The effects of PPAs on the electricity market

TNO Public ❯ TNO 2024 R10051
22 April 2024

Energy & Materials
Transition
www.tno.nl
+31 88 866 50 65
info@tno.nl

TNO 2024 R10051 – 22 April 2024

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Author(s)	Pieter Verstraten, Martin Wevers, Aitazaz Raja
Classification report	TNO Public
Title	TNO Public
Report text	TNO Public
Number of pages	22 (excl. front and back cover)
Number of appendices	0

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The effects of PPAs on the electricity market

Power Purchase Agreements (PPAs) are expected to play an increasingly important role in future energy markets. They are seen as one of the most important tools in the EU electricity market reform, both to decrease price volatility and to increase bankability of future renewable projects. Next to that, the delegated act on green hydrogen specifically mentions PPAs in the additionality requirement as a condition for hydrogen production to be considered green.

The impact of PPAs on the market is unknown and uncertain. There exist several types of PPAs and not every type of PPA affects the market. PPAs can impact the market in two ways:

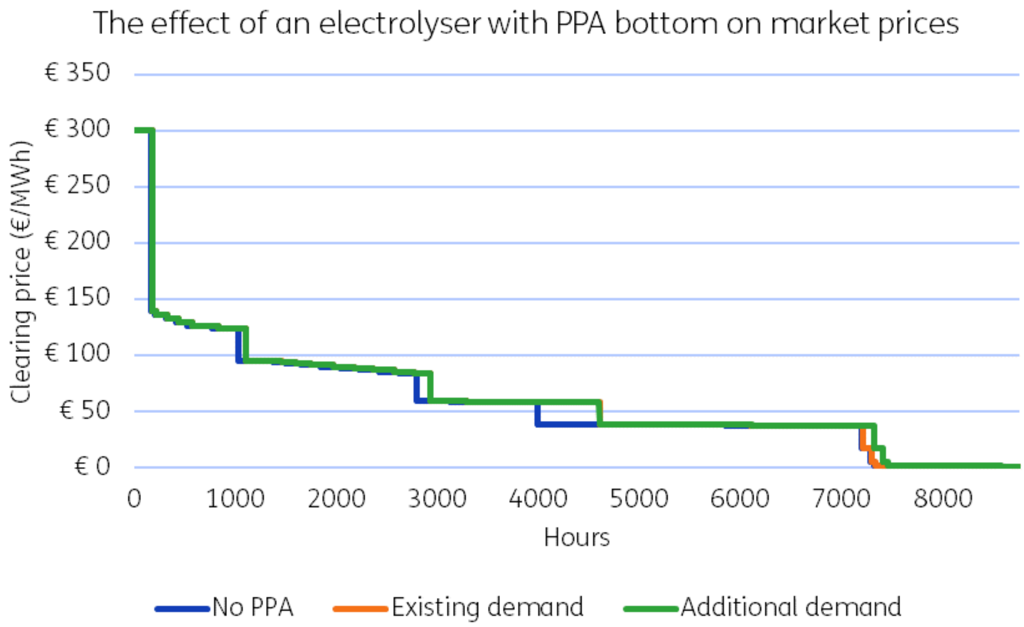
- They can impact the operation of the energy system;
- They can impact the state of the energy system.

Due to PPAs the energy system looks and works differently.

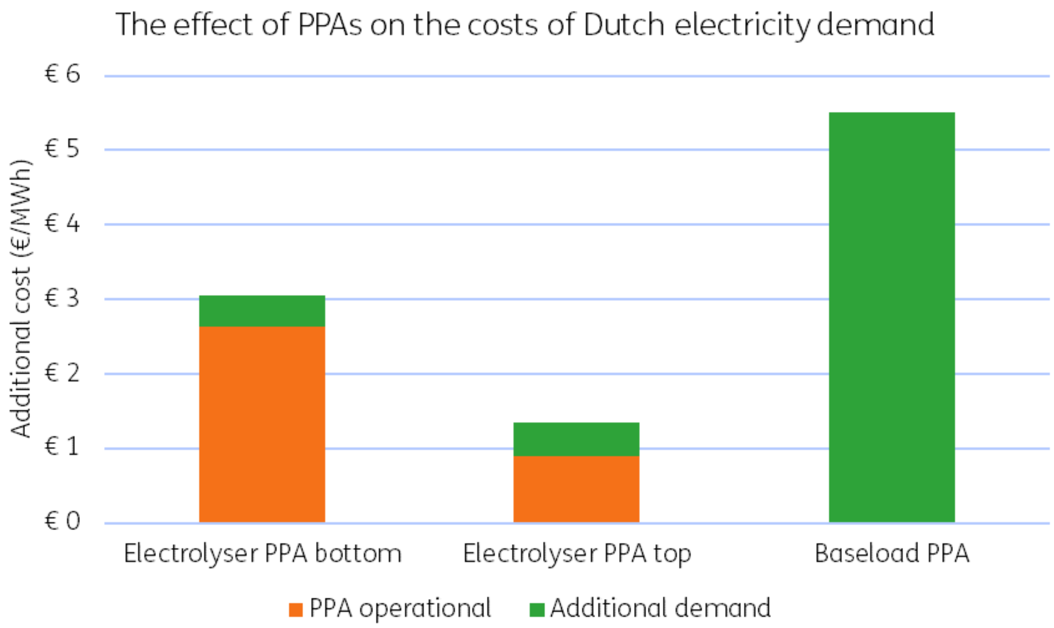
We use 9 cases to showcase the impact of PPAs. With these 9 cases we show that PPAs increase market prices. The impact of a PPA between offshore wind and an electrolyser on the market can be separated into three cases:

- More power plants are necessary to satisfy demand;
- P2H sets the price instead of electrolysers;
- Electrolysers continue to set the price.

More power plants are necessary to satisfy demand when the electrolyser receives renewable wind energy, which is needed to satisfy the inelastic Dutch electricity demand. P2H sets the price instead of electrolysers when in the base case the electrolysers would already set the price on the spot market. This occurs, because less wind energy is available on the spot market, which would satisfy the full P2H capacity. Electrolysers continue to set the price when the PPA causes additional electrolyser capacity. The price is set by biomass power plants when the electrolyser capacity has been fully cleared. When there is more electrolyser capacity, it takes longer before this is the case.



The higher market prices impact the market players active on the spot market, also the market players which do not have a PPA. The Dutch electricity demand has to pay higher prices for its demand than in the base case. Suppliers obtains a higher revenue for the energy put on the spot market. Flexible assets such as electrolysers – the remaining electrolyser capacity which does not have a PPA – and Power2Heat pay a different price for their demand and also clear a different total volume.



This research has been performed as a part of a knowledge investment project.

Contents

1 PPAs will play a role in the future electricity markets

1.1 To reach the Dutch offshore wind goals in 2030, PPAs are expected to play a role

Offshore wind will play a large role in the future Dutch energy system. The goal of the Dutch government is to reach a capacity of 21.5 GW in 2030 and 70 GW in 2050. There are several barriers to reach this goal. Power Purchase Agreements (PPAs) are expected to help in resolving two barriers: system integration and bankability.

PPAs help to ensure the smooth system integration of offshore wind power by providing stability and predictability to both energy producers, consumers and grid operators. Additionally, the financial certainty offered by PPAs incentivizes necessary investments, facilitating the seamless integration of offshore wind power into the energy system.

PPAs enhance the bankability of offshore wind projects by providing a stable revenue stream and reducing financial risks for project developers and investors. These agreements establish a long-term commitment between offshore wind and a consumer. By securing a guaranteed revenue stream, PPAs offer financial certainty, which is particularly crucial for offshore wind projects with high initial capital costs and long payback periods. Moreover, PPAs can help attract financing from lenders and investors by demonstrating a reliable revenue source, thereby lowering the cost of capital and improving the project's overall financial viability.

1.2 The impact of PPAs on the market is unknown and uncertain

The impact of PPAs on the electricity market is uncertain due to various factors influencing market dynamics. While PPAs can provide stability and long-term commitments for renewable energy projects, their broader effects on the electricity market are complex. PPAs have the potential to influence electricity prices, market structure, and investment decisions, but their exact impact depends on factors such as regulatory frameworks, market conditions, and technological advancements. This impact also depends on the type of PPA, of which there are many. The increasing share of PPAs will reshape market dynamics by changing the relationship between generators, utilities, and consumers and incentivizing investments.

1.3 PPAs can have an impact on the market

PPAs establish a long-term commitment between offshore wind and a consumer, and can affect how they behave on the electricity market. This change in behaviour can impact the market dynamics. As the share of PPAs in the electricity market increases, the impact becomes more prominent. How and when PPAs impact the market is the topic of Chapter 2 and the possible extend of this impact and how it translates to market participants is covered in Chapter 3. Finally, the impact of other financial contracts is discussed in Chapter 4.

2 When does a PPA affect the market?

PPAs are expected to play an increasingly important role in future energy markets. They are seen as one of the most important tools in the EU electricity market reform, both to decrease price volatility and to increase bankability of future renewable projects. Next to that, the delegated act on green hydrogen specifically mentions PPAs in the additionality requirement as a condition for hydrogen production to be considered green.

However, the potential impact of PPAs on the electricity market is often overlooked. In this section, we look at how different types of PPAs could affect the market.

2.1 There exist several types of PPAs

A Power Purchase Agreement (PPA) is a long-term agreement between two parties: A producer and a consumer of electricity. There is no standard PPA, as parties are free to define their own conditions on e.g. volume, prices or penalties. However, in general PPAs can be split into two categories: Physical and Virtual PPAs.

In a **Physical PPA** the producer delivers the electricity to the consumer **without using an electricity market**. This can be:

- On-site: when producer and consumer are co-located, in this case the electricity is really physically delivered.
- Off-site: when there is a public grid between the producer and consumer.

In a **Virtual PPA** the physical delivery of electricity is decoupled from the financial settlement. This is done by **bidding the produced electricity on an electricity market** (mostly at the day-ahead market). Next to that, the consumer bids the exact same amount of demand at the same electricity market. After the clearing of the market, there is a financial settlement between the two parties: the difference between the clearing price and the agreed-upon price, multiplied with the delivered electricity.

The important difference between the Physical and the Virtual PPA is that in the Physical PPA both production and consumption are taken out of the market (compared to a situation without a PPA), whereas in the Virtual PPA they are bid into the market.

Next to the division between Physical and Virtual PPAs, another type of PPA is relevant, which we will refer to as the **Operationally Constrained PPA.** Whereas in a normal PPA the consumer is free to do whatever it pleases with the bought electricity (e.g. consume it, sell it back to the market at higher prices), in the operationally constrained PPA **the consumer has to consume (part of) the electricity**. Such a constraint is set in case of limited grid capacity, e.g. for the IJmuiden Ver Beta Tender to limit congestion on the 380kV-grid.

2.2 Not every type of PPA affects the market

As shown in the previous section, a Virtual PPA is just a financial settlement between a producer and consumer of electricity. Both the produced and the demanded electricity are traded on an electricity market, just like it would without a PPA. Therefore**, a Virtual PPA does not affect the market in the short term.** In the long term it can effect investment incentives by impacting the risk exposure of the producer and consumer.

In this section, we will dive deeper into which (and in which cases) PPAs do affect the market. First, market clearing principles are visualized, after which the physical PPA and Operationally Constrained PPA are discussed. This is concluded with some remarks on PPAs for green hydrogen and the effect of additional demand.

2.2.1 Market clearing visualisation

To understand in which cases electricity markets can be affected by PPAs, the clearing mechanism of electricity markets (e.g. day-ahead market) is visualised in a very simplified manner in Figure 1.

GW	1	2	3	4	5	6	7	8	9	10	11	12
Production	0	0	0	0	5	5	5	100	100	100		
Demand	200	200	200	200	200	20	20	20	10	10	10	

Legend		
wind	solar	gas
base	P2G	P2H

Figure 1: Simplified visulisation of market clearing. Cleared 7 GW at €20/MWh.

Imagine a simplified electricity market with three different production types (wind, solar and gas) and three different demand types (baseload, power-to-gas and power-to heat). Each asset type bids its available capacity and its marginal costs (for demand the willingness-to-pay). In Figure 1 the available capacity is represented by the amount of GW blocks (e.g. for wind this is 4 GW) and the marginal costs by the number in the block (e.g. for wind this is €0/MWh). The production is sorted from left to right from the cheapest marginal costs to the most expensive, whereas for the demand this is the other way around.

To determine the market clearing amount, it is checked from the left to the right whether production marginal costs are lower than the willingness-to-pay of the demand. In the example shown in Figure 1 this happens until the 7th GW:

- For the 7th GW cheap solar is used to create hydrogen that is worth more than the solar electricity, so the 7th GW is cleared.
- For the 8th GW an expensive gas power plant should be switched on to create hydrogen that is worth less than the electricity from the gas power plant, so the 8th GW (and the later GWs) are not cleared.

To determine the clearing price, it is checked what is the marginal technology at the point of clearing. In the example of Figure 1, the marginal technology is power-to-gas (at €20/MWh), as for the 8th GW to clear, the marginal production costs of the generator should have been at most €20/MWh.

In the example of Figure 1, the following clearing is observed:

- 4 GW of wind and 3 GW of solar is cleared
- 5 GW of baseload and 2 GW of power-to-gas is cleared
- Rest of the assets not cleared
- Clearing price of €20/MWh

2.2.2 Impact of Physical PPAs on the market

As mentioned at the start of this section, in a Physical PPA both the production and the demand are taken out of the market. To see the effect of this, let's take the example of Figure 1, but assume now that there is a PPA between 3 GWs of wind and 3 GWs of baseload. The resulting market clearing is shown in Figure 2.

GW	1	2	3	4	5	6	7	8	9	10	11	12
Production	0	5	5	5	100	100	100					
Demand	200	200	20	20	20	10	10	10				

Legend		
wind	solar	gas
base	P2G	P2H

Figure 2: Clearing of an example market with 3 GW PPA between wind and baseload. Cleared 4 GW at €20/MWh.

Figure 2 shows that the market dynamics with a PPA between wind and baseload does not really have an effect on the market, the clearing price is still €20/MWh. In this case the most expensive demand and the cheapest supply is taken out of the market, not influencing the order of the technologies further down the merit order. In general it could be stated that **PPAs between the cheapest generation and most expensive demand do not impact the market.**

Now let's assume a PPA between wind and power-to-gas of 3 GW, so they are both taken out of the market. This is visualised in Figure 3.

GW	1	2	3	4	5	6	7	8	9	10	11	12
Production	0	5	5	5	100	100	100					
Demand	200	200	200	200	200	10	10	10				

Legend		
wind	solar	gas
base	P2G	P2H

Figure 3: Clearing of an example market with 3 GW PPA between wind and power-to-gas. Cleared 5 GW at €100/MWh.

The clearing price is now €100/MWh instead of €20/MWh, because for the 6th GW to be cleared, the demand should have a willingness-to-pay of €100/MWh, the marginal costs of the gas power plant. This higher price is explained because now an expensive gas power plant has to be switched on to fulfil the base demand, as cheap wind is already used by the power-to-gas through the PPA.

The power-to-gas operator now has an interesting option. Via the PPA it bought 3 GW of wind power for a price negotiated in the PPA. It now has the option to sell 1 GW back to the market, as the clearing price is €100/MWh, which is most likely higher than the PPA-price. The PPA off-taker can place a bid between €20/MWh and €100/MWh for this 1 GW, with perfect market competition (so no gaming potential) the optimal bid will converge to €20/MWh, back to the situation without the PPA. **In general it could be stated that at high prices the off-taker of the PPA will sell the electricity back to the market, restoring market efficiency like it was without the PPA**. This does assume perfect market conditions and that the offtaker maximizes short-term financial revenue. There may be other reasons to keep the energy, such as presenting a green image and not wanting the overhead associated with trading on spot markets, which will mean that an offtaker will not sell the electricity back to the market.

2.2.3 PPAs in non-perfect market conditions

In the previous subsection it was shown that in perfect market conditions off-takers of PPAs will sell back the bought electricity to the market at the price of their own willingness-to-pay, not effecting the electricity market. However, market conditions are not always perfect. This is shown with the following cases:

- Operationally constrained PPAs
- Green hydrogen PPAs
- Gaming potential of PPA off-takers

2.2.3.1 Operationally constrained PPAs

An increasingly important issue in power systems is transport constraints. Due to the fast development of electrification and renewables, limited grid connection capacities and congestion in the electricity network are more and more common. To deal with this, operationally constrained PPAs are considered as possible mitigation measures. An example is the tender for IJmuiden Ver Beta, in which windfarms should look for geographically 'close' load that is operational at times of high wind output. With such configurations, grid congestion could be decreased by ensuring that generated electricity is consumed nearby.

The operational constraint for PPAs is not only relevant from the perspective of the electricity grid, but also from the perspective of the hydrogen grid. Imagine a PPA between a wind farm and an electrolyser. If there is a certain required demand for hydrogen (e.g. per hour) that the electrolyser should deliver to the user of the hydrogen, missing hydrogen (in case of high electricity prices) could be bought from the hydrogen market. However, if there is limited connection capacity to the hydrogen market, the electrolyser might be forced to produce hydrogen, even though electricity prices are very high, to fulfil its obligation to the hydrogen user.

In these operationally constrained PPAs, the example in Figure 3 becomes relevant again. The off-taker of the electricity (say, the electrolyser) can now not sell the electricity back to the market, which could result in significantly higher prices as gas-fired power plants set the marginal price in some cases. Therefore, **Operationally constrained PPAs can have an impact on the energy markets.**

2.2.3.2 Green Hydrogen PPAs

PPAs are expected to play a big role in the certification of green hydrogen. The delegated act on green hydrogen sets an additionality requirement for hydrogen to be called green:

'The idea of additionality is to ensure that the increased hydrogen production goes hand in hand with new renewable electricity generation capacities. To this end, the rules require hydrogen producers to conclude power purchase agreements (PPAs) with new and unsupported renewable electricity generation capacity.'

Due to high CAPEX/OPEX and low full load hours of electrolysers, it is expected that (at least around 2030) green hydrogen prices will be quite high (e.g. because of subsidies and/or high demand). When green hydrogen prices are so high that in the merit order, the willingness to pay for an electrolyser (with a PPA) is higher than the marginal costs of a gas-fired powerplant, it becomes profitable to switch on the electrolyser at times that gas-fired power plants are running. This means that from a system perspective, an additional gas-fired power plant is switched on to run the electrolyser.

This is also illustrated in Figure 3. The off-taker of the PPA (the electrolyser) now does not sell the electricity from the wind farm back to the market, as the profits for selling green hydrogen is higher than the marginal costs (€100/MWh from the gas-fired power plant). From a system perspective, 1 GW of hydrogen is now produced with 1 GW of a gas-fired power plant, leading to inefficient grey hydrogen production.

This becomes even more complex when gas-fired powerplants should run on green hydrogen themselves (expected for 2035). In this case the gas-fired power plants will have extremely high marginal costs as they are 1-to-1 coupled to the green hydrogen price. High subsidies for green hydrogen could then lead to power-to-hydrogen-to-power cycles, losing 50% of the energy due to inefficiency of both conversion steps.

It can be concluded that **Green Hydrogen PPAs can affect the market when the price of green hydrogen is so high (either by subsidies or high demand) that the willingness-to-pay of electrolysers becomes higher than the marginal cost of gas-fired power plants.**

2.2.3.3 Gaming potential of PPA off-takers

As mentioned at the end of Subsection 2.2.2, PPA off-takers could sell their bought electricity back to the market if the market price of electricity is higher than the price that they would get for producing hydrogen. In Figure 3 this was shown with an example where the electricity price is €100/MWh whereas the willingness-to-pay of an electrolyser is €20/MWh. In perfect market conditions, there is enough competition such that the best bidding strategy for the electrolyser is to bid around €20/MWh, such that the market is not affected.

However, if there is not enough market competition, the off-taker of the PPA could also bid just under €100/MWh to outbid gas-power plants. The off-taker of the PPA likely becomes the marginal 'technology' and earns a lot of money at the expense of higher market prices.

Whereas a lack of market competition in this case is not an unrealistic scenario, it should be noted that the gaming potential of market players is an issue for many existing markets already, also without PPAs.

2.2.4 Note on impact of additional generation/demand

The previous subsections focused on the potential impact of PPAs on electricity markets due to the technicalities of these markets. However, PPAs could also lead to additional generation and/or demand in the market, e.g. because without PPAs the investment in these technologies would be deemed to risky. Additional generation and/or demand also affect the market, respectively decreasing and/or increasing market prices. It is out of the scope of this study to investigate to which extent PPAs could lead to additional generation and/or demand, but in the next section, the effect of potential additional demand is looked into as well.

3 Impact of PPAs on the market and market players

PPAs can impact the market in two ways:

- They can impact the operation of the energy system;
- They can impact the state of the energy system.

Due to PPAs the energy system looks and works differently.

We consider PPAs between offshore wind and either an electrolyser or a baseload demand. We choose two types of demand, because they can have a different effect on the market.

The impact on the operation of the energy system depends on the type of PPA. A PPA can take demand and supply out of the market, but the demand can also sell the electricity from the PPA back to the market. This latter option allows for operational gaming potential. We do not research this option further. Instead we focus on the first option where supply and demand are taken out of the market. This corresponds to the Ijmuiden Ver tender[1] where a demand must be running when offshore wind production exceeds 1 GW.

We define a PPA bottom (Figure 1) and a PPA top (Figure 2), based on the IJmuiden Ver Beta Tender. In PPA bottom the first 1 GW is delivered to the PPA and in PPA top the second 1 GW. This sets a minimum and maximum which will be delivered to the demand, when one follows these criteria. In PPA bottom 70% of the wind production goes towards the PPA. It follows that in PPA top 30% of the wind production goes towards the PPA. Both PPAs are operationally constrained PPAs.

PPAs can also impact the state of the energy system, by allowing for additional investments. The additional investments can occur both for (renewable) supply and demand. In this research we focus on additional demand: 1 GW of additional electrolyser capacity or 1 GW of additional baseload demand.

This results in nine of cases:

- Base case without a PPA;
- An existing electrolyser with PPA bottom;
- An existing electrolyser with PPA top;
- An existing baseload demand with PPA bottom;
- An existing baseload demand with PPA top;
- An additional electrolyser with PPA bottom;
- An additional electrolyser with PPA top;
- An additional baseload demand with PPA bottom;
- An additional baseload demand with PPA top.

[1] Regeling vergunningverlening kavel Beta in windenergiegebied IJmuiden Ver (rvo.nl)

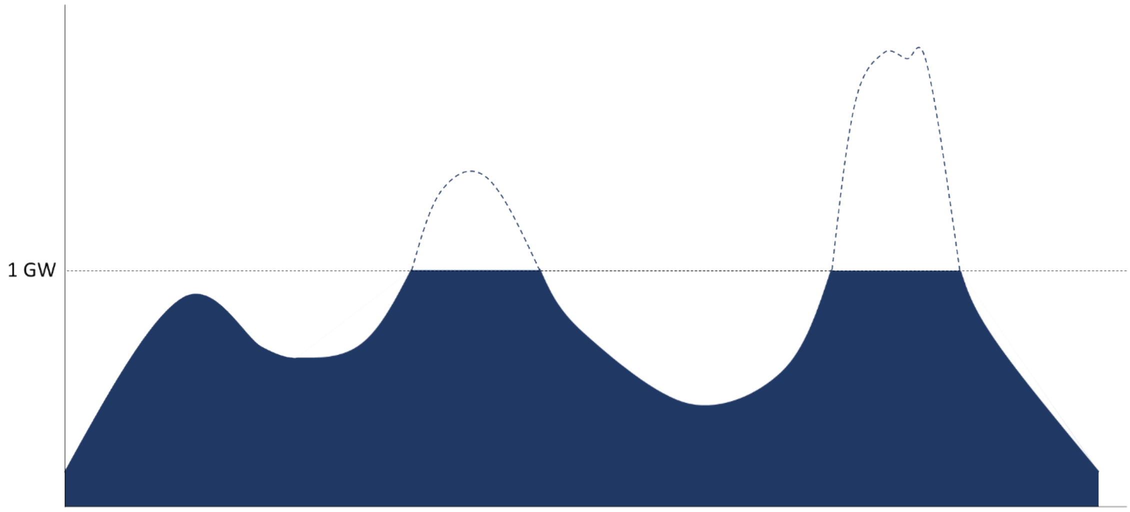


Figure 1 For PPA bottom the first 1 GW goes to the PPA and all wind energy above 1 GW is put on the electricity market. The filled area indicates the supply of wind energy towards the PPA.

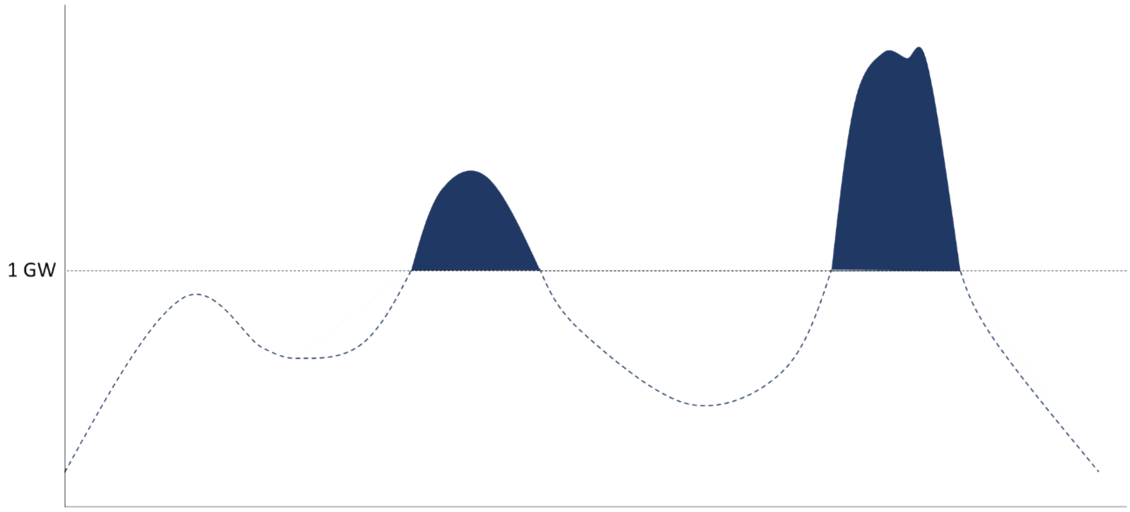


Figure 2 For PPA top the first 1 GW is put on the electricity market and all wind energy above 1 GW goes to the PPA. The filled area indicates the supply of wind energy towards the PPA.

3.1 PPAs increase market prices

In this case, PPAs make the spot market operate less efficient, resulting in higher market prices. To illustrate this, we plot a selection of price duration curves. A price duration curve shows the market prices ordered from high to low and can be used to see how many hours of the year prices exceed a certain value. Figure 3 shows the price duration curves for the base case without PPA; PPA bottom with an existing electrolyser; and PPA bottom with an additional electrolyser. Plateaus can be distinguished in which prices remain somewhat constant. For these hours the price is set by the same technology, e.g. a gas-fired power plant or an electrolyser. For hours with high prices the price is set by power plants. These are the first ~2800 hours for the base case. Next, the price is determined by the flexible assets Power2Heat (P2H) and electrolysers, respectively. Finally, the price is determined by the renewable assets with low marginal costs. Besides solar and wind, this also includes biomass and nuclear power plants. These have lower bidding prices than the flexible assets, so it is possible to produce heat and hydrogen with their electricity. Figure 4 shows the price duration curves for the base case without PPA; PPA top with an existing electrolyser; and PPA top with an additional electrolyser.

The impact of a PPA with an electrolyser on the market can be separated into three cases:
- More power plants are necessary to satisfy demand;
- P2H sets the price instead of electrolysers;
- Electrolysers continue to set the price.

More power plants are necessary to satisfy demand when the electrolyser receives renewable wind energy, which is needed to satisfy the inelastic Dutch electricity demand. Since this wind energy is not available for the Dutch electricity demand, an additional power plant needs to run, which would be shut-off in the base case. Consequently, the price difference with the base case will be the difference between the bidding price of the power plant which would be shut-off and the power plant setting the price in the base case. We see this effect in Figure 3 for the electrolyser with a PPA bottom and do not see it in Figure 4 for the electrolyser with a PPA top. This is caused by the fact that with the PPA bottom the electrolyser gets the first 1 GW, whereas with the PPA top it gets the final 1 GW. When it gets the final 1 GW, usually there is enough renewable power in the system, so there is less or even no need for the power plants to be turned on.

P2H sets the price instead of electrolysers when in the base case the electrolysers would already set the price on the spot market. This occurs, because less wind energy is available on the spot market, which would satisfy the full P2H capacity. When the full P2H capacity is satisfied, the electrolysers turn on and they set the price. The resulting difference in price is the difference between the bidding price of P2H and electrolysers.

Electrolysers continue to set the price when the PPA causes additional electrolyser capacity. The price is set by biomass power plants when the electrolyser capacity has been fully cleared. When there is more electrolyser capacity, it takes longer before this is the case.

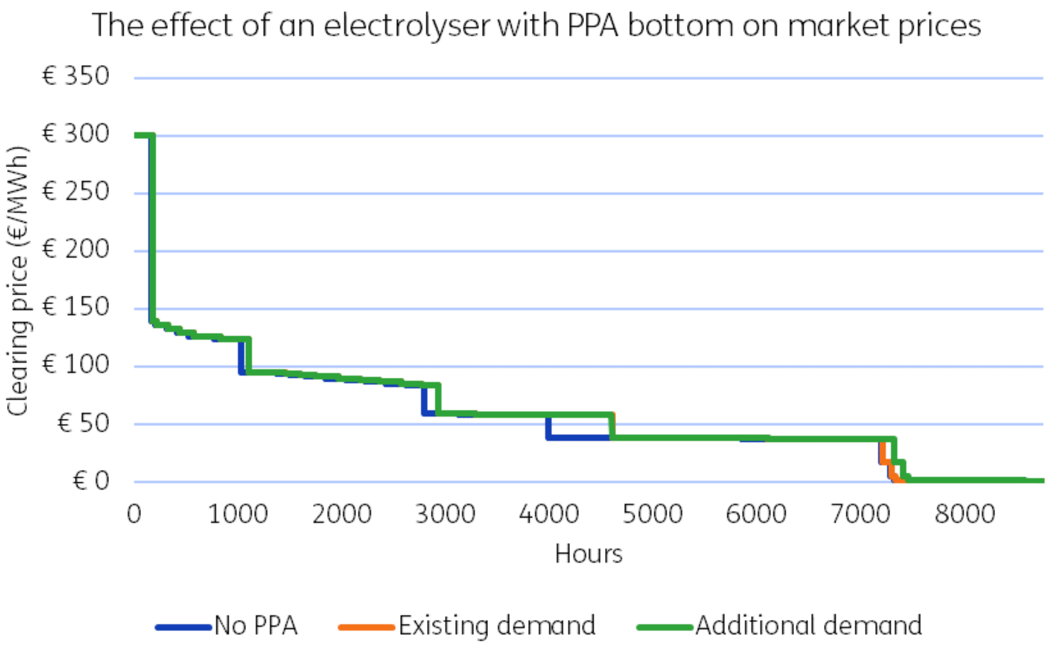


Figure 3 Price duration curves for the base case; PPA bottom with an existing electrolyser; PPA bottom with an additional electrolyser.

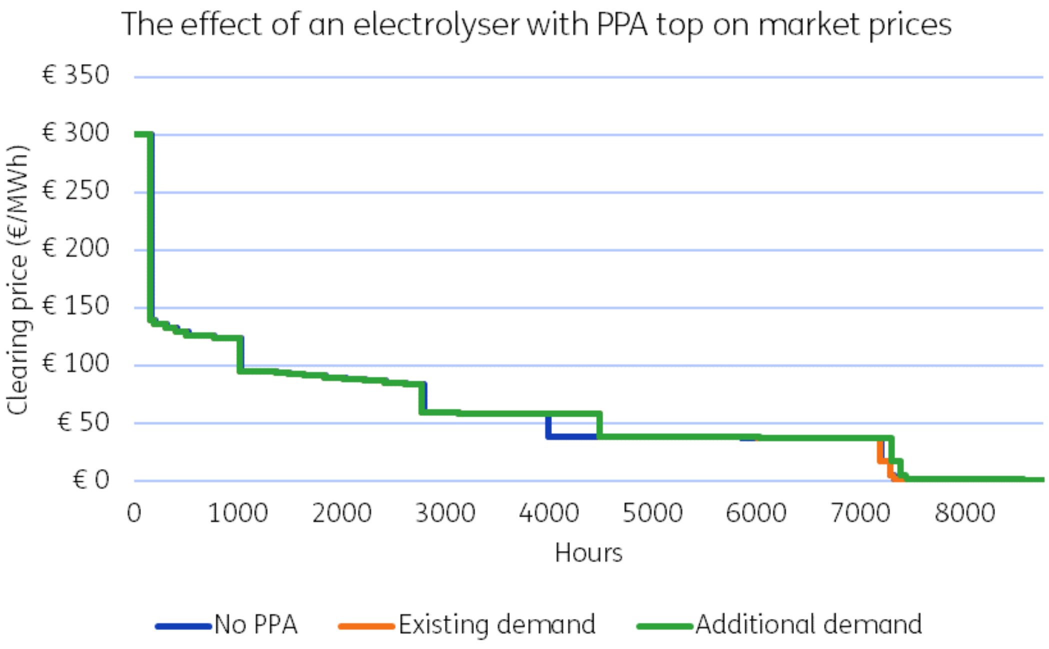


Figure 4 Price duration curves for the base case; PPA top with an existing electrolyser; PPA top with an additional electrolyser.

Figure 5 shows the price duration curves for the base case without PPA; PPA with a baseload demand; and PPA with an additional baseload demand. We do not distinguish between a PPA top or bottom for the baseload demand, since there is no difference between the price duration curves for these types of PPAs. A baseload demand will not change the market results by having a PPA with offshore wind, because it will be cleared anyways. Consequently, it will not cause a situation, as described in Chapter 2, in which it can change the market results. The only way in which a PPA with a baseload demand will change the market results, is when it concerns an additional baseload demand. When this is the case, constantly additional power supply is needed, causing higher prices.

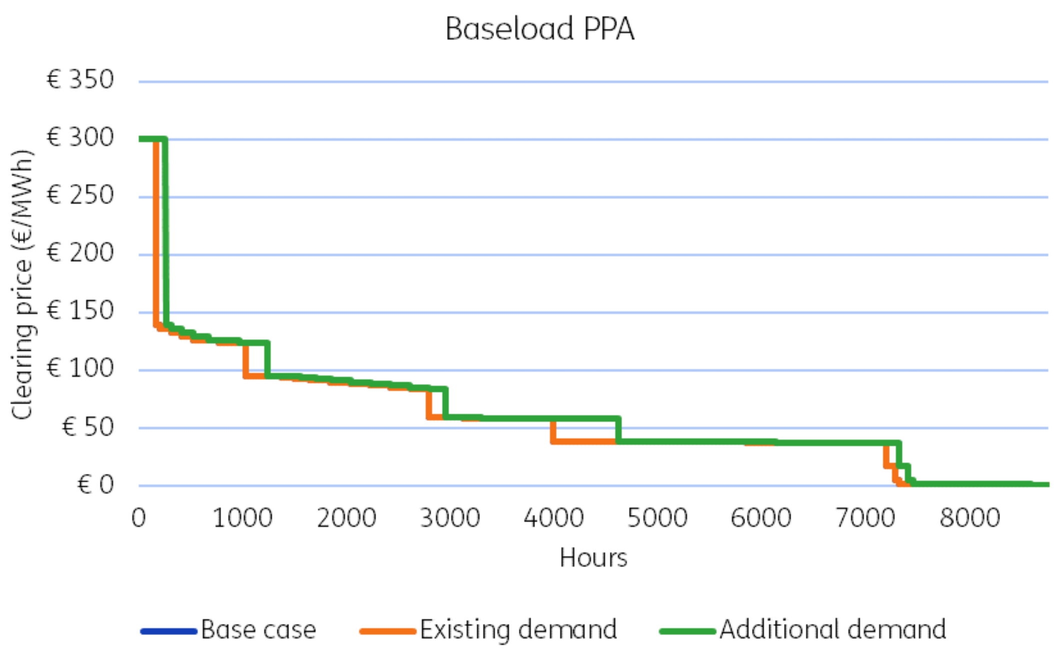


Figure 5 Price duration curves for the base case; PPA with an existing baseload demand; PPA with an additional baseload demand.

3.2 PPAs impact other participants

The higher market prices impact the market players active on the spot market, also the market players which do not have a PPA. The Dutch electricity demand – which is modelled to be inelastic[2], so it does not react to prices – has to pay higher prices for its demand than in the base case. Offshore wind – the remaining 19.5 GW which is modelled to sell all its production on the spot market – obtains a higher revenue for the energy put on the spot market. Flexible assets such as electrolysers – the remaining electrolyser capacity which does not have a PPA – and Power2Heat pay a different price for their demand and also clear a different total volume.

The Dutch electricity demand has to pay a few additional euros per MWh, as can be seen in Figure 6. In the base case the demand has to pay €59 per MWh. With a yearly volume in the order of 100 TWh, this results in additional costs in the order of 100 million euros. For the PPA with an electrolyser the main effect is that the market operates less efficiently, and less in whether or not there is additional demand. The PPA with a baseload demand does not change the operation, so the full effect is caused by additional demand. The additional costs are highest for a PPA with additional baseload demand.

Offshore wind receives a few additional euros per MWh, as can be seen in Figure 7. In the base case offshore wind receives €43 per MWh. Similar as for the Dutch electricity demand, the largest effect from a PPA with electrolyser comes from the operational part, whereas this is completely caused by the additional demand for a PPA with a baseload demand. The additional revenue is again largest for a PPA with additional baseload demand, but the difference with an electrolyser with a PPA bottom is smaller, than for the Dutch electricity demand.

[2] This is a simplification, but short-term elasticity of electricity markets is generally low

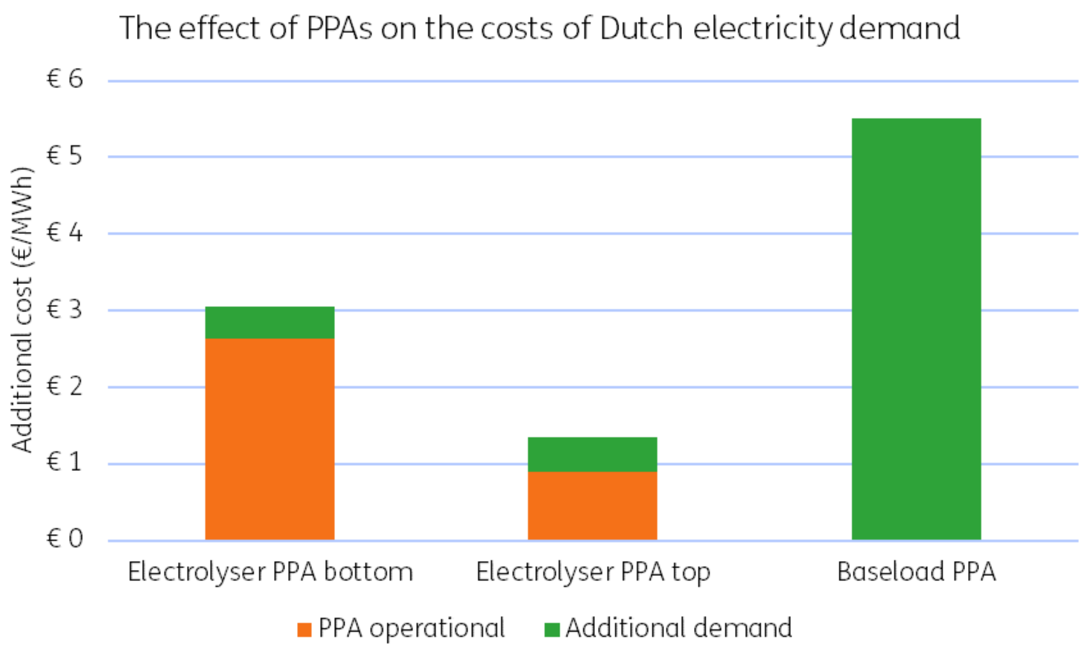


Figure 6 Additional cost (€/MWh) for the Dutch electricity demand as caused by: an electrolyser with PPA bottom; an electrolyser with PPA top; and a baseload demand with a PPA. This is split in two parts: a change in operation due to the PPA; and additional demand caused by the PPA.

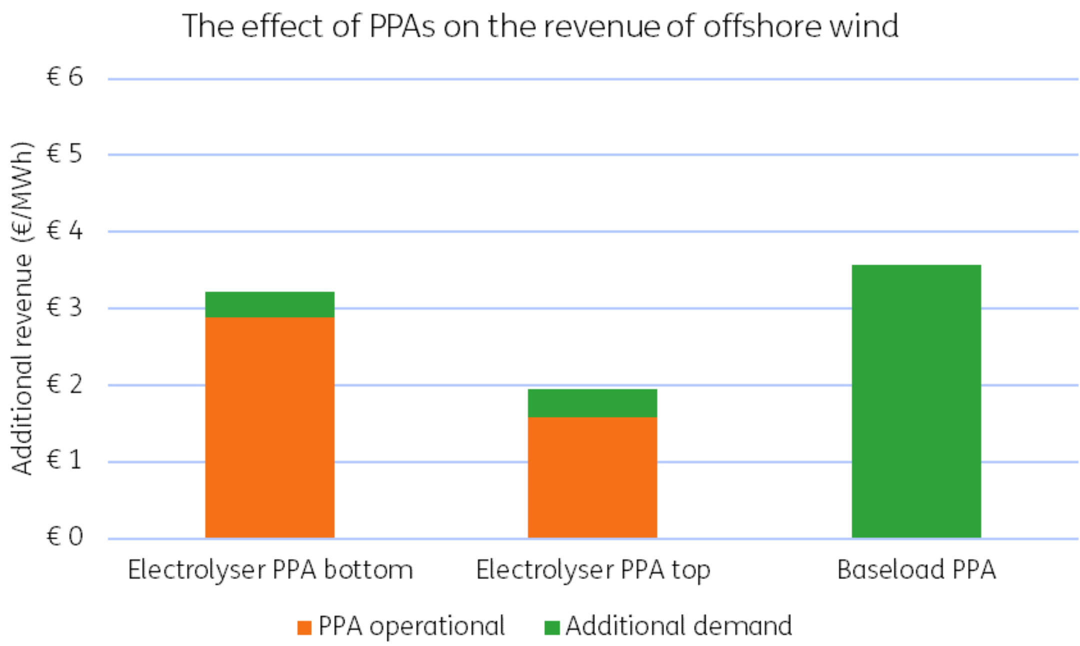


Figure 7 Additional revenue (€/MWh) for offshore as caused by: an electrolyser with PPA bottom; an electrolyser with PPA top; and a baseload demand with a PPA. This is split in two parts: a change in operation due to the PPA; and additional demand caused by the PPA.

The business case of the electrolyser is impacted in two ways: the price it pays for electricity and the amount of electricity received. Figure 8 showcases these effects. On the horizontal axis the capture price of the electrolyser is shown. This is the average price that the electrolyser pays for its electricity demand. The marginal profit of an electrolyser is obtained by subtracting the capture price from the bidding price of the electrolyser. The marginal profit is what the electrolyser earns on average per MWh consumed. The vertical axis indicates the full load hours (FLHs) of the electrolyser. This is the number of hours at which the electrolyser would have to run at maximum capacity to demand the same amount of electricity as it has done in a year. It also incorporates hours in which the electrolysers run at partial load. Multiplying the FLHs and the marginal profit gives a measure of the business case. The black line in Figure 8 indicates a business case similar to the business case in the base case. Above this line there is a better business case and below the line is a worse business case.

PPAs with existing demand do not improve or worsen the business case of the electrolyser, but do cause different FLHs and capture prices. Due to the PPA, the other electrolysers have lower FLHs, since there is less renewable energy available. However, this only occurs when the electrolysers set the price. During these hours, the marginal profit is equal to 0, since the clearing price is equal to the bidding price. To lose clearing volume in these hours does impact the full load hours and the capture price, but it does not impact the business case.

When a PPA causes additional demand, it negatively impacts the business case of the electrolysers. This is mainly due to a loss in FLHs, as there is more competition for the renewable energy. This is the case both for a PPA with an electrolyser and a baseload demand.

The business case of Power2Heat is negatively impacted by PPAs, as can be seen in Figure 9. The FLHs decreases and the capture price increases, both negatively impacting the business case. This is also the case for the PPA with an existing electrolyser, which was not so for the business case of the electrolyser. That is the case, because the electrolysers are in the merit order after Power2Heat. Due to the PPA, the electrolyser is using electricity, which would normally go towards Power2Heat. When it concerns a PPA with an additional electrolyser, then this does not impact the FLHs anymore, but it does increase the capture price. This is because the electrolyser continues to set the price, as we have seen before. The Power2Heat also has to pay this higher price for its demand, thereby increasing its capture price. The business case is worst when the PPA causes additional baseload demand, since this is increasing prices the most.

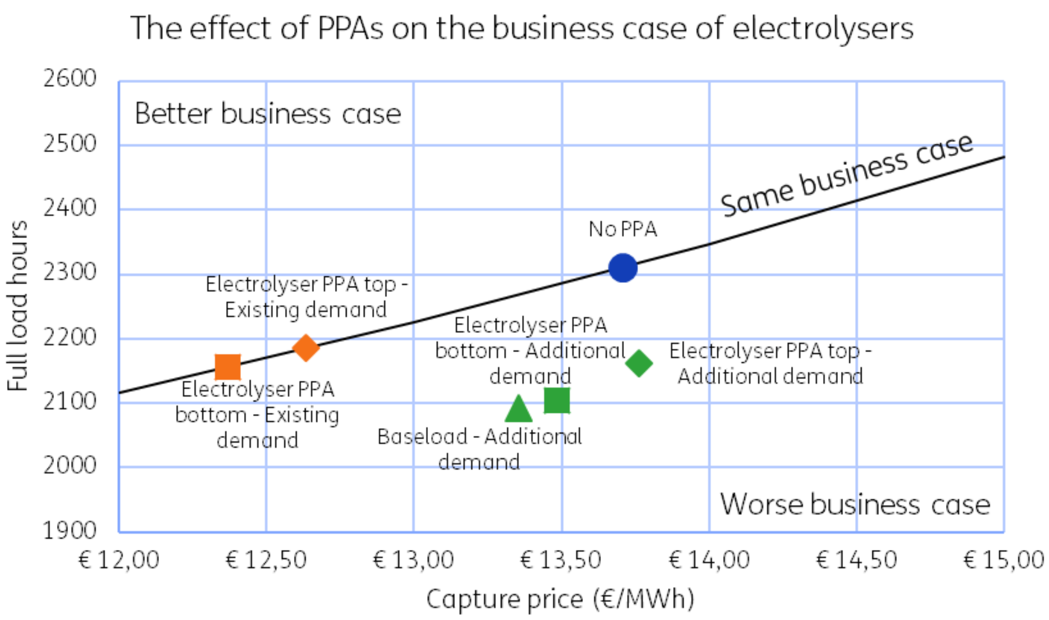


Figure 8 Impact on the business case of an electrolyser: the full load hours on the vertical axis and the capture price on the horizontal axis. The black line indicates a business case similar to when there is no PPA. Above the line indicates a better business case, below the line indicates a worse business case. The PPA with an electrolyser is indicated for PPA top (diamond) and PPA bottom (square), for existing demand (orange) and additional demand (green). The PPA with a baseload demand (triangle) is only indicated for the additional demand (green).

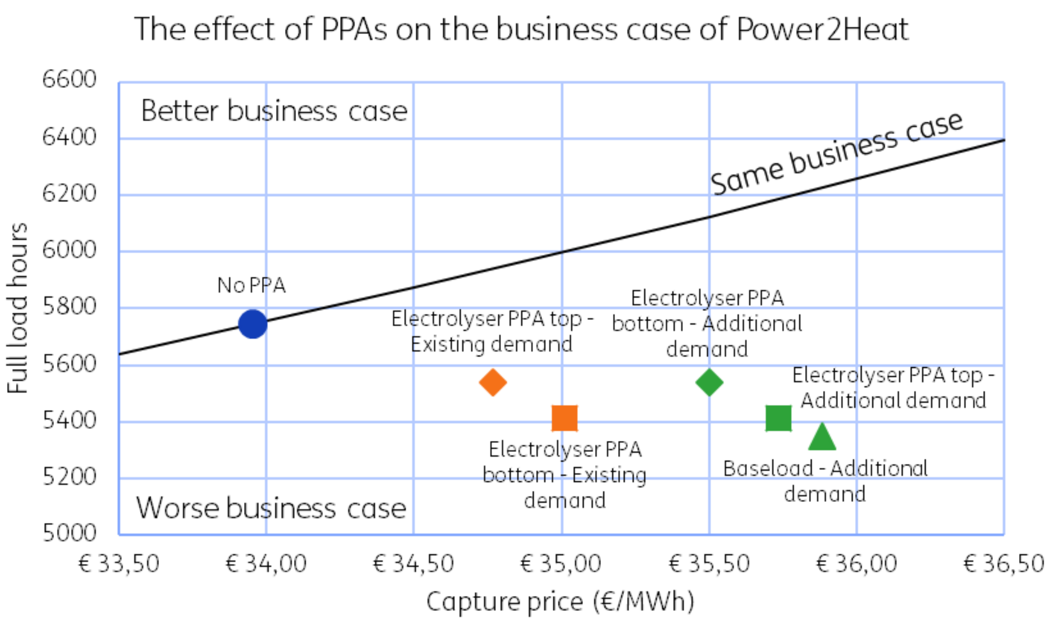


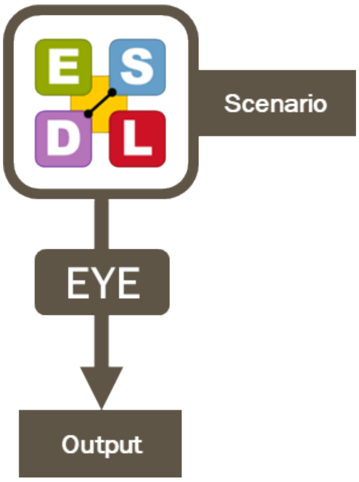
Figure 9 Impact on the business case of Power2Heat: the full load hours on the vertical axis and the capture price on the horizontal axis. The black line indicates a business case similar to when there is no PPA. Above the line indicates a better business case, below the line indicates a worse business case. The PPA with an electrolyser is indicated for PPA top (diamond) and PPA bottom (square), for existing demand (orange) and additional demand (green). The PPA with a baseload demand (triangle) is only indicated for the additional demand (green).

4 Other financial contracts can also affect the market

We have shown the impact of PPAs on the Dutch electricity market. However, PPAs are not the sole drivers of change within the energy market. Other long-term contracts, subsidies such as Contracts for Difference (CfDs) and various financial streams such as green hydrogen certificates also play pivotal roles in shaping market behaviors. These contracts provide stability, predictability, and incentives for renewable energy development. As the energy landscape continues to evolve, understanding the interplay between different long-term contracts and their collective impact on market dynamics remains essential for navigating the transition towards a sustainable energy system.

Appendix A EYE PPA implementation

A.1 Power purchase agreements (PPAs) or a complex bidding behavior implementation in the EYE model



EYE is a TNO-developed merit-order-based electricity market model that takes an energy system's description, profiles, and bidding strategies as input, simulates the hourly day-ahead electricity market, and provides results in the form of clearing prices, clearing volumes, etc.
For simulating a market, the EYE model requires 2 mandatory and 1 optional file:

- **`esdl` file:** includes the complete description of the energy system including generation and consumption assets with respective parameters and associated profiles where required, e.g. Wind generation, inflexible annual demand, etc.
- **`config` file:** is used to specify the markets and the period for which they will be simulated. It also includes the username and access to the particular database where the results of simulations will be stored. We can also specify fuel costs/ marginal costs etc. for the types of assets modeled in the `.esdl` file.

Both `esdl` and `config` files are enough to run market simulations with assets having simple bidding behaviors like specifying marginal costs and willingness to pay. For market simulation without a PPA or a nuanced bidding strategy, i.e., with only `esdl` and `config` files following the online portal is used.
[Eye Simulator API (tno.nl)]

- **`toml`** (optional): is an additional file that can be used to model long-term contracts like PPAs, complex bidding strategies, and also, to some extent, limits on the physical infrastructure. An example of a PPA can be an offshore wind farm that needs to provide generation first to an electrolyzer (up to the capacity) and sell remaining on the market.

For a market simulation with, e.g., PPA modeling using a `toml` file we use
[Eye Simulator API (tno.nl)]

Next, we delve deeper into modeling PPAs and particular bidding strategies by using `toml` files and also provide explanatory examples.

The definitions of bidding strategies in the `TOML` file are translated to sympy equations, so we can use any sympy functions to create logic. The documentation of sympy is available at: https://docs.sympy.org/latest/reference/index.html)

A.1.1 Example:

There is a PPA between an offshore wind producer and an electrolyzer such that a wind producer has to provide all the wind generated up to the capacity of the electrolyzer (if available) to the electrolyzer first and can sell the remaining to the market up to the capacity of the grid connection it has. Further, electrolyzer prioritizes electricity coming from wind and only if its capacity is remaining it buys from the market given that the market price is less than `0.36*CO2Price`.

The `toml` code for modeling this simple PPA example is given below:

```
1. [global]
2. grid_connection = "X"


3. ["#offshoreWind_PPA"]
4. supply_bid.ppa.price = "0"
5. supply_bid.ppa.volume = "min(attribute(electrolyzer_PPA, power),
   profile(offShoreWindProfile, t))"
6. supply_bid.electricitymarket1.price = "0"
7. supply_bid.electricitymarket1.volume = "min(grid_connection,
   total_volume - clearing_volume(ppa))"


8. ["#electrolyzer_PPA"]
9. demand_bid.ppa.price = "400"
10. demand_bid.ppa.volume = "attribute(self, power)/ 1e6"
11. demand_bid.electricitymarket1.price = "0.36*profile(co2Price,
    t)"
12. demand_bid.electricitymarket1.volume = "min(grid_connection,
    attribute(self, power)/ 1e6 - clearing_volume(ppa))"
```

A.1.2 Explanation:

- Line 1: Below this, we can specify global variables that can be used throughout the current `toml` file, e.g., `grid_connection` in line 2.
- Line 3: Specify an asset for which the bidding strategy is to be modeled below. The name of the asset comes from the `esdl` file which for our example is `offshoreWind_PPA`.
- Line 4: With this syntax, we assign a supply bid price, to the asset referred to in line 3, for the market named "`ppa`". The name "`ppa`" comes from the `esdl` file where it is modeled as such.
- Line 5: Here we specify the bidded volume of the same asset, in the market "`ppa`", which is the minimum of the electrolyzer capacity specified in `esdl` file and the offshore wind generation extracted from the profile `offShoreWindProfile` at time `t`. Profiles are again uploaded via an `esdl` file. With the command `attribute(asset, parameter)` we can call any parmeter of an asset assigned in the `esdl`.
- Line 6: Supply bid price into the market named "`electricitymarket1`".

- Line 7: It specifies that the volume bidded in `electricitymarket1` is the minimum of the size of the grid connection and what is remaining from `ppa` market clearing.

So in summary, the wind generator prioritizes the delivery of energy to the electrolyzer, because of a PPA between them, and the remaining goes to the electricity market while abiding by the physical constraint of grid connection size.

- Line 8: The electrolyzer asset is called with a name from the `esdl` file.
- Line 10: `attribute(self, parameter)` command can use `self` after specifying asset like at line 8.

The rest of the commands follow a similar structure for the electrolyzer to first bid demand equal to its capacity in the ”`ppa`” market at a very high price to simulate a PPA between the assets. Note, that the bidding prices and the clearing prices of the “`ppa`” market do not mean anything as the PPA price is assumed to be bilaterally decided between the respective assets. Here low/high price of supply/ demand assets is to ensure the execution of a PPA contract via the exchange of energy.

Energy & Materials Transition

Westerduinweg 3
1755 LE Petten
www.tno.nl