IEA IETS Task XIX: Electrification in Industry

Report on industrial sector coupling potential in Danish industry

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Contribution from PlanEnergi
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Project Description by EUDP:
The project is concerned with Danish participation in the IEA Technology Collaboration Programme on Industrial Energy-Related Technologies and Systems (IETS) task XIX Electrification in Industry. Electrification of the industrial sector has a very significant potential for contributing to the green transition of the industrial energy use, in particular in Denmark. Industrial electrification has been identified as a key option in research and innovation agendas both, at national and international level. The Task Industrial Electrification aims to be a platform for enhancing collaboration between countries in the area of industrial electrification with an emphasis on system aspects. The focus of the Task is on the system aspects of industrial electrification and on the technologies within each specific pathway. Denmark has already been involved in the development of the task during the work in phase 1. The main objective of phase 2 is to develop a platform for exchange of information, experiences and lessons in R&D projects in the area of industrial electrification. In this task industrial electrification covers both direct and indirect electrification.

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1 Danish Electricity Markets

To have a functional and stable electricity system, an equilibrium between the supply and demand of electricity is a necessity. The Danish TSO, Energinet, is responsible to ensure the balance in Denmark. There are two markets where electricity is bought to meet the demand: The Day Ahead market and the Intra-day market.

1.1 Day Ahead market

The largest share of electricity is traded on the Day-ahead market and is traded on the Nordpool-spot market (70 % of electricity is traded here). The bids must contain a specific amount of power and price and must be sent in between 10:00 and 12:00 the day before operation. The bids can either be for a given hour or as a block of at least three hours (Energinet, 2019). For this report, only the hourly bids are used for further investigation. The price setting mechanism is the merit order principle, where the bids and expected demands are matched starting with the cheapest price. The price when the demand is met is the price which all accepted bidders are getting (Energinet, 2019). Since the bidders have to give a bid that is low enough to get accepted but still high enough to cover their costs, there is an incentive to use the marginal production costs price as the bid price, and then achieving to get a higher price by not being the last accepted bid.

As can be seen in Figure 1.1 wind and solar plants are more likely to get their bids accepted compared to fossil fuel-based productions. This is due to their lower marginal costs (production costs) per MWh. Since production from renewable energy sources (RES) often is not large enough to cover the entire demand, fossil fuel-based plants are the price-setting factor. (Capion et al., n.d.)

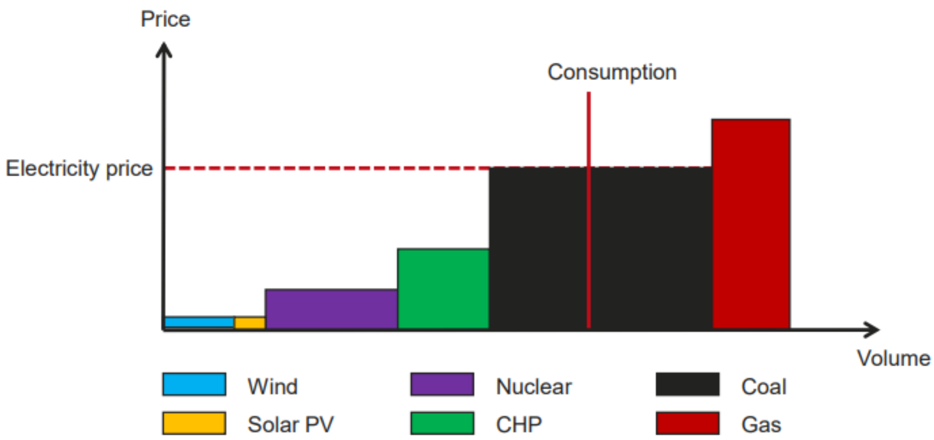


Figure 1.1: Price setting mechanism in the Day-ahead market. (Capion et al., n.d.)

1.2 Intra-day Market

When the Day-ahead Market is closed, the Intra-day Market opens. This market is used for balance trading, e.g., if a wind power plant is not able to produce as much as expected, then the balance between demand and supply is not met. Then the actors on the Intra-day market can get activated to produce or absorb electricity to stabilise the frequency. The shares are much lower compared to the Day-ahead market; this is expected to change when the share of RES is getting bigger which with their fluctuating production is generating more unbalances in the productions.

The Intra-day market opens at 15:00 the day before operation and closes one hour before operation. Since the electricity is traded for every hour of the day, the price-setting mechanism uses the pay-as-bid at the Intra-day market. Actors can give either an hourly bid or a block bid. The main difference between the two is that the hourly bids can be partly accepted with activation of up to the full hour (e.g., 35 min only), whereas the block bids must be accepted entirely (Energinet, 2019).

Hereafter, it is through different system services where Energinet can balance the production in the electricity system. Energinet can either up-regulate the production by buying more electricity or down-regulated by selling electricity on the Regulating Power Market. Furthermore, the grid frequency is stabilised by the activation of automatic reserves at the time of operation (Energinet, 2019).The System Services thereby consist of two services: *Regulating Power* and *Reserves*.

1.3 Regulating Power Market and Frequency Reserves

As stated above the Regulating Power Market consist of up and down-regulation, which are activated manually. Actors give bids for up and down regulation for the specific hour of operation. Actors can either receive payment for being on standby with manual reserves, where the actor must give bids for upregulation in specific hours, otherwise, the actor can give optional regulation bids when this is found attractive. Bids have to be above 5 MW. The bids can be activated for less than one hour.
The bids are paid the marginal hourly price (Regulation Power Price, RP-price), and all activated bids are getting the same price. Besides, the manually activated reserves, automatic reserves are also traded for the hour of operation. (Energinet, 2019)

The Danish electricity grid consists of two grids West Denmark (DK1) and East Denmark (DK2), which are operated as two individual synchronous grids: DK1 is connected to the central European grid and DK2 is connected to the Nordic grid. This means that the frequency for each grid is stabilised independently, why the need and application of reserves are different.

1.3.1 DK1 Reserves

In DK1 there are three types of products for regulation: Primary, Secondary, and Tertiary reserves.
The primary reserve is used for frequency stabilisation and is called Frequency Containment Reserve (FCR). It has a response time of 30 s and must be able to provide power for 15 min. It uses the merit order principle. This reserve is primarily provided by large production and consumption units, which are automatically activated based on changes in grid frequency. The reserves stabilise the frequency by adjusting the production or consumption to achieve an equilibrium between supply and demand. All accepted bids are getting the RP price which is the marginal price. Furthermore, the activated bids are paid the RP price like normal unbalances are. (Energinet, 2021b)

The secondary reserve is used to restore the frequency. This reserve is called the Automatic Frequency Restoration Reserve (aFRR). This reserve is taking over from the primary reserve and has a response time of 15 min and has to be able to provide power for one hour. It is activated based on an activation signal provided by Energinet. This reserve is often provided by large production or consumption units, which can change their production or consumption depending on what is needed. The bids are traded for an entire month at the time and are paid-as-bid. Just like FCR, when activation of aFRR is needed, the provider is paid for activation. In case of upregulation, the price is the spot market price + 100 kr./MWh, but not lower than the RP price. The same applies to downregulation except that the activation price is the spot market price - 100 kr./MWh. and with the RP price as the highest price (Energinet, 2021b).

The third reserve is the manually activated reserve, Manual Frequency Restoration Reserve (mFRR), which is also used for restoring the frequency just like the aFRR. The mFRR has a response time of 15 min. and has to be able to provide regulation for one hour. The manual reserves are traded at the regulating power market and bids must be provided at 17:00 the day before operation. The manual reserves are paid the RP price (Energinet, 2021b).

The activation of the different services is illustrated in Figure 1.2.

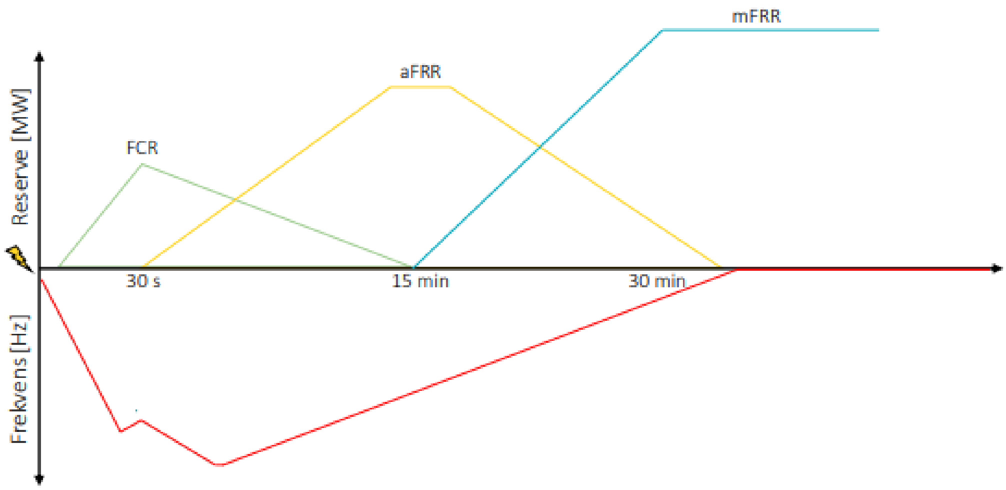


Figure 1.2: Overview of frequency reserves for DK1 and their impact on the restoration of the frequency shown in red (Energinet, 2022).

As can be seen in Figure 1.2 FCR is activated due to a change in frequency, which often is due to a fault in the system, e.g., a fall-out of a larger production plant, or if the equilibrium between production and consumption of electricity is not maintained (Further described in Section 3).

Until the FCR is fully activated the frequency will continue to drop (or rise). The frequency stabilizes shortly (around 30 s from the activation of FCR) since the provider of FCR has delivered enough power to meet the demand. Hereafter the frequency drops again due to the FCR being phased out, and the aFRR is ramping up. The aFRR is used for the restoration of the frequency, and thereby the production has to be higher than the consumption in the system (if the frequency is lower than 50 Hz). If the frequency still is not in the normal operation interval after 15 min of aFRR operation, the mFRR is activated to restore the frequency completely.

A summary of the reserves for DK1 can be found in Table 1.1 below.

Type	Response time	Min. Time of activation	Min. amount
FCR	15-30 s	15 min	1 MW
aFRR	15 min	1 time	1-50 MW
mFRR	15-90 min	1 time (15 min from 2024)	5-50 MW (1 MW from 2024)

Table 1.1: Overview of reserves in DK1 and their characteristics (Centrica, 2022; Energinet, 2021b).

1.3.2 DK2 Reserves

For DK2 there are currently four types of reserves, but from 2024 also aFRR will be used. The aFRR counts 10 MW of regulating power which is provided by DK1 to DK2 (Energinet, 2021b).

The first reserve in DK2 is the Fast Frequency Reserve (FFR). It has a response time of 0,7-1,3 s and has to be able to provide power for 5-30 s. This reserve is used to balance the frequency which is a risk in an electricity grid with low inertia. This reserve is inversely proportional to the inertia in the grid and is therefore mostly activated in the summer months, due to the lower heat and electricity demand and the higher share of RES. An availability payment is given on an hourly basis (Energinet, 2021b).

The second reserve is called Frequency Containment Reserve for Disturbances (FCR-D) and is used to stabilize the frequency if it is outside the normal operation range (49,9-50,1Hz). This is often due to disturbances on the grid e.g., due to fall-out of production or overhead lines. This upregulating reserve is often provided by large production or consumption plants and is activated automatically based on the measured grid frequency. 50% of the FCR-D has to be provided within 5 s. and the rest has to be delivered within 25 s. The amount of FCR-D is traded daily in two steps, where the first and largest share is bought two days before operation and the second share is traded one day before operation. Actors can either give an hourly bid or a block bid. The accepted bids are paid an availability payment (kr./MWh) which is pay-ad-bid. When a bid is activated, the actor is paid an additional payment which is settled with the normal price for unbalance settlements (Energinet, 2021b).

As the FCR-D is only used outside the normal operational range, the Frequency Containment Reserve for Normal Operation (FCR-N) is used to balance the frequency within the range (49,9-50,1 Hz). The FCR-N has a response time of 150 s and has to be able to provide regulation for 15 min. The amount is bought in two steps like the FCR-D, but the payment varies from FCR-D. FCR-N bids are paid an availability price (kr./MW/h) which is pay-as-bid but are also paid for supplying energy (kr./MWh). The prices for supplying energy are following the RP price for up and downregulation (Energinet, 2021b).

The manual reserve for DK2 is equal to the manual reserve in DK1 (Energinet, 2021b).

The activation of the different services is illustrated in Figure 1.3.

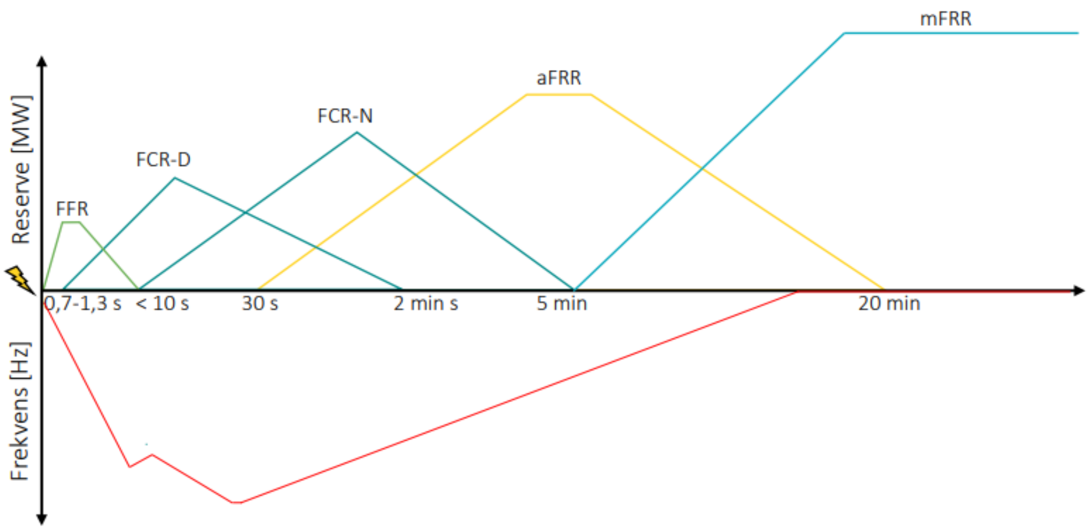


Figure 1.3: Overview of reserves for frequency restoration in DK2 and their impact on the restoration. (Energinet, 2022)

As can be seen in Figure 1.3 the frequency restoration strategy is like the one for DK1, but with other reserves than for DK1.

A summary of the reserves for DK2 can be found in Table 1.2 below.

Type	Response time	Min. Time of activation	Min. amount
FFR	0,7-1,3 s	5-30 s	0,3 MW
FCR-D	50% within 5 s. 100% within 25 s	15 min	Min. 0,3 MW
FCR-N	150 s	15 min	Min. 0,3 MW
(aFRR from 2024)	*5 min*	*1 hour*	*1-50 MW*
mFRR	15 min	1 hour (15 min from 2024)	5 MW (1 MW from 2024)

Table 1.2: Overview of frequency reserves in DK2 and their characteristics (Centrica, 2022; Energinet, 2021a, 2021b).

1.4 Special Regulation

In case of bottlenecks in the transmission grid, special regulation can be used. Energinet selects a specific actor based on the bids on the regulating power market to do the regulation. Thereby does special regulation not necessarily follow the normal price-setting mechanism (a marginal price-setting mechanism) (Energinet, 2021b). Special regulation is settled based on the pay-as-bid principle. The special regulation is mostly used for downregulation in DK1 due to German legislation regarding electricity from RES. This legislation states that RES cannot be stopped (Energinet, 2021b). The German TSO is then paying Danish wind turbine operators to stop their production or get combined heat and power plants (CHPs) to increase their demand by starting electric boilers.

Previously, Danish actors have been able to earn a lot of money on this concept since they were the only actors allowed to bid for the downregulation, but in 2023 a European market should be established for this. This means that the Danish actors have to compete with other European actors for payment, which result in a less favourable price. This can result in less downtime for Danish wind turbines since the Norwegian hydropower plants are assumed to be used for special regulation since the water can be stored for later used, unlike the wind (Laasby, 2022). Furthermore, is Germany planning on implementing a DC-link to Southern Germany by 2026 where the surplus of electricity can be transported away from the north, which results in an even smaller need for special regulation by the Danish wind turbines (Wittrup, 2019).

2 Tariffs and taxes

In Denmark, all consumers and producers of electricity have to pay tariffs to use the transmission grid. The tariffs are paid to Energinet and are used to cover expenses for operating and maintaining the grid, to secure a functioning and balanced grid. The tariffs are proportional to how much each actor uses the grid since it is a price per kWh. The Danish tariffs can be separated into two groups: *consumption* and *production tariffs.* (Energinet, n.d.-b)

2.1 Consumption Tariffs

The consumption tariff can be divided into three categories: *transmission grid tariff, system tariff,* and *balance tariff.*
Energinet has expenses for operating and maintaining the transmission grid and the interconnectors to the neighbouring countries. The transmission tariffs are used to cover these expenses. The system tariff covers expenses related to the security of supply, power quality, and system operation. Finally, the balance tariff is used to cover the expenses related to system services and balancing markets. (Energinet, n.d.-a)

The prices for the specific tariffs can be found in Table 2.1 below.

Consumption tariff	øre/kWh
Transmission grid tariff	4,9
System tariff	6,1
Balancing tariff for consumption	0,229

Table 2.1: consumption tariffs in Denmark in 2022 (Energinet, n.d.-a).

2.2 Production Tariffs

The production tariffs can be divided into two categories: *feed-in tariff* and *production balancing tariff.*
The feed-in tariff covers the expenses related to operation and maintenance of the transmission grid like the transmission grid tariff in Table 2.1. The production balancing tariff is used to cover the expenses Energinet has related to system services and the balancing markets (Energinet, n.d.-a).

The prices for the specific tariffs can be found in Table 2.2 below.

Production tariffs	øre/kWh
Feed-in tariff	0,3
Balancing tariff for production	0,116

Table 2.2: production tariffs in Denmark in 2022 (Energinet, n.d.-a).

2.3 Change in Tariffs

Since greater electrification of the Danish energy system is expected, new tariffs might be needed. As the current tariffs do not consider whether the actors demand power when the electricity grid capacity is challenged or how much the electricity grid is used by the specific actors, there is an expectation that the tariff structure will have to be changed. This can mean that actors can be rewarded for being able to shift their consumption and thereby act flexibly. Furthermore, actors should pay the costs proportionally to their usage of the grid (Energinet, n.d.-b).

Energinet has settled on new tariffs from 2023 for both production and consumption (See Table 2.3)

Øre/kWh	Tariffs in 2023	Change from 2022 to 2023
Consumption tariffs		
Transmission grid tariff	7,60	2,70
System tariff	6,70	0,60
Balancing tariff	0,00	-0,229
Sum of consumption tariffs	**14,30**	**3,07**
Production tariffs		
Feed-in tariff (Production deficit/surplus)	0,30/0,90	0,00/0,60
Balancing tariff	0,16	0,04
Sum of production tariffs	**0,46/1,06**	**0,04/0,64**

Table 2.3: Consumption and production tariffs valid from 2023 (Energinet, n.d.-a).

As can be seen in Table 2.3 Energinet is implementing differentiation in the production tariffs, where actors in areas with a production deficit must pay 0,46 øre/kWh, whereas actors in areas with a surplus must pay 1,06 øre/kWh in tariffs. The areas can be seen in Figure 2.1, where the beige areas have a deficit and the blue have a surplus of production.

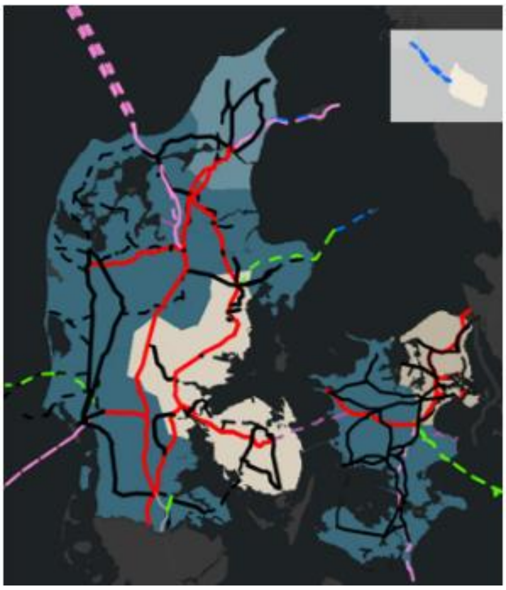


Figure 2.1: Distribution of areas with production deficit (beige) and surplus (blue) (Energinet, n.d.-a).

The introduction of differentiating consumption tariffs in Denmark would provide some corporate financial benefits for future projects. By having the geographical differentiation of new demands, the profitability of the projects is highly affected by a reduction in tariffs, e.g., PtX-projects. The differentiation can give an incentive to utilize the public grid more intelligently, and investments in the grid are not as large and urgent as otherwise. Furthermore, the grid losses are less if the production and consumption are physically located closer to each other (Energistyrelsen, 2021). Since the differentiation is static and thereby does not change with e.g., expected wind production, the areas with are illustrated as surplus areas might not be this at all times. Moreover, the areas for the two categories of tariffs should be updated when more production and consumption are installed. When there is an equilibrium in all areas, the need for differentiating tariffs is not present anymore, and a new tariff structure must be made. Furthermore, there is a risk of an even bigger division of Denmark than the one present currently, where the western parts of Jutland and Zealand will primarily be used for production while the Eastern parts will be used for consumption. This could result in distortion of Denmark due to migration from the Western located areas to the Eastern areas.

2.4 Limited Grid Access

Besides differentiation tariffs, Energinet has also presented a new product, where customers can get a tariff discount by having limited access to the grid. This gives Energinet or the DSO the possibility of reducing the supply or disconnecting the customer in case of risk of an overload of the grid. Previously, all customers were connected with full access, which Energinet had to plan for. In deficit areas where demand is the determining factor for dimensioning the grid, the limited grid access will result in a more efficient utilised grid, and a decrease in the need for expanding the grid. The surplus areas, where production is the determining factor for dimensioning of the grid, the risk of being disconnected is less compared to the deficit areas. This gives an incentive to place flexible demand in surplus areas due to the smaller disconnection risk and due to the tariff discount. The new product is only available for consumption customers (Energinet, 2020).

(Energinet, 2020) is defining two types of flexibility:

- *Flexibility in the energy market:* this relates to energy sufficiency, where supply and demand are matched which is done through the balancing markets and frequency reserves.
- *Flexibility in utilisation of grid capacity:* this relates to grid sufficiency whether the capacity in the grid is sufficient to transport the energy around without having bottlenecks. Production and consumption must be balanced, which is done through price areas. (Energinet, 2020)

It is in cases with grid sufficiency that limited grid access applies.

Due to the risk of being reduced in supply or disconnected, the consumers which are having limited access to the grid are not expected to pay for the fixed costs related to the business of and depreciation of the transmission grid. However, interruptible customers must be tariffed so that they contribute in the same way as non-interruptible customers to the remaining costs, such as the marginal costs for losses in the grid and costs related to operation and maintenance of the transmission grid. This means that the interruptible customers only pay for the costs that they contribute to or benefit from (Energinet, 2020).

Limited grid access is not investigated further in this report due to a lack of data availability. Furthermore, if limited grid access is chosen by the industries, this comes with a risk of losing production time. Moreover, it is impossible to predict when the industry is disconnected from the grid.

2.5 Taxes

In 2021, a green tax reform presenting initiatives to reach a 70 % reduction of greenhouse gasses by 2030 in Denmark, was completed. The main initiative is to ensure a uniformed tax on green house gasses for all industries in Denmark. Three models are presented whereas the 2nd modelled is chosen for further investigations. This model seeks to minimize the leakage of moving CO_2-emitting processes outside of Denmark and instead provide initiatives to decrease the emissions by technological developments and more efficient use of the energy. Previously, an energy taxation was added when purchasing energy products such as electricity, natural gas, or oil. In the new Green Tax Reform, this energy tax for industrial processes is reorganized into a CO_2-taxation instead. Currently, the energy tax is reimbursed so that the industries only are obliged to pay the EU's minimum tax. The CO_2-tax is not refundable. Therefore, the tax restructuring will have an impact on the future choice of energy sources by the companies.

It applies to all industrial sectors, but for industries handling mineralogical processes, which are assessed to be particularly vulnerable to leakage due to the high energy consumptions etc., should therefore have a lower taxation to be competitive in price (Ekspertgruppen for en grøn skattereform, 2022).

Specifically, there should be a CO_2 tax rate of 750 kr. per ton of CO_2 for companies outside the quota sector, corresponding to the expected quota price in 2030, a tax rate of 375 kr. per ton of CO_2 for companies in the quota sector and a reduced tax rate of 100 kr. per ton of CO_2 for mineralogical processes (Ekspertgruppen for en grøn skattereform, 2022).

3 Stability and Balancing of the Grid.

3.1 Stability of the Electricity Grid

There are mainly two types of stability related to the electricity grid: *voltage* and *frequency stability*. Voltage stability describes a system's ability to maintain the voltage after being exposed to a disturbance, e.g., in case of loss of a production unit or fall out of an overhead line. Voltage instability happens if nominal system voltage drops drastically and uncontrollably or is ±10% of nominal voltage (Kundur, 1994).

Frequency stability describes the system's ability to maintain the frequency within the system values due to a significant imbalance between production and consumption. Frequency stability is closely linked to inertia (the ability to resist changes in velocity). Inertia can be seen as an elasticity in the system which will help to keep the frequency around 50 Hz when subjected to imbalance. Power plants have rotating masses due to their generator, which thereby provides inertia to the system. Large power plants are thereby setting and maintaining the frequency around 50 Hz, which converter-based units etc. can follow. Converter-based units have no inertia since their rotating masses e.g., wind turbine wings, are disconnected from the electricity grid in the converter module. A system with many converter-based units is therefore more dynamic and susceptible to changes in frequency since converters are often frequency-following (Kundur, 1994). It is therefore important that the frequency is stabilised differently as the synchronous generators from the power plants are replaced with RES.

The grid frequency is also dependent on the balance between the production and consumption of electricity in the public grid. If more energy is produced than consumed, then the frequency rises, and vice versa if the consumption is higher than production, then the frequency decreases (see Figure 3.1.) (Andresen, 2019).

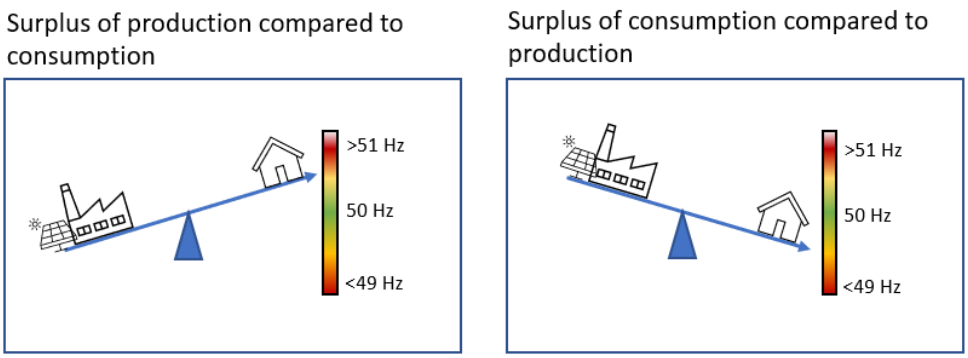


Figure 3.1: Illustration of how deviations between production and consumption affect the frequency of the grid. Based on (Andresen, 2019).

To restore the frequency, two strategies can be used: either change the demand or the supply until the frequency is stabilised at 50 Hz (Figure 3.2). As an example, if the frequency is rising due to a larger supply than demand, the system operator can either increase the demand or decrease the supply of electricity. The forced difference between supply and demand initiated by Energinet is necessary to restore the frequency, since it otherwise would stabilise at a lower point e.g., at 48 Hz.

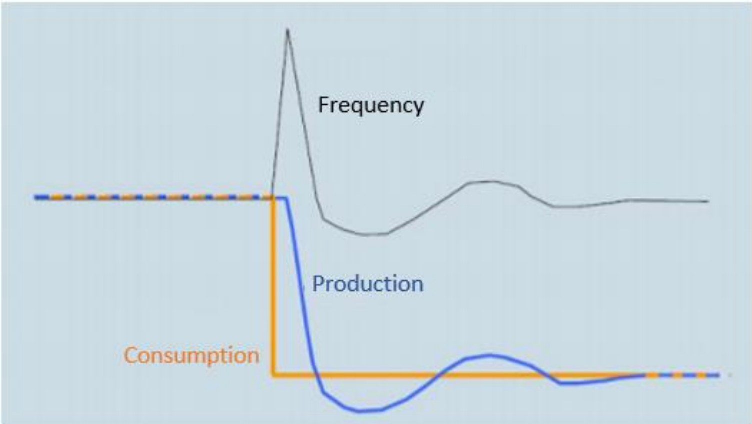


Figure 3.2: Restoration of frequency by controlling demand and supply (Andresen, 2019).

The same applies, though oppositely if the demand is larger than the supply. Then the frequency will decrease, and the operator must either decrease the demand or increase the supply. aFRR can be used for increasing the supply (Andresen, 2019).

3.2 Noise and Harmonic Distortion

The following should be considered by the industries if they are installing own production on their facility. Converter-based components (e.g., in wind turbines and photovoltaics) and frequency-controlled motors (e.g pumps, fans and heat pumps etc.) inject noise and distortions to the electricity grid if they are not connected with a filter. Industries should ensure that their installations are in alignment with the guidelines for production and consumption units by Green Power Denmark: *link to Production and Consumption. Additionally, installation should be under limit values etc. by Danish Standards: DS/EN 61000-series regarding electromagnetic compatibility (EMC).*

Electric equipment like converters/inverters among others are emitting noise. Noise is seen as disturbances in the electricity grid, where the frequency deviates from 50 Hz. The disturbances affect other customers connected to the grid. Disturbances in the electricity grid are often between 2 and 9 kHz. It is the producers who are responsible to ensure that the products comply with the standards regarding the emission of noise (Dansk Energi, 2021; N1, n.d.). But it is the owner that is responsible for the system as a whole is complying with the limits.

3.2.1 Harmonic Distortions

One type of noise is harmonics. Harmonics are electrical disturbances caused by harmonic currents and voltages, which are an integer (h) of the fundamental frequency (e.g., 50 Hz). Between the harmonics, interharmonics are placed. These are non-integers of the fundamental frequency (Figure 3.3) (Dansk Energi, 2021).

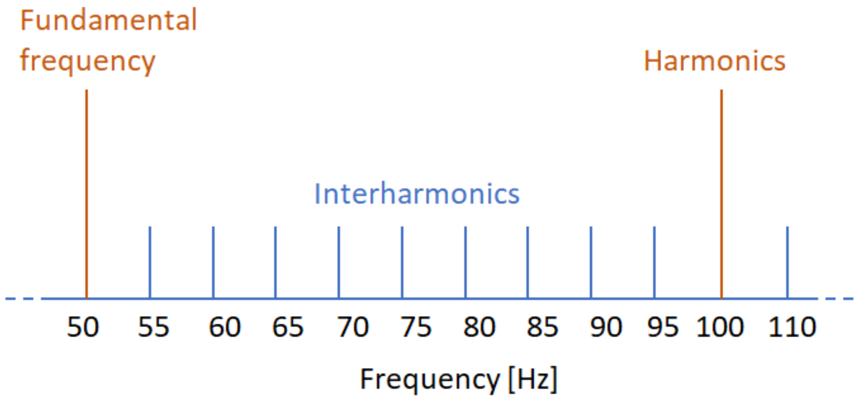


Figure 3.3: Visualisation of harmonics and inter-harmonics. Based on a figure from (Andresen, 2020a).

The harmonic content in a signal must be filtered and limited since these cause disturbances on other signals e.g., TV and internet, higher losses in cables etc. Furthermore, the harmonics contribute to a heat increase in other AC equipment which can lead to over current and over voltage which can be harmful to electric equipment (Kundur, 1994; N1, n.d.).

3.2.2 Examples of Noise Distorts Signals

The following figures are examples of how different components draw current and voltage when they are operating and examples of noise content in a signal and how this distorts the output signal.

Figure 3.4 illustrates an output signal carrying harmonic distortion when a component is connected (around -30 ms). This is seen as a distortion in the sine signal.

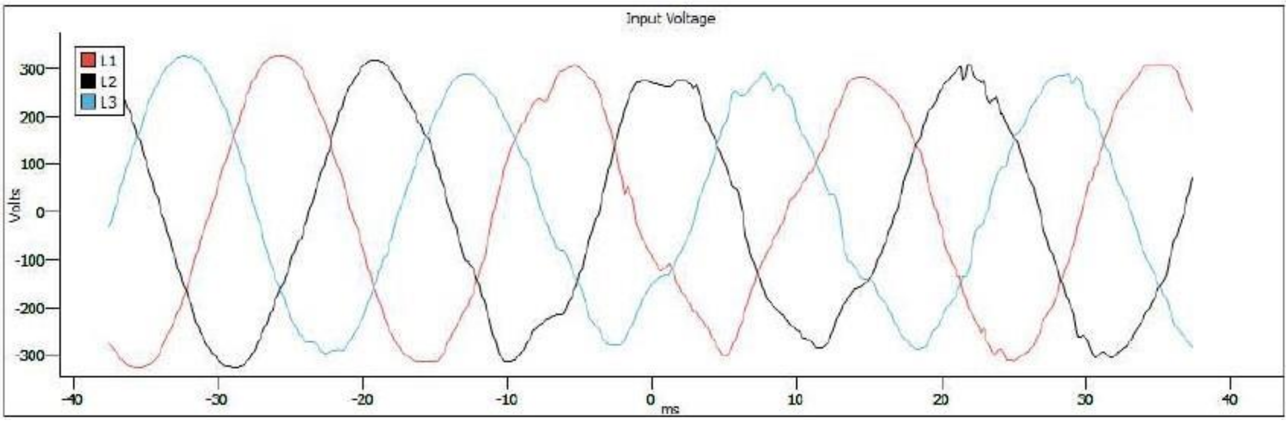


Figure 3.4: Signal with harmonics.

Figure 3.5 is an example of how a converter draws the current when operating. The desired signal is a sine wave, and it is clear to see that the signal below deviates remarkably from this. This signal contains a large number of harmonics and should therefore be filtered before being connected to the grid.

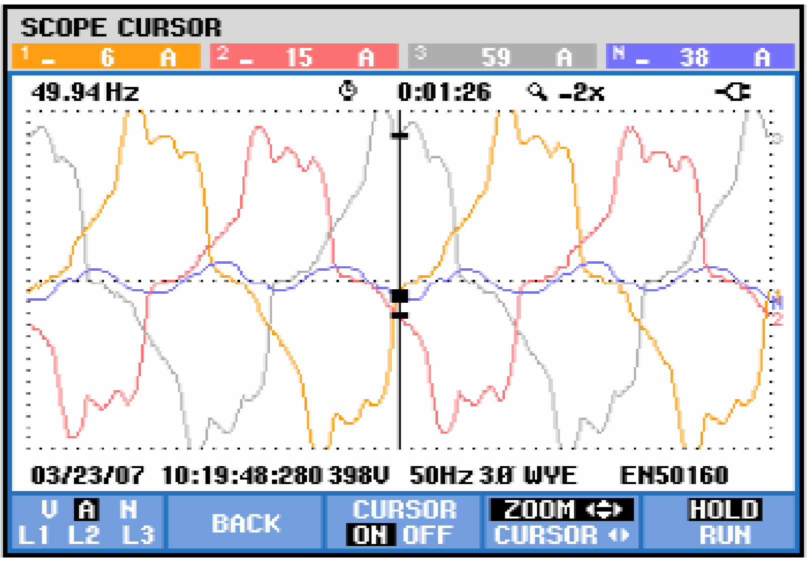


Figure 3.5: Example of current in a converter.

Figure 3.6 is another example of the current in a converter. It is seen that the current is not sinusoidal and will thereby inject harmonics into the output signal of the converter.

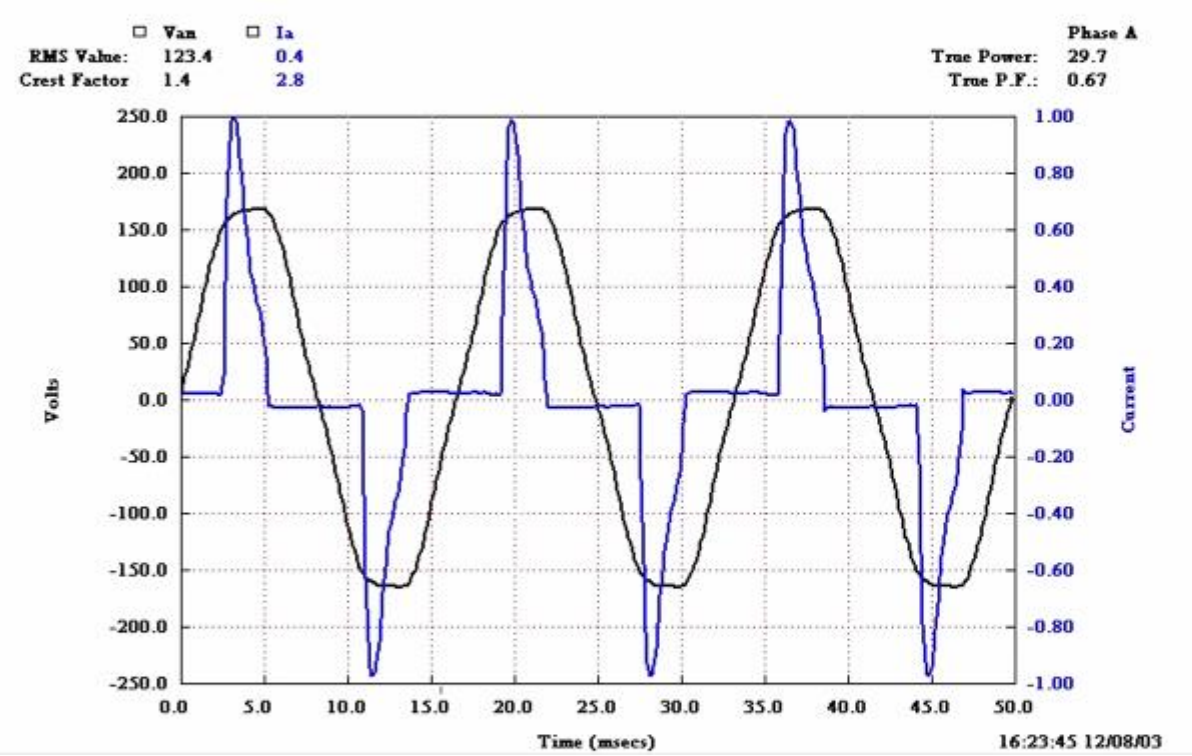


Figure 3.6: current(blue) and voltage(black) for a H-bridge converter.

In Figure 3.7 the effect of having an active filter is illustrated. The first row is the signal without a filter. It is seen that both the voltage and current are not sinusoidal and are therefore injecting harmonics. The harmonic content can be seen in the last column. The 5th, 7th and 11th harmonic orders are high, which are critical orders. This will make noise in the electricity grid if connected.

The second row shows the resulting signal when filtered by an active filter. Both the voltage and current are somewhat sinusoidal, which leads to a reduced harmonic content as shown in the last column which is almost only containing the fundamental frequency.

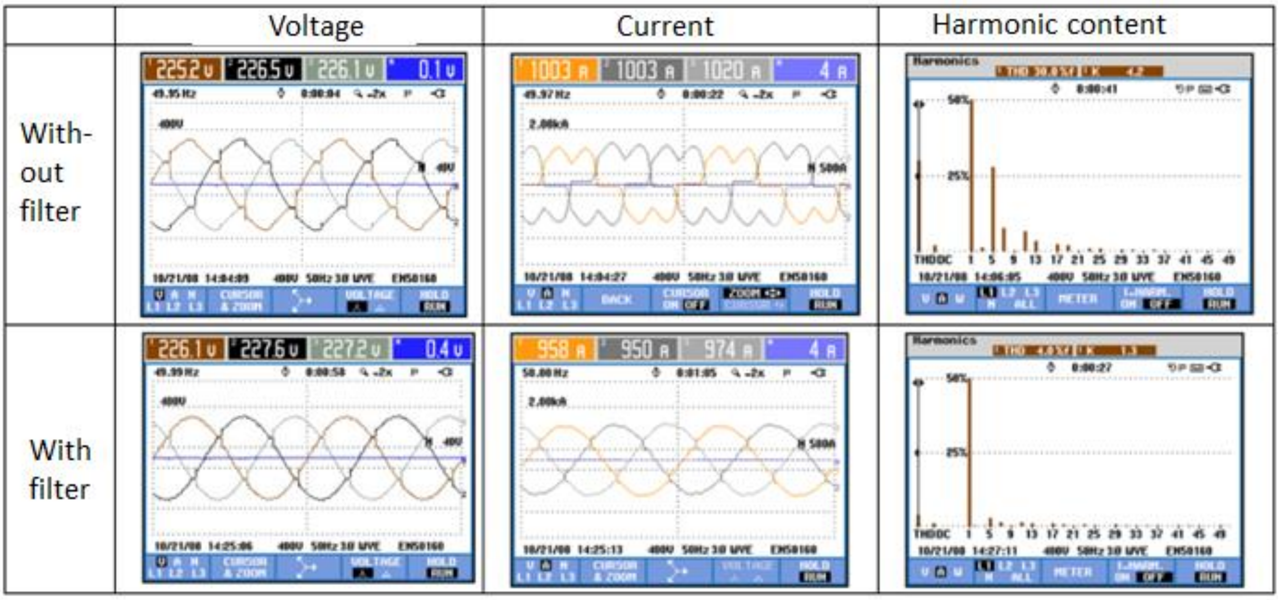


Figure 3.7: Effect of an active filter.

Since the noise content is dependent on the converter configuration etc. it is not possible to provide an overall description of how different components make noise. Though, it can be concluded that an investment in filters should be done since these can reduce the noise content significantly. Active filters are preferred because these filters all frequencies, but passive filters can also be used for some converters.

3.2.3 Voltage Variations

Voltage variations occur when the system voltage is deviating from the expected nominal voltage, e.g., 230 V. The variations can be seen as voltage unbalance where the voltage on the three lines is not symmetrical often caused by an unbalanced consumption in an equipment. Voltage variations should not exceed ± 10 % of nominal voltage.

3.2.4 Voltage Fluctuations (flicker)

A different kind of disturbances are voltage fluctuations. This is due to oscillation in the amplitude of the voltage (see Figure 3.8), where the result is seen as flicker in lights and displays. The light level is increasing when the amplitude of the voltage is increasing. (Andresen, 2020b) Flicker is a distortion of the sinusoidal signal (see Figure 3.9).

Flicker is defined as a signal with a frequency content of 0-30 Hz. Flicker is often seen in light, where the light is flickering, or if data is lost during a transfer.
Flicker often occurs when motors and elevators are starting and stopping but also when renewable energy-based units are producing since the production varies during the year.

Flicker generated by RE-based sources can vary from seconds to minutes and up to years. (Andresen, 2020b) Flicker is relevant to consider if e.g., a wind turbine is connected to a weak grid, due to the fluctuating wind profile (VidenOmVind, n.d.).

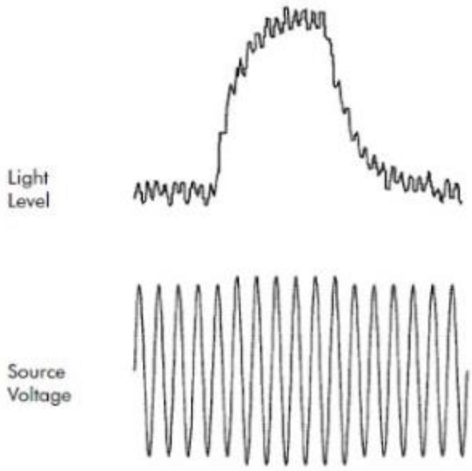


Figure 3.8: Result of voltage variations in the light level (Andresen, 2020b)

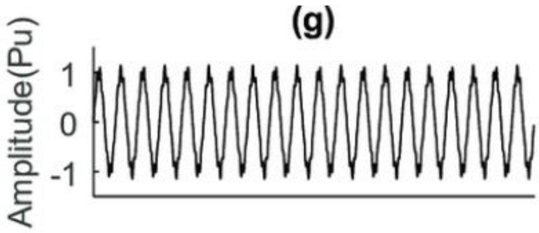


Figure 3.9: flicker is seen as a distortion of the sinusoidal signal

Flicker can be reduced by (Andresen, 2020b):

- Increasing the short circuit ratio (SCR) in the system (e.g., by having parallel cabling to the grid or including a generator in the system)
- Use a soft starter for motors to limit the start current
- Separation of motor and light circuit

Flicker is measured with a flicker meter.

4 Storage Technologies

As described there has always to be balance between the power production and consumption in the grid. In order to decouple the two, storage capacity has to be installed. In order to investigate the impact of installing storage capacity into the industry energy supply system three technologies are introduced in the following.

4.1 Carnot Batteries

Carnot batteries is a general term for storage systems using thermal energy to store electricity. Various thermal technologies (Heat pumps, electric boilers etc.) can be used when charging the battery. Discharging is done through thermodynamic processes. Carnot batteries are thereby a super category containing all storage setups which are using a combination of electricity and heat with heat as the storage medium. Carnot batteries consist of heat pumps, compressors, turbines, and heat exchangers. Moreover, the storage often consists of two (or more) tanks: one for high and one for low temperature (Dumont et al., 2020).

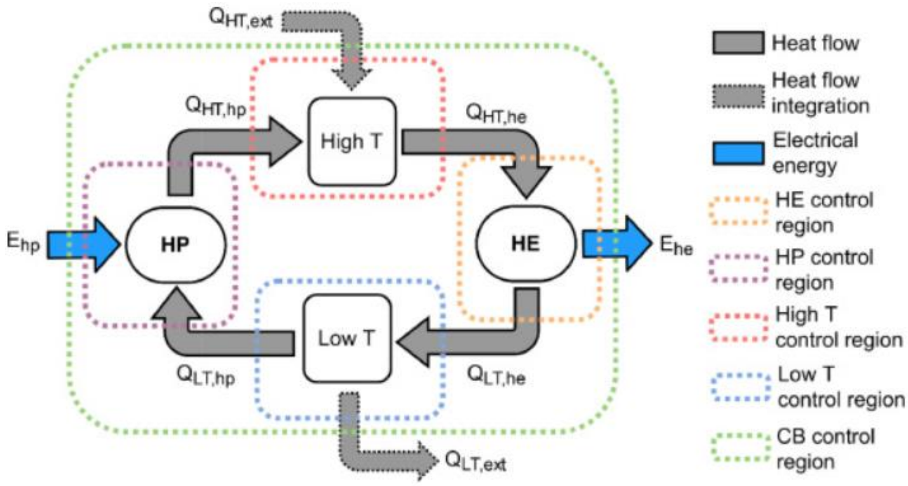


Figure 4.1: General setup for Carnot batteries (Dumont et al., 2020)

When charging the battery, electricity is used to transfer the heat from the low-temperature tank to the high-temperature tank, which often is done by heat pumps, boilers etc. To discharge the battery, the heat is transferred from the high-temperature tank to the low-temperature tank. This is done through thermodynamic processes, e.g., Rankine or Brayton cycles.

One of the main advantages of Carnot batteries is that they are not geographically dependent like e.g., CAES (Compressed Air Energy Storage) or PHES (Pumped Hydro Energy Storage) are. A disadvantage is that the roundtrip efficiency for Carnot batteries is relatively low compared to other storage technologies, given the loss when converting electric energy to heat and back again. The efficiencies depend on the specific cycle and components used in the Carnot battery, but in general, the efficiency is assumed to be around 45-65% (Dumont et al., 2020; Peng et al., 2018).

The most of the loss in Carnot batteries will be heat, and if the battery is connected to the district heating grid, then the efficiency can reach around 80% by utilizing the waste heat.

Since Carnot batteries are a fairly new technology, the technology has high investment costs (Dumont et al., 2020).

4.2 CHEST (Compressed Heat Energy Storage)

CHEST is a specific type of Carnot battery which consists of a specific setup. CHEST consists of a heat pump, thermal storage with phase changing material (PCM) and an Organic Rankine Cycle (ORC)-driven generator for regenerating electricity.

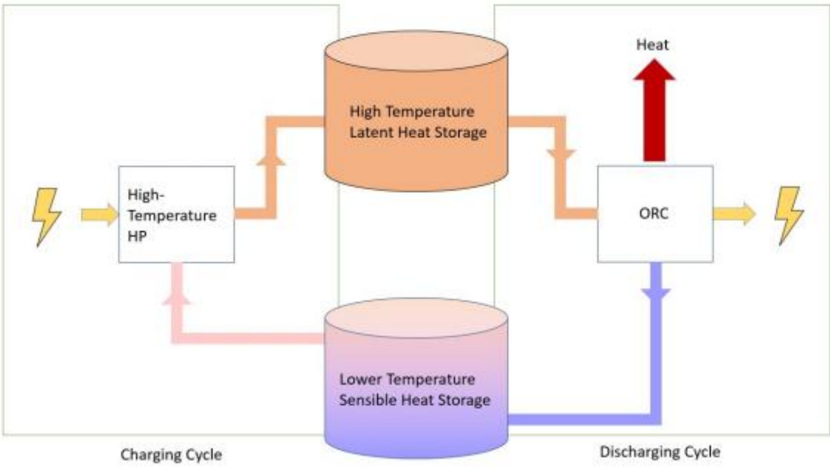


Figure 4.2: General setup for CHEST. Based on (Bava et al., 2020).

CHEST is charged by moving heat from the low-temperature storage to the high-temperature storage by the heat pump. The high temperatures storage is then used as a heat sink when operating the ORC. The heat output from the ORC is now cooled and transferred to lower-temperature storage. The round-trip efficiency for CHEST is approx. 40-50% (Bava et al., 2020; Dumont et al., 2020).

4.3 HeatCube™

HeatCube™ uses electricity to charge a thermal storage, where the storage medium is molten salt. When the HeatCube™ is charged, electricity is used to heat the salt. For discharging, steam is generated due to the high temperatures of the salt. HeatCube™ has a round-trip efficiency of approx. 90% and high flow temperatures of 200 °C (Kyoto Group, n.d.). Since a HeatCube™ produces steam at up to 10 bar g = 180 °C, it can replace the gas boiler in the industrial sector.

Moreover, HeatCube™ is flexible in configuration where charge, discharge, and storage capacities can be customised. Each HeatCube™ has a storage capacity of 16-96 MWh, and a charge capacity of 10, 20 or 30 MW, while the discharge capacity is up to 5 MW. Moreover, the turn-on time for the HeatCube™ is less than a minute. Additionally, the HeatCube™ allows charge and discharge simultaneously. (Kyoto Group, 2022)Due to the flexibility and fast turn on time, the HeatCube™ can participate in the different electricity markets.

4.4 The Role of Technologies on the Electricity Market

The three technologies described above can be integrated into the electricity markets with a high share of fluctuating energy. They can charge the batteries when the electricity price is low and discharge when the prices are high. The batteries can be used to lower electricity prices if the marginal price-setting mechanism is used. The technologies described above can participate in the Day-ahead market, intraday market, and a part of the regulating power market. The Carnot batteries can often participate in aFRR and mFRR due to the response time of the battery, which is in the range of 1,5 min – 10 min (Lagoni et al., 2022). Since HeatCube™ has heat as an output, it can only be used for up and down-regulation by changing the charging capacity. It cannot deliver power to the grid, due to the heat output.

A student project from Aalborg University by (Lagoni et al., 2022) concluded that investments in Carnot batteries are not feasible yet, due to the high investment costs. The same applies to the CHEST project by (Bava et al., 2020) which also concluded that the operational costs cannot be covered by the revenue when participating in the electricity markets. It is therefore necessary that the investment costs are lowered before these technologies can be competitive actors in the Danish electricity markets.

5 Electrification of an industry. Case study

In order to analyse and compare different configurations of electrification of an industry the following case study is set up.

The industry shall be seen as a generic model of an industry using heat for production of a product, having a heat demand of 1 MW and thus easy to scale up to the desired power level.

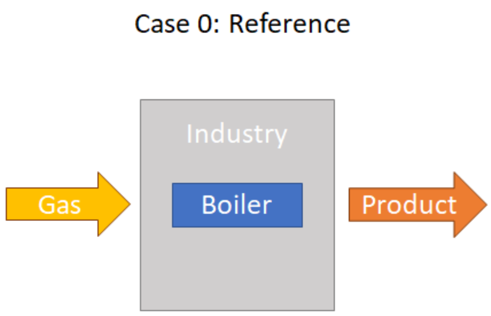
Since it is a generic model, this could have been everywhere in DK1, but in order to base the case study on real energy cost and tariff data the industry is assumed to be located close to PlanEnergi in Skørping, northern Denmark.

The industry is set to have a production stop of 3 weeks during summer (June 1st to June 21st) and 2 weeks during Christmas time (December 16th to December 31st).

The reference scenario used is a natural gas boiler having an output capacity of the needed 1 MW heat.

5.1 Change in Electricity Demand

Case 0: Reference



The industry system consists of a natural gas boiler to produce heat.

The case is investigated for 24h-production, 7-23 production and 7-15 production.
The results of this case are used as a reference for the feasibility study of the following cases related to the electrification of the industry.

The taxations shown in Table 5.1 are applied in the model.

Description	Amount
Electricity Tax	4 kr./MWh
Gas Tax	16,2 kr./MWh
CO_2 Tax	51,12 kr./MWh
NOx Tax	0,8 øre/Nm^3

Table 5.1: Energy-related taxes

Case 1: Electrification of the industry

This case aims to investigate the feasibility of electrifying parts of or the entire production, and if it is feasible to invest in electrical batteries or thermal storage, which allows the industries to move their demand from the electricity grid in time.

The case is separated into five subcases as illustrated in Figure 5.1.

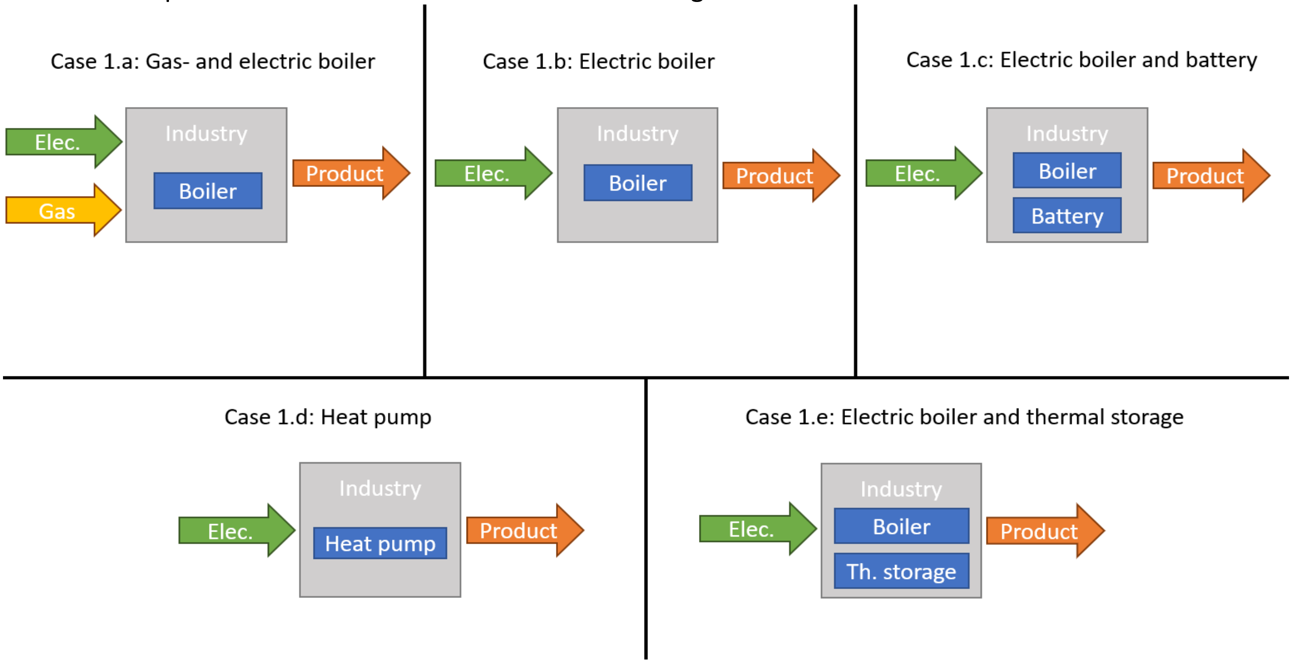


Figure 5.1: Case 1 Industry system configurations

Case 1.a: Natural gas and electric boiler

The industry system has both a natural gas boiler and an electric boiler for heat production. The unit with the lowest production costs is prioritised each hour.

Case 1.b: Electric boiler

The industry system has an electric boiler for heat production.

Case 1.c: Electric boiler and battery

The industry system has an electric boiler for heat production. The industry has a battery where electricity is stored when the electricity price is low. The battery is discharged when electricity prices are high and is then used in the boiler. The feasibility of the case is investigated for different battery capacities (e.g., 5 MWh to 30 MWh in steps of 5 MWh). The charge and discharge capacity for the battery is 1 MW with an efficiency of 98% cf. the *Technology Catalogue for Energy Storages*.

Case 1.d: Heat pump

The industry system has a heat pump for heat production. The thermal output is 1 MW_{th}. The heat output temperature is 70°C.

The COP of the heat pump is highly dependent on the temperature of the available heat source, and to investigate the impact the heat pump scenario is invested for heat pumps with COPs of 1.58, 3.15 and 6.30.

Case 1.e: electric boiler and thermal storage

The industry system has an electric boiler for heat production and a thermal storage. The electric boiler has an electric output of 2 MW. The thermal storage has a capacity of 30 MWh.

Case 2: Electrification and own production
This case aims to investigate the feasibility of different RE-based own production types.

The industry system consists of an electric boiler for heat production as shown in Figure 5.2. Moreover, the industry has own production of electrical energy, which can be used in the electric boiler. In case of a surplus of produced power from the own production, the energy can be sold to the electricity grid.

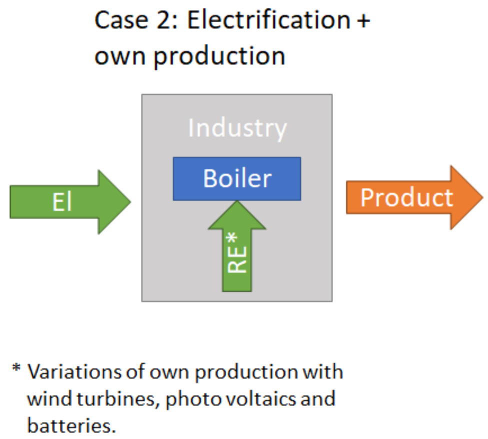


Figure 5.2: Case 2 industry system configuration.

The following configurations are analysed:

- *Case 2.1: Wind turbine (WT) as own production*
  The feasibility is investigated for a WT with a power of 1 MW, 2 MW, and 3 MW.
- *Case 2.2: WT and battery as own production*
  The most feasible WT from case 2.1 and the most feasible battery size from case 1.c is used for this configuration.
- *Case 2.3: Photovoltaics (PV) as own production*
  The feasibility is investigated for a PV with a power of 1 MW, 2 MW, and 3 MW.
- *Case 2.4: PV and battery as own production*
  The most feasible PV from case 2.3 and the most feasible battery size from case 1.c is used for this configuration.
- *Case 2.5: PV and WT as own production*
  The most feasible PV from case 2.3 and the most feasible WT size from case 2.1 are used for this configuration.

5.2 Flexibility Investigations

The following cases 3 to 6 investigate how the production is affected if the industry chooses different strategies for flexibility in buying the electricity.

Case 3: Electrification with price limitation of 544 kr./MWh
This case aims to investigate the effect of buying electricity until a certain price to produce the heat in an electrical boiler as shown in Figure 5.3. The scenario can be that an industry can buy electricity at the El-spot market until a certain price for the revenue of the production to cover the expenses related to buying power.

In this investigation, the industry has a maximum buying price for electricity (e.g., 544 kr./MWh). This is determined by the median value of the spot prices in 2021. This is investigated for a production period of 24h-production, 7-23-production, and 7-15-production.

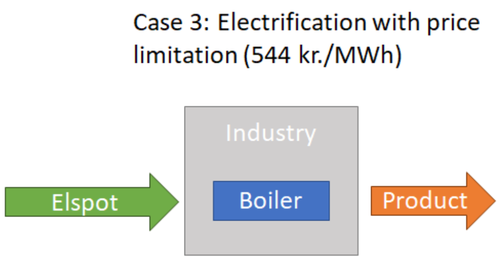


Figure 5.3: Case 3 Industry system configuration having an electrical boiler.

Case 4: Electrification with price limitation of 544 kr./MWh at spot market and down-regulating power market (mFRR).

In this case, the industry can buy power at both El-spot price and the down regulation power market, given that there is volume for regulation for the specific hour. This is investigated for a production period of 24h-production, 7-23-production, and 7-15-production.

The industry system produce the heat in an electrical boiler as shown in Figure 5.4.

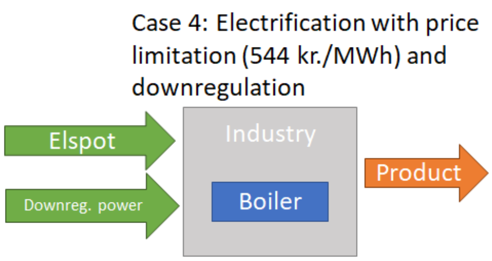


Figure 5.4: Case 4 Industry system configuration having an electrical boiler.

Case 5: Consecutive 8 cheapest hours within a day

The industry must produce for 8 continuous hours every productionday, where the total electricity price for the 8 hours must be as cheap as possible. Production must be within the interval 00:00-24:00 per day and must not enter a new day. It is investigated when the 8 cheapest consecutive hours are in a day, as well as how much variation there is in these over a year, as well as how it varies for 2020, 2021 and 2022.

The industry system produce the heat in an electrical boiler as shown in Figure 5.5.

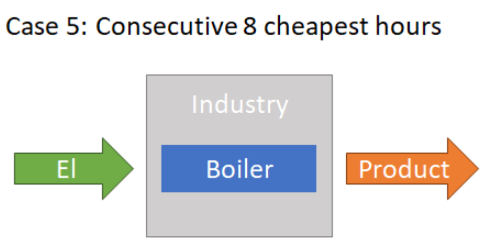


Figure 5.5: Case 5 Industry system configuration having an electrical boiler.

Case 6: Flexibility in periods for charging battery within a day

This case aims to investigate if the savings due to the flexibility in hours for charging, can cover the expenses for investment in the battery technology.

The industry system consists of an electrical boiler and an electrical battery as shown in Figure 5.6.

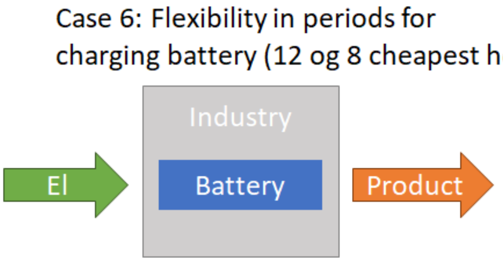


Figure 5.6: Case 6 The industry system consists of an electrical boiler and an electrical battery.

The battery may only charge in the cheapest hours and discharge in the most expensive hours during the day.

This is investigated for both the 12 and 8 cheapest hours every day for 2020, 2021 and 2022. Christmas holidays and summer holidays are disregarded, as well as content in the heat storage (The battery can charge the last 8 hours on the previous day, and again the next 8 on the following day).

6 Methods

The case study is based on an hourly-based simulation of the optimal operation of the specific system configuration and scenarios.

energyPRO has been chosen as the simulation tool for analysing scenarios since a part of the scope of this project is to identify the best energy system setup from a techno-economic perspective.

6.1 energyPRO

energyPRO is a business-economic simulation model tool, which provides the ability to optimise the system operation against different markets. energyPRO is made by EMD International.

energyPRO uses internal optimisation where the tool optimises the operation of different units dependent on internal rules and characteristics assigned in energyPRO (costs, emissions etc.) Optimisation aims to find the most economically feasible operation strategy for the units in the system. This is done by including both the technical behaviour and business economic implications provided due to markets, taxes, subsidies and more (Østergaard et al., 2022).

The geographical scope of energyPRO is to simulate plants and their technologies. Though, countries can be modelled by aggregating units. Furthermore, there is an option to interconnect several sites and apply grid constraints, losses, etc., and thereby get a more detailed result when modelling countries or several plants (Østergaard et al., 2022).

energyPRO provides the ability to make versatile models: the tool has predefined units for energy conversion units (e.g., heat pumps, motors, solar PV, wind turbines etc.), storages (e.g., heat storages, batteries etc.) and demands (heat, electricity, and cooling). Each unit has input parameters which the user can define. This is both by assigning specific time series like electricity prices which vary during the year, or by defining constant parameters such as efficiency or electrical capacities etc. Moreover, the user can customise units by using the *user-defined*-unit.

EMD International provides an online server where different kinds of input data can be downloaded from. This data counts data like wind speed, solar irradiation, temperatures etc. The data have an hourly resolution, which is suited for energyPRO. energyPRO is optimising the systems against the electricity markets, why the resolution of the tool is therefore highly determined by these. The minimum temporal resolution is 5 min. Furthermore, it is possible to simulate from daily operation for up to 100 years.

energyPRO is optimising the total energy production cost. The model is assigning a priority number to each energy technology in each time step, to determine the most economically feasible operation strategy for the system. energyPRO has two types of modelling approaches: *analytic* and *mixed-integer linear programming (MILP).* In analytic, energyPRO has perfect foresight of the optimisation period, and can thereby activate the highest priority numbers first (e.g., the cheapest technology from a business-economic perspective). Units are activated until the energy demand is met. The priority numbers can either be user-defined or calculated by energyPRO. If calculated by energyPRO, the priority number for each hour is determined by the short-term marginal costs for heat production for each unit, since the tool aims to get the lowest total costs for heat production. The reason for this is that energyPRO originally was made for district heating purposes.
For the MILP-approach, the objective of the optimisation strategy is to optimise the operation income (all revenues and operation expenditures). The MILP-approach require operation constraints e.g., minimum loads or minimum electricity buying prices etc. the analytical solver is in general faster than MILP unless when

dealing with energy storages, more production units with minimum loads or when having different types of loads (electricity, heating, cooling, etc.) (Østergaard et al., 2022).

6.2 Simulation input parameters

The input parameters used in the energyPRO simulation of the cases are shown in the following Table 6.1.

Table 6.1: Input Parameters for Cases

Case	Type of input	Input	Value	Source
All	Time series	Day ahead market prices*		Nordpool
Case 0	Time series	Natural gas prices*		(OK, n.d.)
	Expenditures	Gas Taxation	16,2 kr./MWh	
		CO2 taxation	51,12 kr./MWh	
		NOx taxation	0,008 kr./Nm^3	
		O&M	5 kr./MWh	
	Conversion unit	Gas boiler	Input: 1,1 MW Output: 1 MW	(Energistyrelsen & Energinet, 2016)
Case 1	Time series	Temperatures for North Jutland, Denmark*		DRY temperatures
	Expenditures	Price for buying electricity*	Time series – spot	
		Transmission tariff	143 kr./MWh	(Energinet, n.d.-a)
		Tax: "Elvarmeafgift"	4 kr./MWh	Internal source
		O&M	6,75 kr./MWh	(Energistyrelsen & Energinet, 2016)
	Conversion units	Electric boiler	Input: 1 MW Output: 1 MW	(Energistyrelsen & Energinet, 2016)
		Battery	Capacity Efficiency Charge and discharge power (1 MW, η=98%)	(Energistyrelsen & Energinet, 2018)
		Heat pump	COP 1,58, 3,15 and 6,30 MW_{out} 1MW (thermal)	(Energistyrelsen & Energinet, 2016)
Case 2	Time series	Temperatures for North Jutland, Denmark		energyPRO
		Aggregated Solar irradiation zone 1*		energyPRO
		Medium wind speed for Aars, Denmark*		energyPRO
	Income	Sale of electricity*	Time series – spot	
	Expenditures	Price for buying electricity*	Time series – spot	
		Transmission tariff	143 kr./MWh	(Energinet, n.d.-a)
		Tax: "Elvarmeafgift"	4 kr./MWh	Internal source

		O&M	6,75 kr./MWh	(Energistyrelsen & Energinet, 2016)
	Conversion units	Wind turbines	Windspeeds: time series* Power curve (see sources) Height of measurement Hub Height (see sources)	Performance data from the following VESTAS windturbines: V66-1.65MW V90-2.0MW V117-3.3MW
		Solar panel	Capacity Temperatures: time series* Slope	(Energistyrelsen & Energinet, 2016)
		Electric boiler	Input: 1 MW Output: 1 MW	(Energistyrelsen & Energinet, 2016)
		Battery	Capacity Efficiency Charge and discharge power (1 MW, η=98%)	(Energistyrelsen & Energinet, 2018)
Case 3	Income	Sale of electricity*	Time series – spot	
	Expenditures	Price for buying electricity*	Time series – spot	
		Transmission tariff	143 kr./MWh	(Energinet, n.d.-a)
		Tax: ”Elvarmeafgift”	4 kr./MWh	Internal source
		O&M	6,75 kr./MWh	(Energistyrelsen & Energinet, 2016)
	Conversion units	Electric boiler	Input: 1 MW Output: 1 MW	(Energistyrelsen & Energinet, 2016)
Case 4	Time series	Downregulation price*	Time series	
		Downregulation volume*	Time series	
	Income	Sale of electricity*	Time series – spot	
	Expenditures	Price for buying electricity*	Time series – spot	
		Transmission tariff	143 kr./MWh	(Energinet, n.d.-a)
		Tax: ”Elvarmeafgift”	4 kr./MWh	Internal source
		O&M	6,75 kr./MWh	(Energistyrelsen & Energinet, 2016)
	Conversion units	Electric boiler	Input: 1 MW Output: 1 MW	(Energistyrelsen & Energinet, 2016)

*for 2020, 2021 and oct-2021-oct-2022

The different conditions and constraints influencing the energyPRO simulations are shown in Figure 6.1.

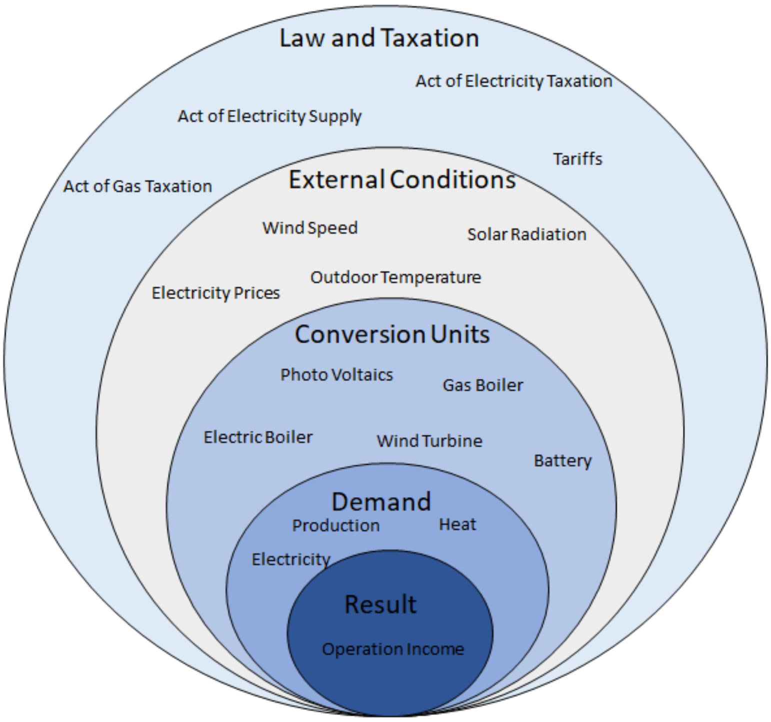


Figure 6.1: The different conditions and constraints influencing the energyPRO simulations.

2021 is chosen as the reference year for all cases in this project. To see variations due to differences in external conditions for 2020 and 2022, then these are also calculated.

6.2.1 Variations in Input Data

Monthly average values are shown in the following: electricity prices: Figure 6.2, gas prices: Figure 6.3, , and windspeeds: Figure 6.4 and solar radiation: Figure 6.5.

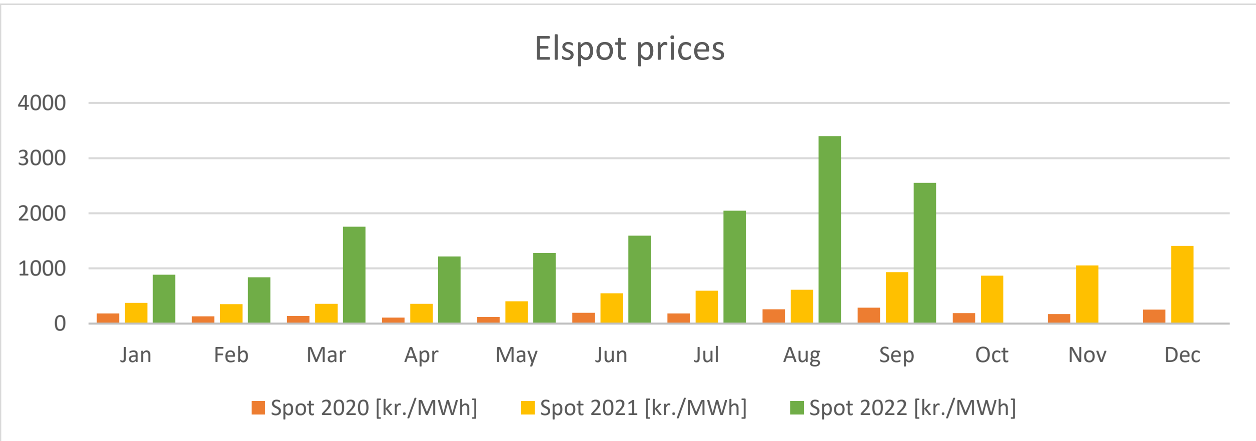


Figure 6.2: monthly average values for elspot prices for 2020, 2021, and 2022.

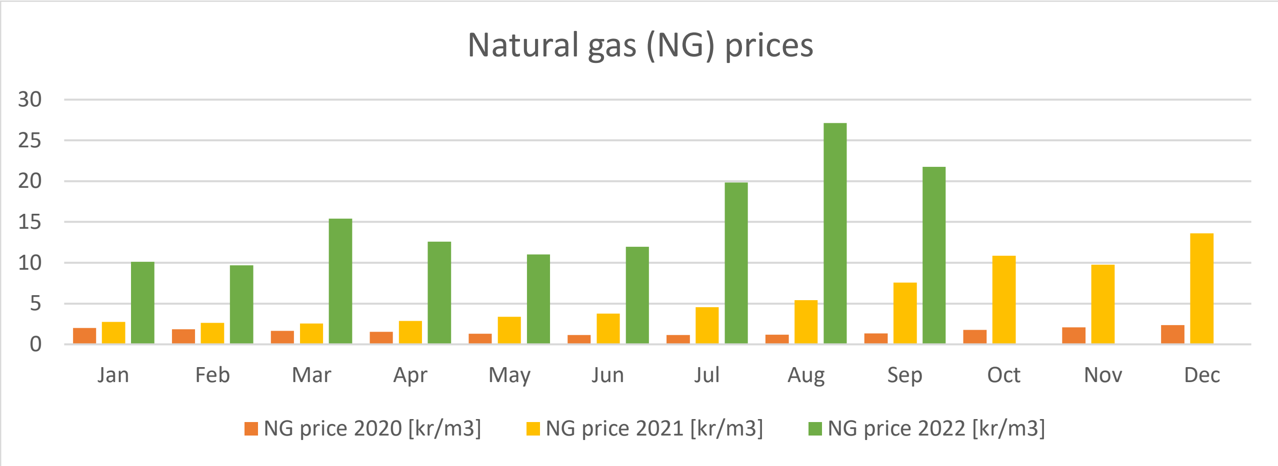


Figure 6.3: monthly average values for Natural prices for 2020, 2021, and 2022.

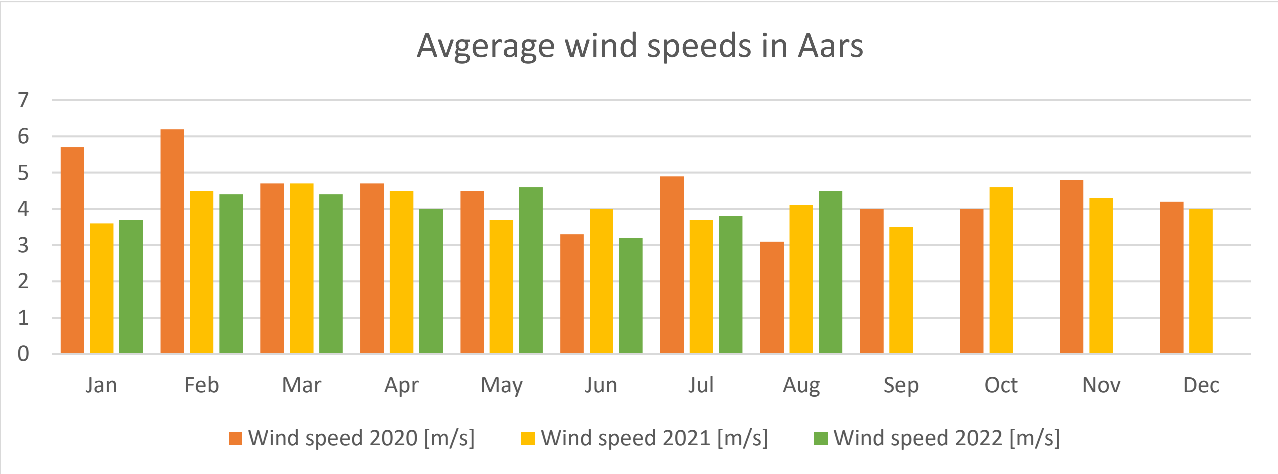


Figure 6.4: monthly average values for wind speeds in Aars for 2020, 2021, and 2022.

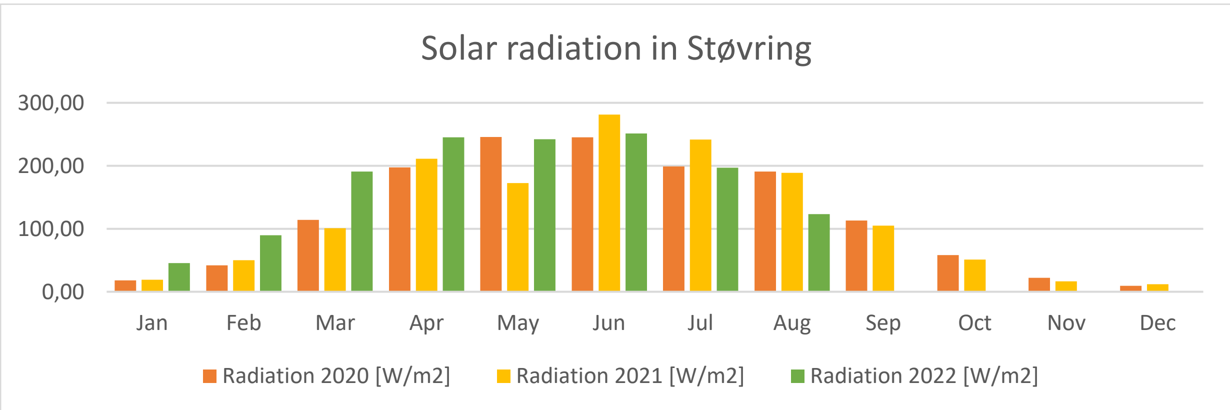


Figure 6.5: monthly average values for solar radiation in Støvring for 2020, 2021, and 2022.

Both electricity and natural gas prices have been rising during the last two years as shown in Figure 6.2 and Figure 6.3. Especially, from September 2021 a large increase in price is seen. The prices have a large influence on the feasibility of the cases in this report, where especially own production is more feasible when the fuel prices are high since the profit when selling surplus and the savings earned when producing energy on RE-based own production instead of buying from the electricity grid are high.

Moreover, it can be seen in Figure 6.4 and Figure 6.5 that the variations in solar radiation and wind speeds are relatively alike in the three years. They are thereby not assumed to have a significant influence on the results of the cases.

6.3 Business Economic Evaluation

A business economic evaluation is used to determine which of the cases are most beneficial for the industry to choose. Each case and their respective scenarios are evaluated by the same parameters: *Net savings, Simple payback time,* and *Savings per operational hour.*

Economic results from the Operation Income report from energyPRO, data from the technology catalogue, and data from Kommunekredit.dk are used in the business case calculation. An example of the calculation can be seen in Table 6.2.

Business case		**Reference**	**Alternative**
Operating expenditures	kr./year	1.500.000	1.000.000
Difference in expenditures	kr./year		-500.000
Financial savings	kr./year		**500.000**
Investment	kr.		400.000
Net amount for borrowing	kr.		400.000
Capital costs	kr./ year		22.971
Net savings	**kr./year**		**477.029**
Simple payback time	**year**		**0,8**
Savings per operational hour	**kr./MWh**		**54,5**

Table 6.2: Example of calculation table for profitability of investing in Alternative compared to Reference

Each of the alternatives which are the different scenarios are compared to the reference, to see the possible benefits for the industry if investing in the specific alternative.

As listed in Table 6.2, the following parameters are required to calculate the business economy for each case:

Operating expenditures: Data are calculated by energyPRO – it consists of expenditures for producing energy subtracted the revenue when selling electricity. The revenue of the product produced (e.g., apricots) are not included in the calculations.

Difference in expenditures: The difference between the expenditures of the alternative compared to the reference.

Financial savings: Is the same as the *Difference in expenditures*

Investment: Data are in alignment with the *Technology Data for Generation of Electricity and District Heating* (Energistyrelsen & Energinet, 2016) and the *Technology Data for Energy Storage* (Energistyrelsen & Energinet, 2018).

Net amount for borrowing: Contains the investments

Capital costs: Calculation of the payments related to the loan by the excel-function PMT. This contains the interest rate (3,3 % defined by (KommuneKredit, 2022), the lifetime for the invested technology being 25 years according to the technology catalogues (Energistyrelsen & Energinet, 2016, 2018) and finally the amount of investment.

Net savings: The *financial savings* subtracted the *capital costs*.

Pay-back time: calculated by dividing the *Net amount for borrowing* with the *financial savings*. This gives the payback time for paying the investment with the savings by investing in the specific setup compared to the reference.

Savings per operational hour: Net savings divided with the hours of operation, which are calculated by energyPRO.

The high savings can be used for reinvestment in the industry, for lowering the price of the product, etc. Regarding the payback time, then this should be below 25 years for the scenario to be feasible. If it is longer than 25 years, then the component is expected to be worn out, and need replacement and thereby reinvestment, why the deficit is higher than the savings, and thereby not feasible. The highest saving per operational hour makes the investments comparable if the operational hours vary. Best case is the alternative with highest net saving, lowest payback time and highest savings per operational hour.

7 Results

The results of the case study is presented in the following.

7.1 Case 0 to 2 Electrification of the Industry

7.1.1 Results for 2021

Based on the economic calculations seen in

, case 1d with 1 MW_{th} heat pump with a COP of 6,30 is at first glance the most feasible solution, but given the fact that the heat pump can only deliver heat at 70°C, which is assumed not to be sufficient for most industries, this solution is not chosen as the most feasible in the following analysis. Moreover, if the industry has lower operating hours (e.g., 8 hours per day) then the net savings for the HP case would be lower. Moreover, the case would then have a longer payback time due to the large investment in the heat pump. For some cases it can be considers whether a setup with a heat pump in a combination with either a gas or electric boiler can be feasible. This applies for all heat pump results for 2020-2022.

As can be seen in Table 7.1 case 2.3 with 3 MW PV is therefore assumed most feasible in 2021, due to the higher output temperatures from the electric boiler. This case has the highest savings and lowest payback time of all the cases analysed. Most investments in batteries are too expensive and the net savings are negative for all battery scenarios. The batteries in the analysed cases were not allowed to sell to the electricity markets: this could have affected the feasibility of the battery scenarios.
Moreover, wind turbines are too expensive compared to photovoltaics, why the cases with PV have a better economy.

Since the prices for electricity and natural gas are closely related, as shown in Figure 6.2 and Figure 6.3, there is a low risk related to the electrification of the industry. If the share of RE is increased in the electricity mix, then the electricity prices are lowered, which makes electrification even more profitable. Furthermore, RE-based production units (wind turbines (WT) and photovoltaics (PV)) have lower production costs and can thereby decrease the electricity price in general if the share of RES is increased in the Danish electricity mix. This is not the case for fossil fuel-based production units, where the costs are much higher.

Table 7.1: Extract of economic feasibility calculation for 2021

Description	Yearly savings [kr./year]	Investment [kr.]	Net savings [kr./year]	Payback time [year]
Case 0 - Reference				
Case 1a – Gas and electric boiler	-861.837	1.100.000	-925.008	-
Case 1b – Electric boiler	-1.145.162	1.100.000	-1.208.333	-
Case 1c - Battery 5 MWh	-415.796	24.238.400	-1.807.756	-
Case 1c - Battery 10 MWh	-195.944	47.376.800	-2.916.693	-
Case 1c - Battery 15 MWh	-76.110	70.515.200	-4.125.648	-
Case 1c - Battery 20 MWh	-4.884	93.653.600	-5.383.211	-
Case 1c - Battery 25 MWh	44.014	116.792.000	-6.663.102	2.654
Case 1c - Battery 30 MWh	83.847	139.930.400	-7.952.058	1.669
Case 1d – 1 MW_{th} heat pump – COP 3,15	3.060.799	7.200.000	2.647.318	2

Case 1d – 1 MW_{th} heat pump – COP 6,30	4.026.105	7.200.000	3.612.624	2
Case 1d – 1 MW_{th} heat pump – COP 1,58	1.130.187	7.200.000	716.706	6
Case 1e – 2 MW electric boiler and 30 MWh thermal storage	121.793	12.920.800	-620.221	106
Case 2.1 - 1 MW WT	-793.481	29.372.000	-2.480.252	-
Case 2.1 - 2 MW WT	-323.766	57.644.000	-3.634.138	-
Case 2.1 - 3 MW WT	196.498	85.916.000	-4.737.475	437
Case 2.2 - 1 MW WT and 5 MWh Battery	-12.077	59.372.000	-3.421.685	-
Case 2.3 - 1 MW PV	-172.455	4.373.600	-423.622	-
Case 2.3 - 2 MW PV	718.530	7.647.200	279.368	11
Case 2.3 - 3 MW PV	1.563.231	10.920.800	936.073	7
Case 2.4 - 3 MW PV and 5 MWh battery	2.237.779	34.059.200	281.832	15
Case 2.5 - 3 MW PV and 1 MW WT	1.760.504	39.192.800	-490.255	22

7.1.2 Results for 2020

As it can be seen in Table 7.2 only case 1d with heat pumps with COPs above 3 are proven feasible for 2020. All of the other alternatives have negative net savings and either negative or very long payback times. Investment in batteries was not feasible for any battery sizes in 2020, due to high investment costs and low electricity prices in 2020. Furthermore, a replacement of the gas boiler with an electric boiler (case 1b) is not feasible either, which is a result of the low electricity prices. Wind turbines as own production are not feasible, due to high investment costs and low electricity prices.

Table 7.2: Extract of economic feasibility calculation for 2020

Description	Yearly savings [kr./year]	Investment [kr.]	Net savings [kr./year]	Payback time [year]
Case 0 - Reference				
Case 1a – Gas and electric boiler	-557.288	1.100.000	-620.459	-
Case 1b - Electric boiler	-820.118	1.100.000	-883.289	-
Case 1c - Battery 5 MWh	-531.322	24.238.400	-1.923.282	-
Case 1c - Battery 10 MWh	-447.154	47.376.800	-3.167.903	-
Case 1c - Battery 15 MWh	-398.039	70.515.200	-4.447.577	-
Case 1c - Battery 20 MWh	-364.539	93.653.600	-5.742.866	-
Case 1c - Battery 25 MWh	-338.983	116.792.000	-7.046.099	-
Case 1c - Battery 30 MWh	-320.008	139.930.400	-8.355.913	-
Case 1d – 1 MW_{th} heat pump – COP 3,15	964.553	7.200.000	551.072	7

Case 1d – 1 MW_{th} heat pump – COP 6,30	1.415.400	7.200.000	1.001.919	5
Case 1d – 1 MW_{th} heat pump – COP 1,58	62.859	7.200.000	-350.622	115
Case 1e – 2 MW electric boiler and 30 MWh thermal storage	-305.781	12.920.800	-1.047.795	-
Case 2.1 - 1 MW WT	-566.846	29.372.000	-2.253.617	-
Case 2.1 - 2 MW WT	-293.128	57.644.000	-3.603.500	-
Case 2.1 - 3 MW WT	1.450	85.916.000	-4.932.523	59.252
Case 2.2 - 1 MW WT and 5 MWh Battery	-313.118	59.372.000	-3.722.726	-
Case 2.3 - 1 MW PV	-403.173	4.373.600	-654.340	-
Case 2.3 - 2 MW PV	-55.235	7.647.200	-494.397	-
Case 2.3 - 3 MW PV	238.863	10.920.800	-388.295	46
Case 2.4 - 3 MW PV and 5 MWh battery	499.065	34.059.200	-1.456.882	68
Case 2.5 - 3 MW PV and 1 MW WT	462.135	39.192.800	-1.788.624	85

7.1.3 Results for 2022

Due to operation parameters in energyPRO data for 8760 hours (a full year) are required. Therefore, data from oct-2021 to sep-2022 is used and is referred to as 2022 in the following.

As it can be seen in Table 7.3 in 2022, a configuration of 3 MW PV and 1 MW WT (case 2.5) is most feasible for the industry due to high net savings and low payback time. Additionally, case 2.4 with 3 MW PV and a 5 MWh battery is close to the result of case 2.5 why this also could be a feasible solution. Alternatively, the industry should invest in 3 MW PV (case 2.3). Due to the lower output temperatures for the heat pumps in case 1d, these are also net seen as a feasible technology, except if investigated with higher output temperature or with an electric boiler.

Table 7.3: Extract of economic feasibility calculation for Oct-2021 to Sep-2022.

Description	Yearly savings [kr./year]	Investment [kr.]	Net savings [kr./year]	Payback time [year]
Case 0 - Reference				
Case 1a – Gas and electric boiler	-1.099.250	1.100.000	-1.162.421	-
Case 1b - Electric boiler	-1.841.795	1.100.000	-1.904.966	-
Case 1c - Battery 5 MWh	18.472	24.238.400	-1.373.488	1.312
Case 1c - Battery 10 MWh	537.509	47.376.800	-2.183.240	88
Case 1c - Battery 15 MWh	825.674	70.515.200	-3.223.864	85
Case 1c - Battery 20 MWh	1.012.618	93.653.600	-4.365.709	92
Case 1c - Battery 25 MWh	1.152.760	116.792.000	-5.554.356	101
Case 1c - Battery 30 MWh	1.260.816	139.930.400	-6.775.089	111

Case 1d – 1 MW_{th} heat pump – COP 3,15	8.182.010	7.200.000	7.768.529	1
Case 1d – 1 MW_{th} heat pump – COP 6,30	10.200.711	7.200.000	9.787.230	1
Case 1d – 1 MW_{th} heat pump – COP 1,58	4.144.609	7.200.000	3.731.128	2
Case 1e – 2 MW electric boiler and 30 MWh thermal storage	1.373.191	12.920.800	631.177	9
Case 2.1 - 1 MW WT	932.422	29.372.000	-754.349	32
Case 2.1 - 2 MW WT	3.184.705	57.644.000	-125.667	18
Case 2.1 - 3 MW WT	6.365.730	85.916.000	1.431.757	13
Case 2.2 - 1 MW WT and 5 MWh Battery	2.875.648	59.372.000	-533.960	21
Case 2.3 - 1 MW PV	664.354	4.373.600	413.187	7
Case 2.3 - 2 MW PV	3.069.100	7.647.200	2.629.938	2
Case 2.3 - 3 MW PV	5.425.745	10.920.800	4.798.587	2
Case 2.4 - 3 MW PV and 5 MWh battery	7.414.690	34.059.200	5.458.743	5
Case 2.5 - 3 MW PV and 1 MW WT	8.156.562	39.192.800	5.905.803	5

7.1.4 Visualisations of Results

It is shown in Figure 7.1 that the electricity price has a large impact on the feasibility of the cases, where most cases are feasible in 2022 but not in 2020. Moreover, there is no linearity between installed capacity and net savings: net savings for 1 MW WT is not 3 times bigger than for 3 MW WT. This is mainly due to the price setting mechanism for the electricity price, where the hours with high production on WTs are the same for all the WTs in the grid, and thereby leads to hours with lower electricity prices. The revenue when selling in these hours is, therefore, lower than other hours.

The electricity price is also affecting the payback time for the different cases. Figure 7.2 illustrates a significant change in payback times over the years, where the payback time for a 3 MW wind turbine in 2020 is 60.000 years compared to 13 years in 2022. Since the payback time for some technologies are above 100 years, these have been modified to 100 instead to see all payback times. The large difference in the payback time underlines the conclusion the feasibility of the cases in the future cannot be predicted.

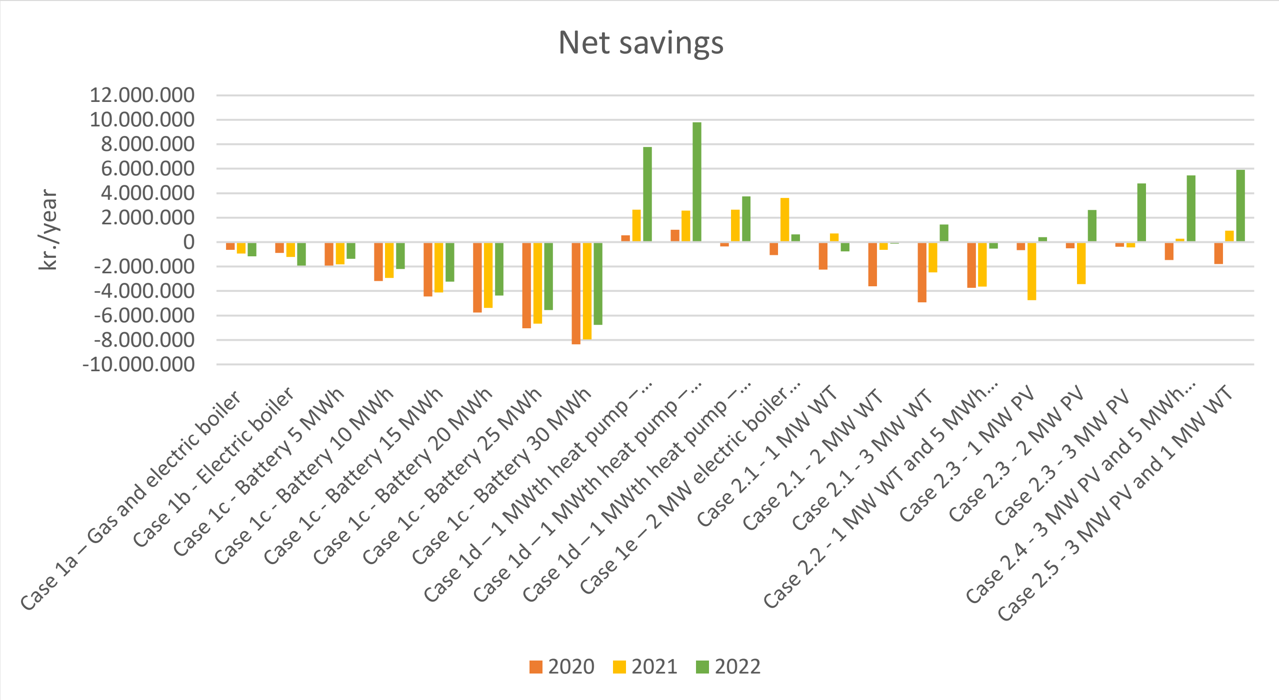


Figure 7.1: Comparison of net savings for 2020 to 2022 for all cases

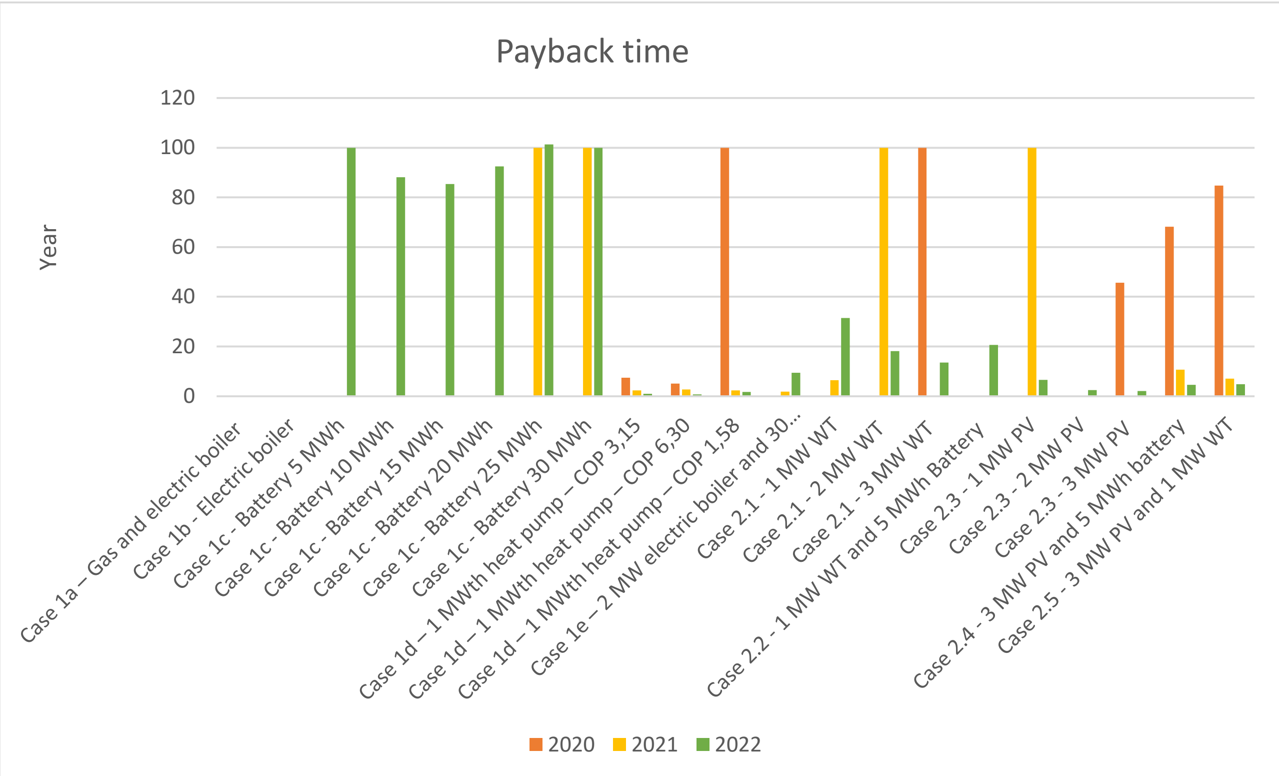


Figure 7.2: Comparison of payback time for 2020 to 2022 for all cases. Technologies with a payback time above 100 years have been modified to 100 to portray the rest of the payback times.

7.2 Case 3-4 – Maximum Limit Buying Price (544 kr./MWh)

If a strategy with a maximum buying price for electricity is chosen, then the hours of operation for the industry vary significantly over the years, as seen in Figure 7.3. in 2020, the industry would have a high number of operating hours of around 87-99 % of the time, whereas this is only 10-17 % in 2022, due to the higher prices in 2022. There is a slight increase in operating hours if the industry can buy from both Elspot and down-regulation, but not enough to ensure 100% operation for any of the years.

As described in section 5.2 on page 21, the price limitation of 544 kr./MWh is used as an example of if the industry buys buying electricity until a certain price. The 544 kr./MWh is the price median of the Elspot price in 2021.

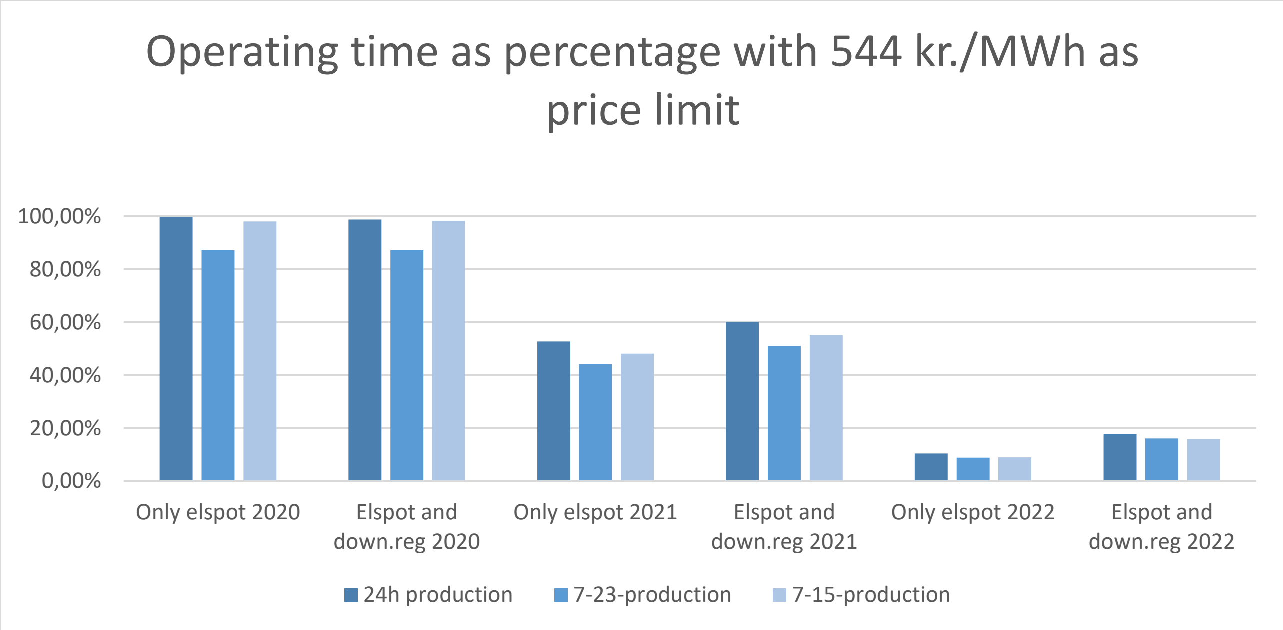


Figure 7.3: Operating hours as a percentage for 2020, 2021, and 2022

Therefor a maximum price as a limitation cannot be recommended as the driver for electrification in the industry.

7.3 Case 5 – Production in the Cheapest 8 Consecutive Hours

In this case, it is investigated how the distribution of the cheapest 8 consecutive hours within a day is, and how this varies over time. As shown in Figure 7.4, the cheapest hours in 2020 were mainly at night (00-08, first collum). In the summer period, however, there are days when it is cheapest for the industry to have the 8-hour production at 8-18. In addition, there are also quite a few cases where the cheapest time slot is 15-23.

In 2021, there are significantly fewer days where 15-23 is the cheapest. On the other hand, quite a few more days, when production from 6-17 in the summer period is cheapest. However, there are still most days when 00-08 is the cheapest time slot.

In 2022, there will be a big change in the number of days when it is cheapest from 8-18. In addition, there is also a decrease in the number of days when it is cheapest from 00-08.

It can therefore be concluded that the variation in the cheapest production hours between the three years varies greatly. The increase in the number of days when it is cheapest in the middle of the day can be linked to the increase in the installed capacity of solar panels during this period.

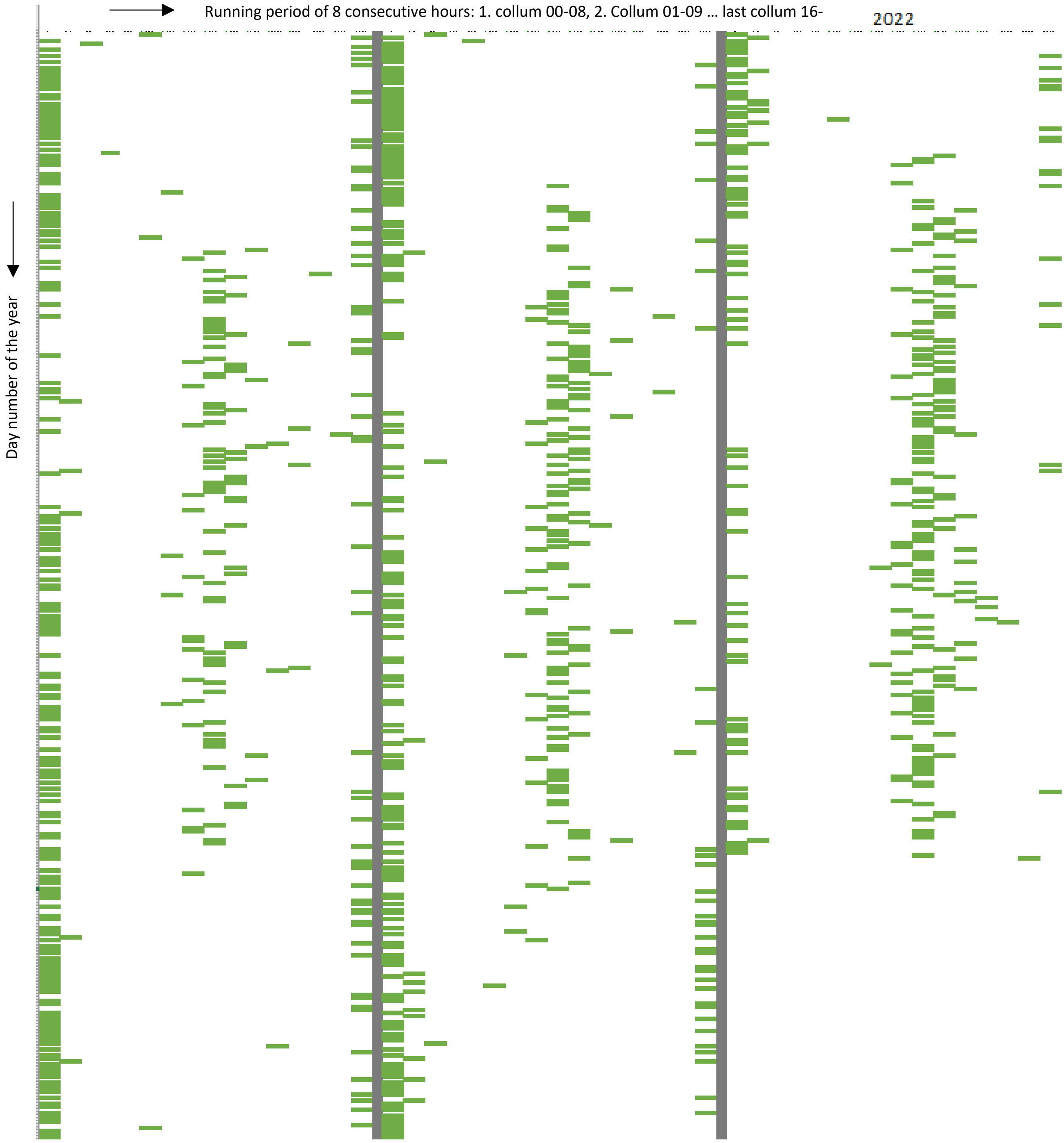


Figure 7.4: Visualisation of the cheapest 8 consecutive hours (green) for 2020, 2021, and until 30/9-2022.

Since the results vary as much as seen, it is difficult to make a recommendation on whether it is profitable for the industry to have flexible production. Since the prices at the Elspot market are set the day before production, duty schedules can only be planned the day before. Moreover, there is a risk that the production runs for the last 8 hours of the previous day and the first 8 of the next day, with results in that the production runs for 16 hours straight. Costs related to this type of flexible production time must therefore be included if it is considered to use this type of flexibility.

7.4 Case 6 – Flexibility in Charging Periods (8 and 12 cheapest Hours)

In this case, it has been investigated how much the industry can save if a storage is charged in the 12 and 8 cheapest hours, respectively. The electricity used to charge the storage is bought on the electricity spot market. It has been investigated for 2020, 2021 and up to and including Sep-2022. The results of the investigation can be seen in Figure 7.5.

The biggest savings are found when charging the battery in the 8 cheapest hours for all three years, which is to be expected. In addition, the savings vary greatly between the three periods, whereas in 2020 it was between 38pprox.. DKK 447.000-605.000 kr., compared to 2.160.000-2.850.000 kr. In 2022. This is primarily due to electricity prices in 2022 being significantly higher than in 2020.

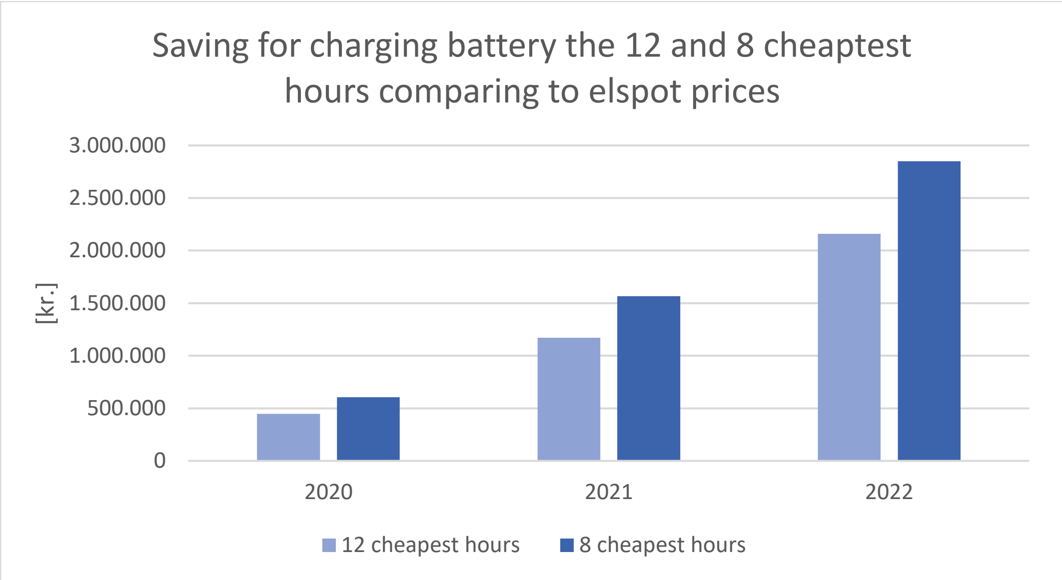


Figure 7.5: Comparison of savings when charging a battery, the 12 and 8 cheapest hours per day. Data is for 2020, 2021, and until 30/9-2022.

The savings can be used for investment in e.g., a thermal storage. If an investment is made for a storage where charging must take place in the 8 cheapest hours, the storage should have a storage capacity of 3 times the charging capacity (e.g., 3 MW charging for 1 MW production) for the production to be covered in the remaining 16 hours where no charging is done. This also applies to a system which charges the 12 cheapest hours, besides that the charging capacity must be twice as large as the production (e.g., 2 MW charging for 1 MW production). In addition, the thermal storage must then be able to last 12 hours instead of 16.

8 Electric boiler as reference

The calculations from Chapter 7 are recalculated in the following with a 1 MW_{th} electric boiler constituting the reference (Case A) replacing the 1 MW_{th} natural gas boiler in case 0. The calculations are made for 2020 to 2022. The results illustrate the expected economic benefit if investing in different technologies along with the electric boiler.

8.1 Results for 2021

As shown in Table 8.1, in 2021, the most feasible configuration is either the 1 MW heat pump with a COP of 6,3 or the Case 2.3 with 3 MW PV, due to the high net savings and low payback time. The WT configurations are not feasible due to the electricity prices and the investment costs, which result in negative net savings.

Table 8.1: Results for 2021

Description	Yearly savings [kr./year]	Investment [kr.]	Net savings [kr./year]	Payback time [year]
Case A – Electric boiler – ref.				
Case 1d – Electric boiler and Heat pump	4.207.156	8.300.000	3.730.505	2
Case 1d – 1 MW_{th} heat pump – COP 3,15	4.205.961	7.200.000	3.792.480	2
Case 1d – 1 MW_{th} heat pump – COP 6,30	5.171.267	7.200.000	4.757.786	1
Case 1d – 1 MW_{th} heat pump – COP 1,58	2.275.349	7.200.000	1.861.868	3
Case 1e – 2 MW electric boiler and 30 MWh thermal storage	1.266.955	12.920.800	524.941	10
Case 2.1 - 1 MW WT	351.681	29.372.000	-1.335.090	84
Case 2.1 - 2 MW WT	821.396	57.644.000	-2.488.976	70
Case 2.1 - 3 MW WT	1.341.660	85.916.000	-3.592.313	64
Case 2.2 - 1 MW WT and 5 MWh Battery	1.133.085	59.372.000	-2.276.523	52
Case 2.3 - 1 MW PV	972.707	4.373.600	721.540	4
Case 2.3 - 2 MW PV	1.863.692	7.647.200	1.424.530	4
Case 2.3 - 3 MW PV	2.708.393	10.920.800	2.081.235	4
Case 2.4 - 3 MW PV and 5 MWh battery	3.382.941	34.059.200	1.426.994	10
Case 2.5 - 3 MW PV and 1 MW WT	2.905.666	39.192.800	654.907	13

8.2 Results for 2020

As shown in Table 8.2, in 2020, the heat pump cases are most feasible for the industry due to low payback times. The PV configurations are also feasible but not as much as in 2021. Due to the high investment costs, the WT configurations are not feasible. The same applies to case 2.5, for the battery investment costs.

Table 8.2: Results for 2020

Description	Yearly savings [kr./year]	Investment [kr.]	Net savings [kr./year]	Payback time [year]
Case A – Electric boiler – ref.				
Case 1d – Electric boiler and Heat pump	1.785.632	8.300.000	1.308.981	5
Case 1d – 1 MW_{th} heat pump – COP 3,15	1.784.671	7.200.000	1.371.190	4
Case 1d – 1 MW_{th} heat pump – COP 6,30	2.235.518	7.200.000	1.822.037	3
Case 1d – 1 MW_{th} heat pump – COP 1,58	882.977	7.200.000	469.496	8
Case 1e – 2 MW electric boiler and 30 MWh thermal storage	514.337	12.920.800	-227.677	25
Case 2.1 - 1 MW WT	253.272	29.372.000	-1.433.499	116
Case 2.1 - 2 MW WT	526.990	57.644.000	-2.783.382	109
Case 2.1 - 3 MW WT	821.568	85.916.000	-4.112.405	105
Case 2.2 - 1 MW WT and 5 MWh Battery	507.000	59.372.000	-2.902.608	117
Case 2.3 - 1 MW PV	416.945	4.373.600	165.778	10
Case 2.3 - 2 MW PV	764.883	7.647.200	325.721	10
Case 2.3 - 3 MW PV	1.058.981	10.920.800	431.823	10
Case 2.4 - 3 MW PV and 5 MWh battery	1.319.183	34.059.200	-636.764	26
Case 2.5 - 3 MW PV and 1 MW WT	1.282.253	39.192.800	-968.506	31

8.3 Results for 2022

As shown in Table 8.3, all cases are feasible in 2022, since all cases have a payback time below the technical lifetime and positive net savings. The most feasible configuration is case 2.3 with 3 MW PV and 1 MW electric boiler dye to highest savings and lowest payback times. As argued previously, the heat pump cases are not seen as feasible for the industries due to lower temperatures.

Table 8.3: Results for 2022

Description	Yearly savings [kr./year]	Investment [kr.]	Net savings [kr./year]	Payback time [year]
Case A – Electric boiler – ref.				
Case 1d – Electric boiler and Heat pump	9.925.587	8.300.000	9.448.936	1
Case 1d – 1 MW_{th} heat pump – COP 3,15	10.023.805	7.200.000	9.610.324	1
Case 1d – 1 MW_{th} heat pump – COP 6,30	12.042.506	7.200.000	11.629.025	1

Case 1d – 1 MW_{th} heat pump – COP 1,58	5.986.404	7.200.000	5.572.923	1
Case 1e – 2 MW electric boiler and 30 MWh thermal storage	3.214.986	12.920.800	2.472.972	4
Case 2.1 - 1 MW WT	2.774.217	29.372.000	1.087.446	11
Case 2.1 - 2 MW WT	5.026.500	57.644.000	1.716.128	11
Case 2.1 - 3 MW WT	8.207.525	85.916.000	3.273.552	10
Case 2.2 - 1 MW WT and 5 MWh Battery	4.717.443	59.372.000	1.307.835	13
Case 2.3 - 1 MW PV	2.506.149	4.373.600	2.254.982	2
Case 2.3 - 2 MW PV	4.910.895	7.647.200	4.471.733	2
Case 2.3 - 3 MW PV	7.267.540	10.920.800	6.640.382	2
Case 2.4 - 3 MW PV and 5 MWh battery	9.256.485	34.059.200	7.300.538	4
Case 2.5 - 3 MW PV and 1 MW WT	9.998.357	39.192.800	7.747.598	4

8.4 Visualisations of results

In Figure 8.1 and Figure 8.2 is shown the net savings and payback time for all three years investigated. It is seen that the electricity price has a large impact on the results, since all the results for 2022 are feasible, mainly due to the high electricity prices. It can therefore be concluded that it is difficult to predict how feasible or if the configurations will be feasible.

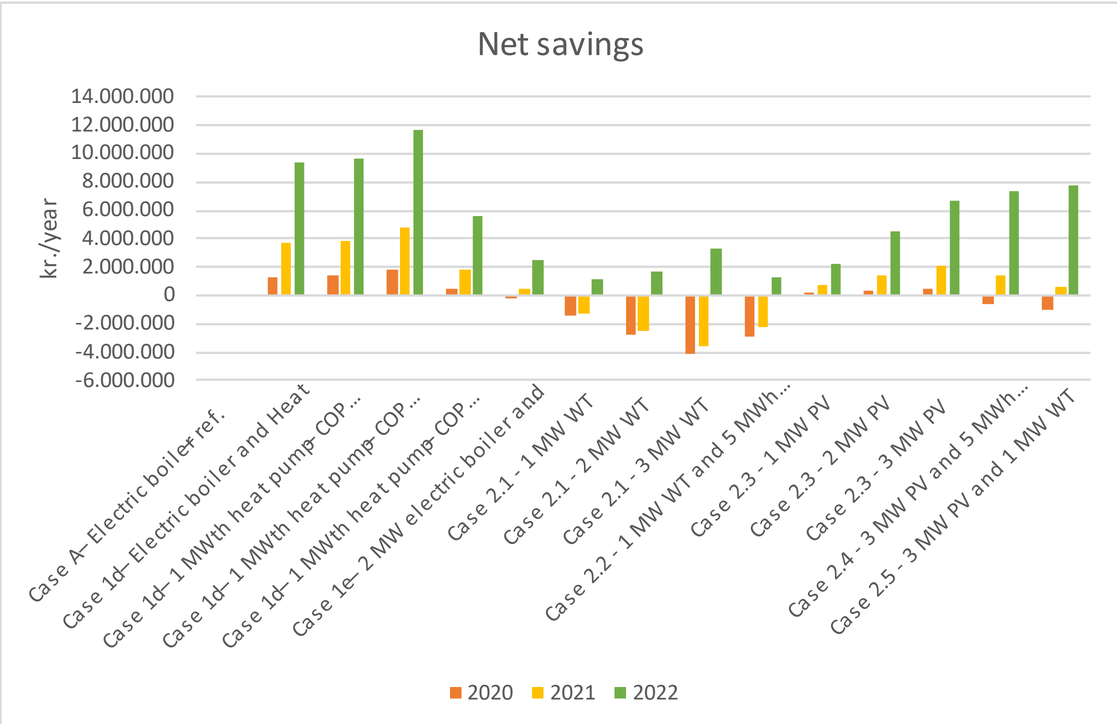


Figure 8.1: Net savings for the case with electric boiler as reference. The results are for 2020, 2021 and 2022

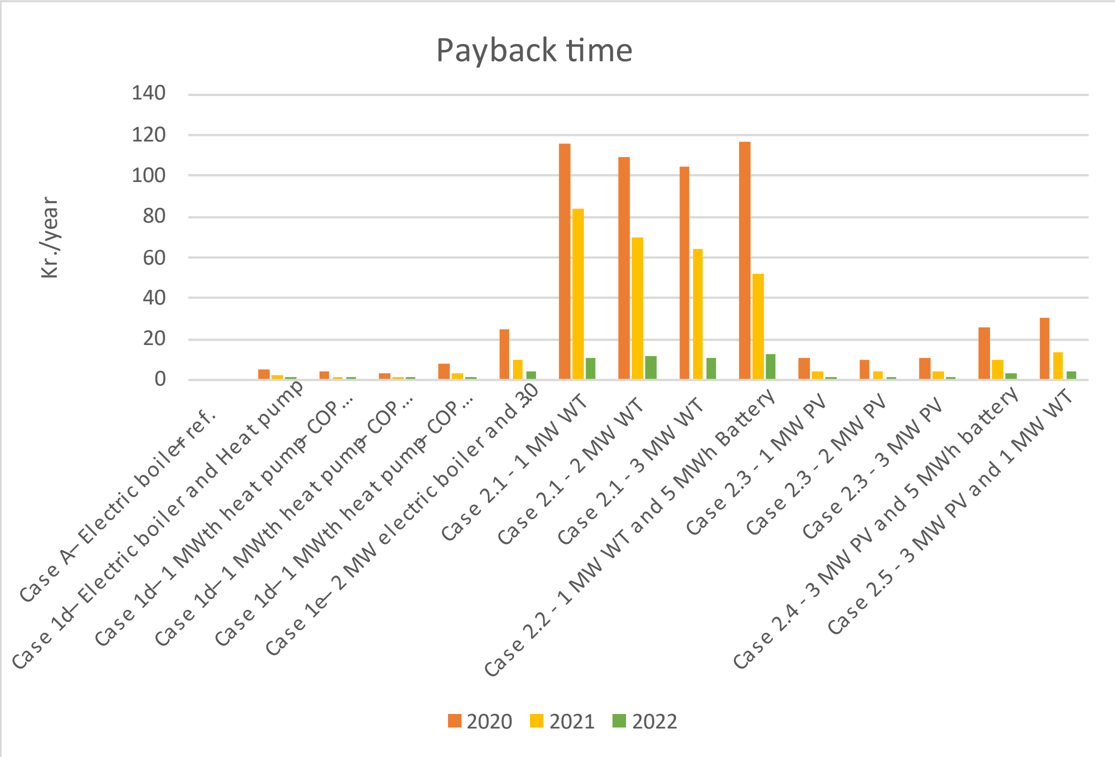


Figure 8.2: Payback time for the case with electric boiler as reference. The results are for 2020, 2021 and 2022.

9 Sensitivity Analyses

Sensitivity analyses have been performed to investigate how the input parameters affect the results. The most profitable solution in 2021 (case 2.3 with 3 MW PV) is used as a baseline for this analysis. The impact of variations in electricity prices in 2020-2022 is used. The technical lifetime of the PV panels is examined with 15 and 30 years of life instead of the used 25 years cf. the Technology Catalogue (Energistyrelsen & Energinet, 2016). The interest rate for the investment is examined for 2% and 5%. Finally, the profitability of case 2.1 with a 1 MW wind turbine is examined if the investment for the wind turbine is lowered. A discount of 50% is assumed when purchasing used turbines.

The results for the first sensitivity calculations are shown in Table 9.1: Sensitivity analysis results for case 2.3 in 2021. The electricity prices have a large influence on the profitability of the case, since the configuration generates a larger net saving in 2022 and is negative and thereby not generating a saving in 2020. This supports the conclusion that there is no predictability in electricity prices, and that it is therefore difficult to give a unilateral recommendation for the electrification of industry.

If the lifetime of the components is lowered to 15 years, the case is still profitable. Reinvestment should then be done after 15 years, but since the payback time for the investment is 3 years, this is possible. Moreover, an expected increase in capital cost is seen because of the shorter term of the loan. If the lifetime is increased to 30 years, the case is still feasible. Again, the capital costs are as expected, this time less than for baseline. The payback time for both 15-year and 30-year lifetime scenarios is unchanged compared to the starting point.

Finally, if different interest rates of 2 and 5% for the investment in the electric boiler and PV panels, an expected change in capital costs is seen. However, the net savings and the payback time do not change significantly. Thus, electricity prices have the biggest impact on the feasibility of the cases.

Table 9.1: Sensitivity analysis results for case 2.3 in 2021

Parameter	Financial savings [kr./ year]	Capital cost [kr./ year]	Net savings [kr./ year]	Payback time [year]
Baseline (Case 2.3 – 2021)	1.563.231	627.158	936.073	7
2020 electricity prices	238.863	627.158	-388.295	46
2022 electricity prices	5.425.745	627.158	4.798.587	2
15 years of technical lifetime	1.563.231	914.798	648.433	7
30 years of technical lifetime	1.563.231	557.171	1.006.060	7
Interest rate of 2%	1.563.231	559.368	1.003.863	7
Interest rate of 5%	1.563.231	774.858	788.373	7

Table 9.2 shows how the monetary size of the investment for a 1 MW wind turbine affects the feasibility of the case. Even if the industry decided to invest in cheaper turbines, the configuration will still not be feasible.

Table 9.2: Sensitivity analysis results for case 2.1 in 2021

Parameter	Investment [kr.]	Capital cost [kr./year]	Net amount for borrowing [kr./ year]	Net savings [kr./ year]	Payback time [year]
Case 2.1 - 1 MW WT (2021)	29.372.000	1.686.771	29.372.000	-103	17
Used turbines (50% of investment price)	15.236.000	874.971	15.236.000	811.697	9

10 Conclusion

Based on the results presented in this report, it can be concluded that the electricity prices have a large influence on which configurations are feasible for different years. Therefore, a general recommendation on an electrification strategy for the industrial sector cannot be presented based on the work in this report. However, as seen in the additional analyses with an electric boiler as reference, some of the cases showed positive yearly net savings and feasible pay back times, where especially for 2021 and 2022 most of the cases were feasible. If it is assumed that the gas prices will not decrease to 2020-prices after the current energy crisis, a system configuration consisting of an electric boiler and an additional component such as heat pumps or photo voltaics can provide an economic benefit for the industry.

If the industry, on the other hand, has a natural gas boiler currently, the industry should invest in own production of electricity, where PV panels are found to be feasible compared to wind turbines. If used turbines can be bought, then wind turbines will also be a feasible technology for own production in 2021 and 2022.

Moreover, this project concludes that that there is net savings associated with flexible charging hours for a battery, for which the 8 and 12 cheapest hours have been investigated and found profitable. These can be reinvested in the storage technology, e.g., in a HeatCube™.

11 Additional Investigations - Reflections

This chapter investigates how different system configurations of own production, and an electric boiler are interacting with the electricity grid. The figures illustrate the import of electricity from the grid, and thereby is a negative value export. The figures present the import for each hour of the year (2021), the import for the first week of January, and the import in the first week of June. This is to get a more detailed picture of the variations during the year.

11.1 Demand

The demand of energy is shown Figure 11.1 showing that the industry is assumed to have a production stop for 3 weeks from July 1st-21st and 2 weeks during Christmas December 16th-31st. If the system configuration consisted of an electric boiler, then the import curve for import of electricity for the boiler would look like Figure 11.1.

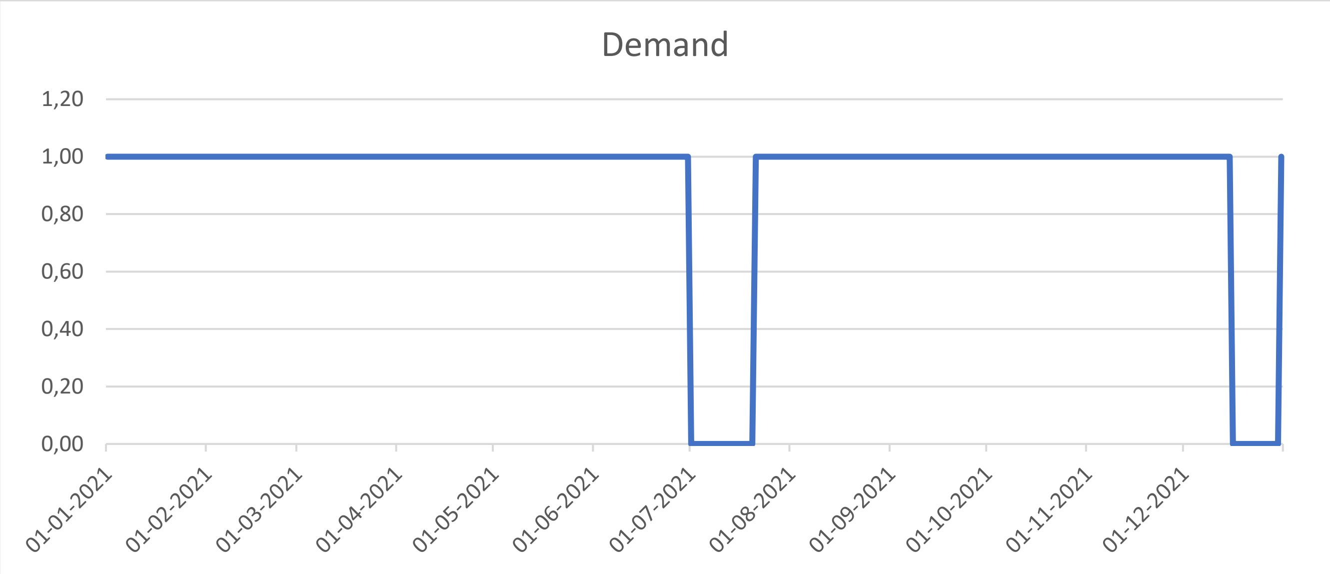


Figure 11.1 Demand curve. Electrical power consumption.

11.2 5 MWh Battery

The 5 MWh battery is chosen based on the economic results presented in chapter 5.

The battery is charged with electricity bought at the Elspot market, as shown in Figure 11.2, Figure 11.3 and Figure 11.4.

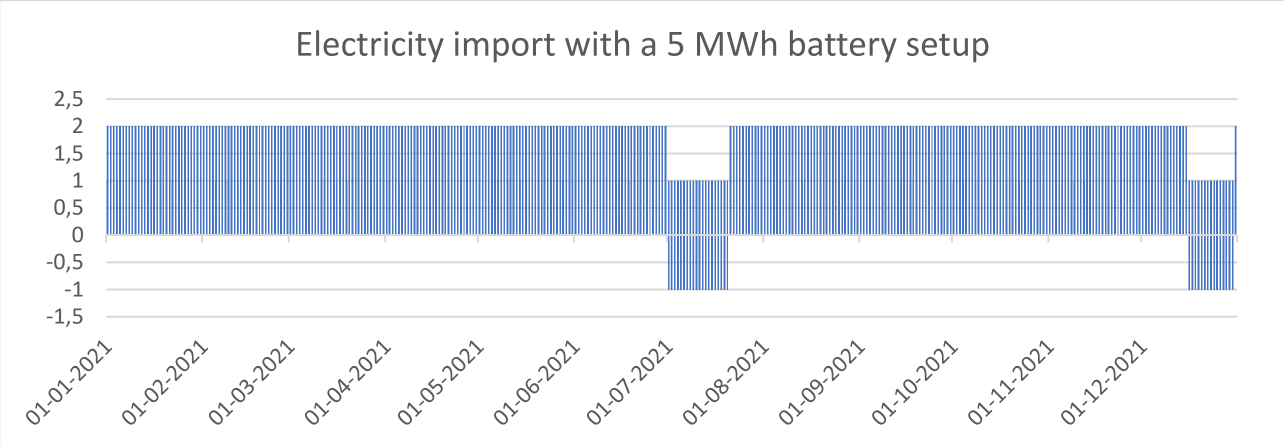


Figure 11.2: Electricity import with a 5 MWh battery setup

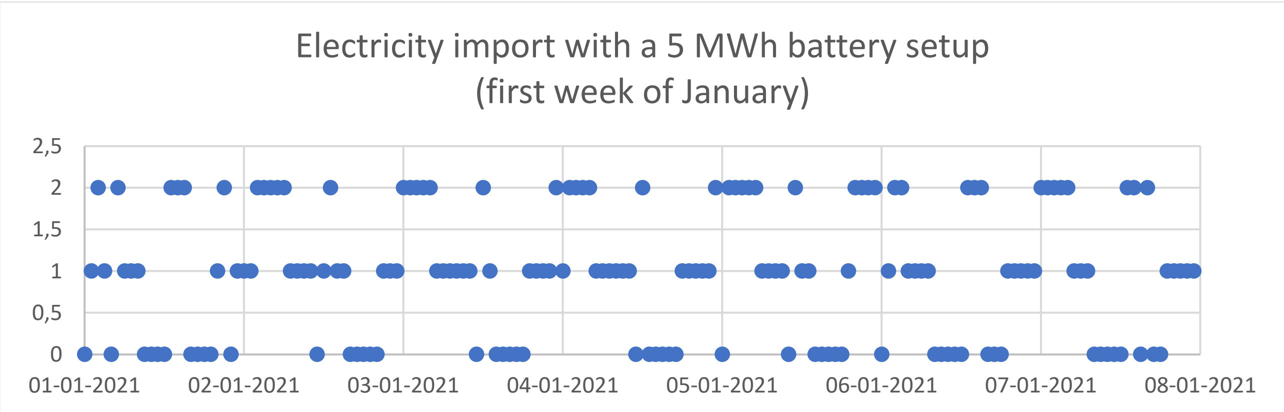


Figure 11.3: Electricity import with a 5 MWh battery setup first week January 2021.

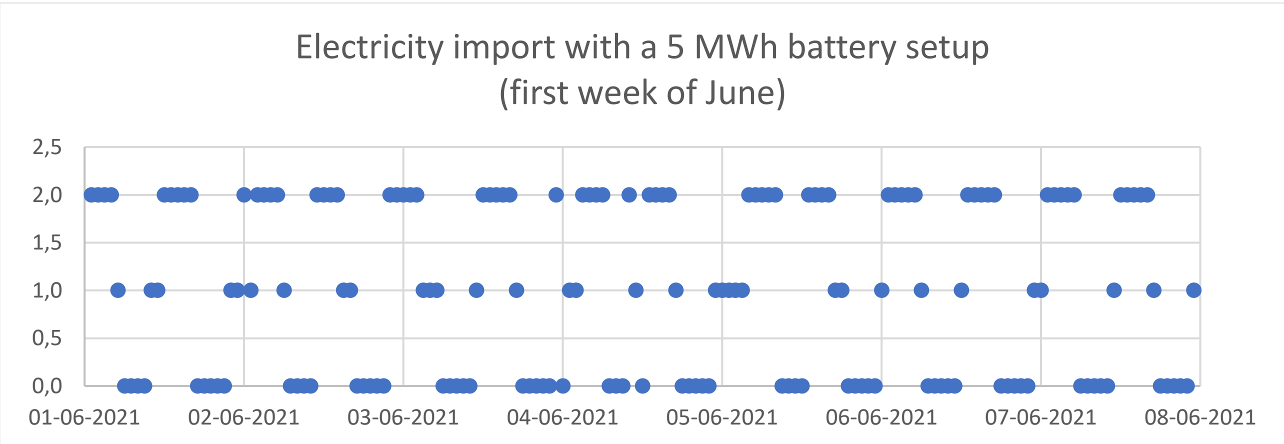


Figure 11.4: Electricity import with a 5 MWh battery setup first week June 2021.

The demand for electricity is fluctuating over the year. In June, there are more hours where the battery is both charging and discharging to meet the production demand compared to January. Though, the system is still heavily reliant on import of electricity from the grid. Due to the large variations, this is difficult to predict.

11.3 3 MW Wind Turbine

Having a 3 MW WT it can be seen in Figure 11.5, Figure 11.6 and Figure 11.7, that the system mostly imports electricity during the year, but for some hours is exporting due to a surplus in electricity production on the wind turbines. This is too difficult to predict for the system operators.

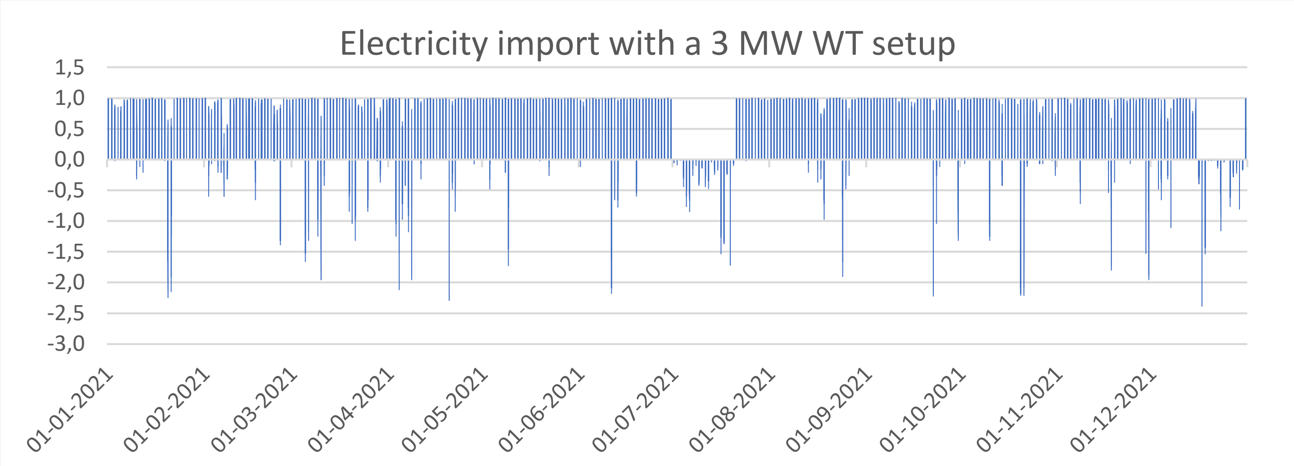


Figure 11.5: Electricity import with a 3 MW WT setup

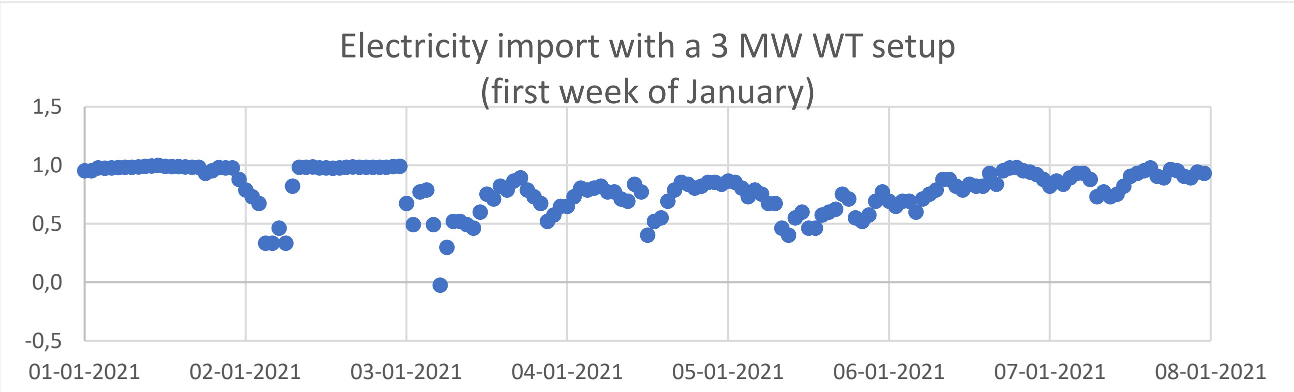


Figure 11.6: Electricity import with a 3 MW WT setup first week January 2021

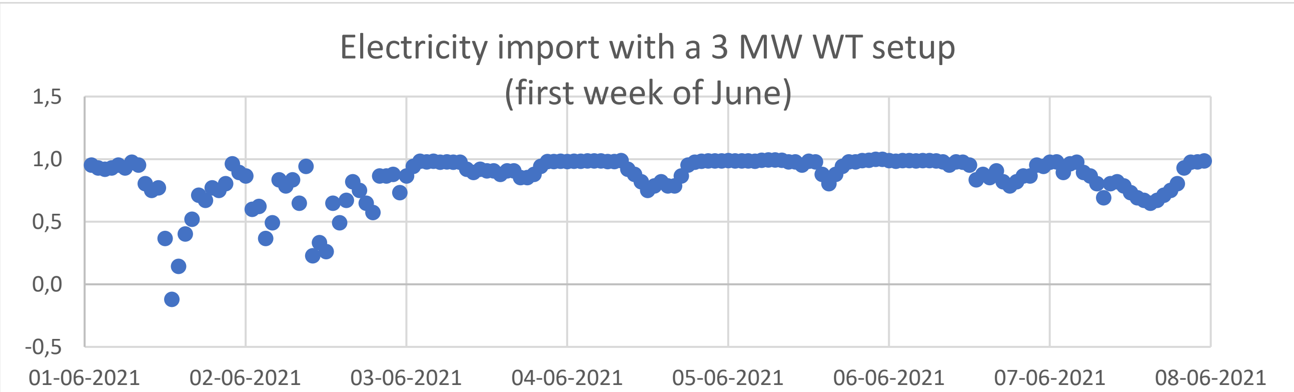


Figure 11.7: : Electricity import with a 3 MW WT setup first week June 2021

11.4 3 MW Wind Turbine and 13 MWh Battery

This case having a 3 MW Wind Turbine and 13 MWh Battery the import of electricity from the grid if the setup contains a 3 MW WT and a 13 MWh battery. The battery size is based on an estimation from the case above.

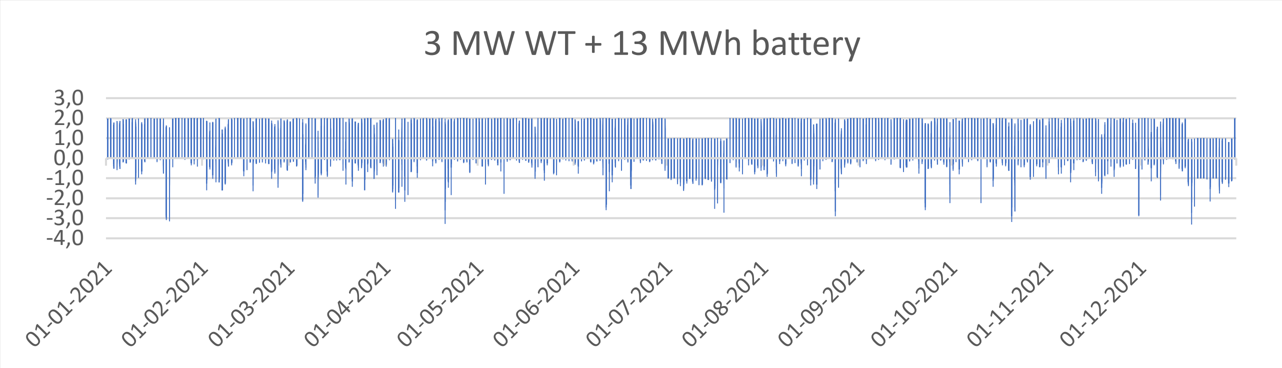


Figure 11.8: 3 MW WT + 13 MWh battery

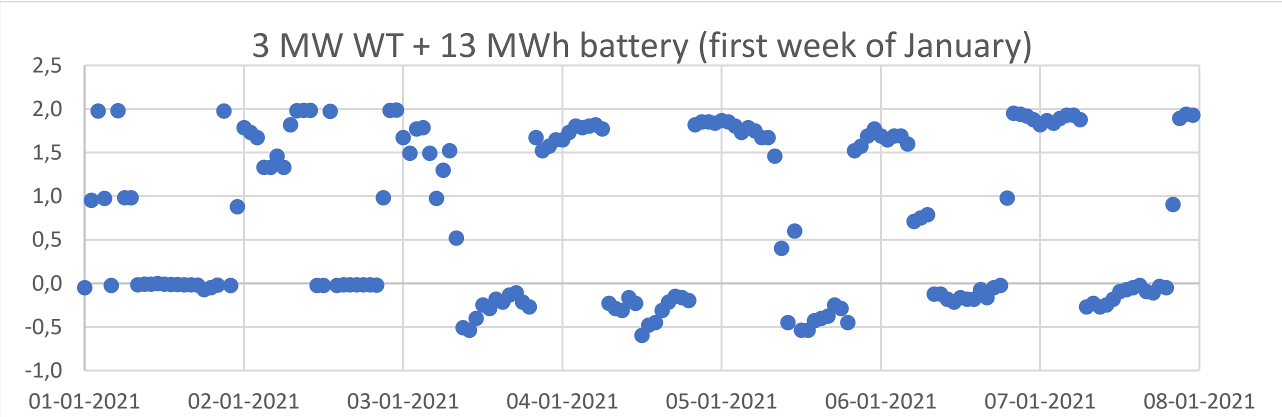


Figure 11.9: 3 MW WT + 13 MWh battery first week of January 2021.

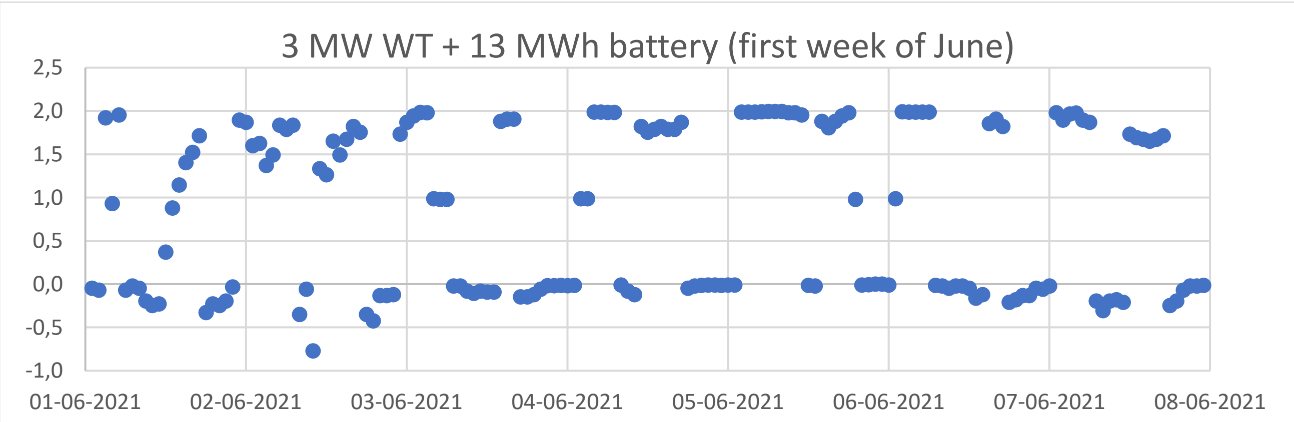


Figure 11.10: 3 MW WT + 13 MWh battery first week of June 2021.

By integrating a battery in the WT configuration, the exported energy can be reduced since this is used for charging the battery. Moreover, are the hours with import of electricity also decreased. Even with a 13 MWh battery it is not possible to ensure a stable import or eliminate the import of electricity.

11.5 3 MW Photovoltaics

In the case having a 3 MW photovoltaics there are large variations in the import and export of electricity throughout the year as shown in Figure 11.11, Figure 11.12 and Figure 11.13. As expected, the share of export of electricity is high in the summertime where the solar radiation is higher compared to winter. This too is difficult to predict for the system operators.

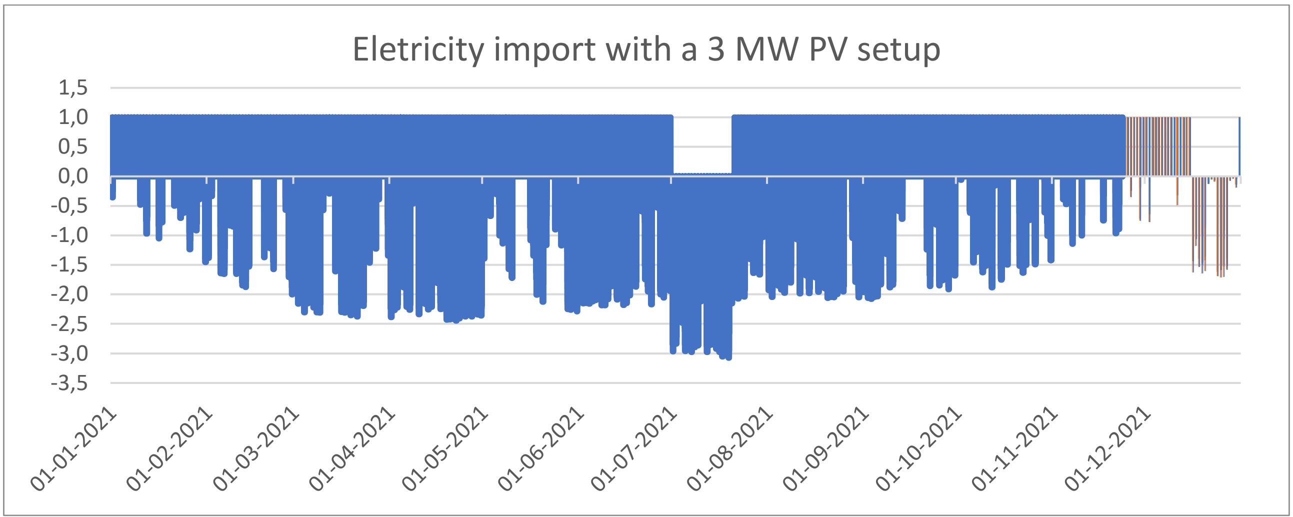


Figure 11.11: Eletricity import with a 3 MW PV setup

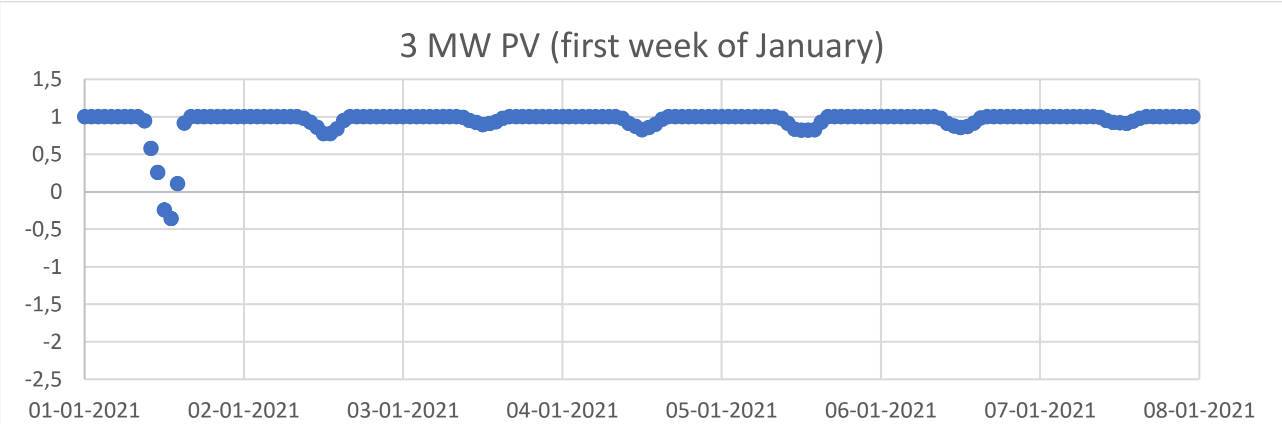


Figure 11.12: Eletricity import with a 3 MW PV setup first week af January 2021.

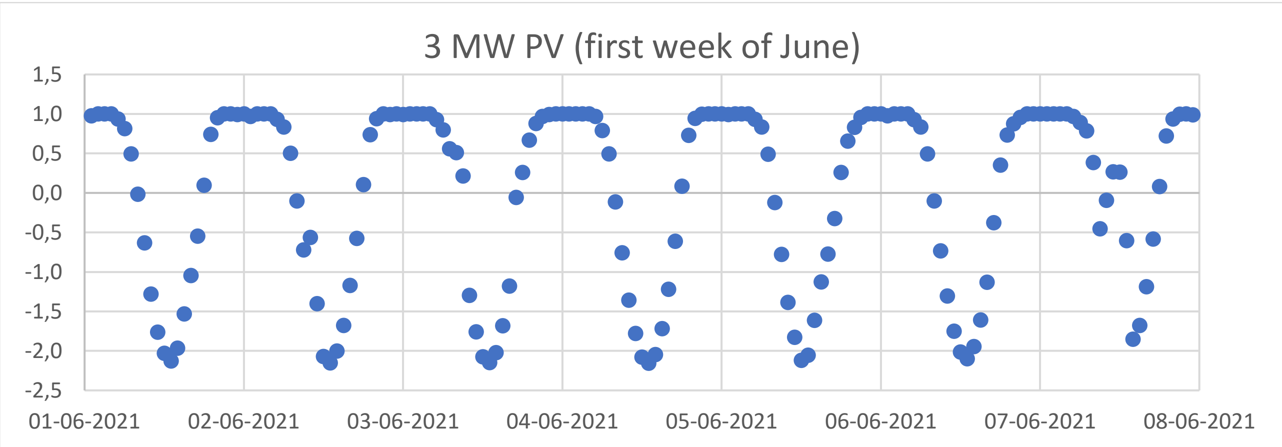


Figure 11.13: Eletricity import with a 3 MW PV setup first week af June 2021.

11.6 3 MW photo voltaics and 13 MWh Battery

In the case having 3 MW photo voltaics a 13 MWh battery some of the hours with export are removed as shown in Figure 11.14, Figure 11.15 and Figure 11.16. Moreover, the size of exported energy is significantly decreased from -2,5 MW to -0,4 MW. Though, the system is still reliant on the grid since the battery is charged some hours, and for the hours without sun or storage content is the system importing power for operation.

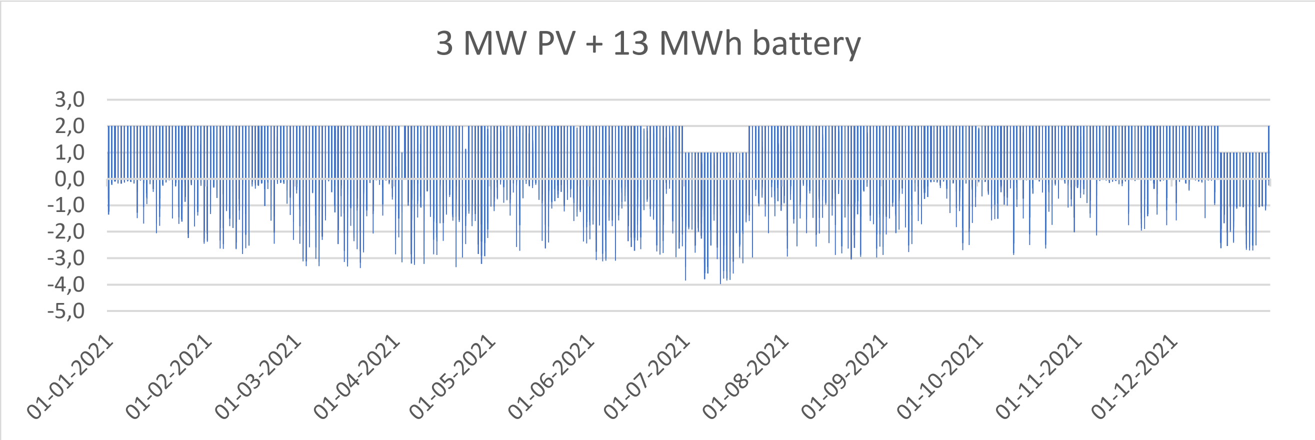


Figure 11.14:3 MW PV + 13 MWh battery

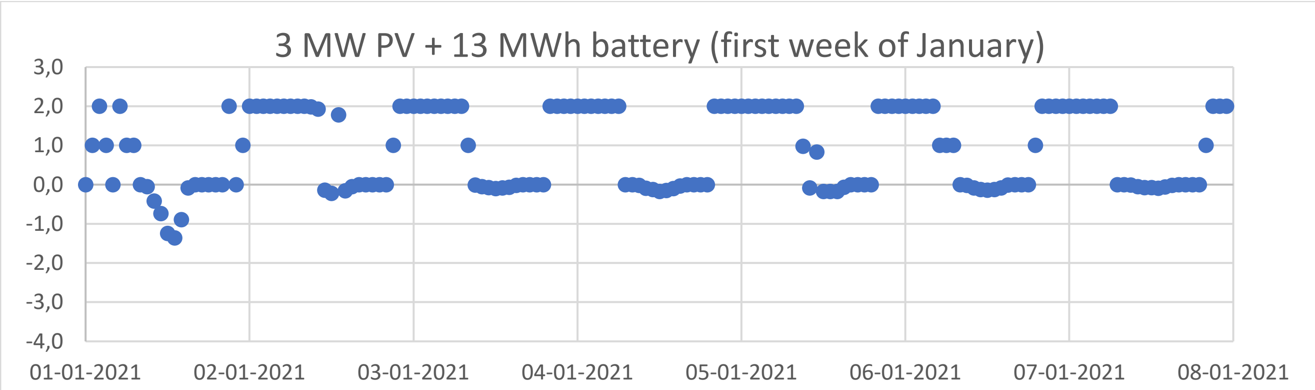


Figure 11.15: 3 MW PV + 13 MWh battery first week of January 2021.

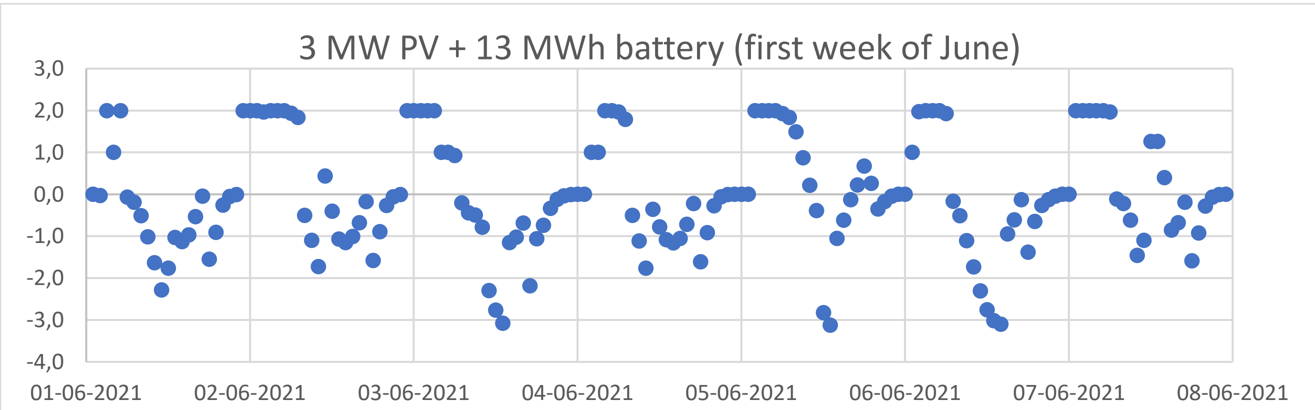


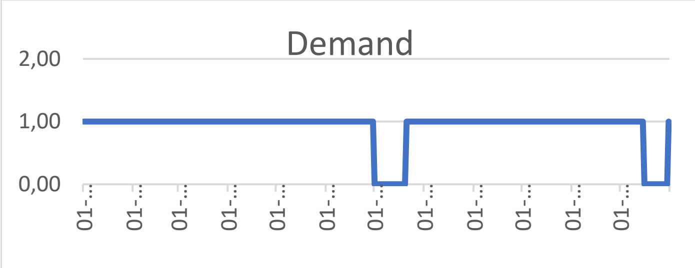
Figure 11.16: 3 MW PV + 13 MWh battery first week of June 2021.

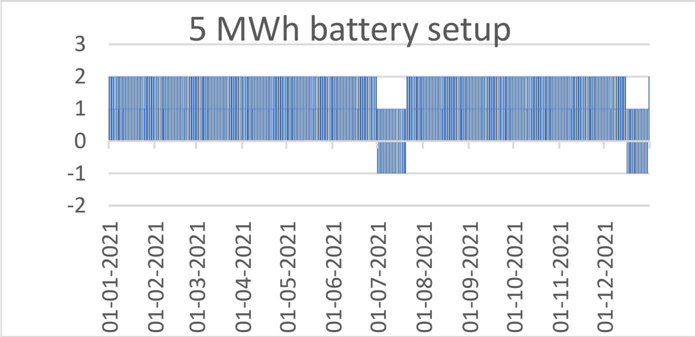
11.7 Conclusion

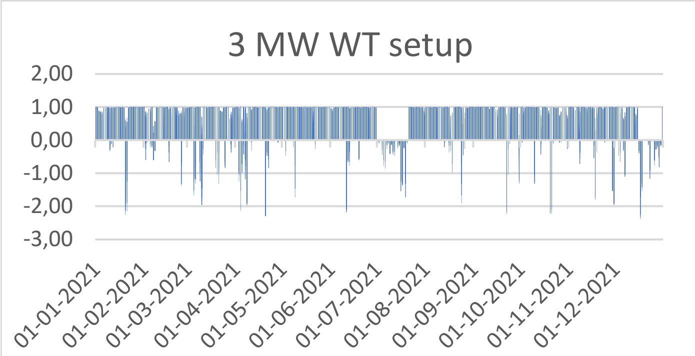
The most optimal operation for the electricity grid is, that the energy from own production with batteries for surplus should be able to cover the demand throughout the year, and thereby making the industry independent on the electricity grid since they would not need to import electricity from the grid. This is not the case for the investigated cases. Based on the results of the investigations above, it can be concluded that the current price signals cannot be used as a strategy for planning the need for import and export in the electricity grid. Dependent on the system configurations, the import curves vary significantly (see figures on the right-hand side and for more details in the individual sections of this chapter).

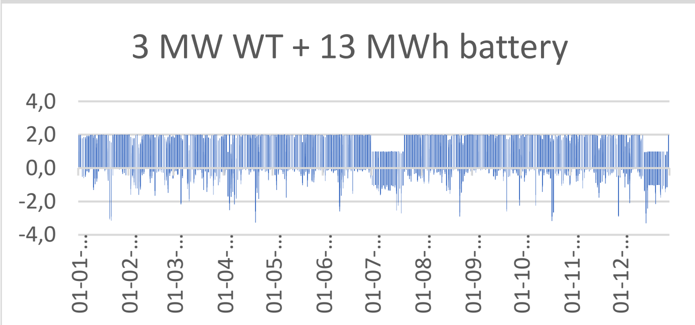
By introducing batteries, the amount of exported energy is reduced compared to setups without batteries, which is beneficial for the grid and the system operator since less available capacity for export is required. However, some hours with a large surplus of electricity will require export or shutting down of production of energy for the own production units.

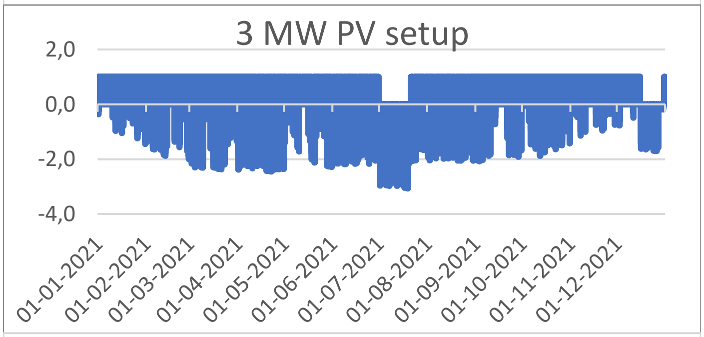
The demand curve is the optimal output for the electricity grid, since the import in that case would be stable for all production hours, the demand would be more predictable for the system operators (DSO, TSO), which is how it used to be when the electricity production came from conventional power plants.

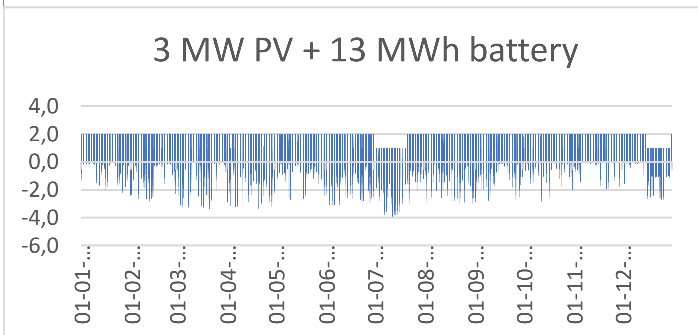












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