivers and climate assessment of a PPA

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Master thesis 2020
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Dokumenttitel och undertitel

Framtida scenarier av elsystemet och elköpsavtal
– Undersökning av faktorer som påverkar framtida elpriset och klimatberäkning av elköpsavtal

Sammandrag

Energisystemet genomgår för närvarande en snabb transformation med allt mer förnybar elproduktion. Ett sätt genom vilket företag kan köpa förnybar el är genom långsiktiga elköpsavtal (Power Purchase Agreements, PPAs), i vilka de enas om ett fast pris och andra villkor med en projektutvecklare. För att bedöma ett rättvist fast pris av PPAn, så behöver först det framtida marknadspriset på el uppskattas. Företaget South Pole som tillhandahåller konsulttjänster inom klimat och energi utvecklar ett ramverk för att bedöma PPAer, i vilket en del ä ren datadriven modell för att beräkna det framtida marknadspriset på el. Denna uppsats bidrar till det ramverket genom att finna data av olika faktorer som påverkar marknadspriset på el från olika rapporter oh scenarier för Storbritannien. I arbetet har även utsläppen från en PPA jämförts med att förbruka el från nätets produktionsmix. Faktorerna som påverkar elpriset har jämförts mellan olika källor och scenarier, och scenarierna analyserades baserat på om de ligger i linje med Storbritanniens nationella klimatmål om netto-noll-utsläpp år 2050. Sedan föreslogs förbättringar av styrmedel baserat på elprisfaktorerna för att bidra till klimatmålet.

Resultaten visar att de viktigaste faktorerna som påverkar elpriset i Storbritannien är priset på gas, koldioxid och mängden producerad förnybar elenergi. Den framtida utvecklingen av dessa faktorer skiljer sig mycket åt mellan de olika källorna och scenarierna. En slutsats är att Storbritannien behöver införa mer kraftfulla styrmedel för att nå målet om netto-noll-utsläpp år 2050. Detta kan göras genom att öka priset på gas och koldioxid samt att stödja utbyggnaden av förnybar elproduktion. Genom en PPA kan företag minska sina utsläpp från elkonsumtion samtidigt som de bidrar till att mer förnybar elkapacitet byggs, vilket bidrar till den generella transformationen till ett energisystem med låga utsläpp av klimatskadliga växthusgaser.

Nyckelord

PPA, Power Purchase Agreement, elköpsavtal, scenarier, elpris, elmarknad, prisdrivare, Storbritannien, klimat, styrmedel

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Abstract

The energy system is currently in a rapid transformation with increasingly growing renewable electricity production. One way through which companies can buy renewable electricity is through long - term corporate Power Purchase Agreements (PPAs), in which they agree on a fix price and other terms with a project developer. To determine a fair fix PPA price, the future electricity market price needs to be estimated. The climate and energy advisor South Pole is developing a PPA assessment framework, including a data driven market price model to create a forward electricity price curve. This thesis is contributing to that assessment framework in finding data of price drivers from different sources and scenarios for the UK, and to calculate the reduction in greenhouse gas emissions through a renewable PPA compared to electricity consumption from the grid production mix. The price drivers were compared across different sources and scenarios, and the scenarios were analysed based on their alignment with the national UK target of net zero greenhouse gas emission in 2050. Then, policy improvements were proposed based on the price drivers to contribute to reach the climate target.

The results show that the most important price drivers for the UK are gas price, the renewable electricity production and the carbon price. Their future development differs clearly across different scenarios from different sources. The UK needs to raise its policy ambitions to be able to reach their net zero target, which can be done through increasing the gas and carbon prices and to support the growth in renewable electricity capacity. Through a PPA, companies can reduce their emissions from electricity consumption and are contributing to additional renewable energy being built, which is contributing to the overall transformation to a low-carbon energy system.

Keywords

PPA, Power Purchase Agreement, scenarios, electricity market price, UK, climate, policy, electricity, emissions

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Preface

This Degree Project in Environmental Studies was written during the academic year 2019/20 by me, Sara Nyberg, at the company South Pole in Stockholm, in parallel to working with greenhouse gas accounting at the same company. The thesis is finalising my studies in Environmental Engineering with the specialisation in Energy Systems at the Faculty of Engineering LTH at Lund University, Sweden.

I would like to acknowledge and thank several people who have supported me in different ways: first, my supervisor at LTH, Max Åhman, who provided valuable inputs to the thesis and who gave super quick replies, and Lars J Nilsson, who has taken on the task to be the examiner.

I am very glad to be part of the multicultural PPA model team at South Pole, and to contribute to the model which will be used to advice clients on corporate PPAs. Thank you, Paolo Gabrielli, my supervisor at South Pole, for all your support with the actual work from the beginning to the end. Thanks to Patrick Horka I got the chance to make my master thesis within the field of energy at the company, which I'm very grateful for. I always appreciated the corporate perspective from Paul Hill and enjoyed every moment listening to your British English. I'm also glad for the collaboration I've had with the other master thesis students where our work has overlapped: Moritz Wüthrich (sorry if I didn't always understand the technical details of your work!), Michael Chow (it was a positive surprise that you joined our group, it was nice to work with you – again!) and Diederick Calkoen (I would have contributed more to the past predictions database if I had have more time…).

Thank you, South Pole, for letting me use my working computer and the desk also for the work with the thesis and thank you Marie Gustafsson for the understanding and flexibility in time management to be able to work with greenhouse gas accounting in parallel to my studies.

I have several friends who supported my motivation and would like to give special thanks to Patrik Olsson for the *great* energy and focus sessions during the final weeks. I never felt bored when we were co-working and probably raised my productivity – even though we took breaks.

Stockholm, 10th of June

Sara Nyberg

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Abbreviations

BEIS	UK department of Business, Energy and Industrial Strategy
BM	Build Margin
CCUS	carbon capture, usage and storage
CfD	Contract for Difference
CHP	combined heat and power
EAC	Energy Attribute Certificate
EEP	Updated Energy and Emissions Projections
EF	emission factor
EU	European Union
EU ETS	EU Emission Trading System
FES	Future Energy Scenarios
GHG	greenhouse gas
GoO	Guarantee of Origin
IRENA	International Renewable Energy Agency
$kgCO_2e$	kilogram carbon dioxide equivalents
kWh	kilowatt-hour
MWh	megawatt-hour
NG	National Grid
OM	Operating Margin
PPA	Power Purchase Agreement
T&D	transmission and distribution
TWh	terawatt-hour
UK	United Kingdom
US	United States of America
WBCSD	World Business Council for Sustainable Development
WRI	World Resources Institute
WTT	well-to-tank

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1. Introduction

The energy system is changing. The net additions of renewable energy capacity have increased nine-fold the latest 17 years globally (Figure 33, Appendix 1), so that in 2019 the share of renewables in capacity expansion reached 72 %. Meanwhile, non-renewable capacity is being decommissioned in Europe and North America. (International Renewable Energy Agency (IRENA), 2020) This is leading to an increased need for power storage and flexibility. Meanwhile, we use the energy more efficiently, but the demand is also expected to increase due to electrification of the transport and industry sectors and digitalization which needs more data capacity and energy. For example, to electrify the energy use and fossil feedstock of basic material production in the European Union (EU), would increase industrial electricity consumption from today's 125 terawatt-hours (TWh) up to 1,713 TWh for the same level of production of basic materials as today (Lechtenböhmer, et al., 2016). According to another study (Andrae, 2020), the global electricity usage of data centers is modeled to increase from around 2,000 TWh/year in 2020 to 4,900 TWh/year in 2030, then making up 14 % of the total energy consumption. (Campanello, 2020) However, a considerable share of this increase could be offset by energy efficiency measures (Masanet, et al., 2020).

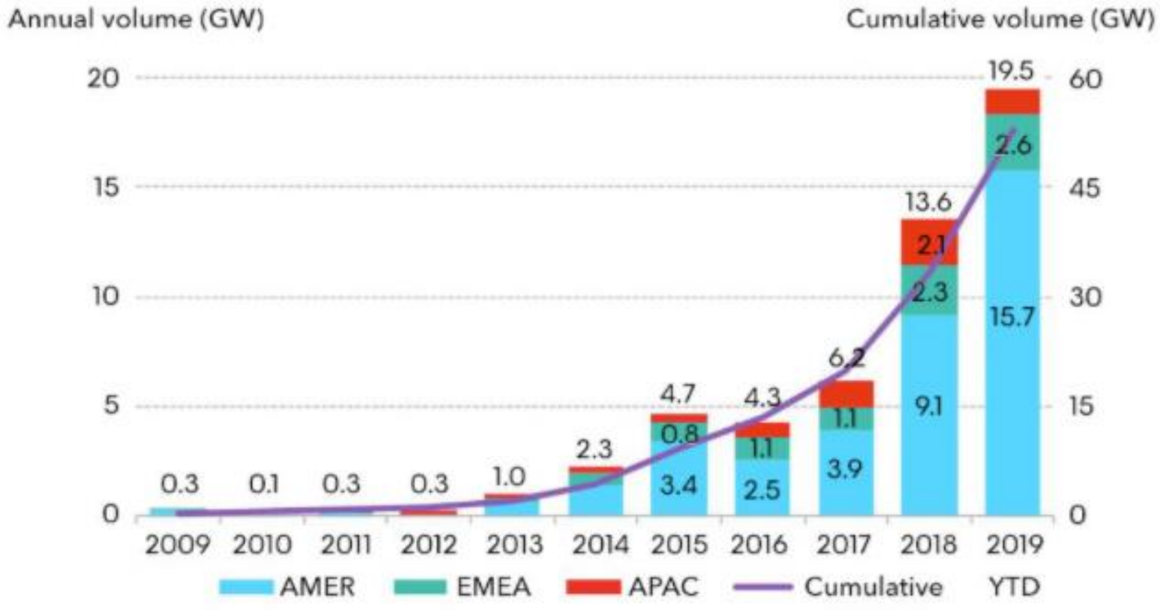
In 2017, energy related greenhouse gas emissions made up 74 % of the total emissions on a global level (Figure 34 in Appendix 1), making it a large contributor to global heating and climate change. To reach the temperature goal established in the Paris Agreement, emissions need to be reduced drastically: According to the "carbon law" global emissions need to be halved every decade, starting from 2020, to be in line with the 1.5-degree target of the Paris Agreement (Rockström, et al., 2017). To reduce energy related greenhouse gas emissions, there are different possibilities, such as increasing energy efficiency, replacing fossil with renewable energy and carbon capture, usage and storage technologies. The largest greenhouse gas emissions reduction potential according to the Emissions Gap Report (United Nations Environment Programme (UNEP), 2019) lies within the power sector.

Due to technology development and scale-up of renewable power technologies such as wind and solar power, the price of those technologies has decreased significantly in the latest years: wind turbine prices have fallen by 30–40 % since the end of 2009 (IRENA, n.d.) and global weighted-average levelized cost of electricity for electricity from utility-scale solar photovoltaics fell by 82 % from 2010 to 2019. In 2019 more than half of the renewable capacity had lower electricity costs than coal, and new solar and wind projects are undercutting the cheapest and least sustainable coal power plants. (IRENA, 2020) Thanks to the decreased cost for renewable electricity and their climate advantage, renewables are on the rise. At the same time, subsidies, feed-in tariffs and other support mechanisms are slowly being phased out. However, wind turbines and solar power plants still need a high investment in the beginning even though they have low operation and maintenance costs compared to thermal power generation which have a high running cost (for the fuel). One way to finance the high initial investment for renewable capacity is through corporate Power Purchase Agreements (PPAs), where corporates agree to buy the produced electricity from a certain plant at a fixed price for 5–20 years. This fixed price benefits the buyer in the way that it reduces the risk of fluctuating future power prices, making the future expenses for electricity unpredictable, and in addition the buyer can make claims about renewable electricity and reduced emissions from electricity consumption, which can improve the branding. Thanks to the agreement, the project developer can secure financing since it can show that someone will buy the electricity for a long period of time and through that make sure that the money will be paid back to e.g. the bank. In general, a PPA leads to that the corporate buyer and the project developer share and reduce the risks.

To determine the fair price of the PPA, you need to assess what the electricity market price will be during the years which the PPA covers, i.e. a forward price curve[1]. The price shouldn't be too far away from the expected market power price for the project developer to be able to cover their investment cost and the offtaker not having to pay much more than the market price. To determine the future electricity market price, a method and model is needed. Different energy companies and organisations are developing their own models to give advice on the fair PPA price to their clients. The company South Pole aims to improve its PPA advisory service by developing such a model. This thesis is contributing to the PPA model developed at the company South Pole, which is explained further in the next section.

1.1. Context and purpose

PPAs only exist since around 13 years in the United States (Gómez, 2017), and started in earnest in 2014 in Europe (RE-Source, 2020), but has only taken off in the latest years, see Figure 1. A sharply increasing amount of companies have set 100 % renewable energy targets (The Climate Group, 2019), but don't have any experience in buying electricity directly from a project developer. Therefore, they often seek advice from companies with the needed technical knowledge.



Source: BloombergNEF. Note: Data are through 2019, reported in MW DC capacity. Onsite PPAs are not included. Australia sleeved PPAs are not included. APAC number is an estimate. Pre-market reform Mexico PPAs are not included. These figures are subject to change and may be updated as more information is made available.

Figure 1: Annual and cumulative volume of power produced through PPAs 2009-2019, split up in the world regions AMER (Americas), EMEA (Europe and Middle East), APAC (Asia and Pacific), adopted from (Henze, 2020)

The company South Pole is offering consultancy services to help companies procure renewable electricity through different approaches, out of which one is through PPAs. For South Pole to be able to give advice in different markets in Europe, the company wants to develop its own PPA assessment model covering several European countries. This model should help to assess the business case for PPAs and compare them against the case of buying electricity directly

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[1] A forward price curve is a curve of current price for a commodity in a specific location on specific dates in the future (Reichelt, 2019))

from the grid. It should also suggest the optimal selection of corporate PPAs regarding type of electricity source, location and size, and determine the fair price of the purchased power across different European markets. Regarding determining the fair price, there are currently public power price forward curves for the United Kingdom (UK) developed by the UK department of Business, Energy and Industrial Strategy (BEIS), which serve as a base to determine the fair PPA price, but there are no such publicly available forward curves for other countries in Europe. For South Pole to give advice to other markets, the company therefore wants to develop its own electricity price forward curve.

In the project to develop the PPA assessment model, several people were involved: two employees at South Pole (Patrick Horka, Paul Hill), one employee working partly at South Pole and partly at the ETH Zürich who also is the second supervisor to this thesis (Paolo Gabrielli) and in total four master thesis students, to date – each contributing to different model components. An overview of the PPA assessment model is seen below in Figure 2 with the topical areas of the four different master thesis students indicated.

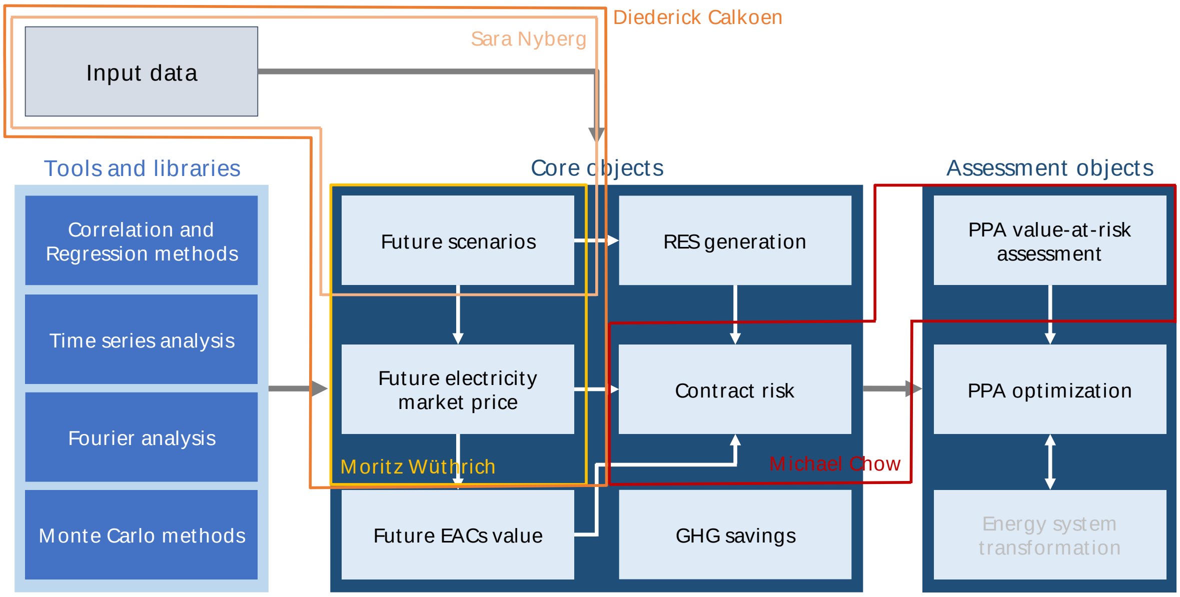

Figure 2: Graphical summary of the PPA assessment model structure with the different responsibilities of students indicated in coloured boxes (Gabrielli, 2020)

Out of the model components, this thesis work is contributing to the determination of the fair PPA price through finding price driver data and to the comparison of a PPA to buying electricity from the grid, with regards to the carbon emission reduction potential. Another master thesis student, Moritz Wüthrich, used the price driver data to model a forward price curve, the student Michael Chow analysed PPA risks, and yet another student, Diederick Calkoen, compared price drivers from future energy projections from different years to determine the uncertainty of those projections.

1.2. Aim and research questions

The aim of this thesis is to develop a ‘Price driver database’, by inserting the future development of price drivers from different sources of energy projections serving as input data to the price model, secondly to analyse those price drivers based on UK’s climate targets and policy, as well as to evaluate the climate impact of a PPA. This work will contribute to a PPA assessment model, including a data-based future electricity market price model, developed at and for the company South Pole.

This approach includes to (1) determine the factors influencing the electricity price, (2) compare the development of the most important price drivers in future energy projections from different sources about the UK, (3) analyse the future scenarios based on their contribution to UK's climate targets and propose policy improvements based on the price drivers, as well as to (4) calculate the avoided greenhouse gas emissions through the engagement in a renewable PPA instead of using grid electricity mix.

To reach this objective the following questions will guide the work:

- Which factors are influencing the market electricity price and which of those price drivers are more crucial in the UK?
- How do future projections of price drivers differ between different sources and their respective scenarios for the UK – and why?
- Do the scenarios from different future energy projections of the UK lead to the fulfilment of UK's national climate targets? What governmental policies relating to the most important price drivers would be needed to reach the climate targets of the UK?
- What is the climate impact of consumption of renewable electricity through PPAs compared to the consumption of electricity from the grid production mix over a certain PPA contract period?

To answer these questions, research on electricity market price drivers and the UK climate targets was conducted. Two sources of future energy system projections were chosen: the Updated Energy and Emissions Projections (EEP) by BEIS (UK Department of Business, Energy & Industrial Strategy, 2019) and the Future Energy Scenarios (FES) by National Grid (NG) (National Grid Electricity System Operator, 2019), see the top box in Figure 3. The scenarios were analysed with regards to their contribution to UK's climate targets. From those sources, data about price drivers were transferred to a self-developed database in Excel (second box in the figure). The gathered data was used in the PPA assessment model to estimate the future electricity market price (third box), which is used by South Pole to give corporate clients advice on a fair PPA price (fourth box). In this thesis work the price drivers from the different scenarios were mapped to three general emissions scenarios and plotted. The graphs of the development of the price drivers according to both the original and general emissions scenarios were compared. Furthermore, an example calculation of emissions from grid electricity and renewable electricity (from a PPA) was conducted and the results compared.

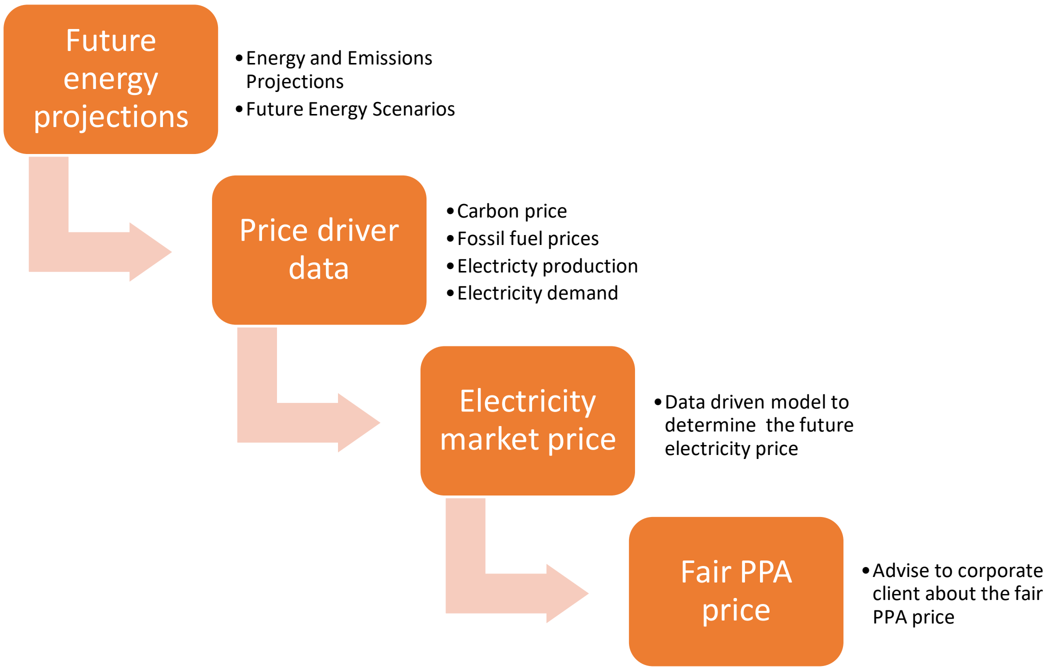

Figure 3: Overview of the steps from the future energy projections to a fair PPA price

1.3. Delimitations

This thesis will focus on the PPA market in Europe. The electricity price differs between different countries, so therefore it was decided to start with one country to model the forward price curve for that country. The data which was found and analysed covers the UK. One of the reasons behind the selection of this country is that there is already a forward market electricity price curve for the UK, against which the model results of the future price can be compared with (see Figure 40, Appendix 3). There were also two good and trustworthy sources which are regularly being updated with future projections of the energy system in the UK. In addition, the language around the data would not be a barrier to find and examine it. Apart from the geographic scope, a temporal delimitation was made to the years which the sources of future energy projections cover, which is until 2050. However, the largest interest is on the coming 15-20 years (until 2035-2040), which is the maximum time span of a PPA, for which the price needs to be assessed.

Another delimitation is the focus on corporate PPAs – which are between project developers and the end-user – and not on other PPAs such as utility PPAs between a project developer and a utility. The focus is also on renewable PPAs, which are most common, but this excludes coal and gas PPAs.

Regarding the analysis of the price drivers, they were assessed individually and not how they influence each other. Since the PPA model takes in the data from the different price drivers separately, there was no need to analyse how they influence each other.

The electricity price to be modelled is the market electricity price, excluding taxes and network charges, as those are dependent on government decisions and not (directly) on the power market.

1.4. Disposition of the text

The thesis follows the IMRAD model with introduction, background, theory, methods, results, analysis, discussion and conclusion. Since the thesis work covers different aspects of PPAs and price drivers, an overview of how those topics are connected is shown in Figure 4 below. In the following paragraph the disposition of the text is described in chronological order.

This first chapter gives a context and background to the thesis subject and introduces the purpose, aim, research questions and describes the delimitations. The next chapter (chapter 2) gives the reader the necessary knowledge about corporate sourcing of renewable electricity (chapter 2.1), what PPAs are (chapter 2.2), including their structures, benefits and risks as well as the terms and pricing mechanisms of PPAs. Furthermore, the chapter describes in brief power markets, price drivers, and forward curves (chapter 2.3). Following, in chapter 3, there is an overview of relevant UK climate and energy targets and policies which are used to analyse which additional policies would be needed to fulfil UK's climate targets. In chapter 4, the concepts for calculating the greenhouse gas (GHG) emissions from electricity consumption are explained. Thereafter, the methodology to find, structure and analyse price drivers is described (chapter 5), followed by the calculation of the avoided emissions from a PPA (chapter 6) and by the future energy projections used as material (chapter 7). The results of the comparison and analysis of the price drivers are found in chapter □. In chapter 9, the results from the climate assessment of the PPAs are shown. This is followed by the discussion (chapter 10) and conclusion in the final chapter. There are four Appendixes, showing additional figures from other sources, excerpts from the Excel calculation sheets, forward price curves and finally additional graphs about the future average development of the three chosen price drivers, which weren't included in the analysis.

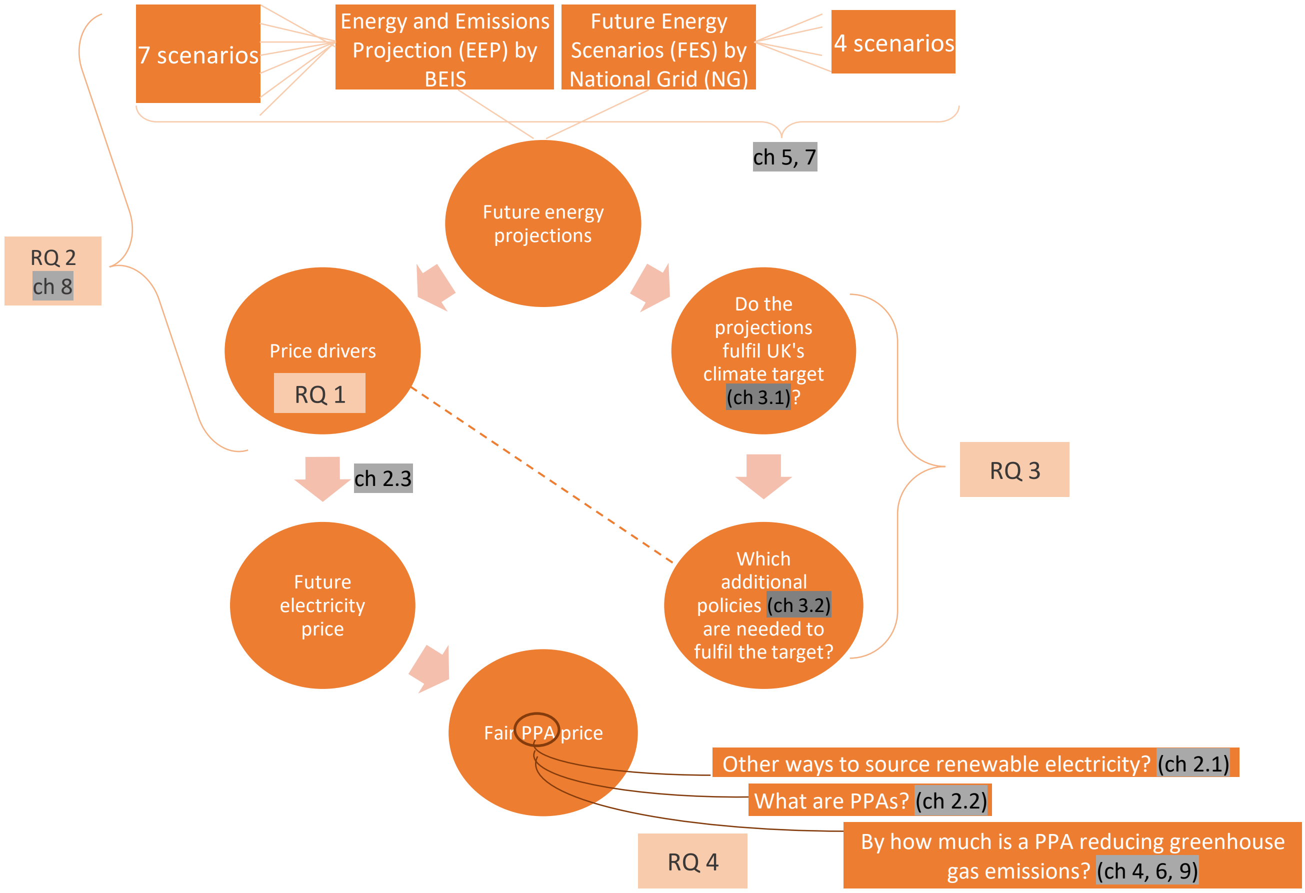

Figure 4: Overview over the thesis work including research questions (RQ) and indication of chapters with the associated content.

2. Corporate Power Purchase Agreements and electricity pricing

2.1 Corporate sourcing of renewable electricity

Several companies have set own targets to reduce their greenhouse gas emissions. For most companies, the major part of their emissions come from their energy use. To reduce these emissions, one way for companies is to use the energy more efficiently – but they still need considerable amounts of energy. Therefore, an emissions reduction strategy needs to be complemented with buying renewable energy. Usually, the most accessible solution within energy is to change the electricity consumption from fossil to renewable. In fact, already 211 large, influential, multinational companies have joined the initiative RE100 and have set a target for 100 % renewable electricity. These companies would together be the 21st largest electricity consumer in the world if they would be a country (after Indonesia and before South Africa) (The Climate Group, 2019). In 2017, the world market for corporate sourcing of renewables reached about 465 terawatt-hours, which is close to the overall electricity demand of France. As of 2018, corporate sourcing of renewables is taking place in more than 75 countries (IRENA, 2018).

For companies to source renewable electricity, there are several options, which are listed below to give an overview of the alternatives. The alternatives are listed and sorted from lower to higher additionality[2] and direct impact, i.e. from market-based solutions to concretely building own renewable power generation (IRENA, 2018). The main sources for the information in the list below were RE-Source (2020), the World Business Council for Sustainable Development (WBCSD, 2016) and LevelTen (2020).

- **Energy Attribute Certificates (EACs)**: EACs verify that one megawatt-hour (MWh) of renewable electricity was generated and fed into the grid and it is a free market instrument. Therefore, they can be bought in one (area of a) country and used in another one. The EACs exist in global markets and are known as Renewable Energy Certificates in North America, Guarantees of Origin (GoO) in the EU and International Renewable Energy Certificates or tradeable instruments for global renewables in developing international markets (Schneider Electric, n.d.). The EACs can be bought bundled (together with the physical electricity) or unbundled (on a separate market). The purchase of GoOs helps support the income of renewable electricity installations, but don't contribute to additional renewable capacity being built. EACs are easy and flexible and can be purchased from quantities of 1 MWh but add an extra cost for the company, and this cost might increase over time if the demand for the certificates increases. The prices of EACs vary depending on the local supply and demand, the energy technology, specific attributes of the location and the contract length. EACs permits consumers to make credible claims of renewable energy use (IRENA, 2018).
- **Green electricity products**: The company pays a green tariff or premium to the utility, which has its own renewable electricity production, or which buys renewable electricity on the wholesale market (or alternatively unbundled renewable energy attribute certificates to cover the demand). This option is relatively easy for the company to do, since it doesn't require an upfront cost or a contract. In addition, smaller amounts of electricity ban be bought (compared to a PPA, see below), which is attractive for smaller companies, but this option is not provided by all utilities. Green electricity products do

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[2] A high additionality means that the way to source renewable electricity is contributing to new renewable capacity being built, while sourcing options with low additionality don't directly lead to new, additional renewable capacity being built. IRENA (2018) defines it as "The net incremental renewable capacity depolyed or renewable energy generated as a direct result of corporate sourcing of renewable energy beyond what would occur in its absence."

not directly contribute to additional renewable installations, but an increased demand of them can send a market signal that additional renewable development is needed in a certain region. Two variants of green electricity products can be distinguished:

  - **Green power/pricing/premium product:**
    - usually a premium price, i.e. the total price for renewable electricity will be more expensive than non-renewable electricity
    - no guaranteed price stability
    - typically shorter contracts, down to a monthly basis
    - often easy to sign up, making it a flexible option
    - the type of source of the renewable electricity is usually determined
    - electricity is often sourced from a project located in the same region, but the customer has no influence on where the electricity plant is situated
  - **Green tariff:**
    - can be cheaper compared to non-renewable electricity, but it depends on the contract
    - some green tariffs can have a stable price
    - usually long-term contracts (3–7 years, but can be even longer)
    - negotiation of a contract is needed, making it more complicated to achieve compared to green power, and there's a minimum amount of electricity needed to be purchased, so the company needs to be large enough
    - the type of source of electricity can be influenced by the customer
    - supports the development of a new renewable project

- **Power Purchase Agreements (PPAs):** A contract between a company, the offtaker, and a developer, which agree on a price and volume of electricity over a long term (5–20 years) from a certain project to be built by the developer. More information on PPAs is given in the next section.
- **Self-owned off-site renewable asset:** The company may hire a third party to build and maintain the installation, but then takes over the ownership over the installation. If the installation if off-site, space constraints at the site are avoided, but a network charge needs to be paid since the electricity passes the grid, and a high upfront investment is required.
- **Leasing of on-site capacity:** A third party builds, manages and owns the installation on-site and leases it to the company which is paying a monthly or annual fee for the service, but nothing for the electricity. This requires no upfront cost. Any excess power not consumed on site can be fed to the grid if there is a connection and then sold to the wholesale market.
- **Self-owned on-site or near-site renewable asset:** The company often hires a third party to build and maintain the installation at or close to the site but owns it itself. An important precondition is that there is enough space and appropriate conditions for an installation. Most common is to install solar photovoltaic systems, but there are also possibilities to self-generate electricity from biomass, fuel cells, geothermal heat, and wind turbines. This option mostly requires a high upfront investment, but where regulation allows, network charges can be reduced or avoided. Any excess power not consumed on site can be fed to the grid if there is a connection and then sold to the wholesale market. EACs can be issued for every megawatt-hour that the installation generates, and excess EACs can be sold on the relevant market. On the contrary, the production from the on-site installation is often not large enough to cover the whole demand of the office or factory, wo that a complementary strategy needs to be used if the company wants to cover their whole demand with renewable electricity.

Companies will choose one or several of the above strategies – at once or over time – depending on their size and level of electricity use, existing electricity tariffs and regulations, their environmental objective, level of ambition, internal knowledge and capacity, their risk tolerance and the degree to which they want direct control over the electricity generation. (WBCSD, 2016) Many companies want their projects to be additional, such as Google and Facebook, to show that their purchasing has a real impact. (Foehringer Merchant, 2019) According to the REmade Index 2018 (IRENA, 2018), the current largest share of global corporate sourcing of renewable electricity comes from production for self-consumption (165 TWh), followed by unbundled EACs (130 TWh), corporate PPAs (114 TWh) and utility green procurement programmes (34 TWh). In the same year, 3.5 % of total electricity demand came from renewables actively sources by companies in the Commercial and Industrial sector. Out of the renewable electricity sourcing options listed above, the focus in this thesis is on Power Purchase Agreements.

2.2 Power Purchase Agreements

What are PPAs?

A Power Purchase Agreement (PPA) is a long-term electricity supply agreement between the buyer (a.k.a. off-taker/consumer) and the electricity producer (a.k.a. project developer/plant operator) to purchase electricity at a pre-agreed price for a pre-agreed period of time, see Figure 5. The electricity is usually transmitted through the public electricity grid. The contract contains commercial terms of the electricity sale, such as contract length, point of delivery, delivery date/times, volume, price, product, accounting and penalties for non-compliance. The purchased electricity can come from either a newly build power plant, or an existing, of which the lifetime is prolonged, e.g. after a feed-in tariff system has expired. (WBCSD, 2016) It is more common that a PPA enables a new plant to be built. The background is that there is a high investment cost involved in building a renewable electricity plant. Therefore, developers often need to turn to banks to get loans for the construction of the plants, in addition to their own funds. From the banks perspective, it's safer to lend out money to a renewable electricity project if they know that the developer already has a long-term (PPA) contract with an offtaker, which will buy the produced electricity, and thereby the developer is more likely to be able to pay back the loan. Therefore, corporate offtakers enable new renewable electricity projects to be built through engaging in a PPA. (LevelTen, 2020)

Since a PPA is a bilateral agreement, it can vary a lot depending on the needs and capacities of the two parties and the specific application. (Next Kraftwerke, n.d.) There are both non-renewable and renewable PPAs, but the majority are renewable PPAs, and these are interesting to reduce the emissions. Therefore, the focus in this thesis is on renewable PPAs. Depending on the market, EACs are issues and delivered with the electricity through the PPA.

Figure 5: Scheme of a PPA between an electricity producer (left) and an offtaker (right), adopted from (Bird & Bird, 2019)

Since when do PPAs exist and where?

In the Unites States (US), PPAs have existed since 2007 (Gómez, 2017), and were later on brought over to Europe, where they took off in 2014 (RE-Source, 2020). The largest contracted capacity comes from onshore wind power, but during the latest years, solar and offshore wind project PPAs have increased, see Figure 6. In the beginning, mainly technology companies and data centre owners were involving in PPAs, since they have ambitious renewable energy targets and large consumption of electricity. (Bird & Bird, 2019) Later on, companies in the chemical, telecom and fossil fuel sectors have also signed PPA contracts.

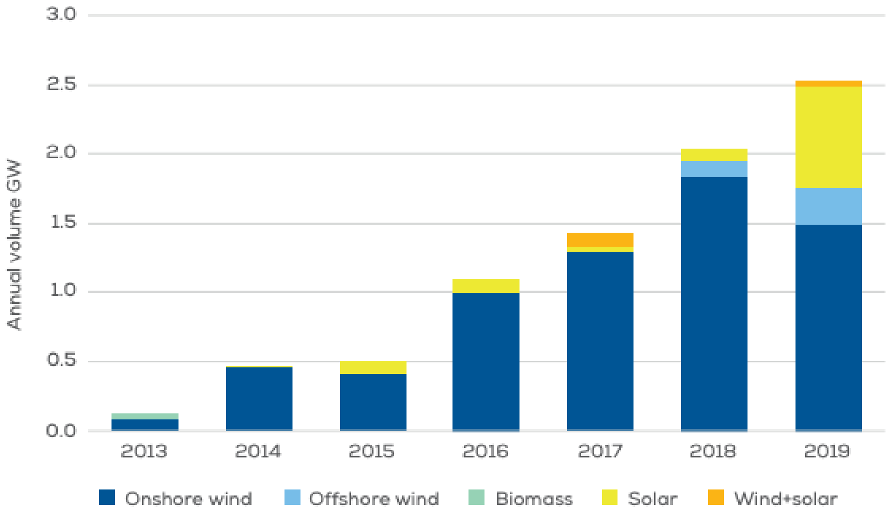

Figure 6: Renewable energy corporate sourcing through PPAs in Europe 2013-2019 split up between different sources of energy, adopted from (Wind Europe Business Intelligence, 2020)

The current trend of PPAs

The current trend is a sharp increase in annual capacity of renewable electricity plants through PPAs globally, mainly driven by a sharp rise in the Americas (Figure 1), but there is a steady increase also in Europe (Figure 6). The main reasons are the falling levelized costs of energy with regard to renewables, as well as phasing out of fiscal incentives such as subsidies feed-in tariffs, which is why the developers need to find other ways to secure a stable long-term income to secure financing of the projects (Bird & Bird, 2019). One example of reduced costs is the world record low solar electricity bid (as of 29 April 2020) of 0.0135 $/kWh for a 1.5 GW solar tender in the United Arab Emirates. (Bellini, 2020) On a European level, EU adopted the recast

Renewable Energy Directive in December 2018. It includes several drivers and enablers for a larger uptake of corporate PPAs in the EU, such as an EU-wide target of 32 % renewable energy in 2030. According to the directive, member states need to assess the regulatory and administrative barriers to corporate PPAs and remove unjustified barriers to corporate PPAs. This will be monitored through the member states' national energy and climate plans, which are submitted to the EU in 2020. One enabler is that member states recognise guarantees of origin and allow the transfer of them directly from renewable generators to corporate offtakers (not necessarily via utilities) – also across borders. (Bird & Bird, 2019)

To the rise of PPAs, an increased climate awareness and ambitions of companies, which set and work towards reaching climate and energy targets. The initiative RE100, through which large and influential companies set targets for 100 % renewable electricity, grew by over a third in 2019 to over 200 members. Companies which were members in 2018 increased their share of renewable electricity by four percentage points to 42 % to 2019, which is showing that they are progressing towards their commitments. Two companies increased their sourcing of renewable electricity significantly, namely Iron Mountain (+39 %) and Facebook (+24 %), thanks to new PPAs. (The Climate Group, 2019) In September 2019, Google made a press release about their recent agreement with developers to build 286 MW new installed capacity in Sweden, to amongst other power their data centre in Finland. It is a part of a package of 1.6 GW renewable electricity in the US, Chile and Europe and is their largest investment ever in renewable energy. Earlier, they have mainly invested in wind power, but as the costs for solar power have declined sharply in the latest years, solar power has become more cost effective. (Nohrstedt/TT, 2019) Another recent PPA announcement was made by Ørsted and Taiwanese semiconductor manufacturer TSMC to produce electricity from offshore wind power plants from a 920 MW large installation with a contract period of 20 years, which is to date the largest single-project corporate renewable deal. (Parnell, 2020)

Another recent development in the area of PPAs is to use blockchain technology. A recent article in PV magazine Australia reported about a solar farm using a blockchain-based PPA infrastructure which allows smaller corporate offtakers to take part of PPAs. This is possible through that the PPA is broken down into smaller "tokenised" pieces, which fit customers who have a smaller electricity consumption than traditional PPA offtakers. The blockchain technology also provides an immutable audit trail, so that the offtakers with certainty know where the electricity is coming from and how it was generated. (Maisch, 2020)

What are the drivers for corporates to engage in PPAs? What are the benefits and risks or challenges for the corporate and the seller respectively?

There are several different drivers for corporates to engage in PPAs. The main ones are listed below: (WBCSD, 2016)

- **Economics:** ability to reduce and fix electricity costs, thereby lowering the electricity price volatility, improving cost predictability and generating savings on energy bills over the long term (RE-Source, 2020);
- **Sustainability:** reduction in carbon emissions and progress towards renewable energy and greenhouse gas emission reduction targets. The reason for this is more stringent environmental policy regulation, stronger requirements from investors and demand from environmentally conscious consumers;
- **Brand and leadership:** recognition for renewable electricity achievements and climate leadership, and to gain a competitive advantage with low-carbon products.

For both the corporate buyer and the project developer, there are benefits as well as risks in engaging in a PPA. The main benefits and risks are listed in Table 1 below, where corporate drivers mentioned in the list above – which also are benefits – are excluded.

Table 1: Benefits and risks of PPAs for corporate buyers and project developers/generators. Information is based on (Bird & Bird, 2019), (WBCSD, 2016) and (Baker & McKenzie, 2015).

Corporate buyer	
Benefits	Risks/challenges
Hedge against rising or fluctuating energy prices in the wholesale markets	Complexity, time and costs of negotiating a PPA contract
Smaller corporates can club together to share risk and enhance bargaining power	Change in laws affecting the commercial balance of the agreement, possibly triggering re-negotiation of the PPA
Reduced risk of future increase in carbon pricing	Power price risk: wholesale electricity prices may decline below the agreed strike price for a longer period of time than anticipated
No upfront capital is needed, compared to investing in renewable power plants for self-generation	Counterparty risk: if energy prices rise above the established strike price, the generator may go bankrupt and therefore not meet its payment obligations
Diversification of electricity procurement	Power consumption risk: the corporate may not be able to consume all electricity produced, but still has to pay for it
Project developer/generator	
Benefits	Risks
Achieve a stable, long-term price for sold electricity	The price which the corporate is willing to pay may not be large enough to bank the project
Higher chances to get project financing, unlocking of lower cost of capital thanks to guaranteed offtake(s)	Creditworthiness of the offtaker
New possibility to secure income as renewable financial incentives and subsidies are being phased out	If wholesale market prices decline, the corporate might want to negotiate out of the agreement
Larger diversity in offtakers, enhancing the resilience	Power price risk: wholesale electricity prices may rise above the agreed strike price for a longer period of time than anticipated
Diversification of customer structures	Counterparty risk: the corporate may go bankrupt and therefore not be able to pay for the electricity if the energy prices fall below the established strike price

What are the risks of a PPA in general?

PPAs are often signed to reduce the risks, such as through securing a certain price, and to increase the diversity of procurement or offtakers, but they also involve some risks. Those which are specific for a certain party are mentioned above, but there are other risks which can be shared among both parties, or which can be shifted to either the developer or the offtaker, and these are listed below in

Table 2. Much of the information is taken from the report ‘Risk mitigation for corporate renewable PPAs’ by the RE-Source Platform (Brindley, et al., 2020), and has been complemented with other sources specific for each risk, see in the table.

Table 2: General risks associated with PPAs

Risk	**Short description**
Development	Risk that the generation facility is not constructed and commissioned in time or at all (Hedges, 2018)
Performance/operational	Risk that the facility does not perform as expected. For wind power it can mean that it doesn’t meet its warranted power curve, and for solar that it doesn’t meet

	its performance ratio. (Hedges, 2018) A facility can also be inefficiently operated so that the project doesn't realise its full potential. (LevelTen, 2020)
Curtailment	There is a risk that the utility or grid operator forces the generator to reduce the amount of energy delivered to lower than what the generator is capable of delivering. (LevelTen, 2020)
Volume	The electricity production over a longer time (season or a year) is different from agreed in the PPA, or from the demand of the offtaker. (Duvoort & Hedges, 2019)
Shape/profile	Even if the production over a month or a year can meet the demand of the offtaker, the demand on a shorter time scale (e.g. hourly) is different from the production profile due to the intermittency of renewables. (Duvoort & Hedges, 2019)
Basis	The agreed price in the PPA contract differs from what the buyer needs to pay to the local utility.
Balancing	Hourly deviation between the expected and actual generation due to an error in the forecast of weather or electricity production. This can lead to changed power system costs. (Duvoort & Hedges, 2019)
Credit	The buyer might pay late or not at all for the electricity delivered.
Counterparty	The counterparty might become insolvent and unable to meet its obligations under the contract. (PricewaterhouseCoopers, 2017)
Price	The wholesale electricity price could turn out to be much lower or higher than the expected future market price (and therefore also the fixed PPA price) for a longer time, which causes losses for either of the parties. For example, if the penetration of renewable electricity (with low marginal costs) increases, the market (equilibrium) electricity price decreases and could even be negative, which would make the developer having to pay for the electricity produced. (LevelTen, 2020)
Legal	Credit support, force majeure, change of control, termination, and conditions precedent amongst other key clauses that need to be negotiated.
Changes in regulation	Risk that laws or other regulation is changing, such as subsidies, taxes or retroactive changes to feed-in tariff systems. Power regulatory and market systems are evolving over time. This might lead to that one of the parties might want to exit the contract, or that it needs to be renegotiated.
Force majeure	Unforeseen circumstances out of the control of any of the parties might have a large adverse effect on the commercial balance of the PPA, on the production or that the project might not be completed in time. (Jordan, 2017) One example of this is the outbreak of a pandemic, such as Covid-19.

What are the commercial terms of a PPA contract?

The PPA is a physical contract between two parties: the producer and the offtaker. It contains commercial terms, on which the parties need to agree on. The most common terms are the following: (WBCSD, 2016) (European Federation of Energy Traders, 2019)

- type of settlement (physical/financial),
- contract period and termination rights,
- balancing responsible party, balancing costs,
- construction and commissioning including the Commercial Operation Date,
- point of delivery,
- delivery date or period,
- times,

- volume/contract quantity,
- product,
- electricity price,
- invoicing and payment,
- certificate, certificate price and regime,
- risk related features: remedies for failure to deliver/accept electricity, non-performance due to force majeure, change in law, etc.,
- confidentiality,
- governing law & dispute resolution.

For certain PPAs (virtual PPAs, explained in the next section), the settlement period is also stated, i.e. after how long time (week/ month/ quarterly) the seller and offtaker should settle up between the agreed price and the price which the offtaker pays to the utility.

Which different structures of PPAs exist?

There are many different structures of PPAs, as the commercial terms mentioned above can vary depending on the situation, regulatory environment, the corporate buyer strategy and the capability of the offtaker. However, there are two main structures, namely the physical (a.k.a. sleeved) PPA and virtual (a.k.a. synthetic/financial) PPA. These two will be explained, as well as other common PPA structures but the latter in less detail.

In a **physical PPA**, the buyer is paying the developer directly for the electricity according to the agreed price. The electricity is transferred physically together with energy attribute certificates via a licensed utility to the buyer. The action of transferring the electricity through the utility is typically known as sleeving because the electricity is sleeved by the utility from the generation asset to the buyer. For the sleeving service of the utility, the buyer pays a fee, see Figure 7. If the power plant is not generating any or not enough electricity (renewable electricity from wind and solar is intermittent), the utility is topping up the delivered electricity to meet the buyer's electricity demand, which is covered in a back-to-back PPA between the utility and the buyer. This structure is only possible if the generation asset and the site of consumption are located in the same grid. (WBCSD, 2016) In Europe, the physical PPA is the contract structure which has been mainly adopted. (Bird & Bird, 2019)

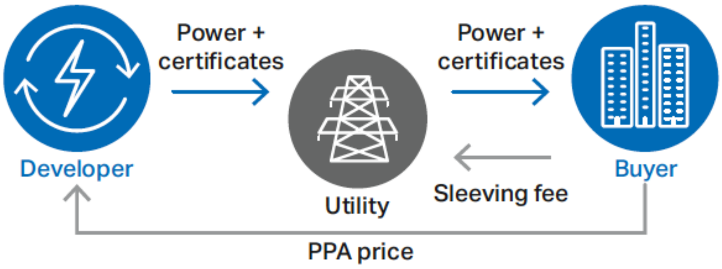

Figure 7: Physical/sleeved PPA structure, adopted from (WBCSD, 2016)

In a **virtual PPA**, the developer sells the electricity to the grid and is paid the spot price by the utility. The buyer purchases the electricity from the utility at the variable market price under a standard electricity supply agreement. Since the spot and market prices vary over time and can differ, the PPA parties set up a Contract for Difference (CfD), so that the buyer pays the developer or vice versa the difference in price between the variable market price and the agreed strike/contract price on a monthly or annual basis, see Figure 8.

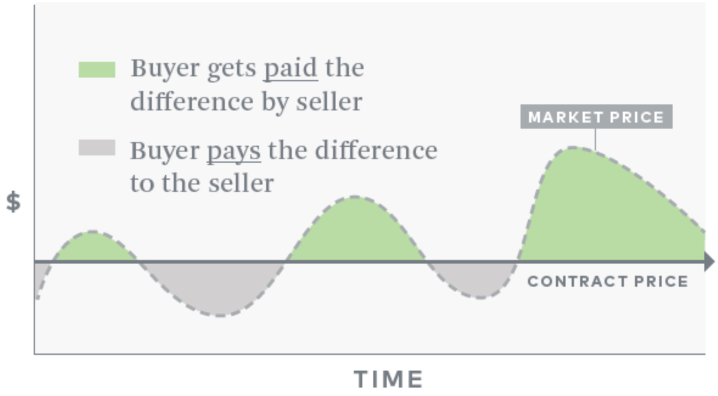

Figure 8: Generalized graph over the market and contract price over time, adopted from (3Degrees, n.d.)

The renewable energy certificates are transferred directly from the developer to the buyer, see Figure 9. This structure is more flexible compared to the physical PPA, since the developer and the buyer do not have to be connected to the same grid provider, i.e. the power can be sold "virtually" across separate energy markets. Virtual PPAs have become the norm in most larger PPA markets (especially in the UK and US) but are also adopted elsewhere. With a virtual PPA, the buyer does not have to pay a sleeving fee. (WBCSD, 2016) (Bird & Bird, 2019)

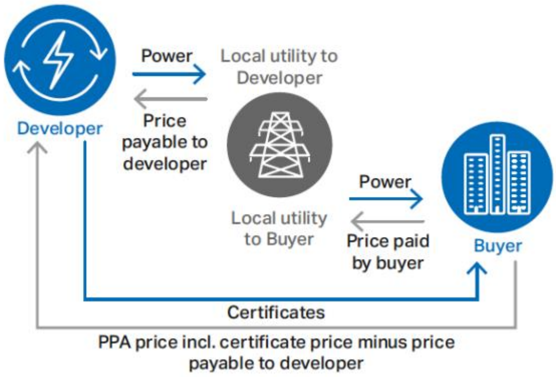

Figure 9: Virtual/synthetic PPA structure, adopted from (WBCSD, 2016)

Apart from the physical and virtual PPA structures, there are more structure variations and aggregation models, which will be explained briefly below: (RE-Source, 2020)

- **On/near-site PPA**: The power plant is located at or close to the site of the corporate offtaker. Then, the electricity from the plant is not passing the grid, but excess electricity is sold to the grid. If the supply from the PPA is not enough to cover the consumption, extra power is purchased from the utility. The on-site installation is usually built, owned, operated and maintained by a third party. A benefit of this structure is the high visibility and additionality, and it creates credibility with employees and other stakeholders. This PPA structure can also be called behind-the meter or private wire PPA.
- **Multi-buyer PPA:** Several companies can form a consortium of buyers which enter identical PPAs with one generator. This diversifies the credit risk of the developer, and it can sell more power under one contract. If the companies come from different sectors, this reduces the risk for the developer, in case one of the companies would go bankrupt or not be able to pay for the electricity. For the offtaker, the legal costs and processes burden can be shared among the consortium members, but at the same time it adds

complexities, and the members need to find each other and agree on the same terms and conditions, which might increase the time to negotiate the contract.

- **Multi-seller PPA:** Several different renewable assets are aggregated into one portfolio, from which the power is contracted through a PPA with an offtaker. This is beneficial if the single installations are small and/or if the offtaker has a high electricity demand. The aggregator takes a fee for the service, which adds an extra cost to this type of PPA structure.
- **Cross-border PPA:** The renewable energy installation and the offtakers point of consumption are in different countries. This adds a basis risk, which is the risk of the market price being different in the wholesale market in country A compared to the settlement market in country B. There is also a foreign currency risk and cross-border accounting complexities.
- **Multi-technology PPA:** Several different renewable electricity technologies can be grouped and connected to one PPA contract with an offtaker. One benefit of this structure is that it is generating a firmer generation shape compared to a single technology PPA. It can reduce the shape/profile risk associated with traditional PPA contracts. This model has been used in the USA, but not yet in Europe.
- **Proxy generation PPA:** The offtaker pays for a theoretical amount of power calculated by a third party based on actual natural resource measurements at the installation site (e.g. wind speed or sun irradiation), a pre-agreed power curve (the relationship between the e.g. wind speed and electricity output) and a reliability factor (usually 80–100 %). In other words, the trade quantity is based on the amount of electricity that *should* have been produced if the plant had been operated according to ideal equipment efficiency factors and operational best practices. If the project performs better than the expected amount of electricity production, then the upside is for the generator. On the contrary, if the project performs worse, the generator will suffer. This method transfers the operational risk away from the corporate (who does not have control over the operation of the installation) to the generator, who is actually responsible for the operations. In this way, the generator is incentivised to operate at maximum efficiency levels, and it eliminates risks such as misaligned financial incentives or unexpected curtailment. (Tunderman, 2019) However, an additional cost for the third party monitoring the natural resource conditions and which performs proxy generation calculations for each hour is incurred. Lastly, the project's renewable electricity certificates are still created by actual generation and not by the proxy generation. Therefore, if the actual electricity production is low, the offtaker needs to acquire supplemental certificates, which adds another extra cost. The proxy generation structure has been recently developed in the US.

PPA pricing mechanisms

One of the most important terms in the PPA is the price of the electricity. There are different options of how it can be determined. The chosen option depends on the corporate buyer strategy and the capabilities of the developer, as well as on the risk appetite of both parts. Ideally, the developer wants to have an as high price as possible and the offtaker a low price, so they need to compromise in some way to find a fair purchase price. Some of the main pricing mechanisms are described below. (WBCSD, 2016) (RE-Source, 2020) (Huneke, et al., 2018)

Fixed-price PPA; involving an upfront agreement on how the price will move over the contract period:

- Agreed price per MWh with no escalation, such as in Figure 8
- Indexation by reference to inflation or other relevant indexes

- Step prices based on agreed escalations in real terms, or linked to inflation

Discount to market PPA; only able to be applied in markets with a fluctuating wholesale power price:

- Floating: the buyer gets a fixed percentage discount to the wholesale electricity price per MWh.
- Minimum prices: The buyer pays the wholesale price, but only down to a certain floor price – if the market price sinks even further, the buyer pays the floor price, see the dashed red line in Figure 10. Through this, the developer secures a certain minimum value of the electricity.
- Maximum prices: The buyer pays the wholesale price, but only up to a certain cap price. If the market price increases even further, the buyer pays the cap price, see the dashed green line in Figure 10. Through this, the buyer secures a maximum level of costs.
- Hybrid forms; the above price mechanisms can also be combined, for example:
    - a price corridor is agreed with both a floor and a cap (as in Figure 10); or
    - a fixed price is agreed for e.g. 80% of the volume produced, while the remaining production is purchased via spot price indexation. Adopted from (Huneke & Claussner, 2019)

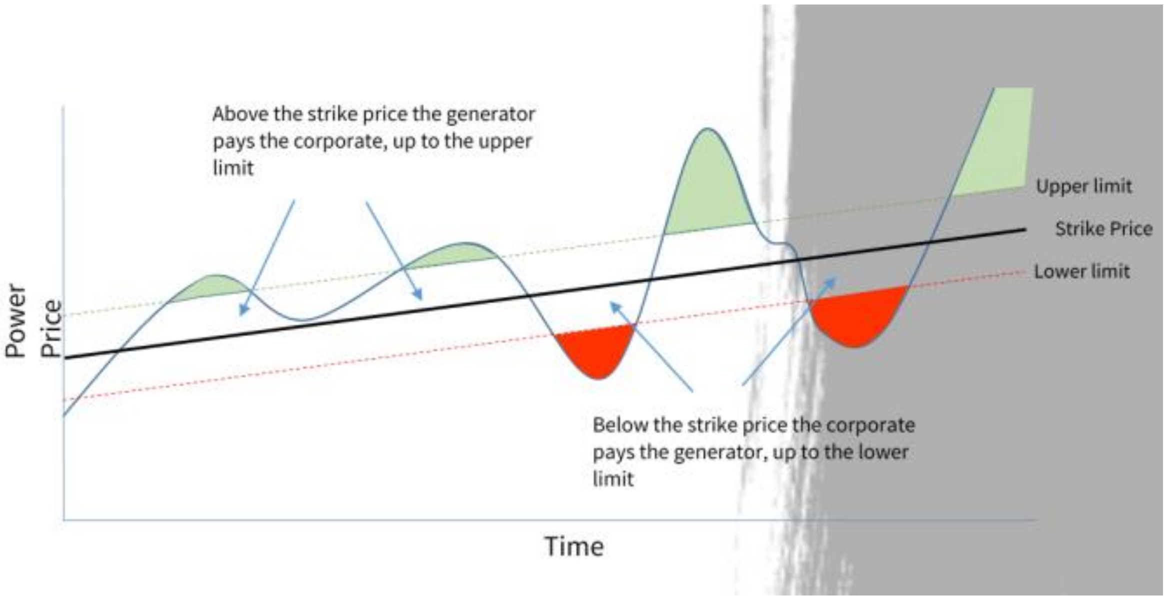

Figure 10: Generalised graph showing the short term power market price (blue line) relative to the strike price (black line) and its lower and upper limits over time, adopted from (Jones Lang Lasalle IP, 2018)

For the developer and offtaker to determine a fair price within the framework of a PPA with a renewable power plant, the future value of the generated electricity must be assessed. For up to 3–6 years (Huneke, et al., 2018) there is an electricity futures market to base the value on (see the time span from 2018 market with blue in Figure 11). On the electricity futures market, units of electricity in the coming 3–6 years are traded, which give an indication on the market price in those coming years. For the remaining time horizon of the PPA – which can have a period of up to 20 years or even longer – there are no futures (bright red time span in Figure 11). Therefore, different actors in the energy sector have developed models to predict the future market price, indicated by the dark blue lines in the same figure. These actors can be both governmental agencies, such as the UK BEIS, larger utilities, as well as consultancy firms which advise companies who don't have the capacity to develop these models themselves.

Ideally, the fair price should be close to the future average market electricity price. Even if the market electricity price for wind power in a near future can be expected to decrease (marked with number 1 in Figure 11, which in the example is due to financial support through the German Renewable Energies Act), the market price on a somewhat longer term is expected to increase (from number 2 onwards in the same figure). However, there is an uncertainty which is increasing with time of how the market price on for example wind power will develop. In a high price scenario, such as the upper dark blue line in Figure 11 (in this example for wind power), the buyer benefits since the PPA price which it is paying is considerably lower, so the buyer saves money according to the field with number 3. In a low-price scenario, such as the lower dark blue line in the same figure, the seller benefits since it receives a higher payment compared to if it had sold the wind electricity to the spot market. The PPA would have a fair price if, from today's point of view, the probability of opportunities and risks (from the possible development of power prices) are equally distributed. (Huneke, et al., 2018)

One part of the South Pole PPA project is to develop a forward price curve to enable better price setting for PPAs. The following chapter gives information on such forward curves, as well as how the electricity market price is influenced by different price drivers.

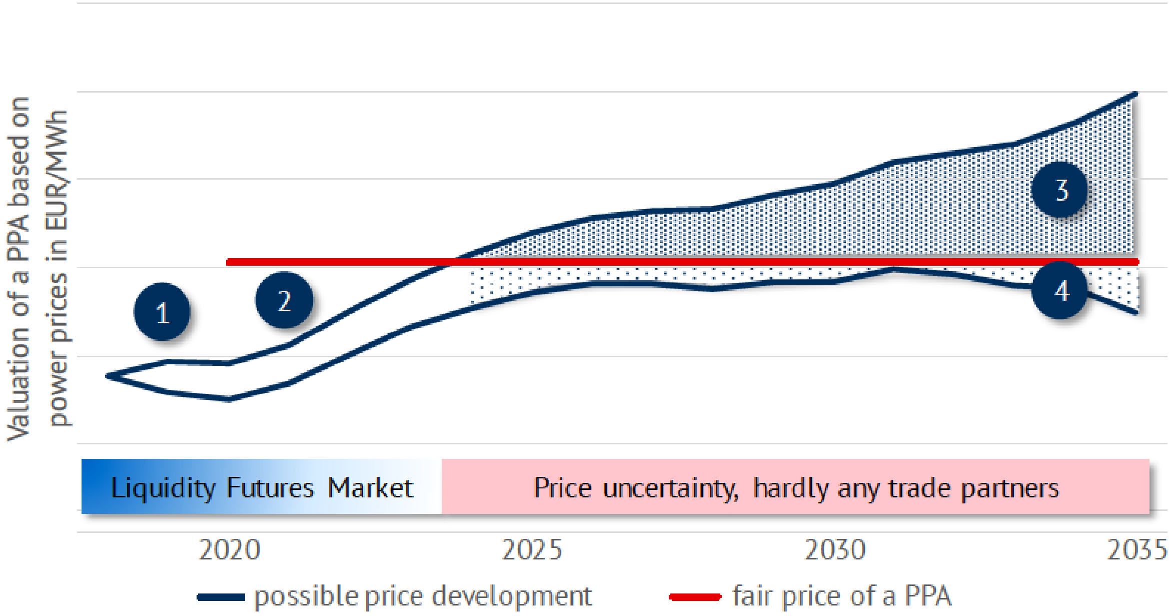

Figure 11: Agreed fair price of a PPA compared to possible market electricity price development for wind power from 2018 to 2035, adopted from (Huneke, et al., 2018)

2.3 Forward curves, electricity price forecasting and price drivers

The definition of a forward curve is the current price for a commodity in a specific location on a specified date in the future. It consists of a series of forward prices plotted together, reflecting a range of today's tradable values for specified dates in the future. (Reichelt, 2019) As mentioned above, a forward curve is needed for the future wholesale electricity price which is a basis to decide the fair price of a PPA.

There are many different methods to model the future electricity price within the area of electricity price forecasting, see chart in Figure 12 from a review article by Weron (2014). Some models are market based, such as the Multi-agent and Fundamental approaches, and others are data-driven, such as the Statistical and Computational intelligence approaches. As part of the project at South Pole, a data driven approach was chosen. Different regression models – mainly the Gaussian Process Regression – and Feed-forward neural networks were used, which is explained in the master thesis work by Wüthrich (2020).

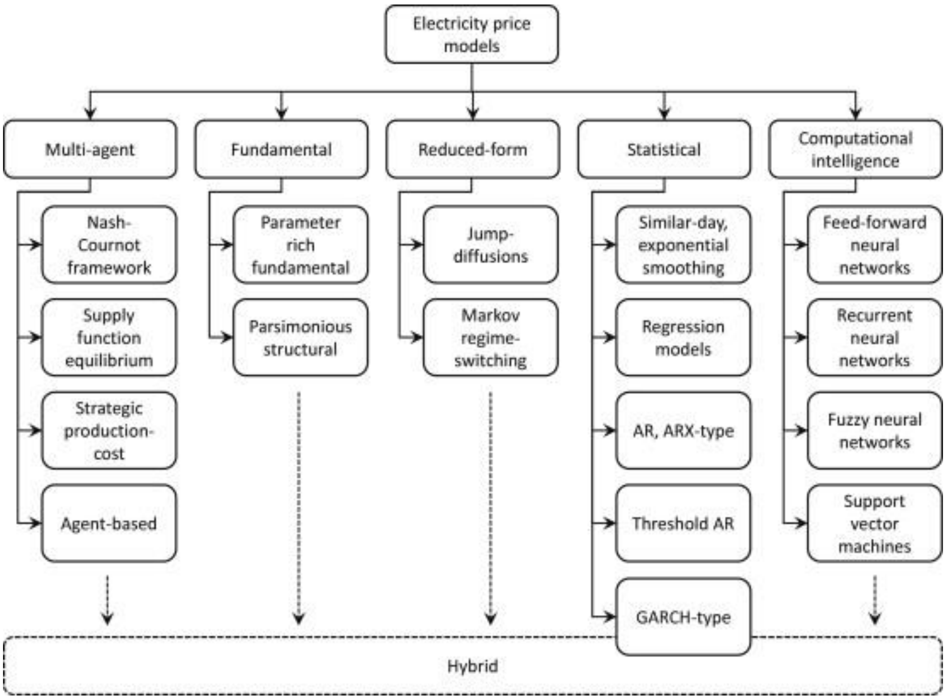

Figure 12: Taxonomy of approaches for electricity spot price modeling, adopted from (Weron, 2014)

As input to the model, different price drivers are needed, i.e. factors influencing the market electricity price. In Table 3 below, the more common price drivers are listed.

Table 3: Drivers of the market electricity price, where the main price driver categories are filled with bright orange and have an explanation in the second column of the (short-term) effect on the electricity price. A description and/or example of the price drivers are given in the third column. (European Commission, 2019) (European Commission, 2020) (Weron, 2014)

Price driver	**(short-term) Effect on electricity price**	**Short description or examples**
Carbon price	Higher carbon price ⇒ higher electricity price	Traded carbon price referring to the electricity supply sector under the EU ETS, which began in 2005 (€/tCO$_2$)
Fossil fuel prices	higher fossil fuel price ⇒ higher electricity price	Commodity costs
oil price		Wholesale oil price reflecting the internationally traded price by gas and electricity utilities, as well as by oil refineries, for their bulk supplies (€/GJ)
coal price		Wholesale coal price reflecting the internationally traded price by gas and electricity utilities for their bulk supplies (€/ton)
natural gas price		Wholesale gas price reflecting the internationally traded price by gas and electricity utilities for their bulk supplies (€/GJ)
Electricity demand	higher electricity demand ⇒ higher electricity price	
industry sector		e.g. manufacturing, whose demand often is correlated with economic growth
households		residential electricity consumption, varying with the need of lighting, heating and using household appliances

commercial sector		e.g. data centres
transport sector		e.g. aviation, maritime, rail, road; increasing with larger number of electrically chargeable vehicles
Electricity production	higher electricity production ⇒ lower electricity price	
hydro power		the production of hydro power is largely influenced by precipitation levels
wind power		including both onshore and offshore wind power
solar power		mainly utility scale solar power, since off-grid solar power is usually not covered in the statistics
electricity from biofuels		power plants fuelled by biomass
coal power		includes both lignite and hard coal power plants
gas power		power plants fuelled by fossil natural gas
nuclear power		fission reactors
other fossil power production		e.g. power plants fuelled by oil, or waste incineration plants, where amongst other fossil plastic material is burned
Imports/exports	Often imported electricity has a higher electricity price than national electricity production. Limited cross-border transmission capacities can drive up the electricity price if the national demand is very high at the same time as the production is low.	Import and export of electricity to/from the respective country, driven by cross border electricity trade

Regarding both the electricity production and demand, they vary depending on weather variables such as temperatures, wind speed, precipitation and solar radiation, as well as scheduled maintenance, mining restrictions (for coal power plants) or forced outages of important power grid components. Another driver, which depends on the combination of electricity production and demand is the reserve margin, or surplus generation, i.e. the available generation minus the predicted demand. (Weron, 2014) The prices of coal and natural gas are important price drivers, as coal- and gas-fired plants are the marginal generators (at least in the UK) and therefore normally set the marginal cost on the electricity market; they are on the higher end of the electricity supply curve (the so-called merit order curve, Figure 13). The marginal costs come in general from operating (fuel) costs, labour and maintenance costs. For fossil fuelled plants, the fuel price is dominating those marginal costs. To each fossil power plant's marginal cost, the carbon price is added, which increases the overall wholesale price. According to a report (Deloitte, 2018), an increase of 1 €/tCO$_2$ result in a rise of wholesale prices of 0.7 €/MWh. Renewable electricity production has a low marginal cost, because of low maintenance and operational costs (and zero fuel costs), and therefore shifts the marginal cost curve to the right, see Figure 13. This results in a lower equilibrium price assuming the same electricity demand curve. (European Commission, 2019) A study from 2018 estimates that an increase in the share of renewables in Germany by one percentage point results in a decrease of the wholesale electricity price by 0.5 €/MWh. (Trinomics, 2019) Electricity production from renewable electricity, which is subsidised can even accept a negative price, in some cases making the whole electricity market price negative. This happened for example the first time in Sweden this year in February, when the prices on the NordPool spot market landed at around 0.02 €/kWh for the hour from 1 to 2 am. According to the news article about it in NyTeknik, factors behind the low price were mild weather and night time (low electricity demand), high precipitation during the autumn and winter (filling the hydro dams, making the hydro power plants produce much electricity) and a steady increase in new wind power plants and storm (increasing the production from wind power plants). (Lindström/TT, 2020)

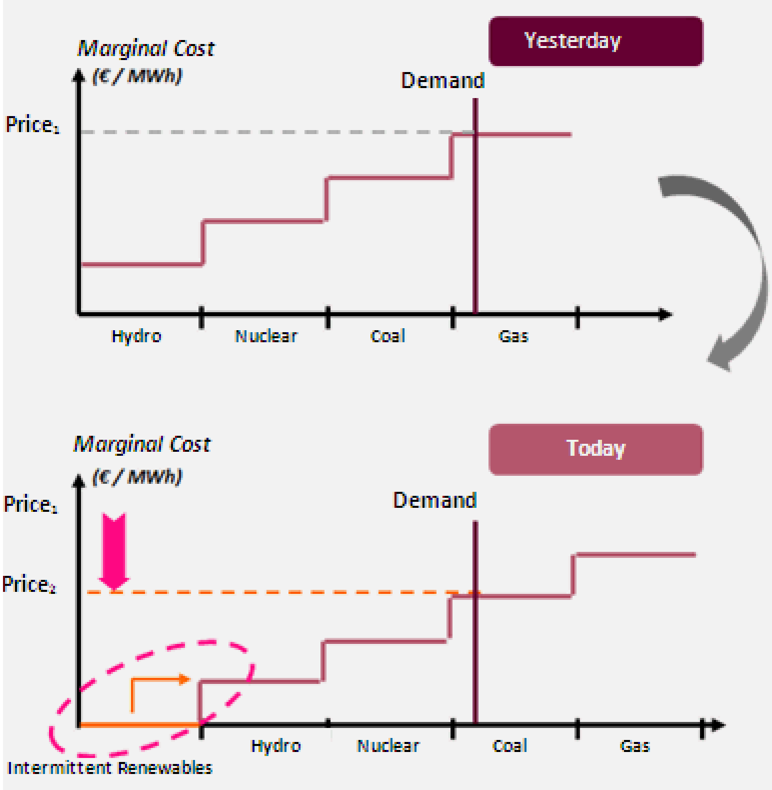

Figure 13: Marginal cost curve without and with intermittent renewables, such as wind and solar electricity production, adopted from (SIA partners, 2013)

3. Climate and energy targets and policy overview for the UK

3.1. Climate and energy targets of the UK

In this section, the climate and energy targets of the UK are described, in order to assess if the scenarios from the EEP and FES contribute to the fulfilment of those targets, which is documented in chapter 8.1 and responding to the first part of research question 3.

Climate targets

In the year 2008, the UK adopted the Climate Change Act (UK Government, 2008). It includes a legally bound target for achieving 80 % greenhouse gas emission reductions by 2050, compared to 1990 levels via series of five-yearly carbon budgets, starting in 2008. In fact, UK was the first country to set legally binding carbon targets. The carbon budgets place a restriction on the total amount of greenhouse gases which the country can emit during a 5-year period. (BEIS, 2016) So far, the UK government has adopted carbon budgets until 2032 and in December 2020, the UK's advisory body Committee on Climate Change will publish its recommendations for the sixth carbon budget (for the years 2033–2037). (Committee on Climate Change, 2020) In 2019, an amendment to the Climate Change Act was made, which increased the ambition to 100 % lower emissions in 2050 compared to the same base year, which often is referred to as the net zero target. (Skidmore, 2019) The background to the target enhancement was the IPCC Special Report on 1.5 °C which was released in October 2018 and which outlines that the world would need to reach net zero emissions in 2050 to reach the 1.5 °C target. (Masson-Delmotte et al., 2018) After the release of the report, the UK Committee on Climate Change recommended the Government to revise the target in line with the latest available climate science, which it did. Net zero emissions means that no more greenhouse gas emissions are released to the atmosphere than those being removed. Any emissions which unavoidably occur need to be offset by an equivalent amount of greenhouse gases removed from the atmosphere through methods such as planting trees or through technologies such as bioenergy carbon capture and storage. (BEIS, 2019)

Energy targets

In 2009, the EU enacted a directive, under which the UK has been asked to procure 15 % of its final energy consumption from renewable energy sources in 2020. (European Parliament and the Council, 2009) The preliminary share of renewable energy in final energy consumption in 2019 is 13.2 %, which is promising to reach the 2020 target. See the historical development of the progress against Renewable Energy Directive and UK targets in Figure 35 in Appendix 1. (BEIS, 2020) The UK does currently not have any national targets for renewable energy for further into the future and no target for renewable electricity. However, in 2015 it set a deadline for coal phase-out to 2025, but in February 2020, Prime Minister Boris Johnson announced that they might bring forward the phase-out date. One of the main reasons is the dramatic fall in coal-fired electricity production in the latest years, which in turn mainly depends on an increased carbon price. (Petrova, 2020) Since there are no current national energy targets in the UK, these cannot be assessed against the development of the energy system in the scenarios in the EEP and FES.

3.2. Overview of current climate and energy policies in the UK

In this section, the most important and relevant climate and energy policies in the UK are described, in order to reply to the third research question about which additional policies are needed, or which existing policies need to be enhanced.

Climate policies

The current main climate policy of the UK is the participation in the EU Emission Trading System (EU ETS). It has a cap of total emissions allowed per year for the participating EU countries, under which emission allowances are traded. Each year, the cap of emissions is reduced to decrease the overall emissions. The allowances are allocated either for free or sold via auctions to the participants, which mainly are power generators and industrial plants but also airline companies. In the last years, a larger share of the allowances is auctioned. Through the ETS, the carbon emissions get a cost, which gives incentives to reduce the carbon emissions. (BEIS, 2020) Due to the earlier surplus in allowances, the UK introduced a Carbon Price Support for the power sector in 2013 to top up the EU ETS price, and in that way a Carbon Price Floor of the allowances is set. (BEIS, 2017)

Due to the exit of the UK from the EU, the future participation of the UK in the EU ETS will be changed. The Committee of Climate Change recommended in its letter in August 2019 firstly that the UK shouldn’t rely on carbon pricing alone. Secondly, it agrees with the Government’s preference to create a UK ETS linked to the EU ETS. In the case that it wouldn’t be possible, the Committee would come back with further recommendations, where one possibility could be the implementation of a carbon tax. In case of a linked or standalone ETS, it should be at least as ambitious as the existing EU ETS (BEIS, 2017) and in line with the 2050 net zero target. (Deben, 2019) In June 2020, the outcome from a consultation was published, in which a majority was in favour of a UK ETS (either linked or not to the EU ETS), with a first phase from 2021 to 2030. The UK ETS will have similar features as the current mechanism, such as the type of participants, a majority of auctioning and a minimum price level of the allowances, and a small emitter and hospital opt-out. Later in 2020, there will be another consultation about the design of a Carbon Emissions Tax. (UK Government and Devolved Administrations, 2020)

In addition to the participation in an ETS, the UK published The Clean Growth Strategy in 2017. It contains policy measures to enable economic growth and at the same time decarbonise the economy. In the strategy there is a list of 50 key policies and proposals. It states that the government will invest more than 2.5 bn £ in low-carbon innovation by 2021. The strategy includes ambitious proposals for many different areas, such as housing, business, transport, the natural environment and green finance. (BEIS, 2017)

Energy and renewable electricity policies

The Clean Growth Strategy contains several key policies and proposals to deliver clean, smart and flexible power. Some of them are to phase out coal power production until 2025, to produce nuclear power from the new power plant Hinkley Point C, to support the expansion of renewable energy technologies (e.g. through Contract for Difference (CfD) auctions) and to invest around 900 million £ of public funds in areas such as smart electricity storage, demand response technologies, nuclear, and offshore wind turbine technology. (BEIS, 2017)

Another government policy is the Electricity Market Reform (EMR) from 2012. It incentivises investment in secure, low-carbon electricity, improves the security of supply and improves the affordability for consumers. It introduced two mechanisms to enhance investment in clean infrastructure, namely the Contract for Difference auctions and the Capacity Market. CfD are long-term contracts for low-carbon power and can be seen as a type of Feed-in Tariff. Through the CfD, the difference between (an estimate of the) market price and an estimate of the long-term price to cover the investment and production costs (‘strike price’) is paid. If the market power price is lower than the strike price, the CfD pays a top-up, and for the opposite situation, the generator needs to pay the difference back. The CfD has many benefits, as it stabilises the income for the generator, removing its long-term exposure to price volatility, reducing commercial risks, which lowers the cost of raising finance and ultimately encourages investments in more low-carbon technologies. The second mechanism is the Capacity Market, which ensures a security of supply by providing a payment for reliable sources of capacity. The participants can be both generation and non-generation providers of capacity, such as demand side response and electricity storage. Apart from the two mechanisms, two other key elements were introduced, namely the Carbon Price Floor (mentioned above) and the Emissions Performance Standard. The latter is a regulatory back stop of emissions from new power plants. It prevents unabated coal power stations being built, which contributes to UK’s decarbonisation objectives. (Department of Energy and Climate Change (DECC), 2012)

Moreover, some further concrete policy measures have been introduced relatively recently, namely the Offshore Wind Sector Deal from 2019 to raise productivity and competitiveness of the UK offshore wind power industry (BEIS, 2020); the Smart Systems and Flexibility Plan from 2017 to enable smart homes, businesses and technologies (BEIS & Ofgem, 2018); and the Smart Export Guarantee which ensures that homes and businesses installing low-carbon generation up to 5 GW receive a payment for the electricity they export to the grid (BEIS, 2019).

4. Accounting for greenhouse gas emissions from electricity

One part of the aim and the fourth research question is about calculating the avoided emissions from a renewable PPA compared to certain baseline emissions, i.e. emissions from the electricity which the company would have consumed if they hadn't signed a PPA contract. From the perspective of South Pole, a calculation of these avoided emissions will show the corporate how large the climate impact of their decision to choose a PPA could be. In order to make this calculation credible, some kind of theoretical background and method should be used, and it should be in line with possible reporting requirements from organisations such as the Greenhouse Gas Protocol and CDP reporting.

These types of reporting requirements relate to emissions from single companies, which is what the corporate client is interested in. Therefore, the boundaries are framed around the company and do not cover any wider scope. However, if the boundary is widened to consider whole Europe, the EU ETS is needed to be taken into account. In the EU-ETS, there is a cap on emissions, under which emission allowances are traded. (European Commission, 2016) Therefore, if emissions from e.g. power production are reduced in one geographical area through for example the replacement of fossil by renewable electricity production, the corresponding emission allowances can be sold to another organisation in the system, by which the carbon can be emitted. From this point of view, PPAs wouldn't have a net positive impact on total carbon emissions. In January 2019, the Market Stability Reserve began its operation, with the aim of improving EU ETS's resilience to future shocks. To the reserve, unallocated surplus allowances are being transferred, so that they are no longer in circulation. Allowances can also be released from the reserve. (European Commission, n.d.) Due to the limitation of allowances in circulation, PPAs can then be considered to have a positive climate impact anyhow. The topic of PPAs having an impact on total emissions or not will be discussed later in the thesis, but since South Pole takes the corporate perspective, this perspective will be used for the climate assessment of PPAs.

There are different standards and methodologies for calculating the greenhouse gas emissions for organisations and projects. The construction of a renewable electricity facility can be seen as a project and therefore, project accounting should be applied, unlike greenhouse gas accounting for a whole organisation for a certain year. For project accounting there are different standards and methodologies. One of them is The GHG Protocol for Project Accounting, in short called the Project Protocol, developed by the World Resources Institute (WRI) and WBCSD (2005), which is supplemented by the Guidelines for Quantifying GHG Reductions from Grid-Connected Electricity Projects (WRI, 2007). Another standard is provided by the International Organization for Standardization (ISO), namely ISO 14064, which includes an international standard on greenhouse gas accounting and reporting for greenhouse gas mitigation projects. Furthermore, there is the 'Tool to calculate the emission factor for an electricity system' used for Clean Development Mechanism (CDM) projects. (United Nations Framework Convention of Climate Change, 2018) Although, CDM projects are done in developing countries and economies in transition, so therefore it shouldn't be applied to developed countries, such as the UK or most other European countries.

For the calculation, the Project Protocol and the Guidelines for Quantifying GHG Reductions from Grid-Connected Electricity Projects were chosen as a basis because the Project Protocol and the Guidelines can easily be applied to a PPA project and because they are the state-of-the-art reference used to perform these calculations. In addition, the student was already familiar with the Greenhouse Gas Protocol Corporate Accounting and Reporting Standard by the same organisation, which uses the same underlying principles. In both the Project Protocol and the Corporate Standard, there are some common principles which are applied in their appropriate contexts, namely: relevance, completeness, consistency, transparency, and accuracy. The purpose of using these principles is to ensure credible accounting of both corporate greenhouse gas emissions and project-based greenhouse gas reductions. In the following paragraphs, some key concepts from the Project Protocol and the Guidelines for Electricity Projects will be explained and put in relation to calculation of future avoided emissions from corporate renewable PPAs. The information is mainly based on WRI and WBCSD (2005). These concepts and technical terms are used in section 6 in the methodology chapter ('Calculation of avoided greenhouse gas emissions from PPAs') to describe how the Protocol and Guidance were applied. The words and expressions relevant for the thesis work and important recurring terms are underlined.

According to the Project Protocol, a "GHG project consists of a specific activity or set of activities intended to reduce GHG emissions, increase the storage of carbon, or enhance GHG removals from the atmosphere." In the case of corporate PPAs, the GHG project usually consists of *one* activity (if not a multi-seller or a multi-technology PPA, described in section 2.2) and the company is interested in *reducing* their greenhouse gas emissions. Furthermore, a project activity is described as "a specific action or intervention targeted at changing GHG emissions, removals, or storage. It may include modifications to existing production, process, consumption, service, delivery or management systems, as well as the introduction of new systems." The project activity in the scope of this thesis is to generate electricity from a renewable source (such as wind turbines or solar photovoltaic cells) instead of non-renewable sources.

The baseline emissions, i.e. the emissions that would have happened if the corporate wouldn't have signed a PPA, can be compared with the project activity emissions to assess the avoided emissions, i.e. GHG reductions relative to the baseline scenario in Figure 14. There are two different described baseline procedures to estimate baseline emissions, namely the project-specific procedure and the performance standard procedure. The latter can be used if there are several different project activities in the GHG project, but most common is to sign a PPA for one project developer from one technology and one site, so therefore the project-specific procedure is mostly relevant to PPAs. Through the project-specific procedure, the baseline scenario is identified through an analysis of the project activity and its alternatives. For the project-specific procedure, a project activity is presumed to be additional if it and its baseline scenario involve different technologies or practices. Additionality is a criterion often applied for GHG reduction activities, to say that the emission reductions wouldn't have happened if the project hadn't been realised, meaning that the project activity wouldn't have been implemented in the baseline scenario. Many companies want to show that they have a real impact, and then PPAs offers a stronger additionality compared to e.g. green tariffs or buying Renewable Electricity Certificates (which were described in section 2.1).

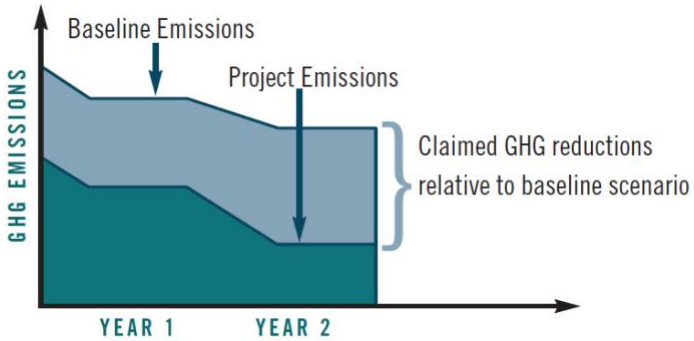

Figure 14: Comparison against a baseline scenario for project accounting, adopted from (WRI and WBCSD, 2005)

The Project Protocol lists five different GHG source categories, out of which one is "combustion emissions from generating grid-connected electricity", which is the category relevant for PPAs. Changes in GHG emissions give rise to GHG effects, which can be categorised in primary and secondary effects. The primary effect is defined as a change in the direct emissions relative to the baseline emissions (where emissions occur continuously or at least annually). For a renewable electricity project, the primary effect is a reduction in emissions from combustion of (fossil) fuels in a thermal power plant. A secondary effect is either a change in indirect upstream emissions (from inputs to the project activity) or downstream emissions (from products from the project activity), or a one-time effect in emissions (from e.g. construction or decommissioning of the project activity). Non-significant secondary effects (those negligible compared to the primary effect, or a positive effect, i.e. baseline emissions are lower than project emissions) can be excluded from the GHG assessment boundary.

For electricity consumption from thermal power plants, the primary effects come from direct emissions from the incineration of (fossil) fuels, while the secondary effects come from the upstream emissions from the extraction, refining and transportation of the fuels (so called well-to-tank emissions), downstream transmission and distribution losses, as well as construction and decommissioning of the power plants, and losses in the transmission and distribution grid (also known as life cycle emissions). For electricity consumption from renewable sources, there are no direct emissions, so there are no primary effects. There are though secondary effects from the construction and decommissioning of the renewable power plants (life cycle emissions), and from losses in the transmission and distribution grid. (WRI and WBCSD, 2005)

As the aim is to calculate the avoided emissions from a renewable PPA, you need to compare the emissions from renewable electricity production with another type of electricity production, which would happen in a different scenario. That other scenario is called baseline scenario according to the Project Protocol and is a “hypothetical description of what would have most likely occurred in the absence of any considerations about climate change mitigation”, i.e. if the corporate wouldn’t have been interested in reducing their emissions from electricity consumption. The baseline scenario is used to estimate baseline emissions which come from either e.g. continuation of current activities, technologies or practices (continuation of the current electricity contract of the company, or from same electricity production mix, e.g. grid electricity production mix) or a baseline candidate. A baseline candidate is an “alternative technology or practice within a specified geographic area and temporal range that could provide the same product or service as the project activity”. In this context it can be another type of renewable electricity technology, or a fossil fuelled power plant. If the company needs a PPA for an increased power consumption, e.g. for a newly built data centre, the baseline can also be to buy power through a standard electricity contract with a utility, because it would still not be a “continuation of current practice”. To determine the baseline scenario in the case of South Pole consulting a corporate client, South Pole could simply ask the client, what they would have done otherwise, if they hadn’t signed a PPA. Possible replies could be that they would continue with the same or a similar electricity contract as to date (usually not renewable electricity, and if no specific electricity contract is given, the average grid electricity mix would be assumed), or to choose another option for corporate sourcing of renewable electricity (listed in section 2.1). The baseline scenario should be valid only for a certain time, and for the comparison to a renewable PPA, it is appropriate to assume the same number of years for the baseline scenario as the PPA contract term (commonly 5–15 years). (WRI and WBCSD, 2005)

So far, the concepts from the Project Protocol have been described. As written earlier, that Protocol is supplemented by the Guidelines for Quantifying GHG Reductions from Grid-Connected Electricity Projects (WRI, 2007). It describes simplified and practical methods to estimate GHG reductions. Apart from projects supplying electricity to the grid, it is also describing how to account for emission reductions from project activities which reduce the consumption of grid electricity, such as energy efficiency measures. The latter type of project activities is not relevant for PPAs and will therefore not be described in this text. Figure 15 below shows an overview of the terms used and of calculating the avoided emissions (the GHG reduction) from a project, such as a wind or solar power plant enabled through a PPA. The different terms are explained below, and the more precise calculation method described in chapter 6.

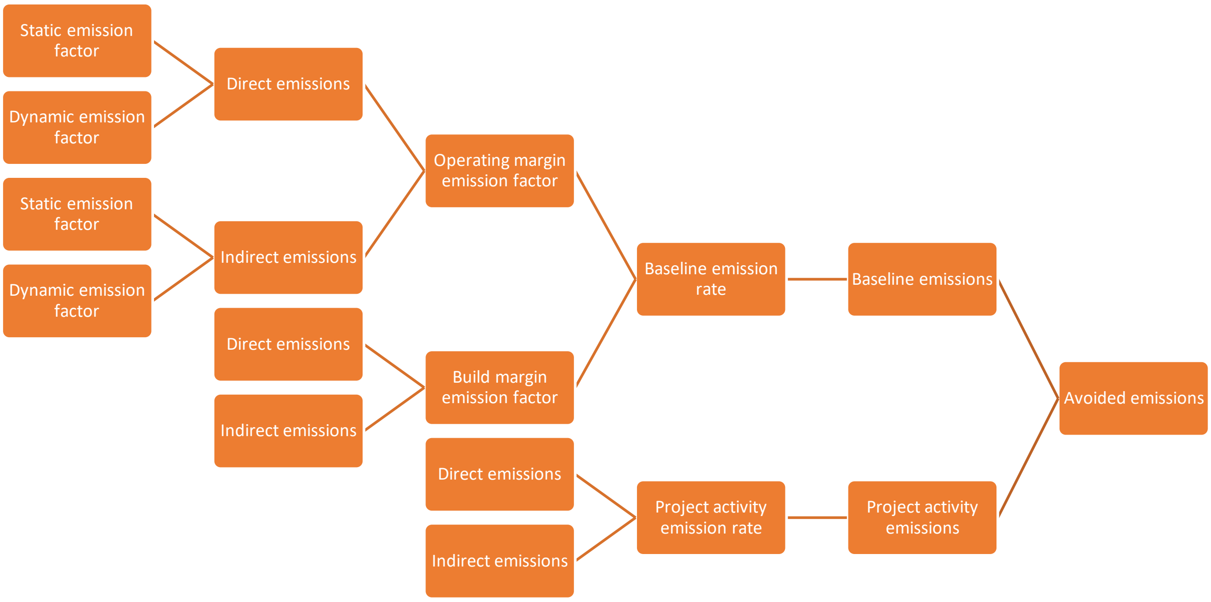

Figure 15: Flow chart with an overview of the calculation of avoided emissions

The basis of greenhouse gas accounting is that an activity is multiplied with an emission rate or an emission factor. For electricity production, the activity is usually expressed as kilowatt-hour (kWh) or megawatt-hour (MWh) produced electricity, and the emission factors are expressed in kilogram carbon dioxide equivalents per energy unit (kgCO2e/MWh). To calculate both the project emissions and the baseline emissions, a respective project and baseline emission rate is needed.

The project activity emissions rate is the amount of emissions per unit of production in a certain year for the project activity and can be expressed in kgCO2e/MWh. In the scope of this thesis, it would be the emissions from a wind or solar power plant built through a renewable PPA. The project activity emissions rate is multiplied with the production level, e.g. MWh, to calculate the project activity emissions. The direct emissions, contributing to the primary effects, are zero for wind and solar plants. The indirect emissions, contributing to the secondary effects, from the production and construction of the technologies (upstream emissions) as well as from the decommissioning of the plants (downstream emissions) can be calculated through a life cycle analysis. According to the Project Protocol, the primary and secondary effects are calculated separately, but in the thesis work, the direct and indirect emissions were combined to the project activity emissions rate.

The baseline emission rate can be either static or dynamic. A static baseline emission rate doesn’t change over time, while a dynamic baseline emission rate does so, see Figure 16. A static emission rate can also be called ex-ante emission factor, because one single emission rate is calculated using historical data and used over the whole project period. A dynamic emission rate can also be called ex-post emission factor because it is updated over time to reflect changes in the electricity production composition.

For electricity supply projects it can be suitable to use a dynamic baseline emission rate because the grid electricity production mix varies over time. Especially in the coming 10–20 years, the electricity system is projected to transform, largely due to the penetration of renewable electricity. The more renewable electricity production there is in a grid system, the lower the emission factor of the grid production mix is, and the lower is the baseline emission rate (in opposite to the example of an increasing baseline emission rate as shown to the right in Figure 16).

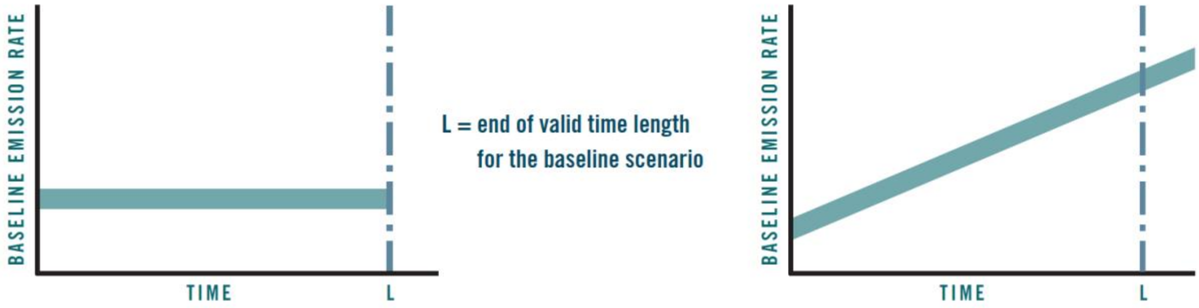

Figure 16: Static (left) and dynamic (right) baseline emission rate estimates, adopted from (WRI and WBCSD, 2005)

A key assumption in the guidelines is that a project activity can displace the operation of existing grid-connected power plants, and/or that it can displace or avoid the building (and operation) of new power plants. Since the project activity (a PPA in this case) can displace either one or both alternatives, they need to be assessed and combined into the baseline emission rate. The details of this are explained in the method in chapter 6, but in short, it combines the so-called build margin emission factor and the operating margin emission factor. The build margin emission factor relates to the build margin (BM), i.e. potential new capacity, such as a CHP (combined heat and power) plant, which is avoided being built because of the (PPA) project (a wind or solar plant in this case). The operating margin emission factor relates to the operating margin (OM), which is the generation from existing power plants displaced by, in this case, the PPA power production. In this thesis, both the primary and the secondary effects have been added for each emission factor. Otherwise, the Guidelines say that you calculate the primary and secondary effects (emissions) first, and then combine them.

After the BM and OM emission factors have been determined, they are combined according to a formula in chapter 6 to determine the baseline emission rate. This rate is multiplied with the electricity generated to calculate the baseline emissions. The same is done with the project emissions rate, to calculate the project emissions. Finally, the project emissions are subtracted from the baseline emissions, which gives the total reduction in greenhouse gas emissions from the PPA.

5. Finding, structuring and analysing price drivers

To find information about Power Purchase Agreements (section 2.2) and price drivers (section 2.3), a literature study was conducted. Useful sources were collected and the relevant content for the thesis was chosen primarily from the sources seen as most reliable and comprehensive.

To be able to reply to the second research question “How do future projections of price drivers differ between different sources and their respective scenarios for the UK – and why?”, available literature and future energy projections over the energy system in the UK were reviewed. If the reports contained useful time series data of one or several price drivers, that data was added to the ‘Price driver database’ (excerpts shown in Appendix 2, full file available upon request). If one data source contained different scenarios, data from those different scenarios was added. This database was created to be able to compare data sets from different sources and scenarios (which is the scope of this master thesis), as well as for the other master thesis student Moritz Wüthrich to model the future market electricity price. Table 4 shows an overview over the different data sources, their geographical scope and their different scenarios, from which data about price drivers were added to the 'Price driver database'.

Table 4: Overview over data sources, their geographical scope and their respective scenario(s).

Data source	**Report name**	**Geographical scope**	**Name of the scenario(s)**
Statkraft (Statkraft AS, 2019)	*Global energy trends 2019 – Statkraft's Low Emissions Scenario*	Global	• Low emissions prices
DNV-GL (DNV-GL AS, 2019)	*Energy Transition Outlook 2019*	Global and Europe	• Best estimate forecast
McKinsey (McKinsey Solutions Sprl, 2019)	*Global Energy perspective 2019: Reference Case*	Global	• Reference case
International Renewable Energy Agency (IRENA, 2019)	*Global energy transformation: A roadmap to 2050*	Global	• REmap Case
Shell (Shell International B.V., 2018)	*Shell Scenarios: Sky – meeting the goals of the Paris Agreement*	Global and Europe	• Sky scenario
National Grid (National Grid Electricity System Operator, 2019)	*Future Energy Scenarios (FES) 2019*[3]	UK	• Community Renewables • Two Degrees • Steady Progression • Consumer Evolution
BEIS (UK Department of Business, Energy & Industrial Strategy, 2019)	*Updated Energy and Emissions Projections (EEP) 2018*	UK	• Reference scenario • Low fossil fuel prices • High fossil fuel prices • Low economic growth • High economic growth • Existing policies • Baseline policies

In addition to price drivers, the electricity price itself was also included in the database if the source had data about it. Compared to the price drivers mentioned in Table 3 further up, imports and exports were left out from the 'Price driver database' since those factors were not seen as important as the other price drivers. Table 5 shows an overview of the price drivers added to the 'Price driver database' together with their unit and the different data sources. Some sources had separate data sheets in Excel, or tables, from which the data could be copied. Other reports only showed the data in figures – then the data was extracted using the WebPlotDigitizer (Rohatgi, 2019). To be able to compare data between different sources, a common unit for each price driver needed to be chosen, see Table 5. Several of the sources also had historical data of the price drivers. That data could differ between different sources, because they had different boundaries or scopes, for example one future projection of the energy system in the UK could include decentralised electricity production not connected to the grid, but not the other source; or the prices of fossil fuels came from different markets. To be consistent, historical data for the UK was only added to the database from the FES, because it had more recent historical values (until 2018) in comparison to the EEP, which had historical data only until 2017. If the

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[3] The FES also contains the special scenario Net Zero, but there was much more limited data for that scenario, so it was not added to the database.

FES didn't contain any historical data, it was taken from the EEP. Since the focus of this thesis is on Europe, the currency Euro (€) was chosen for the different prices.

Table 5: Overview of price drivers (and electricity price) included in the 'Price driver database' including the respective units and sources of data

Price driver	**Unit**	**Data source(s), reference only at first mentioning**
Electricity price (no price driver)	€/GJ	• BEIS, including Annexes F about final energy demand, Annex J about electricity generation, Annex L about total installed capacity and Annex M about growth assumptions and prices (UK Department of Business, Energy & Industrial Strategy, 2019)
Carbon price	€/tCO$_2$	• DNV-GL, including the dataset in Excel (DNV-GL AS, 2019) • BEIS 2019 • NG, including the data workbook (National Grid Electricity System Operator, 2019)
Oil price	€/GJ	• BEIS 2019 • NG 2019
Coal price	€/tCO$_2$	• Statkraft (Statkraft AS, 2019) • BEIS 2019 • NG 2019
Gas price	€/GJ	• Statkraft 2019 • BEIS 2019 • NG 2019
Electrification of transport/electricity use in the transport sector	PJ/year	• Shell (Shell International B.V., 2018) • DNV-GL 2019 • BEIS 2019 • NG 2019
Renewable electricity penetration • Hydro penetration • Wind penetration • Solar penetration	TWh/year	• Statkraft 2019 • DNV-GL 2019 • McKinsey (McKinsey Solutions Sprl, 2019) • Shell 2018 • BEIS 2019 • NG 2019
Electricity demand	TWh/year	• Statkraft 2019 • DNV-GL 2019 • McKinsey 2019 • International Renewable Energy Agency (IRENA, 2019) • Shell 2018 • BEIS 2019 • NG 2019
Coal capacity	TW	• DNV-GL 2019 • BEIS 2019 • NG 2019
Gas capacity	TW	• DNV-GL 2019 • BEIS 2019 • NG 2019
Nuclear capacity	TW	• DNV-GL 2019 • BEIS 2019 • NG 2019

The next step was to plot graphs of the price drivers from different sources and scenarios to be able to compare and analyse them. (See Figure 36 in Appendix 2 for an excerpt of the 'Price driver database' with the plots.) This was only done for the UK (and not for a wider scope of several countries, such as European or global level) because the PPA advisory service from

South Pole will be given for certain projects in specific countries, and the fair PPA price determined based on the future market electricity price in that specific country. The UK was also chosen because there are two good data sources of the future energy system, namely the *Updated Energy and Emissions Projections* (EEP) from BEIS and *Future Energy Scenarios* (FES) by National Grid, which are updated year to year. In addition, BEIS also publishes the future electricity price forecast, to which the modelled electricity price could be compared to. Since the database will be used for several years by South Pole, it should be updated with the latest forecasts and predictions, so therefore it is preferred to use data sources which are updated year to year. See a further explanation of the selection of these two sources in the beginning of chapter 7. Furthermore, UK was chosen because all project team members and employees at South Pole understand the language and could also in the future understand and add data from those sources to the database.

After the graphs of the price drivers of each scenario were plotted separately, the aim was to combine different scenarios from different sources to three general scenarios. Since the overall aim for companies which use consultancy services from South Pole is to reduce their greenhouse gas emissions, the general scenarios were developed to cover a high-emissions (business-as-usual) scenario, a medium-emissions (reference) scenario and a low-emissions (science based) scenario. The combining of different sources needs some consideration though, because the different sources come from actors spanning from government bodies and government nationalised companies to NGOs and corporations. The interest/agenda of the respective actor influences the resulting forecast. For example, actors in the fossil fuel industry are inclined to predict less, and actors such as IRENA are inclined to predict more renewable energy production in a certain year in the future. Therefore, a method is needed to choose and possibly combine different data sources which are used as input to the model. For the model to be trustworthy from the South Pole clients' perspective, the selection of data sources should include more trustworthy and reputable sources (if such exist for the relevant country/region) at first hand, and less reputable sources should only be used if no trustworthier source exist. See the decided hierarchy of data sources in Table 6 with some examples. Seven different types of organisations which publish some type of energy outlooks were identified and ranked. The idea was to use the source from the highest rank for a respective country, but to be able to include more reports for the combination into general scenarios, several types of organisations were grouped into a main rank. For example, commercial data platforms and companies not in the fossil energy sector were seen as similarly trustworthy as supported non-profit organisations. If one or two data sources for a certain country in a higher rank wouldn't contain information about all price drivers, a source from a lower rank would be used to complement information to cover all price drivers.

Table 6: Hierarchy of data sources based on trustworthiness and reputability

Rank	Type of organisation	Examples
1.1	Academia	Nexus-e model by ETH, IPCC (Intergovernmental Panel on Climate Change)
1.2	Government	Energy or Environmental governmental agency (e.g. BEIS in the UK, Swedish Energy Agency and PBL, Netherlands Environmental Assessment Agency), office of statistics or equivalent department (e.g. CBS, Statistics Netherlands), EU Commission
1.3	Government nationalised company	Transmission company (e.g. National Grid in the UK, Swissgrid, Swedish national grid)
1.4	Non- or Intergovernmental organisations	International Energy Agency, IRENA, OPEC

2.1	Commercial data platforms and companies not in the fossil energy sector	Bloomberg, McKinsey, DNV-GL
2.2	Supported non-profit organisations	RE-Source
3	Corporations (incl. Those in the fossil energy sector)	BP, Statkraft, Shell, Exxon, Equinor

If two sources from the same country come from the same main rank, those are combined by using an average. For the UK, the data from the EEP by BEIS and the FES by National Grid were combined, to be able to plot the price drivers for the three general scenarios. EEP is modelling the energy system until 2035 while FES is modelling the energy system until 2050. Therefore, the combined values were only calculated until 2035 to cover both sources. Before the combination of the values, the different scenarios from the two sources were analysed regarding their emission projections to be able to map them to one of the three general emissions scenarios, which can be seen in the result section in Table 8. Each scenario from the respective source then became a tag for if it was a low-, medium- or high-emissions scenario.

For each price driver and each scenario (example shown for the price driver renewable electricity production in Figure 17), the respective average of the low-, medium-, and high-emissions scenario price driver data was calculated separately for future values, which is the thick line in Figure 18. To see the spread in actual values behind the average, the minimum and maximum value of the price driver in each general scenario was found and plotted together with the average to show the uncertainty of the future projections, which are the shaded areas around the thick line in Figure 18. The same figure is shown in Figure 27, but added here to easier compare with Figure 17.

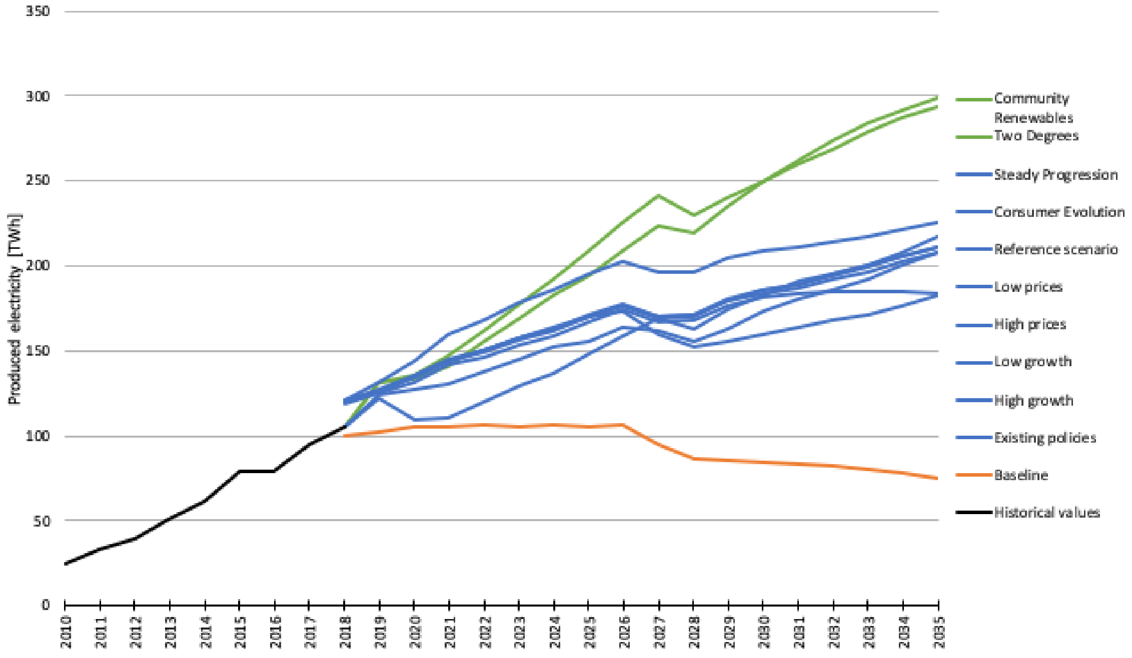

Figure 17: Historical data and future projected development of renewable electricity production according to the different scenarios in the EEP and the FES. The scenarios tagged as the low-emissions scenario are shown in green, those tagged as medium-emissions scenario in blue and those tagged as high-emissions scenario in orange. Data retrieved from the UK Department of Business, Energy & Industrial Strategy (2019) and the National Grid Electricity System Operator (2019).

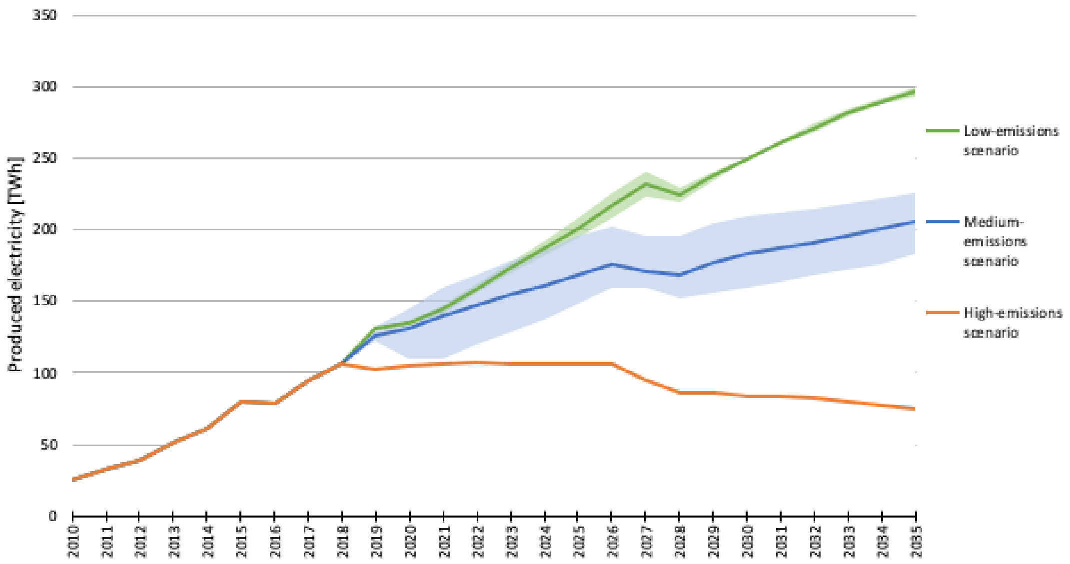

Figure 18: Historical data and future projected development of renewable electricity production according to the developed low-, medium- and high-emissions scenarios including uncertainties.

For the average value to be calculated more fair from different sources, and not favour a source with more scenarios, the average was calculated of the average of the EEP data and of the FES data, i.e. the excel formula =AVERAGE(AVERAGE(EEP price driver data in year X);AVERAGE(FES price driver data in year X) was used. See Figure 37 in Appendix 2 for an excerpt of the database with shown formulas. If there would be no data for a certain general scenario, the data from the closest scenario of the source would be used. For example, if none of the sources would have data for the high-emissions general scenario, data from the medium-emissions scenario from the source would be used for the high-emissions general scenario. If the values in the medium-emissions scenario on average were higher than in the low emissions scenario, the highest values in the medium emissions scenario (from either the min, average or max column) were transferred to all three columns of the high-emissions scenario. The reason for this is that a complete set of data was needed from a modelling perspective. For the UK sources, this was done for electricity production from hydro, wind and solar power, because only FES had data for those renewable electricity production technologies separately and not the EEP.

The sources also gave some historical data, which differed slightly even if they covered the same country. This probably depends on differing scopes of each price driver between the EEP (by BEIS) and FES (by National Grid). Since it is interesting to plot the future development together with the historical data, the average across all likely scenarios[4] from both data sources was calculated and plotted. To visualise the developments of the future price drivers, plots for the most important price drivers – which were assumed to be the future gas price, renewable electricity production and the carbon price, explained in the following paragraph – were created to compare their development in different scenarios (described in chapters 8.3 to 8.5) and analyse them with respect to their relation to UK's climate and energy targets and policies.

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[4] The baseline policies scenario from BEIS was excluded, since it only includes effects from policies which existed before the UK Low Carbon Transition Plan of July 2009. According to (UK Department of Business, Energy & Industrial Strategy, 2019), 79% of the reduction in non-traded GHG emissions (outside the EU ETS) during the fourth UK carbon budget period (2023–2027) comes from policies adopted since after the Low Carbon Transition Plan of 2009. Since it's unlikely that these policies will be removed, the baseline scenario is unlikely to be fulfilled.

The most important price driver categories were considered to be the price of fossil fuel commodities, the penetration of renewable electricity and the carbon price. As long as a considerable amount of the electricity is produced by the incineration of fossil fuels, the price of those will be of importance for the general market electricity price. Out of the different fossil fuel prices, the price of gas is the most important one for the UK, since a lot of electricity is produced from gas power plants in that country (UK Department of Business, Energy & Industrial Strategy, 2019). Therefore, it is one of three analysed price drivers in chapter □, more precisely in the section 8.3. According to a correlation analysis performed by another student in the South Pole project (Wüthrich, 2020), which included to examine the coefficients of linear regression models in order to estimate the impact of price drivers on the electricity prices, the gas price had a higher correlation coefficient on almost all time horizons than the coefficients of the oil and coal price (only exception is the coefficient on annual basis where the gas price has the same coefficient as the oil price), see Figure 19.

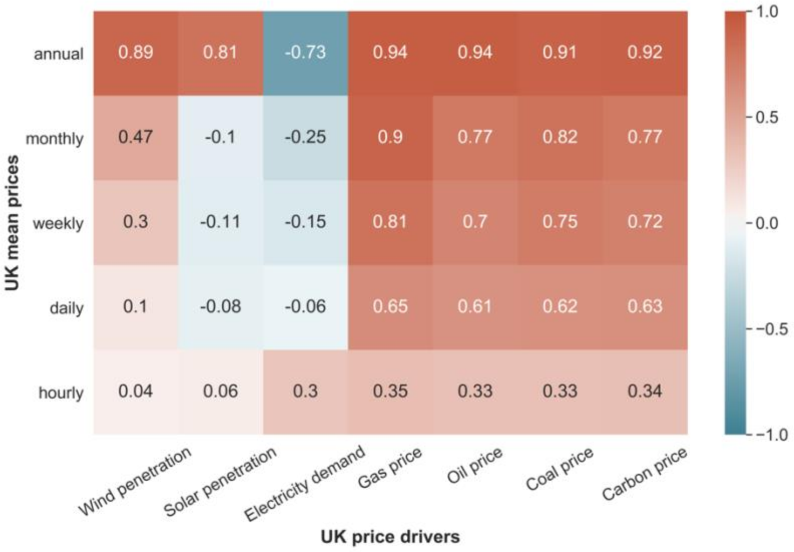

Figure 19: Pearson Correlation Coefficients of UK prices and price drivers with different time resolution, adopted from (Wüthrich, 2020)

Out of the different electricity production generators, the plot was created for overall renewable electricity capacity, because its development is most uncertain and has the largest spread across the scenarios. In addition, the wind and solar penetration show a high correlation with the market power price on an annual basis (0.89 and 0.81 respectively, see Figure 19). Relating to the marginal cost curve (Figure 13), the renewable power production is an important price driver because more of it shifts the curve to the right, which is lowering the electricity market price. In the advisory on renewable PPAs it can also be encouraging to see that renewable electricity is expected to increase, so that there are less doubts from the corporate perspective about it being a good choice. For these reasons, the development of the renewable electricity production was compared and analysed in the chapter 8.4. The third important price driver is the carbon price. It was found to have a significant impact on the predictions according to the correlation analysis by (Wüthrich, 2020), since the correlation coefficient is 0.92. It’s also an important policy instrument impacting the transformation of the energy system and was therefore analysed in section 8.5.

One important note about the strong correlation between the electricity price and the renewable energy capacity and carbon price respectively is that both those price drivers are projected to increase a lot in the future (more than the rise of e.g. gas price, see Figure 40 in Appendix 3) and therefore have a tendency to show a stronger correlation. To validate the selection of the more important price drivers further, one of the developers of the electricity market model in the Nexus-e project (developed by the ETH Zürich and the Energy Science Center) was consulted. Even if their model is market based (where the price of the marginal generation unit in the electricity production mix determines the electricity price) in difference to the South Pole model which is data driven, they affirm that the dominating price drivers are the fossil fuel and carbon prices.[5]

The two different types of plots of the price drivers 'gas price', 'renewable electricity penetration' and 'carbon price', i.e. the plots of the scenarios from the sources and the three general emissions scenarios, were analysed, of which the result can be seen in the sections 8.3 to 8.5. The graphs of the original scenario price drivers were compared across the different sources and scenarios, and the trend explained based on the characteristics of the respective scenario. Then, the graphs of the three general emissions scenarios were compared and explained, and it was examined if there was a trend of the price driver based on the change from the low- to high-emissions scenario.

6. Calculation of avoided greenhouse gas emissions from PPAs

The second contribution of the thesis work to the South Pole PPA assessment model was to calculate by how much the greenhouse gas emissions can be reduced through a renewable PPA compared to a certain baseline, e.g. what type of electricity the corporate offtaker would have otherwise consumed.

In chapter 4 the theory of calculating avoided emissions was explained. However, the method of calculating the baseline emission rate was only briefly mentioned. Therefore, it will be explained here, together with formulas of calculating the baseline emissions and the total greenhouse gas reductions. An excerpt of the calculations can be seen in Figure 38 in Appendix 2.

To calculate the baseline emissions rate, the build margin (BM) and operating margin (OM) emission factors need to be combined. According to the GHG Protocol Guidelines for Electricity Projects, it is calculated as followed:

$$ER_{baseline} = w \times BM + (1 - w) \times OM \qquad (1)$$

Where:

- $ER_{baseline}$ is the baseline emission rate with respect to generation, e.g. $kgCO_2e/MWh$;
- w is the weight (between 0 and 1) assigned to the build margin;
- BM is the build margin emission factor, e.g. $kgCO_2e/MWh$;
- OM is the operating margin emission factor, e.g. $kgCO_2e/MWh$.

To combine the BM and OM, a weight *w* (between 0 and 1) is assigned to the BM, and the rest is assigned to the OM. There is a detailed methodology on how to asses *w* in the Guidelines for Electricity Projects, depending on the grid's demand for new capacity, whether the project meets capacity demand, and the project's capacity value. For the thesis work, it was simplified and assumed that no weight is assumed to the BM (*w*=0), i.e. the baseline emission rate only depends on the OM.

The BM can be the EF of a baseline candidate. To determine it, in the South Pole context, you could for example ask the corporate client if they would have let being built another generation

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[5] Dr. Blazhe Gjorgiev, Postdoctoral researcher at ETH Zürich, Reliability and Risk Engineering, e-mail conversation on 26 May 2020.

capacity, e.g. a CHP or a diesel generator (instead of the wind or solar power plant under the PPA), and assume an emission factor for that generator. However, following the method described in the previous paragraph, this was not done since no weight was assigned to the BM.

The OM can be the EF of continuation of current activities. To determine it, in the South Pole context, you would need to find out what type of electricity the corporate client is using currently and its corresponding emission factor. It can for example be the EF of the grid electricity production mix if the company hasn't made an active choice (according to location-based method[6]), the EF of the residual mix, the utility emission factor, or the EF of an energy attribute certificate (according to the market-based method[7]). According to the Guidelines for Electricity Projects, the primary and secondary effects are calculated separately, but in the thesis work, the emission factors of direct and indirect emissions were combined already in the BM. Since the calculations were made with both static and dynamic emission factors, the location-based method was chosen, because there was data in the EEP about future EFs of the grid electricity production mix, but for example not of future residual mix EFs.

After calculating the baseline emission rate, the total baseline emissions were calculated according to the formula:

$$BE_t = \sum_{t=1}^{t} ER_{baseline,t1} \times GEN_{proj,t1} \qquad (2)$$

Where:

- t is the contract time period;
- $t1$ is a one-year time period during the contract period;
- BE_t is the total baseline emissions for time period t;
- $ER_{baseline,t1}$ is the baseline emission rate for time period t1;
- $GEN_{proj,t1}$ is the electricity generated by the project activity over time period t1.

For the calculation of the emissions with a static emission factor, the $ER_{baseline,t1}$ was constant over the contract period. For the calculation of the emissions with a dynamic emission factor, the $ER_{baseline,t1}$ was unique for each year of the contract period, so to calculate the BE_t, the $ER_{baseline,t1}$ for each year was multiplied with the $GEN_{proj,t1}$ of that year, and then summed up. The $GEN_{proj,t1}$ is in this context the amount of electricity under the PPA and was assumed to be constant.

Furthermore, the project activity emissions (PAE_t) over the contract period were calculated as follows:

$$PAE_t = \sum_{t=1}^{t} ER_{project\ activity,t1} \times GEN_{proj,t1} \qquad (3)$$

With corresponding terms as the baseline emissions. Finally, the avoided emissions, or the GHG reduction, was calculated with:

$$GHG\ Reduction_t = BE_t - PAE_t \qquad (4)$$

Where:

- t is the contract time period;
- $GHG\ Reduction_t$ is the avoided GHG emissions for time period t;

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[6] The location based method is "A method to quantify GHG emissions based on average energy generation emission factors for defined geographic locations, including local, subnational, or national boundaries." (WRI, 2015)

[7] The market based method is "A method to quantify the GHG emissions of a reporter based on GHG emissions emitted by the generators from which the reporter contractually purchases electricity bundled with contractual instruments, or contractual instruments on their own" (WRI, 2015)

The avoided greenhouse gas emissions from a PPA were calculated based on two hypothetical projects: one wind power PPA and one solar power PPA assessed independently. These projects were both assumed to be situated in the UK and each producing 30,000 MWh/year ($GEN_{proj,t}$) for the contract period of 10 years (*t*). The assumption of the produced amount of electricity is based on a common size of a PPA and expert knowledge, and the contract period of ten years is also an often-applied time period of PPAs signed today. The imagined company is based in the UK and is assumed to consume grid electricity at present and would continue to do so if they wouldn't engage in a PPA. This means that the baseline scenario is a continuation of today's activities. Therefore, the weight assigned to the build margin is 0, so only the operating margin (OM) is needed to be taken into account. The example calculation was performed both with static ex-ante emission factors and with dynamic ex-post emission factors. The calculation was first done with static emission factors, but since it is projected that the electricity production mix will include more low-carbon plants in the future, the emission factor of the grid production mix will decrease. Therefore, the results based on dynamic emission factors are more plausible.

For the calculation of the baseline emissions based on static ex-ante emission factors, the emission factors for direct emissions (from generation), and indirect emissions (losses from transmission and distribution (T&D) as well as well-to-tank (WTT) emissions from the grid electricity production mix) were taken from the latest UK BEIS Conversion factors (BEIS, 2019), see Table 7. The emissions associated with T&D losses, but associated with the upstream extraction, refining and transportation of fuels for electricity generation (prior to the point of combustion) were excluded because they were considered not to be significant because those emissions are very low compared to the direct emissions and T&D and WTT emissions. The baseline emission rate was calculated to be $ER_{baseline}$ = 0.313 tCO_2e/MWh (see Table 7, Grid average production mix for the OM and equation (1) above), assigning no weight to the build margin, i.e. the baseline emission rate only depends on the operating margin as explained in chapter 3 and in the previous paragraph. The baseline emission rate $ER_{baseline,t1}$ was multiplied with the expected electricity generation for one year $GEN_{proj,t1}$ and then multiplied with the number of years (t=10) of the contract period, to obtain the baseline emissions BE_t, according to equation (2).

Table 7: Ex-ante static emission factors (EF) of grid production mix, wind and solar power production in $kgCO_2e/MWh$.

[$kgCO_2e/MWh$]	**EF of direct emissions**	**Source**	**EF of indirect emis-sions**	**Source**	**EF of indirect emis-sions**	**Source**	**Total Emission Rate**
Source of emissions:	Generation		WTT (up/down stream)		T&D losses		Whole life cycle[8]
Grid average production mix	255.6	(BEIS, 2019)	35.7	(BEIS, 2019)	21.7	(BEIS, 2019)	313.0
Wind power	0.0	(Schlömer, et al., 2014)	11.0	(Schlömer, et al., 2014)	1.8	(BEIS, 2019) and (AIB, 2019)	12.8
Solar power	0.0	(Schlömer, et al., 2014)	48.0	(Schlömer, et al., 2014)	1.8	(BEIS, 2019) and (AIB, 2019)	49.8

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[8] Apart from the WTT emissions from T&D losses

To calculate the project emissions for wind and solar power plants, the EFs from direct and indirect emissions (see Table 7) were summed up to the $ER_{project\ activity,t1}$ and was multiplied with the produced electricity $GEN_{proj,t1}$ to obtain the project emissions PAE_t, see equation (3). This PAE_t was used to calculate the avoided emissions using the baseline emissions based on both static and dynamic emission factors, because there was no data of future life cycle emission factors of renewable technologies.

The calculation of the baseline emissions was also made with dynamic ex-post emission factors. The EFs for direct emissions contributing to primary effects were directly used from the FES (National Grid Electricity System Operator, 2019), and the 10-year contract period *t* was assumed to last from 2021 until 2030. The EFs are based only on electricity produced domestically, i.e. interconnector imports are considered as zero carbon and emissions from interconnector exports are included in the emissions in the UK and therefore in the emission factor. (National Grid, 2019) The emission factors were given for all of the four respective scenarios, so therefore the baseline emissions were calculated for all of them. See Figure 39 in Appendix 2 for an excerpt of the calculation of the dynamic emission factors.

The EFs for indirect emissions contributing to the secondary effects were calculated based on both the BEIS Conversion factors (BEIS, 2019) and the EFs from the FES (National Grid Electricity System Operator, 2019). To calculate the emissions from T&D losses, the share of the T&D EF of the sum of the generation EF and T&D losses EF in 2019 was first calculated as a percentage.

$$T\&D\ loss_{share} = \frac{T\&D\ loss_{2019}}{T\&D\ loss_{2019} + GEN_{2019}} = \frac{21.7\,\frac{kgCO_2}{MWh}}{21.7\,\frac{kgCO_2}{MWh} + 255.6\,\frac{kgCO_2}{MWh}} = 7.8\ \% \qquad (5)$$

Where $T\&D\ loss_{2019}$ and GEN_{2019} were taken from (BEIS, 2019). The share of T&D losses was assumed to be constant for the contract period and multiplied with the emission factor of direct emissions from generation of a certain year, GEN_{t1}, from (National Grid Electricity System Operator, 2019) to get the T&D emission factor for each year during the contract period.

$$T\&D\ loss_{t1} = GEN_{t1} \times T\&D\ loss_{share} \qquad (6)$$

This and the previous equations are based on South Pole's internal method to quantify losses from the T&D network.

For the dynamic WTT emissions, the WTT EF was divided by the sum of the generation and WTT emission factors for 2019, to get a percentage share of WTT compared to the generation emission factor.

$$WTT_{share} = \frac{WTT_{2019}}{WTT_{2019} + GEN_{2019}} = \frac{35.7\,\frac{kgCO_2}{MWh}}{35.7\,\frac{kgCO_2}{MWh} + 255.6\,\frac{kgCO_2}{MWh}} = 12.2\ \% \qquad (7)$$

Where WTT_{2019} and GEN_{2019} were taken from (BEIS, 2019). The share of WTT emissions was multiplied with the direct emission factor of generation, GEN_{t1}, for the respective year to get the WTT emission factor for that year.

$$WTT_{t1} = GEN_{t1} \times WTT_{share} \qquad (8)$$

This and the previous equation (7), i.e. the method to calculate the dynamic WTT emissions, were developed by the author while consulting the supervisor.

For each year, the baseline emission rate $ER_{baseline,t1}$ was calculated by adding up the direct EF from generation with the indirect EFs from T&D ($T\&D\ loss_{t1}$ from equation 6) and WTT (WTT_{t1} from equation 8). Similar to the calculation of baseline emissions with the *static* emission factors, only the operating margin was included for the baseline emission rate based on the *dynamic* emission factors. For each year, the specific baseline emission rate $ER_{baseline,t1}$

was multiplied with the consumed electricity in that year $GEN_{proj,t1}$, i.e. 30,000 MWh, and added up to total baseline emissions BE_t according to equation (2).

Following, the project emissions PAE_t were subtracted from the baseline emissions BE_t to obtain the expected avoided emissions, according to equation (4). The results of the calculation are found in the chapter 9.

7. Future energy system projections and scenarios

In the research for future energy scenarios, several other reports were found than those listed in Table 4. Some were not chosen because they either didn't have time series of the price drivers (only a value for e.g. 2030 and 2050) or only very few of the price drivers, or they weren't as trustworthy, or the organisations behind the reports were not or less known. Out of the sources listed in Table 4, the reports and their price drivers from the UK were analysed, so therefore these will be described below.

For the UK, two sources of future energy projections were used, namely the *Updated Energy and Emission Projections 2018* (EEP) by BEIS (UK Department of Business, Energy & Industrial Strategy, 2019) and the *Future Energy Scenarios 2019* (FES) by National Grid (National Grid Electricity System Operator, 2019). Since both are trustworthy and of high reputability (rank 1.2 and 1.3 according to Table 6), no efforts were made to look for other sources about future energy projections for the UK. Both sources are also updated annually, which is good to be able to update the 'Price driver database' with the latest available data.

To clarify, the term projection is used in this thesis in general for any "description of the future and the pathway leading to it" (definition of projection according to (IPCC, n.d.)). According to the source, a projection becomes a forecast, or a prediction is it is considered as "most likely". Furthermore, the IPCC defines a scenario as "a coherent, internally consistent and plausible description of a possible future state of the world" and it states that "a set of scenarios is often adopted to reflect, as well as possible, the range of uncertainty in projections". Considering these definitions, what differs the EEP from the FES is that the Energy and Emissions *Projections* (EEP) is based on existing and planned policies (with variations in fossil fuel prices and economic growth), while the Future Energy *Scenarios* gives a set of scenarios based on expert knowledge and stakeholder input and therefore has some scenarios leading to lower emissions compared to the EEP.

7.1. Updated Energy and Emission Projections 2018

Regarding the source EEP from BEIS, that department publishes updated energy projections each year, analysing and projecting the future energy use and greenhouse gas emissions in the UK. The purpose of those projections is to allow them to monitor the progress towards meeting the UK's carbon budgets. They are also used to inform energy policy and associated analytical work of different governmental departments. The projections are based on assumptions of future economic growth, prices of fossil fuels, costs for electricity generation, UK population and other relevant variables which are regularly updated. (BEIS, 2019) These types of projections of the UK energy supply and demand have been performed since the late 1970s. In the 1990s they were extended to also include projections of greenhouse gas emissions. The Updated Energy Projections 2018 are based on policy analysis from July 2018 and modelling from September 2018, and it was released in April 2019. The projections contain data of all the price drivers listed in Table 5 until the year 2035, which were added to the 'Price driver database'.

The energy projections in 2018 contain seven different scenarios. The main projection is the 'reference case', which is one view of how the energy system in the UK could evolve under implemented, adopted and agreed (planned) government policies if no new policies or changes to existing policies were introduced. It is based on central assumptions for the key drivers of energy and emissions, such as fossil fuel prices, Gross Domestic Product and population. The 'existing policies' projection is similar to the 'reference case' in that it includes implemented and adopted policies, but it excludes agreed (planned) policies. There is also a 'baseline scenario', which excludes the impact of all climate change policies brought since the 2009 Low Carbon Transition Plan, to be able to compare it to the 'reference scenario' to see what impact the Low Carbon Transition Plan has and is projected to have. Furthermore, there are additional scenarios of 'low fossil fuel price', 'high fossil fuel price', 'low economic growth' and 'high economic growth', which are self-explanatory.

7.2. Future Energy Scenarios 2019

The second source of future energy scenarios of the UK is the *Future Energy Scenarios 2019* (FES) by the National Grid Energy System Operator. The scenarios outline different credible pathways for the future of energy for the next 30 years and beyond. They include projections of energy supply and demand on a whole system basis. The FES is created based on the insights by National Grid, expertise of industry specialists and stakeholder insights, and has been released annually since 2011. National Grid is holding stakeholder consultations and perform detailed network analysis to develop and improve their scenarios, to reflect the changing energy landscape. The data inputs for the earlier years of the scenarios are mainly based on market intelligence, and commercial contracts for planned capacity additions are considered. From the mid-2020s and until the final year of the forecast, 2050, more assumptions are made as there is less market intelligence available for the development of the energy system further into the future. (National Grid ESO, 2019)

The purpose of developing such scenarios is foremost to plan for strategic gas and electricity network investment requirements for the future. The scenarios are needed to know in which directions the energy system could evolve, because due to the rapid technological advancements, the need for decarbonisation, policy and behavioural changes, it is harder than earlier to make only one most probable scenario or forecast. The Future Energy Scenarios contain data on all price drivers listed in Table 5.

FES contains four different main scenarios which are differing in their level of decentralisation and speed of decarbonisation, and they are called Community Renewables, Two Degrees, Steady Progression and Consumer Evolution – see the scenario matrix in Figure 20 where the scenarios are fit in the matrix of speed of decarbonisation and level of decentralisation. The speed of decarbonisation is influenced by how fast low-carbon solutions are being taken up. The level of decentralisation depends on how close the energy supply is to the customer, and if electric vehicles are mainly charged at homes or more centralised. The scenarios Two Degrees and Community Renewables meet the previous UK 2050 carbon reduction target of achieving an 80 % reduction in greenhouse gases in 2050 compared to 1990 levels, but not the other two scenarios. In addition to the four main scenarios, FES also contains a fifth scenario named Net Zero. It was developed after the net zero legislation by the UK government was approved in June 2019 (shortly before the FES was published), moving the legally binding greenhouse gas target to net zero emissions in 2050 (see information in chapter 3). Compared to the GHG emissions in 1990, the emissions in 2050 are 96 % lower in the Net Zero scenario.

All scenarios have in common that they cover Great Britain, take a whole system view, maximise efficiency and value for customers, are technology neutral and model the progress from the publication year until 2050. The scenarios differ in their level of policy support, economic growth, consumer engagement, technology development and energy efficiency.

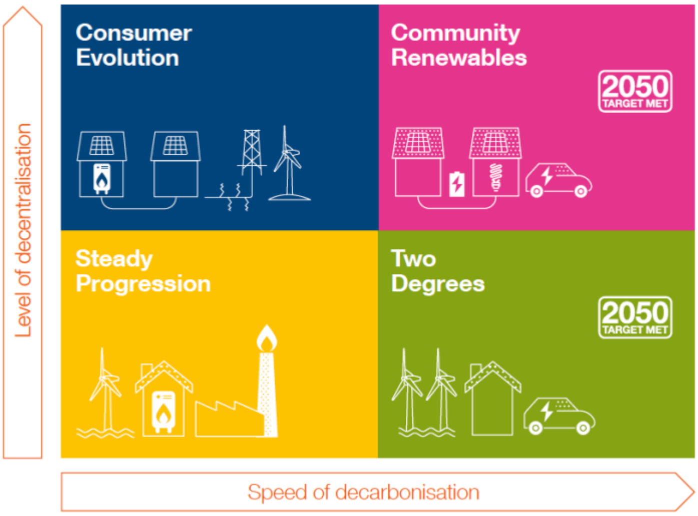

Figure 20: Future Energy Scenarios matrix, adopted from National Grid Electricity System Operator (2019)

These are the main features of each scenario, apart from the features visualised in Figure 20:

- **Community Renewables**: very high level of consumer engagement both in electric efficiency and in local electricity production. The economic growth and technology development are high. High policy support, mainly for onshore wind power generation, electric storage technologies and local energy production, but also for interconnector capacity.
- **Two Degrees**: large-scale and central solutions are supported by policy and developed, both for renewable electricity production, energy efficiency, carbon capture, usage and storage (CCUS) as well as interconnector capacities. Hydrogen for heating is common and economic growth is high.
- **Steady Progression**: the consumer engagement is lower, as well as the economic development and energy efficiency improvements. New technologies develop slowly due to limited policy support for low-carbon technologies such as CCUS and battery technologies.
- **Consumer Evolution**: somewhat similar to Steady Progression, but the consumer engagement is higher, and there is more local electricity generation and stronger interest in electricity efficiency, while the policy support is lower and mainly targeted to local energy solutions.

Another scenario in the FES report, but not included in ‘Price driver database’ because there was very little data about this scenario, is:

- **Net Zero**: based on the two high speed decarbonisation scenarios (especially Two Degrees), with tweaked assumptions to reach net zero emissions in 2050. It has greater electrification, a higher level of industrial and commercial demand side response, somewhat higher use of hydrogen (especially for heating) as well as CCUS, partly with incineration of bioenergy. Early action is needed, and coordinated policy changes, technology and infrastructure development and significant behaviour changes are required.

8. Development and analysis of future price drivers

8.1. Mapping to general scenarios and comparison to climate targets of the UK

As described in section 5, the scenarios in the EEP and FES were mapped to three general scenarios, namely to a low-, medium- or high-emissions scenario, based on the total emissions in the year 2035 which was found in the datasets. The result can be seen in Table 8 and Figure 21.

Table 8: Mapping of the scenarios in the EEP (BEIS) and FES (National Grid) to the three general emissions scenarios. The table is filled according to: Scenario name (source, greenhouse gas emissions in 2035 in MtCO$_2$*e).*

Low greenhouse gas emissions	**Medium greenhouse gas emissions**	**High greenhouse gas emissions**
Community Renewables (FES, 277)	Reference case (EEP, 350)	Baseline policies scenario (EEP, 486)
Two Degrees (FES, 287)	Low fossil fuel prices (EEP, 361)	
	High fossil fuel prices (EEP, 342)	
	Low economic growth (EEP, 346)	
	High economic growth (EEP, 353)	
	Existing policies scenario (EEP, 356)	
	Steady Progression (FES, 394)	
	Consumer Evolution (FES, 392)	

The graphic visualization of the greenhouse gas emissions in 2035 from the different scenarios is shown in Figure 21 below. The two low-emissions scenarios from the FES are shown in light orange, the eight medium-emissions scenarios (two from the FES and six from BEIS) are shown in orange and the only high-emissions scenario, the ‘baseline scenario’ from BEIS is shown in dark orange.

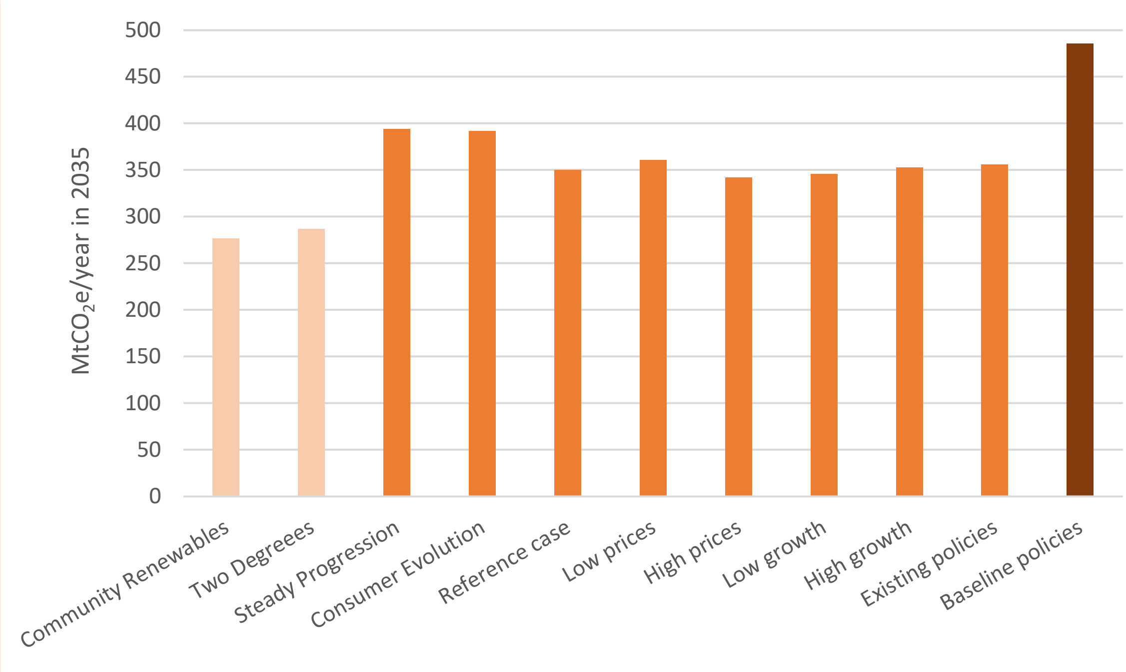

Figure 21: Projected greenhouse gas emissions in MtCO2e in the UK in 2035. Low-emissions scenarios in light orange, medium-emissions scenarios in medium orange and the high-emissions scenario in dark orange. Adapted from Annex A of UK Department of Business, Energy & Industrial Strategy (2019) and data workbook of National Grid Electricity System Operator (2019).

One of the research questions is if the scenarios lead to the fulfilment of UK's climate targets. The UK climate targets were described in chapter 3. To reply to the research question, the emissions in 2050 according to the different scenarios and the respective percentage reduction since the base year 1990 are compared with the previous UK target of -80 % emissions reductions until 2050 and the new net zero target in 2050, see Table 9 below. Since the scenarios in the EEP only are projected until 2035, emission values and relative reduction since 1990 are shown for that year as well and compared with a hypothetical emission target for 2035. The UK has five-year carbon budgets, but not a specified emission reduction target for 2035. Therefore, the hypothetical emission target for 2035 is based on the official 2050 Pathways Analysis (Department of Energy and Climate Change, 2010), describing six pathways leading to a reduction in GHGs in 2050 of 80 %. In the year 2035, those pathways have 60–70 % lower emissions compared to the base year, so the hypothetical climate target was chosen to be 65 %.

Table 9: Comparison table of emissions in different scenarios for 2035 and 2050 and the relative change from the 1990 baseline emission year. Data retrieved from Annex A of the UK Department of Business, Energy & Industrial Strategy (2019) and the data workbook from the National Grid Electricity System Operator (2019). Cells in the columns of the relative change are marked in bright green if their scenario fulfils the previous UK climate target of 80 % emission reductions in 2050 and in dark green if they fulfil the new net zero target for 2050.

Scenario	**Source**	**Emissions in 2035 [MtCO2e]**	**Relative change from 1990**	**Emissions in 2050 [MtCO2e]**	**Relative change from 1990**
Baseline policies	EEP	486	-39 %		
Existing policies	EEP	356	-55 %		
Reference	EEP	350	-56 %		
Low fossil fuel price	EEP	361	-54 %		
High fossil fuel price	EEP	342	-57 %		
Low economic growth	EEP	346	-56 %		

High economic growth	EEP	353	-55 %		
Community Renewables	FES	277	-65 %	165	-79 %
Two Degrees	FES	287	-64 %	165	-79 %
Steady Progression	FES	394	-50 %	345	-57 %
Consumer Evolution	FES	392	-51 %	344	-57 %
Net Zero	FES			32	-96 %
Targets		**277**	**-65 %**	**159 or 32**	**-80 or -96 %**

In the table above it can be seen that none of the EEP scenarios are in line with any of the UK climate targets for 2050. Since the ‘reference scenario’ and its variants are based on implemented, adopted and agreed (planned) policies, it implies that more ambitious policies are needed to fulfil the UK climate target for 2050. The EEP was released in 2019 and therefore, the policies agreed on in that year might not be included in the analysis, such as the Offshore Wind Sector Deal and the Smart Export Guarantee, mentioned in chapter 3.2. However, it is unlikely that only those two policies would add up to the fulfilment of the UK climate target, so it is still safe to state that the existing policies need to be enhanced, and that additional policies are needed. Two of the core scenarios in FES, Community Renewables and Two Degrees, are in line with the previous target of 80 % reduction in greenhouse gases. Only the special Net Zero scenario from FES is in line with the new UK climate target of net zero emissions of greenhouse gases in 2050. In chapter 10.2 it will be discussed, which policies relating to the price drivers that could be introduced to close the emission gap based on today’s existing or planned policies.

The same conclusion, i.e. that the Government’s current policies and plans are insufficient to meet medium-term emission targets, is made by the UK’s statutory advisory body on climate change, the Committee on Climate Change (CCC, 2019). According to the Climate Action Tracker, the UK is neither on track to meet its fourth (2023–2027) nor its fifth (2028–2032) carbon budgets and emission reductions are set to stall between 2022 and 2027, which can be seen in Figure 22 below (Climate Action Tracker, 2019).

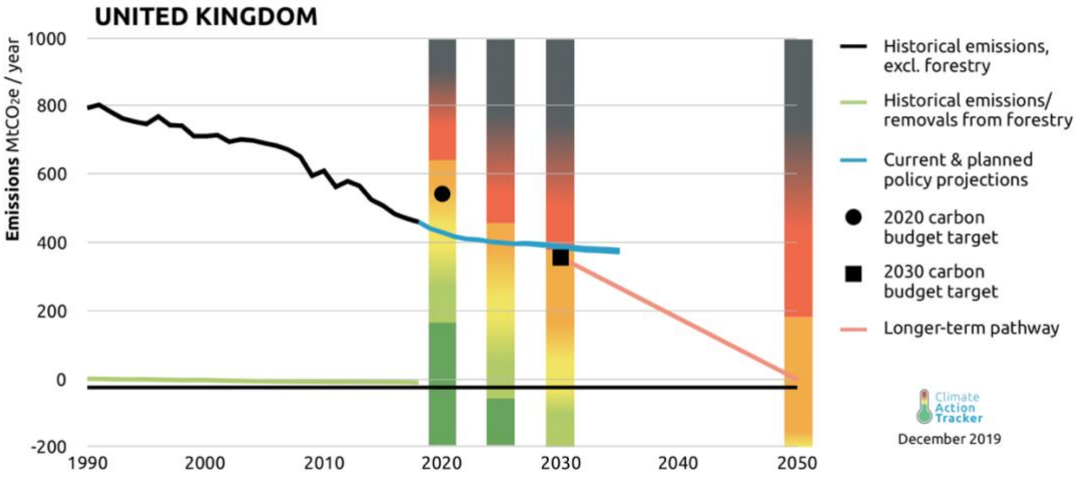

Figure 22: Graphic showing historical emissions of the UK, current and planned policy projections, carbon budget targets and long-term pathway of the UK together with temperature scales indicating fair share ranges. The fair share ranges go from black (critically insufficient), to red (highly insufficient), orange (insufficient), yellow (2 ℃ compatible), light green (1.5 ℃ Paris Agreement compatible) and dark green (role model). Adopted from Climate Action Tracker (2019).

8.2. Future electricity price

As described in the method (section 5), the ‘Price driver database’ was filled out with the data of the different price drivers from different sources and scenarios. The database is the basis for Moritz Wüthrich, another master student in the PPA team, to model the future electricity price. To the Price driver database, also the future electricity price from the EEP was added, so that Wüthrich could compare it with the modeled electricity price which can be seen in Appendix 3. The FES only models the marginal electricity generation price, and not the market price, so therefore, this was not included in the database (National Grid, 2019). The forward price curves from the different scenarios from the EEP were plotted in a graph shown in Figure 23 below to give an understanding of the possible future development of the electricity price.

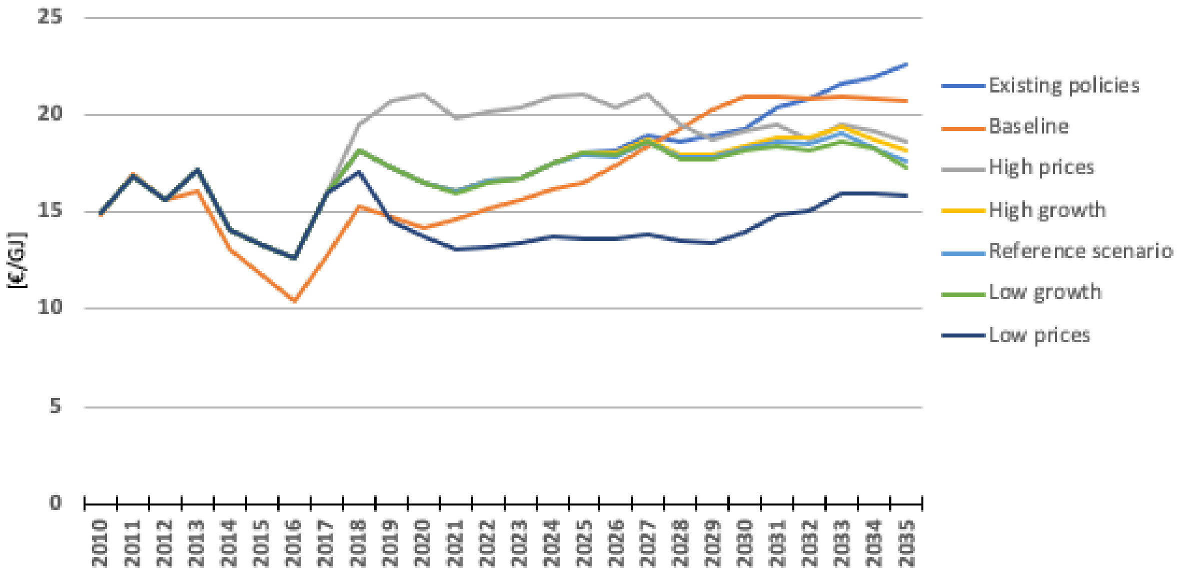

Figure 23: Historic prices and forward price curves for different scenarios in the EEP, based on data in the Annex m to the EEP (UK Department of Business, Energy & Industrial Strategy, 2019)

It can be seen that the price of fossil fuels is a strong price driver, because the ‘low fossil fuel prices’ scenario gives rise to lower electricity prices compared to the other scenarios, and the ‘high fossil fuel prices’ scenario gives rise to higher electricity prices. Most other scenarios based on the implemented, adopted and agreed policies (excluding ‘baseline scenario’ and ‘existing policies scenario’) show a small price variation between 16 and 19 €/GJ until 2035.

8.3. Future gas price

Out of the ten price drivers included in the ‘Price driver database’ (Table 5), a few of the most important price drivers will be analysed. As explained above, the fossil fuel prices are some of the most important price drivers. The fossil fuel prices covered in the EEP and FES are those of oil, coal and gas. In the UK it is very rare with electricity production from oil, so therefore this price is not of a large importance for the overall electricity price. Earlier, the electricity production from coal was important, but in the latest years, gas electricity production has overtaken coal electricity production. According to the future projected development of coal and gas in both the EEP and FES, coal is expected to decline quickly and reach zero installed capacity in 2026 latest. On the other hand, the projected installed capacity of gas power plants is stable or decreased by around a third until 2035 from today’s amount. Therefore, it is likely the price of gas will the most important one out of the three fossil fuel prices. Below, in Figure 24, the future gas price development is plotted for the respective scenarios from the EEP (in cyan) and FES (in magenta).

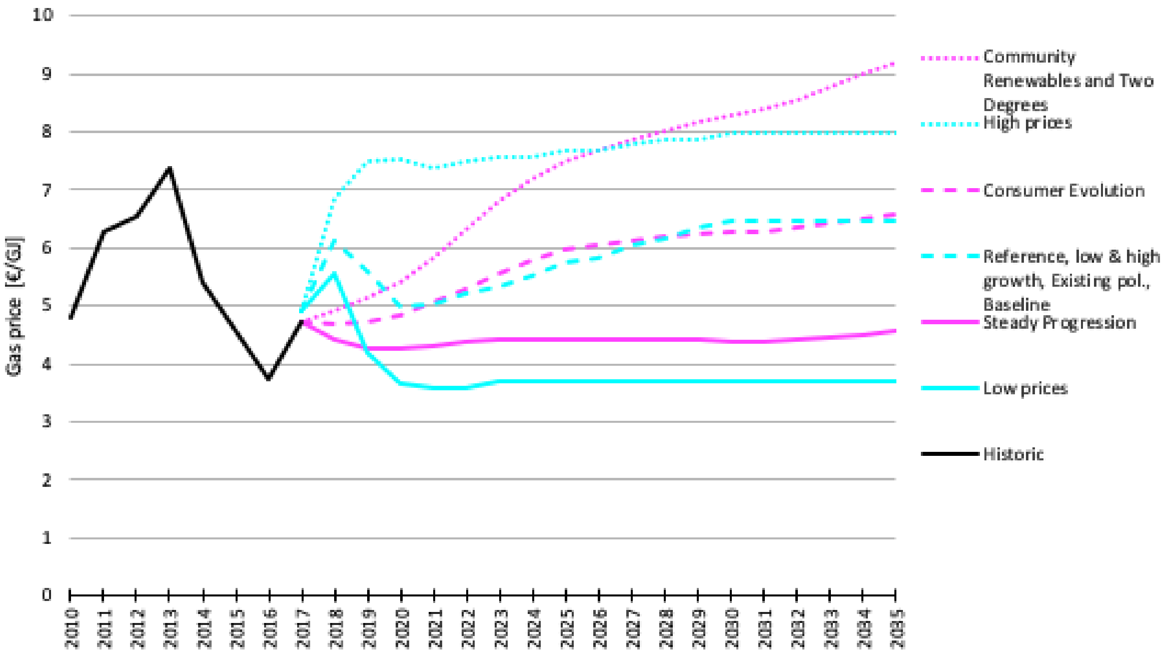

Figure 24: Historic and future natural gas price of different scenarios based on data in the EEP, in cyan (UK Department of Business, Energy & Industrial Strategy, 2019) and in FES, in magenta (National Grid Electricity System Operator, 2019).

Regarding the historic gas prices, they differ between the scenarios in EEP and FES. The explanation to this is that the EEP refers to the internationally traded prices paid by gas and electricity utilities, while the FES refers to the UK natural gas National Balancing Point spot price, which is somewhat lower, but follows a similar pattern. In 2017, which is the last year of historic data, the prices were very similar, so even if the prices refer to different markets, the overall trend can be compared anyhow. In Figure 24, only the National Balancing Point spot price from the FES is shown because it has more recent data (until 2018 compared to the EEP which had data only until 2017). Regarding the future development of the gas price, the FES models the values until 2050, but for the comparison with the EEP, the values are plotted only until 2035. All scenarios show different development of the gas price from a relatively flat development (no lower prices than in 2016) to an increased gas price, but not much higher than the maximum price in 2013. The shape of the curves in the EEP (cyan) show a strong divergence in the first few years (until around 2020), and then stay relatively flat. The shape of the curves in the FES (magenta) show in contrast a gradually change in the future gas price.

Looking at the end values in 2035, both sources have a similar spread in the gas price. At least for the highest and lowest value, the scenarios in FES (magenta) show a higher value compared to the scenarios in the EEP (cyan). The spread in development of the gas price in the EEP scenarios is connected to that the ‘low prices’ and ‘high prices’ scenarios show a lower respectively higher gas price, while the other scenarios have the same price development. In the ‘low prices’ scenario, the emissions in 2035 are somewhat higher compared to the ‘high prices scenario’.

Regarding the spread of gas prices from the FES, Steady Progression (solid line) shows the lowest prices. In that scenario, the demand for gas is high because there is still a significant demand for gas-fired electricity generation, partly combines with CCUS technologies to lower the carbon emissions (National Grid Electricity System Operator, 2019). There is no clear explanation to the low price on gas in the FES scenario framework assumptions, but a low price on a commodity often leads to higher demand for that commodity. In the FES document it is shown that there is less shale gas production in the Steady Progression scenario, which can lead to lower gas prices if the price of the imported gas is lower. In the Consumer Evolution scenario (dashed line), the gas demand is also high, but more of it comes from UK shale gas, and the gas price is higher compared to for Steady Progression. The two low-emissions scenarios Community Renewables and Two Degrees scenarios (dotted lines) show the same high price development, and in both cases, the demand for gas is lower which might be a consequence of the high gas price. The FES is similar to the EEP in the way that the gas price is high in a low-emissions scenario and vice versa.

As described in chapter 5, three general emissions scenarios were created, and the most important price drivers plotted according to those. One of the price drivers is the gas price, which can be seen plotted according to the general scenarios in Figure 25.

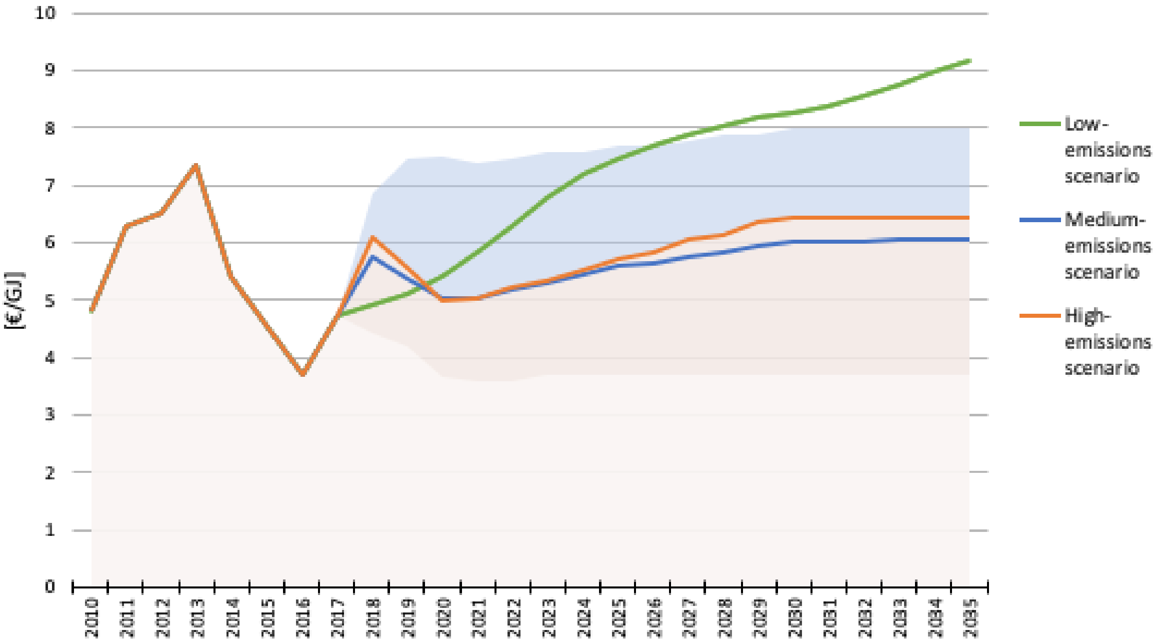

Figure 25: Historic and calculated future gas price for three general emissions scenarios until 2035, including uncertainty ranges

As noted in the previous paragraph, the gas price is high in the low-emissions scenarios of both the EEP and FES. This is also reflected in Figure 25 above, which is combining the two sources. Since the low emissions scenario (green line) only consists of the average of data from the Community Renewables and Two Degrees scenarios – which have the same price development – it doesn't have any uncertainty in this graph. The medium-emissions scenario (blue line) is based on six scenarios from BEIS ('reference scenario', 'low prices', 'high prices', 'low growth', 'high growth', 'existing policies') and two scenarios from National Grid (Steady Progression, Consumer Evolution). The medium-emissions scenario has a relatively wide uncertainty. The high-emissions scenario (orange line) is only based on the 'baseline scenario' from BEIS. The medium and high emissions scenarios are closer to one another than to the line of the low emissions scenario. No clear trend of the gas price in relation to the emissions scenario can be seen, because the high-emissions scenario shows a higher gas price than the medium-emissions scenario, but a lower gas price than the low-emissions scenario. In Appendix 4, a figure of the average of all likely scenarios with an uncertainty bound can be found, which however is not analysed.

8.4. Future development of renewable electricity production

Out of the price drivers in the ‘Price driver database’, another important price driver is the amount or share of electricity produced by renewable electricity generators in an electricity system. As described in section 2.3, renewable electricity production has a very low marginal cost, and is therefore shifting the marginal cost curve to the right, lowering the equilibrium price. In addition to being an important price driver, the future penetration of renewable electricity is also interesting to examine because it gives an indication to corporates interested in PPAs about the trend and that it will be long-lasting and therefore giving trust in that it is a good choice to support the development of new renewable electricity capacity. For these reasons, the future production of renewable electricity was chosen to be plotted and examined. In Figure 26, the historic and future production of renewable electricity according to the scenarios in the EEP and FES can be seen.

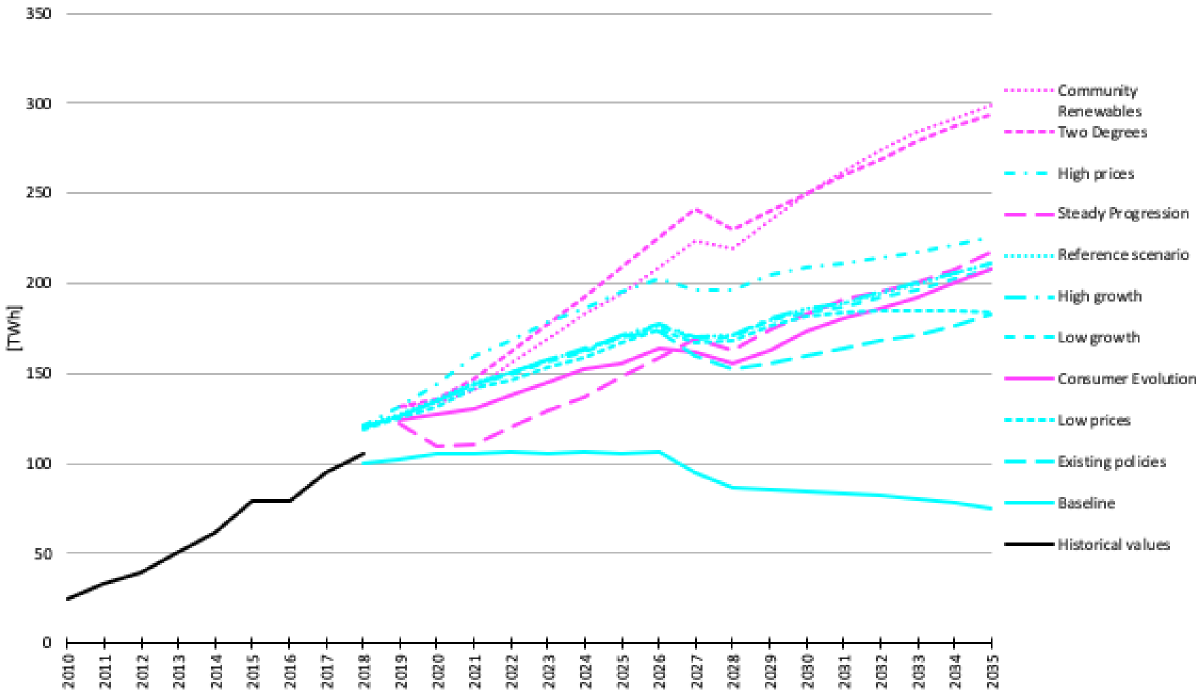

Figure 26: Historic and future production of renewable electricity according to the scenarios in EEP, in cyan (UK Department of Business, Energy & Industrial Strategy, 2019) and in FES, in magenta (National Grid Electricity System Operator, 2019) until 2035

The figure above shows that renewable electricity production has increased from 25 TWh/year in 2010 to around 106 TWh/year in 2018. Beware that the ‘baseline scenario’ (solid line) in the EEP shows the evolution if the policies part of the Low Carbon Transition Plan of 2009 would not have been enforced and is therefore not likely to be fulfilled. All other scenarios show an upward trend in renewable electricity production, apart from a depression in 2027-2028. In 2035 the values range from 183 TWh/year to 299 TWh/year, and in 2050 the values range from 239 to 366 TWh/year (not shown in the figure since it only shows the years from which there is data from both the EEP and FES). Most of the scenarios in the EEP (cyan) are close to the lower two renewable electricity projections (Steady Progression and Consumer Evolution) in the FES (magenta).

Out of the scenarios in the EEP, the ‘high fossil fuel prices’ scenario (dash-dotted line) shows the highest renewable electricity penetration. This is reasonable because renewable electricity in that scenario is relatively seen cheaper compared to fossil electricity generation and the attractiveness to invest in renewable electricity generation is higher. On the contrary, the ‘low fossil fuel prices' scenario shows somewhat lower penetration of renewable electricity, but the difference to the 'reference scenario' (dotted line, but similar to 'high growth' scenario) is not as large as from the 'high prices' scenario. Another observation is that the 'existing policies' scenario (long dashed line) shows a lower renewable electricity production than the 'reference scenario'. This means that agreed or planned policies probably will have a positive effect on the production of renewable electricity. The difference in renewable electricity production is not very large comparing the 'low growth' and 'high growth' scenarios. The 'high growth' scenario causes only 3 TWh higher renewable electricity production in 2035 compared to the 'low growth' scenario.

Out of the scenarios in the FES (magenta), the two medium-emissions scenarios Steady Progression and Consumer Evolution show a similar trend to the 'reference scenario' in the EEP, while the two low-emissions scenarios Community Renewables and Two Degrees show a significantly higher renewable electricity production, and after the final year of the EEP projections, 2035, the electricity production continues to rise according to those scenarios.

Following the method, the scenarios in the EEP and FES were mapped to the three general low-, medium- and high-emissions scenarios, and an average development with uncertainty was calculated and plotted, which can be seen for the renewable electricity penetration from 2010 until 2035 in Figure 27.

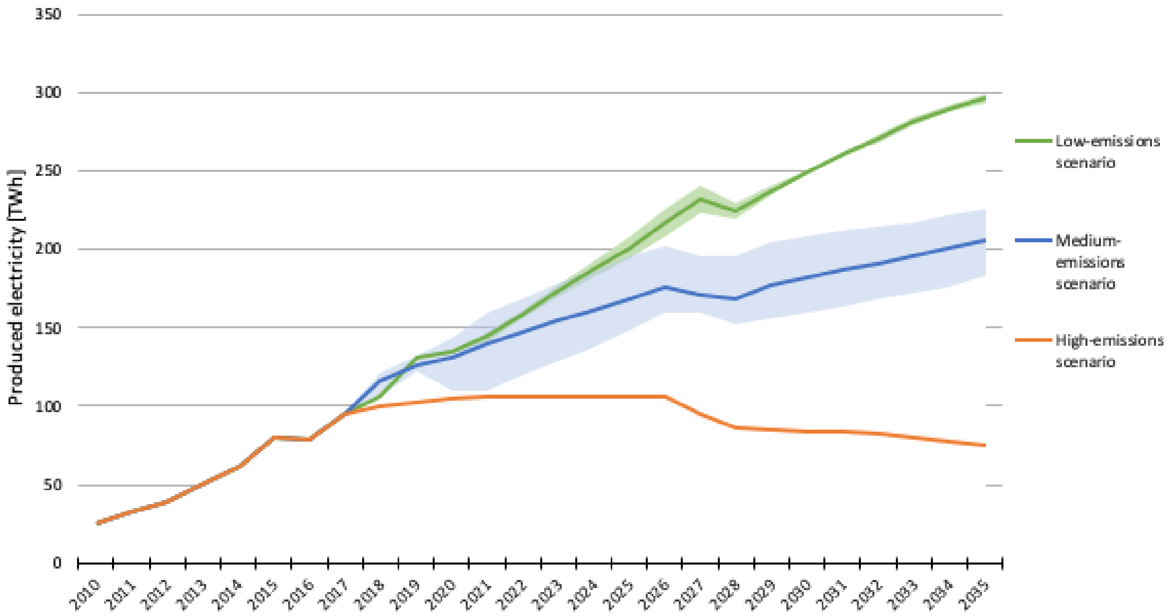

Figure 27: Historic and calculated future renewable electricity production, including uncertainty, for three general emissions scenarios until 2035

The figure above shows that the lower the emissions are in a scenario, the higher is the penetration of renewable electricity. This relates to the fact that renewable electricity causes very low greenhouse gas emissions (12.8 and 49.8 kgCO$_2$e/MWh for wind and solar power respectively, see Table 7) compared to the other forms of electricity production in the UK, such as gas fired power plants, which have an emission factor of around 490 kgCO$_2$e/MWh (Schlömer, et al., 2014). The uncertainty between the general emissions scenarios is varying. The low-emissions scenario (green line) combines only the Community Renewables and Two Degrees scenarios, which have a similar development. The uncertainty of the medium-emissions scenario (blue line) stretches from the 'existing policies' (lower bound) until the 'high fossil fuel prices' (upper bound) scenario. The high-emissions scenario (orange) is only based in the 'baseline scenario' in the EEP and therefore doesn't show any uncertainty. In Appendix 4, a figure of the average of all likely scenarios with an uncertainty bound can be found, which however is not analysed.

8.5. Future price on carbon dioxide

The third important price driver which will be compared across sources and scenarios and which is analysed is the price on carbon. In this thesis, the data comes from sources about UK, so the current carbon price is the combined price of the EU ETS allowances and the Carbon Price Support. As mentioned earlier, UK will exit the EU ETS and likely create a UK ETS, but with similar features. Therefore, we can still assume that there will be some kind of carbon price in the future. Figure 28 below shows the historic values and the future development of the carbon price according to the scenarios in EEP and FES.

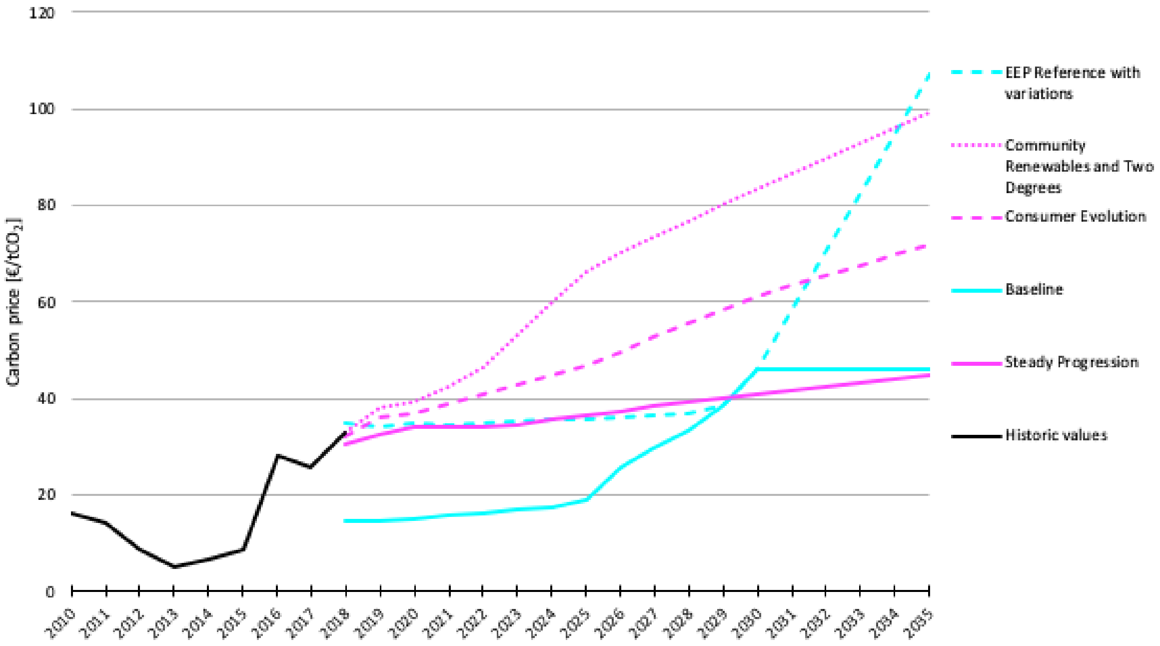

Figure 28: Historic values and future development of the carbon price, consisting of the EU ETS allowance price and the Carbon Price Support, based on data from the EEP, in cyan (UK Department of Business, Energy & Industrial Strategy, 2019) and FES, in magenta (National Grid Electricity System Operator, 2019)

In the figure it can be seen that the carbon price has varied quite significantly over time, historically seen. Regarding the future values, the 'baseline scenario' (solid cyan line) from EEP assumes a low carbon price until around 2025 and doesn't rise to current levels until 2030, where it stabilises. Since it's the least ambitious scenario with regards to climate action, it is not surprising that it has a low carbon price. The reason is that the higher the climate ambitions are, and the stricter climate policies a country has, the higher is usually the carbon price. All the other scenarios show between a slightly increasing trend from today's levels to reach ca 45 €/tCO_2 in 2035, up to steady increasing carbon price to around 100 €/tCO_2 in 2035. All the EEP scenarios (cyan) apart from the 'baseline scenario' assume the same carbon price. Regarding the FES (magenta), Steady Progression (which is one of the high-emissions scenarios, solid magenta line) shows a slow increase in the carbon price, while the two low-emissions scenarios show a fast increase in the carbon price. The scenario Consumer Evolution shows a carbon price in between the other FES scenarios.

As for the other important price drivers, three general emissions scenarios were calculated based on the scenarios from the EEP and FES. The plotted values can be seen below in Figure 29.

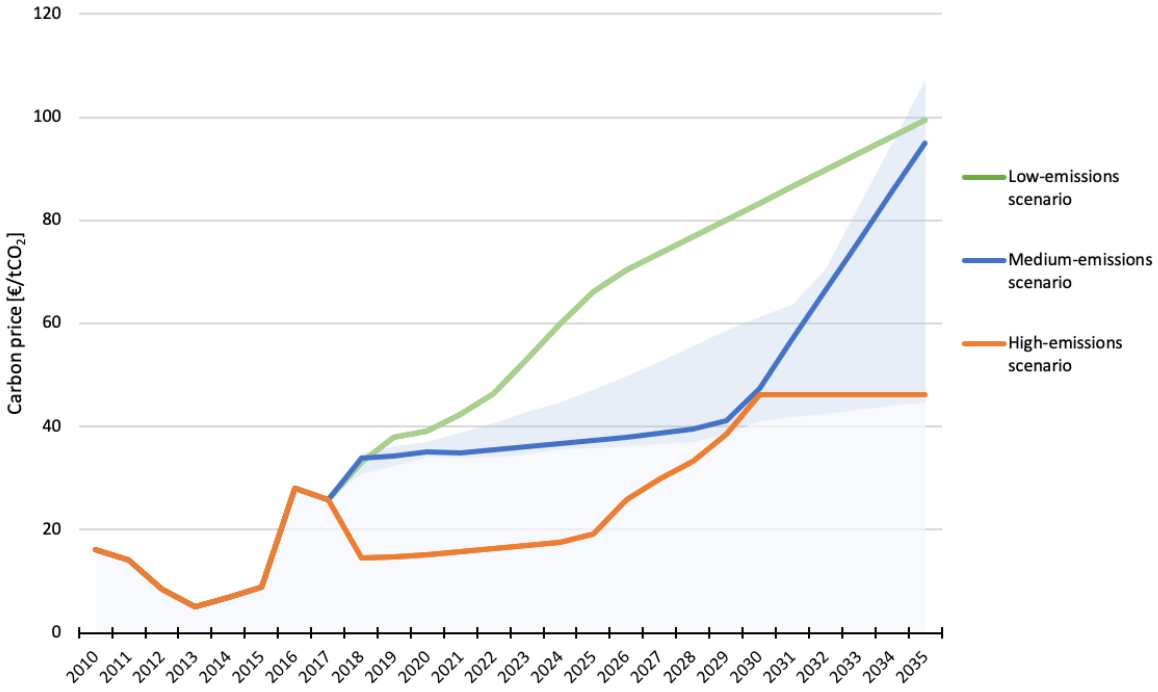

Figure 29: Carbon price: historic values and future values for the three general emissions scenarios including uncertainty until 2035

The figure above shows that the carbon price is higher, the lower the emissions are in the general emissions scenario. The high- and low-emissions scenarios don't show an uncertainty because they are only based on one EEP scenario (high-emissions scenario) or based on two scenarios with the same values (low-emissions scenario). In Appendix 4, a figure of the average of all likely scenarios with an uncertainty bound can be found, which however is not analysed.

9. Results from climate assessment of PPAs

The results from the calculation of the expected avoided emissions from the example wind and solar PPA are presented based on static emission factors (in Table 10) and based on dynamic emission factors (in Figure 30).

Table 10: Baseline and project emissions and avoided emissions over the whole PPA contract period based on static ex-ante emission factors

			[tCO$_2$e]	
Emissions:	Baseline emissions	Grid electricity mix	93,885	
	Project emissions	Wind PPA	3,839	
	Project emissions	Solar PPA	14,939	
Avoided emissions:	**Baseline emissions**	**Project emissions**		**Reduction**
	Grid electricity mix	Wind PPA	90,046	-96 %
	Grid electricity mix	Solar PPA	78,946	-84 %

In the table above it can be observed that the emissions from a solar PPA are higher than those from a wind PPA, because the life cycle emissions from the solar photovoltaic technology is higher than those from the wind power technology. Therefore, the avoided emissions are larger with a wind PPA (-96 % change in emissions) compared to with a solar PPA (-84 % change in emissions).

The results of the calculation of the reduced emissions based on the dynamic baseline emission factors are shown in Figure 30 below, and in a table format in the Appendix 5 in Table 11. The baseline emissions are shown with the orange bars and the project emissions in blue (for the wind PPA) and yellow (for the solar PPA) bars. Two examples of relative change in emissions are indicated with grey arrows.

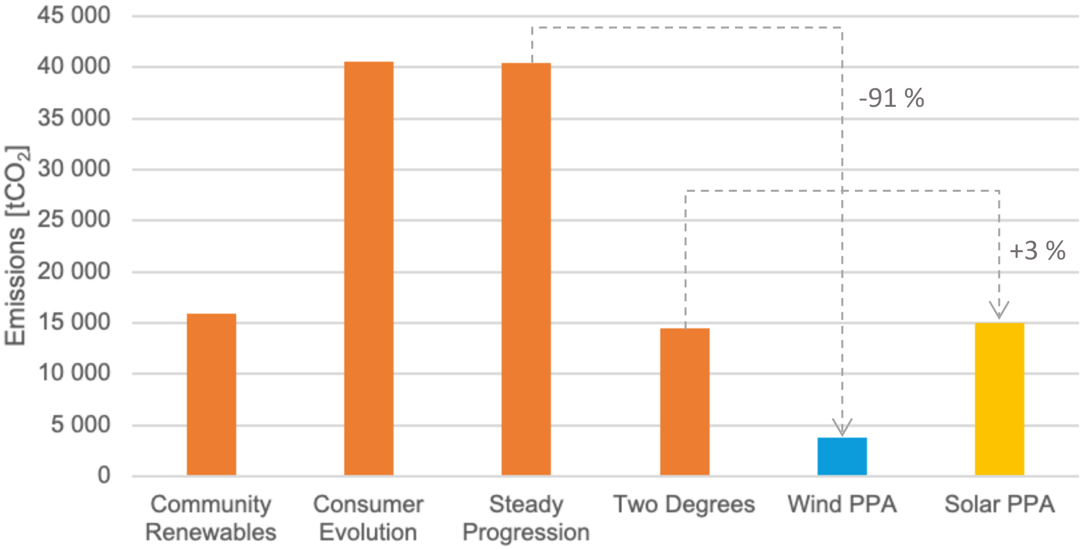

Figure 30: Baseline emissions based on dynamic emission factors for the four scenarios in the FES (orange bars) as well as project emissions based on static emission factors (wind PPA in light blue and solar PPA in yellow). Two examples of avoided emissions are shown with arrows.

In the figure it can be seen that the two high-emissions scenarios (Consumer Evolution, Steady Progression) lead to higher baseline emissions compared to the other two scenarios from FES, which is due to a higher share of fossil electricity production in the Consumer Evolution and Steady Progression scenarios. The emissions from the wind and solar PPA are the same as in Table 10 because there were no future dynamic EFs available for renewable electricity technologies. Similar to the results from the calculation using static EFs, the avoided emissions are higher for the wind PPA compared to the solar PPA. Interestingly, the avoided emissions are negative from the solar PPA compared to the Two Degrees grid mix (i.e. the PPA would lead to 3 % higher emissions compared to consuming the grid electricity). This means that the grid emissions in the Two Degrees scenario are lower than the emissions from the solar PPA. However, the life cycle emissions of renewable technologies are expected to decrease with time as the production mix emissions decrease (or as the solar and wind technology manufacturers actively decide to purchase renewable electricity for their factories), so a solar PPA could then still cause lower emissions compared to the grid mix emissions in the Two Degrees scenario.

Comparing the results from the calculations using static and dynamic EFs (see Table 11 in Appendix 5 for the actual numbers from using dynamic EFs), it can be seen that the avoided emissions are considerably larger for the case with the static EFs, due to the higher grid emission factor. From a corporate perspective it would be appealing to use that number, but since it is closer to reality to use dynamic EFs, the recommendation would be to use the results based on the dynamic emission factors.

10. Discussion

10.1. Discussion of methodology and suggestions for refinement

During the literature study about PPAs, an effort was made to evaluate the reliability of different sources and only (or mainly) use those which were considered to be more trustworthy, such as from the organisations WBCSD, WRI and the platform RE-Source. These were complemented with other sources, for example large PPA actors with extensive expertise on PPAs, such as Bird&Bird and LevelTen.

Regarding the 'Price driver database', data from sources covering global and European projections were first added, and then sources for the UK. However, the global and European data was not used since the future power price is only determined for one country at a time. In retrospect, the work to find and add data for larger geographical areas could have been saved. Furthermore, regarding the database, there were several discussions about and changes in how to make the averages across different scenarios, which took time. However, sometimes it is necessary to try something first and only after that you learn, how to make it better. Another aspect to consider is the large uncertainty in the future development of the price drivers, and the un-foreseeability of e.g. Black Swan events such as an outbreak of a pandemic (such as Covid-19), which is influencing the electricity demand and therefore also the electricity prices. This risk was built into the model by the other master thesis student Moritz Wüthrich, where a sudden drop of power prices was introduced after a random number of years into the future.

The calculation of the avoided GHG emissions from a PPA was done for a specific example PPA. In the future, the calculation will be adopted based on the specific consultancy project. However, it could be interesting to make the calculation for a different PPA in another country, or of another size, or contract period and compare those. Since the corporate client mainly is interested in the single number of avoided emissions and not exactly in how it has been calculated, a simplified approach of the Project Protocol and the Guidelines for Electricity Projects was chosen. Nevertheless, refinements can be made, such as: find and use dynamic emission factors for solar and wind power, differentiate on- and offshore wind power; differentiate utility scale and roof-top solar power, use grid emission factors with hourly resolution, estimate the weight w assigned to the build margin exactly according to the Guidelines, and finally to estimate and calculate the build margin emission factor.

10.2. Answering the research questions

Which factors are influencing the market electricity price and which of those price drivers are more crucial?

The price drivers based on the literature review are listed in Table 3 and the ones added to the 'Price driver database' listed in Table 5. In general, they are related to the price of fossil fuels, the carbon price, electricity production and demand as well as imports and exports. However, there are other price drivers as well and there can be unforeseen or black swan events such as an outbreak of a pandemic disease (such as Covid-19) where the confinement measures lead to a much lower demand for electricity, which is reducing the market electricity prices to levels not expected earlier. (Aurora Energy Research, 2020) Regarding which price drivers are more crucial, the selection was based on information found in literature and on correlation analysis (see chapter 5). For the UK, the most important price drivers were found to be the price of gas, development of renewable electricity production and the carbon price. Other judging or analysis can say differently though – for example, electricity demand is also an important price driver, as it shifts the equilibrium point in the marginal cost curve. This was especially observed in March 2020 during the outbreak of Covid-19 in Europe when the electricity demand was drastically reduced, which led to a lower electricity market price. Price drivers differ between different countries as well, e.g. for the UK the gas price is important, but for Poland the coal price is important. Sweden has a negligible fossil electricity production, so here the fossil fuel price is not as important as in countries with a larger share of fossil electricity production. However, Sweden needs to import electricity at times from countries with a large share of fossil electricity production, and then the fossil fuel prices have an influence on the Swedish electricity market price. For Sweden, which relies largely on hydro and nuclear power and an increasing wind power production, the more important price drivers are weather and interruptions in nuclear power production. Regarding the weather, more precipitation and warmer spring temperatures fill up the hydro reservoirs, colder winters increase the electricity demand during that season, and more wind increases the wind electricity production. (Persson, 2020)

Another aspect is that the importance of different price drivers can change over time. For example, the UK had considerably more coal power production earlier, so then the coal price was more important for the overall electricity price than the gas price. Another example can be a country which currently doesn't have a lot of renewable electricity production, so at the moment the production of renewable electricity is not an important price driver. When the electricity production from renewables is increasing, that price driver becomes more important. In both these examples it is the amount of produced electricity which is changing and thereby shifting the marginal cost curve (see Figure 13) to the right or left. What also can happen is that the marginal cost of production is changing for certain plants or technologies. For fossil fuelled plants, their marginal production cost increases as the carbon price increases. However, some gas turbines might switch to run on biofuels or (renewable) hydrogen in the future, and then they probably wouldn't have to pay a carbon price. Then, the power price will not increase as much when the carbon price increases. For renewable electricity technologies, their marginal cost might decrease when the investment has been paid off.

In the previous paragraph it was discussed, how the current electricity production technologies can change, and it was assumed that the pricing is still done through marginal cost setting. Yet, the technologies themselves or even the pricing mechanism can change. In the future, new emerging technologies, such as maritime power, hydrogen production and storage, battery storage technologies, demand response etc., might rise faster than anyone can foresee. It is clear that such electricity shifting and shedding technologies are needed when there is more intermittent electricity production. If those technologies grow to a certain scale, they will influence the electricity price, which can be hard to foresee today. Electricity storage technologies can lower electricity peak prices, but they can also avoid electricity prices going negative. Furthermore, the way of setting the electricity market price might change or complemented with for example a capacity market.

How do future projections of price drivers differ between different sources and their respective scenarios for the UK – and why?

The studied future projections for the UK show a stable or rising gas price. The gas price is not clearly correlated with higher or lower emissions scenarios according to the results. In Figure 25 the gas price is higher in the low emissions scenario compared to the other scenarios, but the lowest gas price is not found in the high emissions scenario, but in the medium emissions scenario. Although, the gas price of the medium emissions scenario was close to that of the high emissions scenario. In the analysis, the low gas price in the low emissions scenario was explained by that a low demand on a commodity is leading to lower prices of that commodity. However, if the (final) gas price in the low emissions scenario is low, the demand would likely increase, leading to higher emissions. An assumption is therefore made that the low gas price in the low emissions scenario is the market price without (carbon) taxes, and that the final consumer gas price is higher to make gas consumption less economically attractive, in order to reduce carbon emissions.

For the penetration of renewables, all likely scenarios show an increase in future renewable electricity production – what is to be seen is how fast the rise will be. There is a clear trend towards more renewable electricity production, the lower the emissions are in the general scenario. This relationship is very easy to comprehend as the emissions from renewable technologies are very low.

Regarding the carbon price, it is expected to increase in all scenarios from the EEP and FES. The lower the emissions in a general scenario, the higher is the carbon price, because it is one policy instrument to incentivise emission reductions.

In general, regarding future projections, their scenarios depend a lot on the assumptions behind them. For the EEP, not as many assumptions need to be made since those projections mainly are based on policies which are already implemented, adopted and planned. However, it includes scenarios which are variations of the 'reference scenario', namely with low or high fossil fuel prices and economic growth. For the FES, more assumptions need to be made since it doesn't only base the scenarios on implemented, adopted and planned policies, but also on ideas about what could happen in the future, which come from experts and other stakeholders. All in all, it is not possible to predict exactly how the future will be, but through modelling different scenarios you can show different ways of how the energy system can develop, and it is more likely that one of them will be close to the future reality. It can also be good to show an uncertainty span to account for variations within a scenario. The EEP and FES haven't included uncertainties in their projections, but in the figures of the three general scenarios in this report, uncertainties have been included.

The statement that one of different future scenarios will lie closer to the future reality can be made, but some earlier projections of the energy system have been very wrong. One example of this is the future prediction of annual additions of solar photovoltaic capacity, made by the IEA in the World Energy Outlooks (Hoekstra, 2019). As can be seen in Figure 31, the IEA has continuously underestimated the future additions of global capacity additions of solar photovoltaic technology. The organisation IEA has a high reputation and many experts (and are categorized to the highest general rank according to Table 6), but still don't seem to learn from previous deviations and seem not to grasp the exponential growth in solar electricity production. In general, the model of the IEA and other organisations performing future projections of the energy system can be improved by using learnings from the previous deviations of a certain price driver to the actual historical development.

It will be interesting to follow the future development of the build-out of renewable electricity capacities, and to see for how long the growth will follow an exponential shape. To reach the 1.5 °C goal of the Paris Agreement, nearly all power production globally needs to be renewable, and today we are still very far from that. In order to reach the climate goal, the renewable electricity capacity additions need to rise for many more years. This can only be achieved if there is a strong political will and policies supporting the development of renewable energy. In addition to the political level, companies can also contribute to the expansion through supporting additional capacity through for example PPAs, and more individuals can demand renewable energy through switching to a renewable electricity contract where it is possible to choose utilities which provide such renewable electricity contracts.

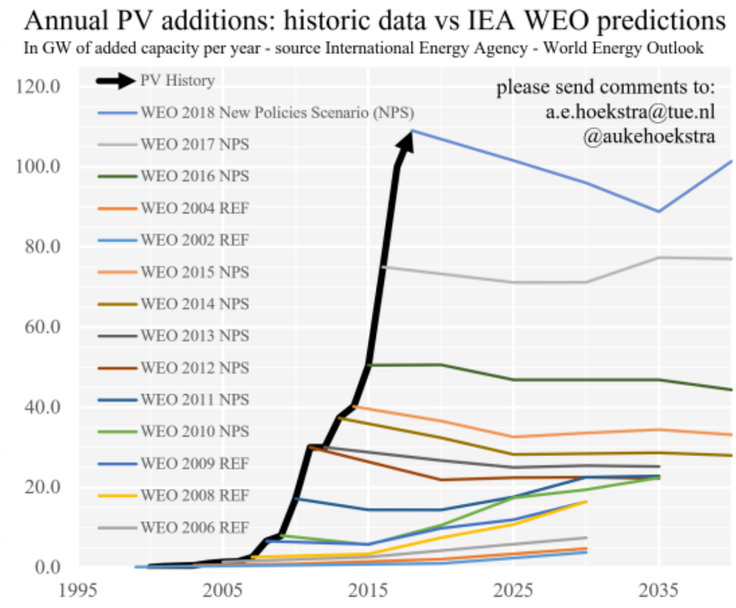

Figure 31: Historic data and predictions in the World Energy Outlook (WEO) from 2002 until 2018 by the IEA of annual additions of solar photovoltaic capacity in GW. Adopted from Hoekstra (2019).

Another master thesis student in the South Pole PPA assessment project, Diederick Calkoen, compared earlier projections from a certain agency and inferred an uncertainty based on earlier projections for the latest future energy projections based on a methodology by Lynn Kaack. (Lynn, 2017) One example shown in Figure 32 is the aggregation of the past long-term prognoses by the Swedish Energy Agency about the future wind electricity production. (Energimyndigheten, 2019) It can be seen that all projections until 2014 underestimated the future wind electricity production, because the highest level of the highest forecast (around 18 TWh) in 2030 was reached already three years later, in 2017. Another interesting comparison is the prognosed wind electricity production for 2030, which in 2008 was prognosed to be 6.7 TWh, but in the latest forecast from 2019, the prognose for that year is 35 TWh – more than a five-fold increase.

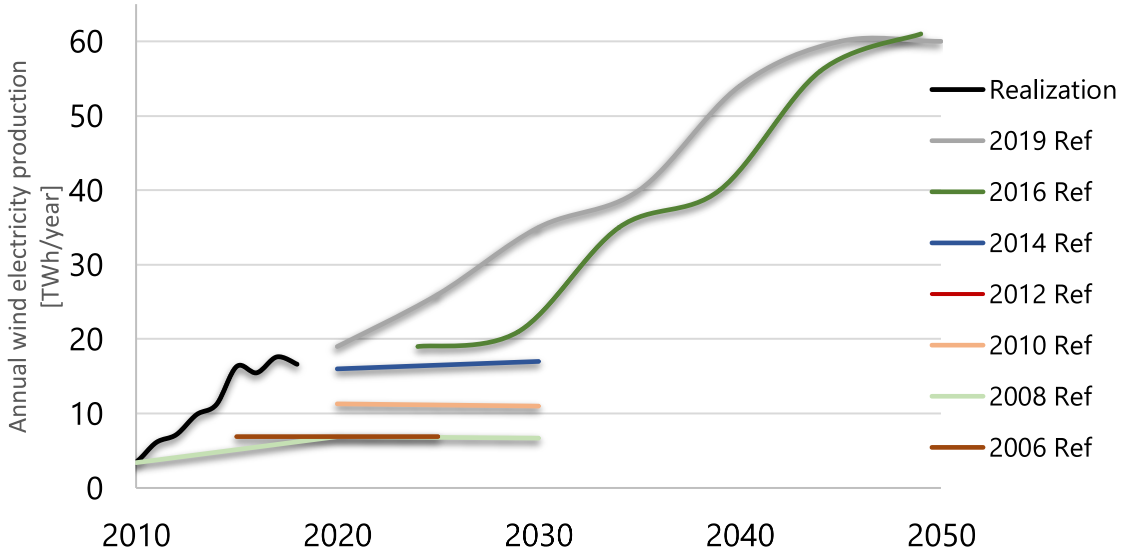

Figure 32: Historical values and past projections of wind electricity production in Sweden, data retrieved from (Energimyndigheten, 2019)

Do the scenarios from different future energy projections for the UK lead to the fulfilment of UK's national climate targets? What governmental policies relating to the most important price drivers would be needed to reach the climate targets of the UK?

As described in section 8.1, none of the scenarios in the EEP, which are all based on implemented, adopted and planned policies, lead to the fulfilment of UK's national climate target. Therefore, a conclusion can be made that more stringent climate policies are needed to be able to reach the climate target. Both the current policies (described in section 3.2) can be enhanced, and additional policies can be developed. Only the Net Zero scenario from the FES is leading to the fulfilment of UK's target of net zero emissions in 2050 (presented in section 3.1). The Net Zero scenario doesn't state any concrete policies, but rather mentions which types of technologies that are supported or not supported, or how the consumer engagement and economic growth is. The Net Zero scenario is characterized by high electrification, high level of industrial and commercial demand side response, high energy efficiency, a high use of hydrogen, and CCUS paired with biomass. Policies based on these characteristics are suggested to be implemented in the coming years to faster approach the UK climate target.

Regarding the second part of the research question, an attempt will be made to suggest policies to decrease greenhouse gas emissions related to the three analysed price drivers. The first price driver was the gas price. There was no clear trend in the price relating to the emissions scenarios, but assuming that the gas price includes (carbon) taxes, the gas price is higher, the lower the emissions are in a scenario. Therefore, a policy suggestion is to increase taxes on gas – especially for power production. The market price of gas is projected to increase, so there might be a lower demand due to that, but some scenarios show a very small increase in the gas price (perhaps not larger than the inflation rate), so then a higher (carbon) tax on gas would still be needed. The reason for why it was specified that the tax on gas for power production should be increased is that gas is widely used for heating in the UK today. Many households have difficulties already to pay their gas bills, so therefore the tax on gas needs to be for specific purposes, in order not to worsen the situation for low-income households. In 2018, the proportion of households in England in fuel poverty was estimated to be 10.3 %. (BEIS, 2020)

The second price driver was the production of renewable electricity, which is higher, the lower the emissions are in a general scenario. Therefore, more policies supporting renewable electricity could be introduced, or current policies (such as the Contracts for Difference, Capacity Market, Offshore Wind Sector Deal and the Smart Export Guarantee mentioned in chapter 3.2) could be strengthened to enhance the expansion of renewable electricity capacity. Recently, the CfD auction prices have decreased, which are positive for the expansion, and wind power don't need direct subsidies anymore, which reflects the maturity of the technology. However, risks remain for the investors. Therefore, the UK Energy Research Centre mentions in its 'Review of Energy Policy 2019' that a continued CfD would reduce financial uncertainty and reduce the cost of capital. Furthermore, it suggests amongst other that "Policies to support renewable electricity generation should be more ambitious, building on deployment and cost reduction successes. Action is also needed to ensure electricity market rules are fit for a fully decarbonised power sector.". It also suggests that the plans to meet the net zero target should maximise environmental co-benefits and that "Potential negative impacts on ecosystems should be assessed and mitigated.". (Hastings et al., 2019)

However, policies need to be introduced and revised in a thought-through way. As renewable electricity capacity is increased, policies need to be revised in order to keep them effective. One example of where this is needed is in Sweden, where there is an electricity certificate system. In this system, renewable electricity producers get a certificate from the state for each MWh produced, which is sold via a market, from which utilities and other market actors need to buy electricity certificates to cover a certain quota of their total bought electricity. (Swedish Energy

Agency, 2017) This gives an extra income to the renewable electricity power producers and has led to a fast development of renewable electricity and reduction in carbon emissions. However, since the increase in production has been much faster than expected, there are excess certificates and the price on them goes down and the power producers don't receive as much support. The certificate system was revised in 2015 and in 2017, but the price on the certificates is still too low. For some renewable energy technologies, the support is still needed, but wind power is now compatible enough on the electricity market and does not need any market based financial support anymore. In addition, investors are less willing to invest in renewable electricity plants as long as the price on the electricity certificate is very low. Therefore, the Swedish Wind Power Association is demanding to remove already profitable electricity producers from the system, and a group of investors are demanding the government to revise the system, so that the price on electricity certificates will not be too low. (Tripodi, et al., 2020) The aim of mentioning this example is to highlight that there are effective policy instruments to support the expansion on renewable electricity infrastructure, but they need to be revised in order to stay effective. When developing the policies to support the expansion of renewable electricity, the security of supply also needs to be taken into account. Renewable electricity production, especially wind and solar power production, is intermittent and cannot be controlled in the same way as gas or hydro power plants. Therefore, to avoid situations with too low frequency (due to lacking electric power), power shortages or even outages, systems for more flexible electricity consumptions and electrical storage need to be created, and needed infrastructure built out.

Another recommendation for the UK is to set a new target for renewable energy and especially for renewable electricity, as the UK currently doesn't have such a target for any year after 2020 (as stated in chapter 3.1). To have a national target would give a market signal for more renewable electricity capacity to be built. The current trend of the development of renewable energy is promising though. According to the latest quarterly report EnergyTrends for the first quarter in 2020 made by BEIS (2020), the total renewable generation increased by 30 % from 2019 Q1 (31.5 TWh) to 2020 Q1 (40.8 TWh), which is a record increase for year on year quarterly renewable generation. As a result, the share of renewables in electricity generation increased by 11.1 percentage points to 47.0 %. This share has never exceeded 40 % before. Main factors for this increase are increased capacity and high load factors for wind technologies (thanks to high average wind speeds), and especially offshore wind. Onshore wind power generation rose by 29 % and offshore wind by 53 %, both improving the quarterly record by almost a third. Several of the offshore wind installations which came online are supported by the Contracts for Difference scheme, showing that it is an effective policy instrument. During the quarter, coal power generation reached a record low level, 26 % lower compared to the first quarter in 2019. A historic milestone was passed when coal was kept off the grid over two months between April and June in 2020, thanks to increased electricity production from renewables and a lower electricity demand due to the confinement measures due to Covid-19. (Lempriere, 2020a) For the first time ever, more electricity came from renewables than from fossil fuels during the whole first quarter in 2020. During the last decade, coal capacity has decreased from 28 GW to 5 GW today. (Lempriere, 2020b)

The third price driver important for the UK is the carbon price, which is higher, the lower the emissions are in a scenario. The EU (or later the UK) ETS price is itself a policy, so to get closer to the 2050 target, the price on the emissions allowances should be increased. The current Carbon Price Floor and Emissions Performance Standard are good and should be kept, but only set a minimum price and don't increase the carbon price in a systematic way. As written in section 3.2, the UK will quite likely create a UK ETS due to the exit out of the EU. It is still not decided upon, but the Committee on Climate Change (Deben, 2019) is recommending that the UK ETS should be in line with the 2050 target. This can be done by increasing the linear reduction factor (the factor by which the total emissions are reduced by each year). If it became reality, it would be very supportive towards the net zero target.

A reflection on Covid-19 is the importance of recovery measures being in line with the net zero target. After the financial crisis in 2008, recovery measures mostly supported carbon intensive industries and project and only 16 % of the governmental financial support went to green purposes[9], but with the climate crisis now being even worse, it is of utmost importance that the recovery measures and policies are in line with the Paris Agreement climate target.

What is the climate impact of consumption of renewable electricity through PPAs compared to the consumption of electricity from the grid production mix over the contracted period?

The avoided emissions from a PPA contract of 10 years and 30,000 MWh electricity produced/consumed each year in the UK is 78,946 tCO_2e for a solar and 90,046 tCO_2e for a wind PPA using static emission factors. This means that the PPA would lead to 84 % respectively 96 % lower greenhouse gas emissions from the consumed electricity.

A more likely emission reduction is given based on dynamic emission factors. Using those, the avoided emissions varies from 10,623 to 36,734 tCO_2e for a wind PPA and from -477 to 25,643 tCO_2e for a solar PPA depending on the scenario from the FES. In relative change, a wind PPA can give reduce the emissions by between 73 and 91 %, and a solar PPA can change the emissions between -63 % and +3 %, depending on the scenario used. To get a better understanding of how large these avoided emissions are, 36,734 tCO_2e equal the greenhouse gas emissions from 7,936 passenger vehicles driven for one year, or 4,239 homes' energy use for one year, or avoided emissions by 1,395,510 incandescent lamps switched to LEDs. Mind that these equivalencies stem from United States Environmental Protection Agency (2020), which has a different electricity production and car fuel efficiency compared to the UK, but it is to give an estimation.

Having said that, it should still be discussed whether a company can actually claim those avoided emissions. As explained in chapter 4, a broader perspective can be used and consider that all emissions from larger electricity production plants are traded under the cap of the EU ETS, so if emissions are reduced in one place, the corresponding emission allowances can be sold to another participant in the system. Talking against that is the Market Stability Reserve, which removes excess emission allowances from the system. Furthermore, a PPA doesn't necessarily decrease the power production of a fossil plant, but instead produces extra electricity. Therefore, there wouldn't be any excess emission allowances which could be sold to another participant. Another argument against that the overall emissions are reduced is that if the corporate offtaker is switching from a standard electricity contract with a utility to a PPA, that electricity from the utility would just be sold to another customer instead, and the emissions from the production would still occur.

The amount of avoided emissions depends on which perspective you take. From a corporate GHG accounting perspective, the company reduces its emissions from electricity consumption through engaging in a PPA (unless it had very low-carbon electricity before the PPA contract).

Furthermore, the company (usually) contributes to additional renewable capacity being built through the PPA and through that contributing to the overall energy transition from a fossil to a renewable energy system. Globally, the share of energy consumption of the Commercial and Industrial sector on 2016 was 38 %, so a change in the energy procurement of that sector can

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[9] Maria Wetterstrand, VD at Miltton Purpose, sustainability consultant and public debater. Worganised by Young Sustainability Professionals (YSP) with the topic of Green Recovery (Grön omstart). Online on 2 June 2020.

have a large influence on the global emissions. An energy transition is urgently needed as we are in a climate crisis which has to be solved within one generation if we humans and other species want to continue to prosper on this planet for many years to come. To achieve a global energy transformation which are in line with the climate goals set in the Paris Agreement, the overall share of renewables in total electricity consumption needs to reach at least 85 % by 2050. This translates into 19,000 TWh for the Commercial and Industry sector. However, the current trajectory is far from that (IRENA, 2018). Therefore, companies need to increase their consumption of renewable energy, and not only electricity, but also renewable energy for transports and heating.

There are different ways for companies to increase their sourcing of renewable energy. One good start is to set a target for it and develop a renewable energy sourcing strategy describing how to reach the target. Companies should furthermore consider renewable energy sourcing options with a higher level of additionality (rather PPAs and self-production than EACs), to actively contribute to the development of renewable electricity capacity. Companies can also encourage the actors in their supply chains to switch to renewable electricity. Even if companies do their best to increase their uptake of renewable electricity, there are structural barriers which might stop or slow down that process. Therefore, policy support is needed to stimulate corporate sourcing of renewable electricity. Some policy suggestions described by IRENA (2018) are to: support a credible and transparent system for certification and tracking of renewable energy attributes; change the market structure so that companies can trade directly with renewable energy developers; provide green corporate procurement options together through work with utilities and electric suppliers; and encourage companies to invest in self-generation.

11. Conclusion

Based on the analysis of price drivers in future energy scenarios of the UK and the calculation of avoided emissions from a PPA, the following conclusions are made:

The current most important electricity market price drivers in the UK are the gas price, the renewable electricity production and the carbon price.

There is a large spread in the development of future price drivers across different sources and scenarios, which is indicating that the future can develop in many different ways. Based on the analysis of the development of price drivers in the general emissions scenarios, a low-emissions scenario consists of a high gas price (including carbon taxes), high penetration of renewable electricity and high carbon price.

The current policies of the UK are not in line with its target of net zero emissions in 2050. For the UK to reach the climate target, the country could strengthen existing or introduce new policies which (1) raise the carbon tax on the price for gas used in electricity production, (2) support the expansion of renewable energy technologies and (3) create a UK ETS with an emissions trajectory in line with the net zero target.

Through a PPA, companies can reduce their own emissions by up to 96 %, using static emission factors. The result is more likely to be correct if dynamic emission factors are used, where the emissions in most cases are reduced by between 63 and 91 % depending on the scenario and the type of renewable electricity technology of the PPA. However, when comparing a solar PPA with the grid emissions from a low-emissions scenario, the emissions do not change considerably (-6 to +3 % change in emissions). The emission reductions which would occur contribute to national climate targets and at the same time contribute to additional renewable electricity capacity needed for the energy transition to a low-carbon society.

Future work in this area can be to do a similar analysis for other countries, and to include more than the chosen three price drivers in the analysis. The analysis could also be expanded to not only assess the price drivers separately, but also how they influence each other. It would also be interesting to raise the level and look at and compare future energy projections on a European and global level. Regarding the suggestions for policies for enhanced climate ambition, policies relating to other price drivers than the three chosen ones could be suggested. As written in section 10.1, the calculation of avoided emissions could be made more sophisticated and include more different types of renewable electricity technologies.

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Appendices

Appendix 1: Additional figures

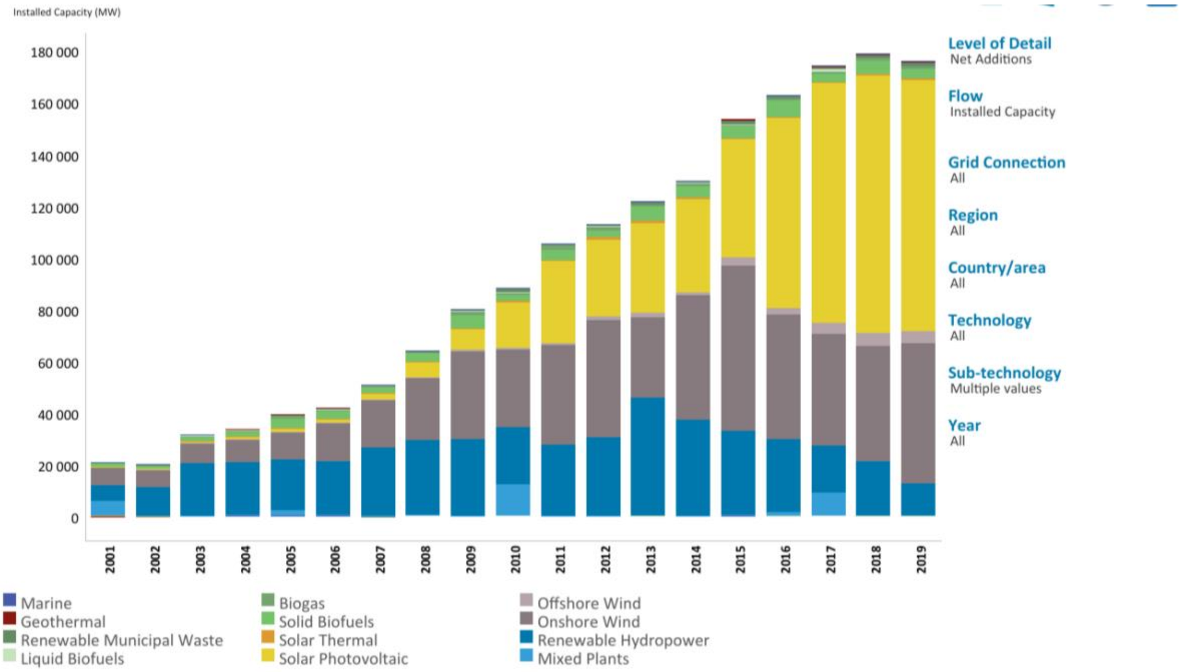


Figure 33: Global net additions of renewable capacity, adopted from (IRENA, 2020)

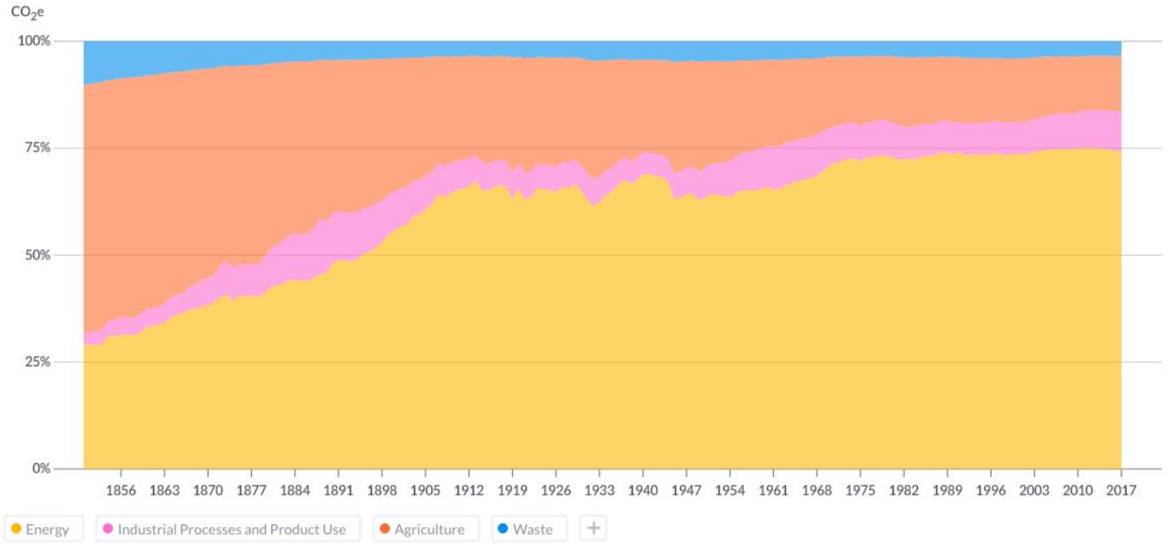


Figure 34: Historical global sectoral GHG emissions excluding Land Use, Land Use Change and Forestry, adopted from (Gütschow, et al., 2019)

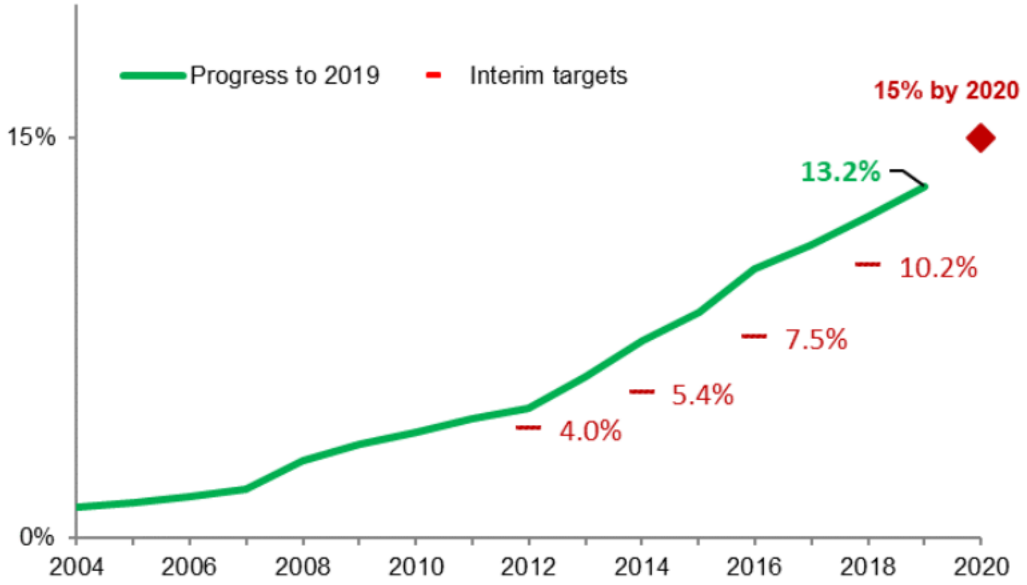


Figure 35: Progress against Renewable Energy Directive and UK targets, share of renewable energy in final energy consumption

Appendix 2: Excerpts from the 'Price driver database' and calculation of avoided emissions

In Figure 36 below, a screenshot from the 'Price driver database' and the price driver renewable electricity can be seen. Figure 37 shows a zoomed in area of the previous Figure, but with formulas shown. Two experts are also shown from the calculation of the avoided emissions: Figure 38 showing the calculation of the emissions, and Figure 39 showing the dynamic emission factors.

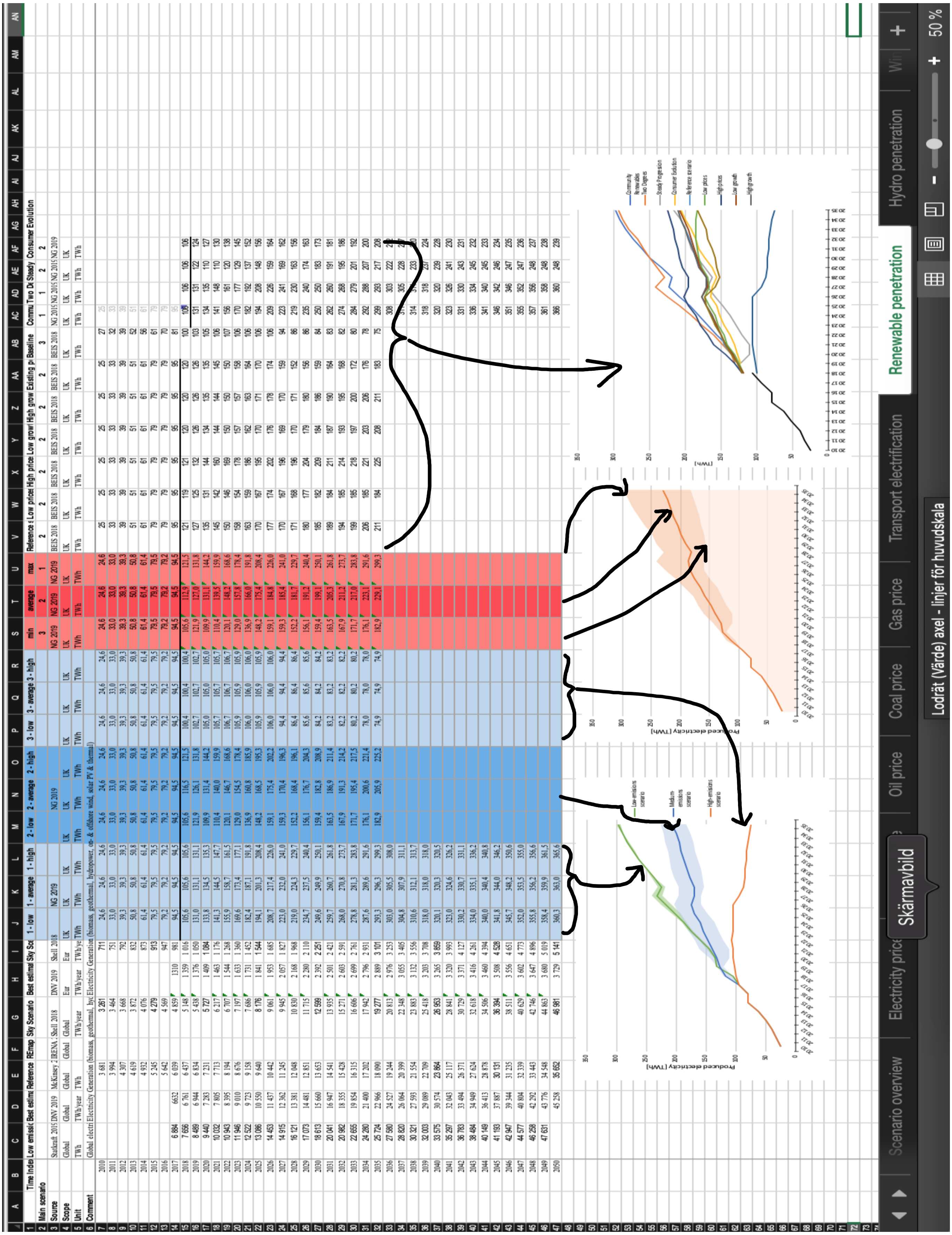
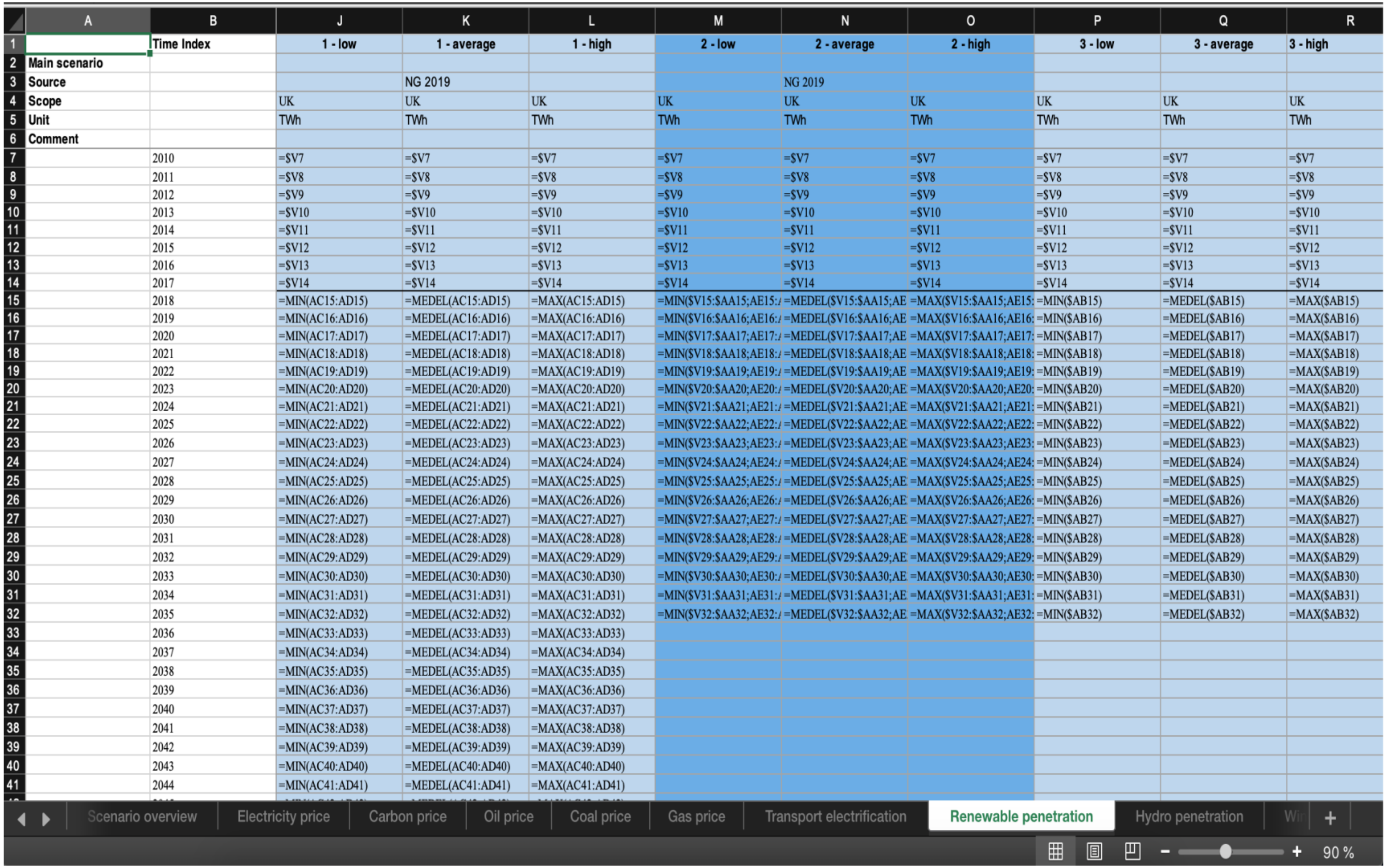
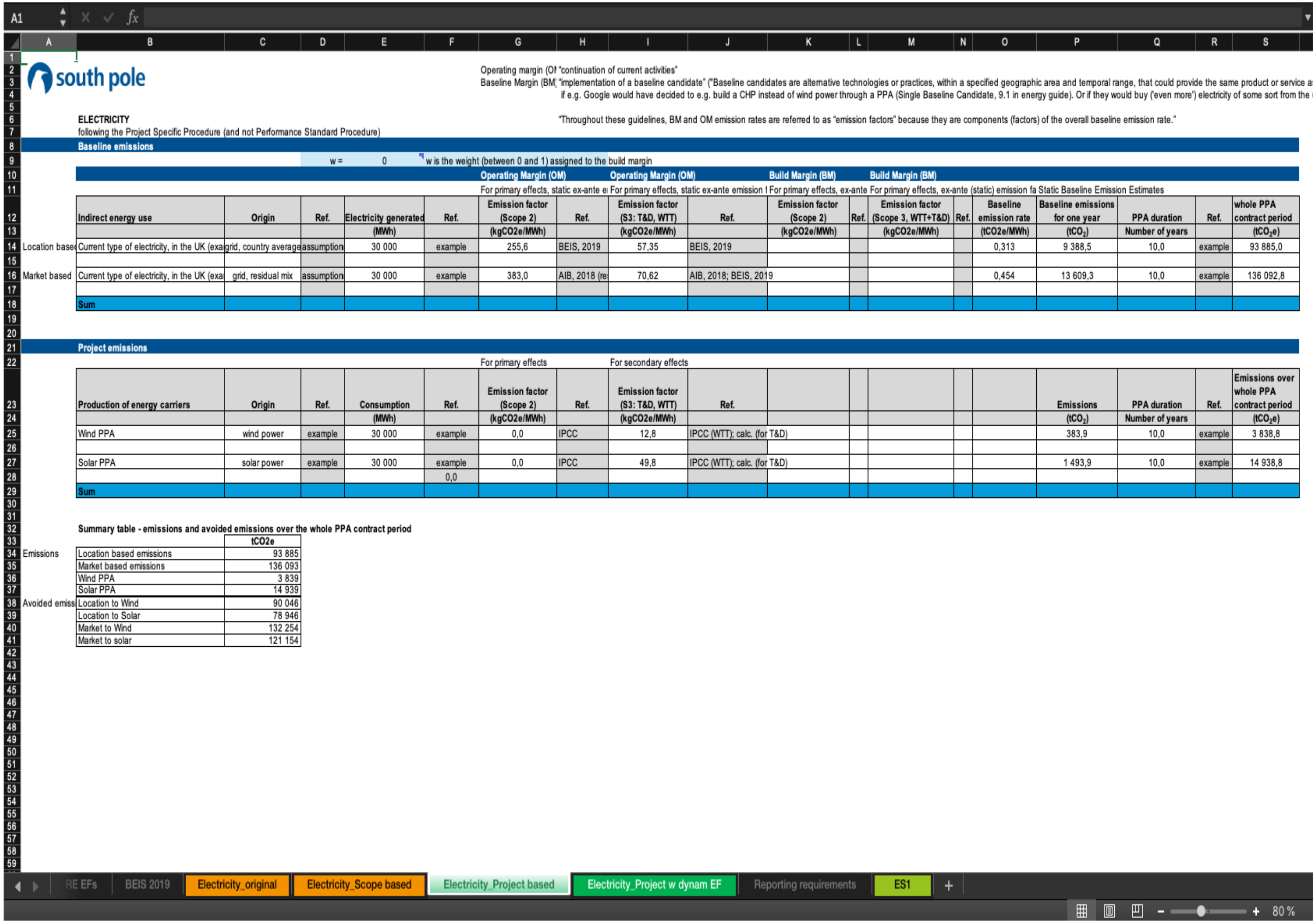


Figure 36: Excerpt from the 'Price driver database' showing the data and calculation for the price driver renewable electricity. Arrows are pointing from columns with data to the graphs in the figures.



	A	B	J	K	L	M	N	O	P	Q	R
1		Time Index	1 - low	1 - average	1 - high	2 - low	2 - average	2 - high	3 - low	3 - average	3 - high
2	Main scenario										
3	Source			NG 2019			NG 2019				
4	Scope		UK	UK	UK	UK	UK	UK	UK	UK	UK
5	Unit		TWh	TWh	TWh	TWh	TWh	TWh	TWh	TWh	TWh
6	Comment										
7		2010	=$V7	=$V7	=$V7	=$V7	=$V7	=$V7	=$V7	=$V7	=$V7
8		2011	=$V8	=$V8	=$V8	=$V8	=$V8	=$V8	=$V8	=$V8	=$V8
9		2012	=$V9	=$V9	=$V9	=$V9	=$V9	=$V9	=$V9	=$V9	=$V9
10		2013	=$V10	=$V10	=$V10	=$V10	=$V10	=$V10	=$V10	=$V10	=$V10
11		2014	=$V11	=$V11	=$V11	=$V11	=$V11	=$V11	=$V11	=$V11	=$V11
12		2015	=$V12	=$V12	=$V12	=$V12	=$V12	=$V12	=$V12	=$V12	=$V12
13		2016	=$V13	=$V13	=$V13	=$V13	=$V13	=$V13	=$V13	=$V13	=$V13
14		2017	=$V14	=$V14	=$V14	=$V14	=$V14	=$V14	=$V14	=$V14	=$V14
15		2018	=MIN(AC15:AD15)	=MEDEL(AC15:AD15)	=MAX(AC15:AD15)	=MIN($V15:$AA15;AE15:	=MEDEL($V15:$AA15;AE	=MAX($V15:$AA15;AE15:	=MIN($AB15)	=MEDEL($AB15)	=MAX($AB15)
16		2019	=MIN(AC16:AD16)	=MEDEL(AC16:AD16)	=MAX(AC16:AD16)	=MIN($V16:$AA16;AE16:	=MEDEL($V16:$AA16;AE	=MAX($V16:$AA16;AE16:	=MIN($AB16)	=MEDEL($AB16)	=MAX($AB16)
17		2020	=MIN(AC17:AD17)	=MEDEL(AC17:AD17)	=MAX(AC17:AD17)	=MIN($V17:$AA17;AE17:	=MEDEL($V17:$AA17;AE	=MAX($V17:$AA17;AE17:	=MIN($AB17)	=MEDEL($AB17)	=MAX($AB17)
18		2021	=MIN(AC18:AD18)	=MEDEL(AC18:AD18)	=MAX(AC18:AD18)	=MIN($V18:$AA18;AE18:	=MEDEL($V18:$AA18;AE	=MAX($V18:$AA18;AE18:	=MIN($AB18)	=MEDEL($AB18)	=MAX($AB18)
19		2022	=MIN(AC19:AD19)	=MEDEL(AC19:AD19)	=MAX(AC19:AD19)	=MIN($V19:$AA19;AE19:	=MEDEL($V19:$AA19;AE	=MAX($V19:$AA19;AE19:	=MIN($AB19)	=MEDEL($AB19)	=MAX($AB19)
20		2023	=MIN(AC20:AD20)	=MEDEL(AC20:AD20)	=MAX(AC20:AD20)	=MIN($V20:$AA20;AE20:	=MEDEL($V20:$AA20;AE	=MAX($V20:$AA20;AE20:	=MIN($AB20)	=MEDEL($AB20)	=MAX($AB20)
21		2024	=MIN(AC21:AD21)	=MEDEL(AC21:AD21)	=MAX(AC21:AD21)	=MIN($V21:$AA21;AE21:	=MEDEL($V21:$AA21;AE	=MAX($V21:$AA21;AE21:	=MIN($AB21)	=MEDEL($AB21)	=MAX($AB21)
22		2025	=MIN(AC22:AD22)	=MEDEL(AC22:AD22)	=MAX(AC22:AD22)	=MIN($V22:$AA22;AE22:	=MEDEL($V22:$AA22;AE	=MAX($V22:$AA22;AE22:	=MIN($AB22)	=MEDEL($AB22)	=MAX($AB22)
23		2026	=MIN(AC23:AD23)	=MEDEL(AC23:AD23)	=MAX(AC23:AD23)	=MIN($V23:$AA23;AE23:	=MEDEL($V23:$AA23;AE	=MAX($V23:$AA23;AE23:	=MIN($AB23)	=MEDEL($AB23)	=MAX($AB23)
24		2027	=MIN(AC24:AD24)	=MEDEL(AC24:AD24)	=MAX(AC24:AD24)	=MIN($V24:$AA24;AE24:	=MEDEL($V24:$AA24;AE	=MAX($V24:$AA24;AE24:	=MIN($AB24)	=MEDEL($AB24)	=MAX($AB24)
25		2028	=MIN(AC25:AD25)	=MEDEL(AC25:AD25)	=MAX(AC25:AD25)	=MIN($V25:$AA25;AE25:	=MEDEL($V25:$AA25;AE	=MAX($V25:$AA25;AE25:	=MIN($AB25)	=MEDEL($AB25)	=MAX($AB25)
26		2029	=MIN(AC26:AD26)	=MEDEL(AC26:AD26)	=MAX(AC26:AD26)	=MIN($V26:$AA26;AE26:	=MEDEL($V26:$AA26;AE	=MAX($V26:$AA26;AE26:	=MIN($AB26)	=MEDEL($AB26)	=MAX($AB26)
27		2030	=MIN(AC27:AD27)	=MEDEL(AC27:AD27)	=MAX(AC27:AD27)	=MIN($V27:$AA27;AE27:	=MEDEL($V27:$AA27;AE	=MAX($V27:$AA27;AE27:	=MIN($AB27)	=MEDEL($AB27)	=MAX($AB27)
28		2031	=MIN(AC28:AD28)	=MEDEL(AC28:AD28)	=MAX(AC28:AD28)	=MIN($V28:$AA28;AE28:	=MEDEL($V28:$AA28;AE	=MAX($V28:$AA28;AE28:	=MIN($AB28)	=MEDEL($AB28)	=MAX($AB28)
29		2032	=MIN(AC29:AD29)	=MEDEL(AC29:AD29)	=MAX(AC29:AD29)	=MIN($V29:$AA29;AE29:	=MEDEL($V29:$AA29;AE	=MAX($V29:$AA29;AE29:	=MIN($AB29)	=MEDEL($AB29)	=MAX($AB29)
30		2033	=MIN(AC30:AD30)	=MEDEL(AC30:AD30)	=MAX(AC30:AD30)	=MIN($V30:$AA30;AE30:	=MEDEL($V30:$AA30;AE	=MAX($V30:$AA30;AE30:	=MIN($AB30)	=MEDEL($AB30)	=MAX($AB30)
31		2034	=MIN(AC31:AD31)	=MEDEL(AC31:AD31)	=MAX(AC31:AD31)	=MIN($V31:$AA31;AE31:	=MEDEL($V31:$AA31;AE	=MAX($V31:$AA31;AE31:	=MIN($AB31)	=MEDEL($AB31)	=MAX($AB31)
32		2035	=MIN(AC32:AD32)	=MEDEL(AC32:AD32)	=MAX(AC32:AD32)	=MIN($V32:$AA32;AE32:	=MEDEL($V32:$AA32;AE	=MAX($V32:$AA32;AE32:	=MIN($AB32)	=MEDEL($AB32)	=MAX($AB32)
33		2036	=MIN(AC33:AD33)	=MEDEL(AC33:AD33)	=MAX(AC33:AD33)						
34		2037	=MIN(AC34:AD34)	=MEDEL(AC34:AD34)	=MAX(AC34:AD34)						
35		2038	=MIN(AC35:AD35)	=MEDEL(AC35:AD35)	=MAX(AC35:AD35)						
36		2039	=MIN(AC36:AD36)	=MEDEL(AC36:AD36)	=MAX(AC36:AD36)						
37		2040	=MIN(AC37:AD37)	=MEDEL(AC37:AD37)	=MAX(AC37:AD37)						
38		2041	=MIN(AC38:AD38)	=MEDEL(AC38:AD38)	=MAX(AC38:AD38)						
39		2042	=MIN(AC39:AD39)	=MEDEL(AC39:AD39)	=MAX(AC39:AD39)						
40		2043	=MIN(AC40:AD40)	=MEDEL(AC40:AD40)	=MAX(AC40:AD40)						
41		2044	=MIN(AC41:AD41)	=MEDEL(AC41:AD41)	=MAX(AC41:AD41)						

Figure 37: Excerpt from 'Price driver database' from the price driver renewable electricity, showing the formulas for calculating the emissions for the three general emissions scenarios, where 1 is low-emissions scenario, 2 is medium-emissions scenario and 3 is high-emissions scenario. The terms low, average and high indicate the minumum, average and maximum values for each general emissions scenario.



A1

south pole

Operating margin (OI "continuation of current activities"

Baseline Margin (BM) "implementation of a baseline candidate" ("Baseline candidates are alternative technologies or practices, within a specified geographic area and temporal range, that could provide the same product or service a

if e.g. Google would have decided to e.g. build a CHP instead of wind power through a PPA (Single Baseline Candidate, 9.1 in energy guide). Or if they would buy ('even more') electricity of some sort from the

"Throughout these guidelines, BM and OM emission rates are referred to as "emission factors" because they are components (factors) of the overall baseline emission rate."

ELECTRICITY

following the Project Specific Procedure (and not Performance Standard Procedure)

Baseline emissions

w = 0 w is the weight (between 0 and 1) assigned to the build margin

						Operating Margin (OM) For primary effects, static ex-ante e		Operating Margin (OM) For primary effects, static ex-ante emission f		Build Margin (BM) For primary effects, ex-ante		Build Margin (BM) For primary effects, ex-ante (static) emission fa		Static Baseline Emission Estimates				
	Indirect energy use	Origin	Ref.	Electricity generated (MWh)	Ref.	Emission factor (Scope 2) (kgCO2e/MWh)	Ref.	Emission factor (S3: T&D, WTT) (kgCO2e/MWh)	Ref.	Emission factor (Scope 2) (kgCO2e/MWh)	Ref.	Emission factor (Scope 3, WTT+T&D) (kgCO2e/MWh)	Ref.	Baseline emission rate (tCO2e/MWh)	Baseline emissions for one year (tCO$_2$)	PPA duration Number of years	Ref.	whole PPA contract period (tCO$_2$e)
Location base	Current type of electricity, in the UK (exa	grid, country average	assumption	30 000	example	255,6	BEIS, 2019	57,35	BEIS, 2019					0,313	9 388,5	10,0	example	93 885,0
Market based	Current type of electricity, in the UK (exa	grid, residual mix	assumption	30 000	example	383,0	AIB, 2018 (re	70,62	AIB, 2018; BEIS, 2019					0,454	13 609,3	10,0	example	136 092,8
	Sum																	

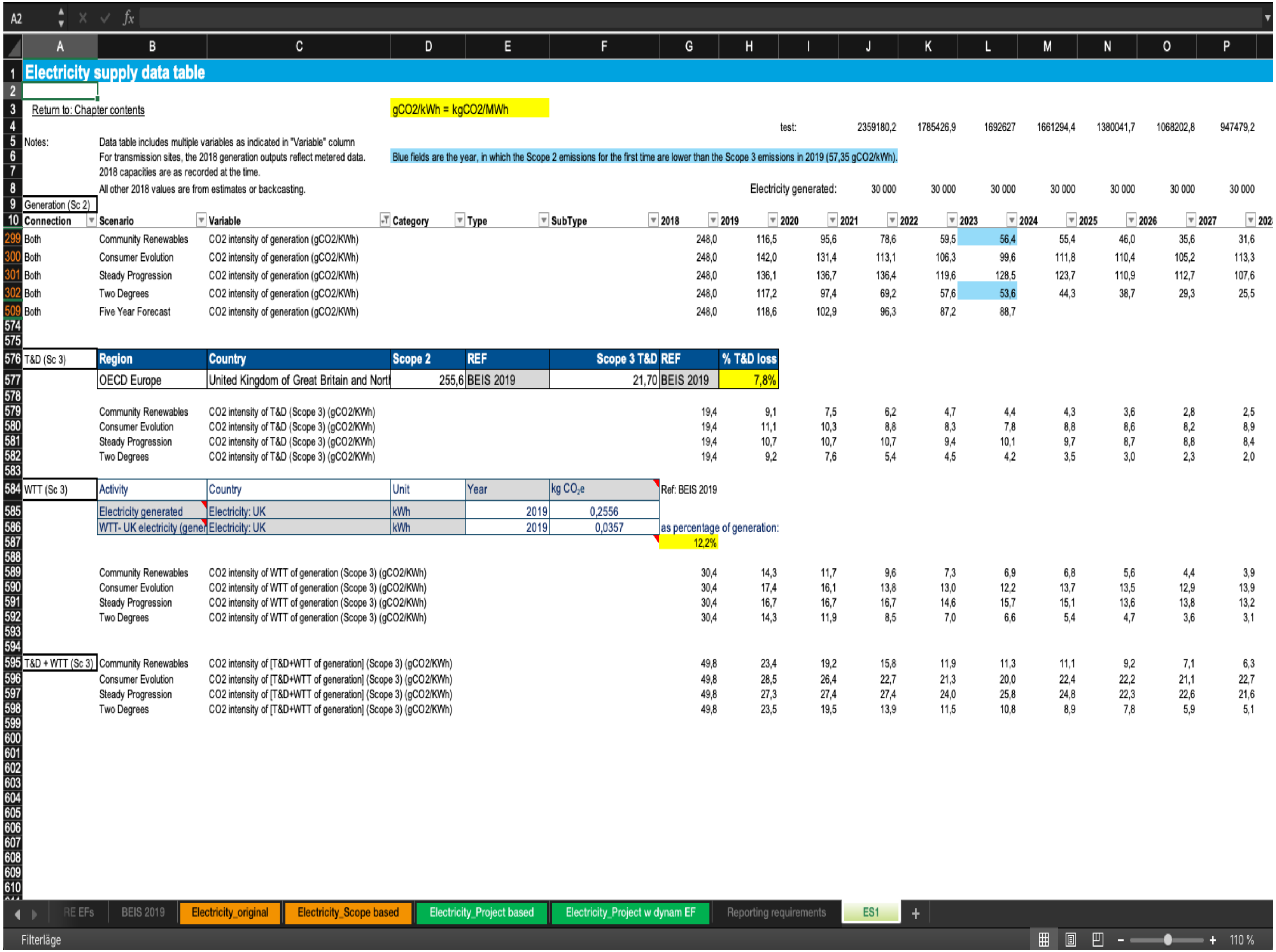
Project emissions

	For primary effects		For secondary effects														
Production of energy carriers	Origin	Ref.	Consumption (MWh)	Ref.	Emission factor (Scope 2) (kgCO2e/MWh)	Ref.	Emission factor (S3: T&D, WTT) (kgCO2e/MWh)	Ref.						Emissions (tCO$_2$)	PPA duration Number of years	Ref.	Emissions over whole PPA contract period (tCO$_2$e)
Wind PPA	wind power	example	30 000	example	0,0	IPCC	12,8	IPCC (WTT); calc. (for T&D)						383,9	10,0	example	3 838,8
Solar PPA	solar power	example	30 000	example	0,0	IPCC	49,8	IPCC (WTT); calc. (for T&D)						1 493,9	10,0	example	14 938,8
				0,0													
Sum																	

Summary table - emissions and avoided emissions over the whole PPA contract period

		tCO2e
Emissions	Location based emissions	93 885
	Market based emissions	136 093
	Wind PPA	3 839
	Solar PPA	14 939
Avoided emiss	Location to Wind	90 046
	Location to Solar	78 946
	Market to Wind	132 254
	Market to solar	121 154

Figure 38: Excerpt from the data sheet with calculation of the avoided emissions using static emission factors



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	Electricity supply data table															
2																
3		Return to: Chapter contents		gCO2/kWh = kgCO2/MWh												
4									test:	2359180,2	1785426,9	1692627	1661294,4	1380041,7	1068202,8	947479,2
5	Notes:	Data table includes multiple variables as indicated in "Variable" column														
6		For transmission sites, the 2018 generation outputs reflect metered data.		Blue fields are the year, in which the Scope 2 emissions for the first time are lower than the Scope 3 emissions in 2019 (57,35 gCO2/kWh).												
7		2018 capacities are as recorded at the time.														
8		All other 2018 values are from estimates or backcasting.							Electricity generated:	30 000	30 000	30 000	30 000	30 000	30 000	30 000
9	Generation (Sc 2)															
10	Connection	Scenario	Variable	Category	Type	SubType	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
299	Both	Community Renewables	CO2 intensity of generation (gCO2/KWh)				248,0	116,5	95,6	78,6	59,5	56,4	55,4	46,0	35,6	31,6
300	Both	Consumer Evolution	CO2 intensity of generation (gCO2/KWh)				248,0	142,0	131,4	113,1	106,3	99,6	111,8	110,4	105,2	113,3
301	Both	Steady Progression	CO2 intensity of generation (gCO2/KWh)				248,0	136,1	136,7	136,4	119,6	128,5	123,7	110,9	112,7	107,6
302	Both	Two Degrees	CO2 intensity of generation (gCO2/KWh)				248,0	117,2	97,4	69,2	57,6	53,6	44,3	38,7	29,3	25,5
509	Both	Five Year Forecast	CO2 intensity of generation (gCO2/KWh)				248,0	118,6	102,9	96,3	87,2	88,7				
574																
575																
576	T&D (Sc 3)	Region	Country	Scope 2	REF	Scope 3 T&D	REF	% T&D loss								
577		OECD Europe	United Kingdom of Great Britain and North	255,6	BEIS 2019	21,70	BEIS 2019	7,8%								
578																
579		Community Renewables	CO2 intensity of T&D (Scope 3) (gCO2/KWh)				19,4	9,1	7,5	6,2	4,7	4,4	4,3	3,6	2,8	2,5
580		Consumer Evolution	CO2 intensity of T&D (Scope 3) (gCO2/KWh)				19,4	11,1	10,3	8,8	8,3	7,8	8,8	8,6	8,2	8,9
581		Steady Progression	CO2 intensity of T&D (Scope 3) (gCO2/KWh)				19,4	10,7	10,7	10,7	9,4	10,1	9,7	8,7	8,8	8,4
582		Two Degrees	CO2 intensity of T&D (Scope 3) (gCO2/KWh)				19,4	9,2	7,6	5,4	4,5	4,2	3,5	3,0	2,3	2,0
583																
584	WTT (Sc 3)	Activity	Country	Unit	Year	kg CO_2e	Ref: BEIS 2019									
585		Electricity generated	Electricity: UK	kWh	2019	0,2556										
586		WTT- UK electricity (gener	Electricity: UK	kWh	2019	0,0357	as percentage of generation:									
587							12,2%									
588																
589		Community Renewables	CO2 intensity of WTT of generation (Scope 3) (gCO2/KWh)				30,4	14,3	11,7	9,6	7,3	6,9	6,8	5,6	4,4	3,9
590		Consumer Evolution	CO2 intensity of WTT of generation (Scope 3) (gCO2/KWh)				30,4	17,4	16,1	13,8	13,0	12,2	13,7	13,5	12,9	13,9
591		Steady Progression	CO2 intensity of WTT of generation (Scope 3) (gCO2/KWh)				30,4	16,7	16,7	16,7	14,6	15,7	15,1	13,6	13,8	13,2
592		Two Degrees	CO2 intensity of WTT of generation (Scope 3) (gCO2/KWh)				30,4	14,3	11,9	8,5	7,0	6,6	5,4	4,7	3,6	3,1
593																
594																
595	T&D + WTT (Sc 3)	Community Renewables	CO2 intensity of [T&D+WTT of generation] (Scope 3) (gCO2/KWh)				49,8	23,4	19,2	15,8	11,9	11,3	11,1	9,2	7,1	6,3
596		Consumer Evolution	CO2 intensity of [T&D+WTT of generation] (Scope 3) (gCO2/KWh)				49,8	28,5	26,4	22,7	21,3	20,0	22,4	22,2	21,1	22,7
597		Steady Progression	CO2 intensity of [T&D+WTT of generation] (Scope 3) (gCO2/KWh)				49,8	27,3	27,4	27,4	24,0	25,8	24,8	22,3	22,6	21,6
598		Two Degrees	CO2 intensity of [T&D+WTT of generation] (Scope 3) (gCO2/KWh)				49,8	23,5	19,5	13,9	11,5	10,8	8,9	7,8	5,9	5,1

Figure 39: Excerpt from the data workbook of the calculation of avoided emissions, showing the dynamic emission factors

Appendix 3: Price drivers, and forward curves from BEIS and the PPA price model

As written in section 8.2 about the future electricity price from BEIS, it was added to the 'Price driver database' for the other master thesis student Moritz Wüthrich to compare it to the modeled power price. The result of this is shown in Figure 40 below, together with the normalized price drivers.

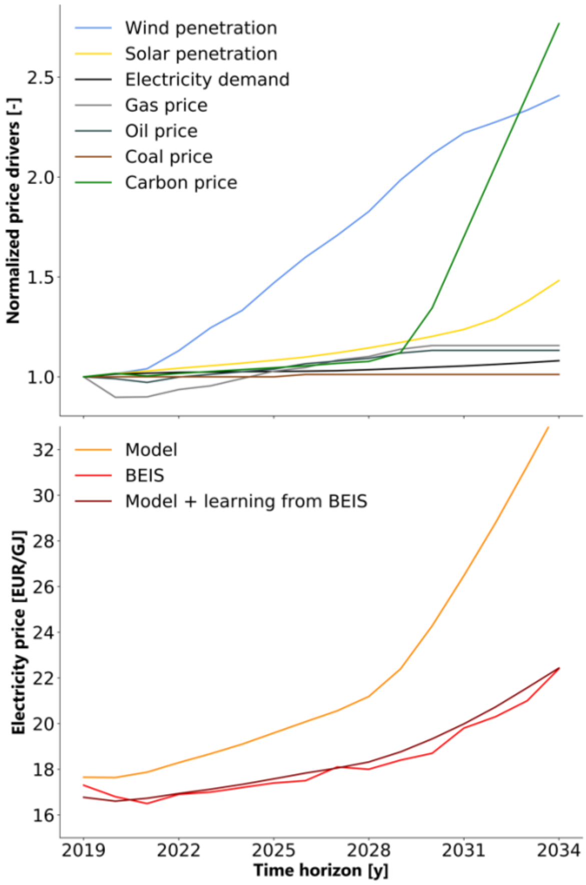


Figure 40: Normalised price drivers from BEIS and FES, and comparison of the electricity price from BEIS with the South Pole PPA price model, adopted from (Wüthrich, 2020)

Appendix 4: Average future main price drivers with uncertainty

In the sections 8.3 to 8.5, the text referred to extra figures created, but which weren't relevant for the analysis. These are shown below.

For the results of the general emissions scenarios to be useful to corporate clients to South Pole, they were needed to be simplified. Instead of modelling the future electricity price based on three emissions scenarios with respective uncertainties (giving rise to nine different values), only an average of all the price drivers from all likely[10] scenarios were calculated and plotted together with an uncertainty (minimum and maximum of the likely scenarios), which is shown in Figure 41 below.

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[10] Excluding the EEP 'baseline emissions scenario' because it only shows what would have happened if the Low Carbon Transition Plan from 2009 wouldn't have been enforced.

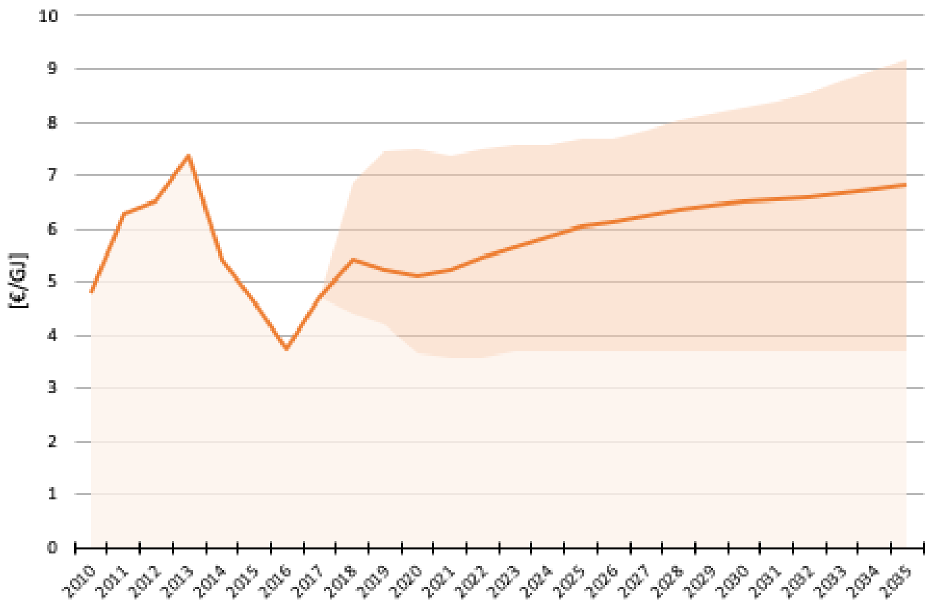

Figure 41: Historic and future gas price based on an average across all likely scenarios and uncertainty bands from the absolute maximum and minimum values until 2035

The figure shows that the average trend of the future gas price is upward sloping after a decline until 2020. The uncertainty band is relatively broad, and especially broad towards the lower uncertainty limit.

Similar to the gas price, an overall average, maximum and minimum value of all the likely scenarios were calculated and plotted for the renewable electricity production. The result can be seen in Figure 42.

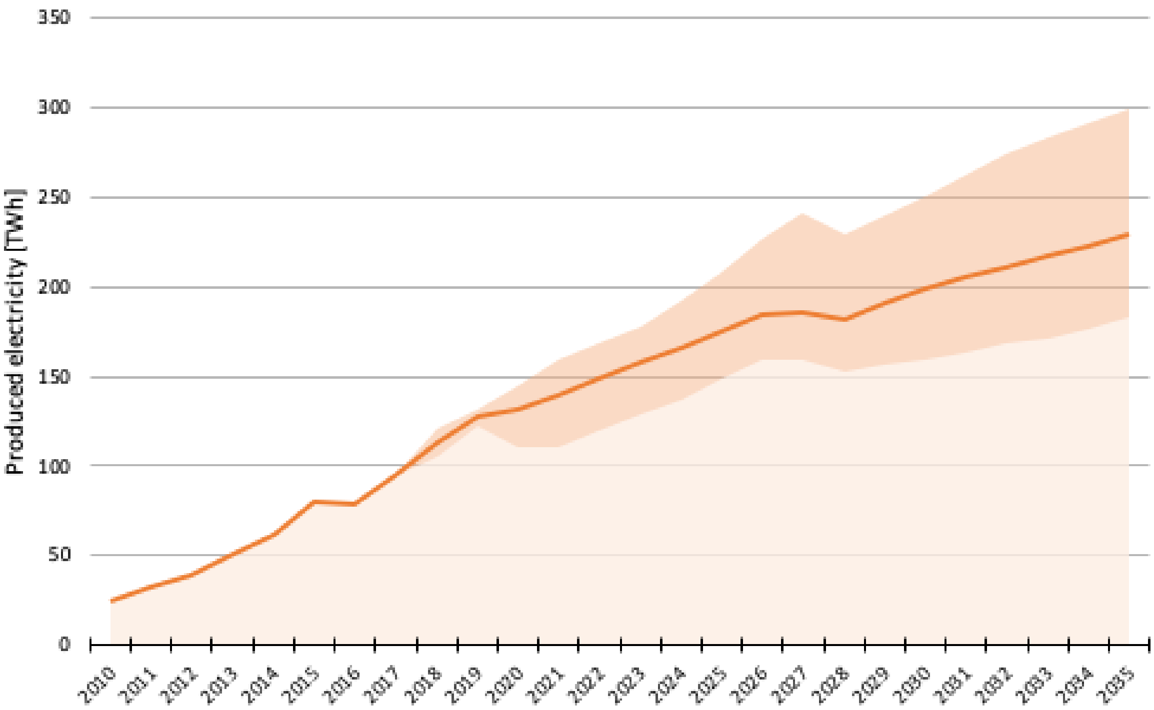

Figure 42: Renewable electricity production: historic values and future development based on an average of all future likely scenarios and uncertainty bands from the absolute maximum and minimum values until 2035

The future penetration of renewable electricity based on an average across all scenarios shows an upward sloping trend until 2035, where it reaches 229 TWh/year, with a depression in 2027–2028. The uncertainty is increasing the longer into the future it is shown.

The same type of graph was also made for the carbon price, which can be seen below in Figure 43. The overall average is increasing until 2030, after which the curve rises more sharply until 2035, ending at 93 €/tCO_2.

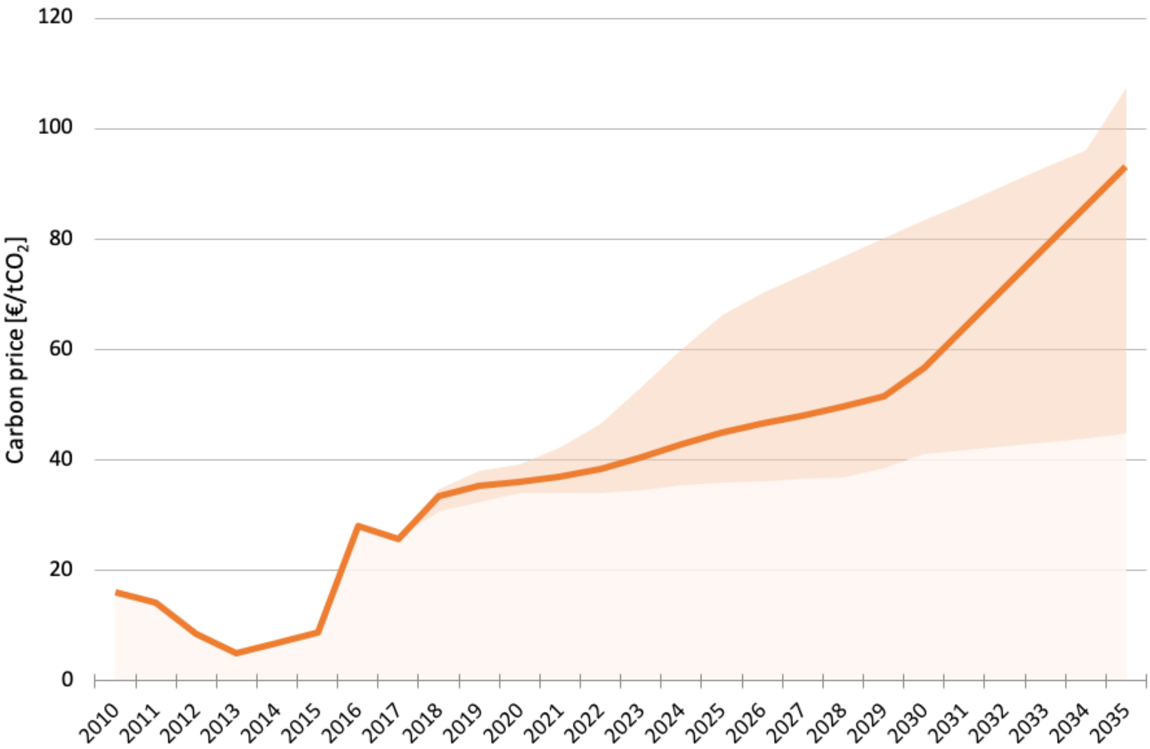

Figure 43: Historic carbon price and future development based on all likely scenarios, including uncertainty bands between the absolute maximum and minimum values until 2035

Appendix 5: Results in table format from calculation of reduced emissions using dynamic baseline emission factors

Table 11: Baseline, project emissions and avoided emissions over the whole PPA contract period based on dynamic ex-post emission factors. The relative emission changes indicated with an asterisk are the ones exemplified in Figure 30.

			[tCO_2e]	
Emissions	Baseline emissions	Community Renewables (grid mix)	15,973	
	Baseline emissions	Consumer Evolution (grid mix)	40,573	
	Baseline emissions	Steady Progression (grid mix)	40,415	
	Baseline emissions	Two Degrees (grid mix)	14,462	
	Project emissions	Wind PPA	3,839	
	Project emissions	Solar PPA	14,939	
Avoided emissions	**Baseline emissions**	**Project emissions**		**Reduction**
	Community Renewables (grid mix)	Wind PPA	12,135	-76 %
	Consumer Evolution (grid mix)	Wind PPA	36,734	-91 %

	Steady Progression (grid mix)	Wind PPA	36,576	-91 %*
	Two Degrees (grid mix)	Wind PPA	10,623	-73 %
	Community Renewables (grid mix)	Solar PPA	1,035	-6 %
	Consumer Evolution (grid mix)	Solar PPA	25,634	-63 %
	Steady Progression (grid mix)	Solar PPA	25,476	-63 %
	Two Degrees (grid mix)	Solar PPA	-477	+3 %*