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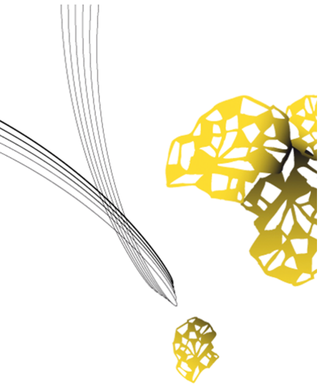
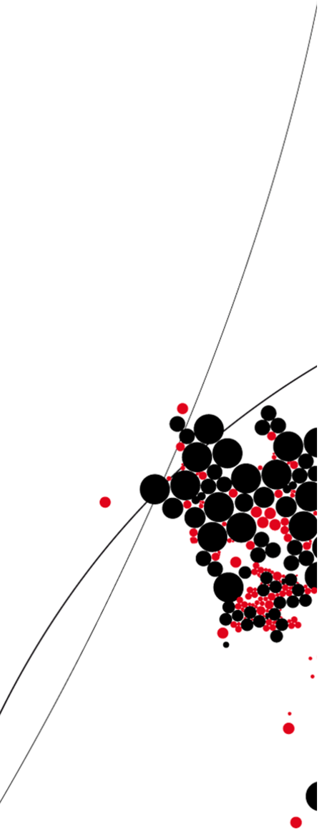


Master Thesis

Sustainable Energy Technology



Electricity grid congestion and application of a novel tariff in the Netherlands

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Abstract

In recent years, the Dutch electricity grid has experienced increased congestion due to the ongoing energy transition, resulting in a growing shortage in grid connection capacity. Various measures, including regulatory updates, grid reinforcement efforts, and the introduction of new electricity contract forms, have been implemented to alleviate congestion. However, these measures, when combined, did not reduce significantly peak grid utilization or address the capacity shortage

This research introduces a novel approach named the Rush-Hour tariff, aimed at optimizing grid utilization. The Rush-Hour tariff introduces fees on supply and demand bids for specific hour blocks of the day-ahead electricity market. By doing so, it reduces the volume of electricity traded and subsequently lowers grid utilization in these hours. While the tariff achieves its intended purpose, it does impact electricity prices.

Therefore further research is recommended for tariff implementation, focusing on the following three key areas: feasibility of implementation in the electricity price calculation algorithm EUPHEMIA; bidding strategy adjustments based on market feedback; and assessment of international market impact due to interconnect electricity flows.

Key words: Electricity grid, Congestion, Day-ahead market, Rush Hour tariff, Netherlands

Nomenclature

ACM - Autoriteit Consument en Markt (Translates to Authority of Consumer and Market)
BRP - Balancing Responsible Party
CSP - Congestion Service Provider
DSO - Distributed System Operator
ENTSO-E - European Network of Transmission System Operators for Electricity
EUPHEMIA - Pan-European Hybrid Electricity Market Integration Algorithm
EV - Electric Vehicle
GOPACS - Congestion market in the Netherlands
GW - Gigawatt
HV - High Voltage (110-380 kilovolt)
kV - Kilovolt
LV - Low Voltage (<10 kilovolt)
MV - medium voltage (10-50 kilovolt)
MVA - Mega Volt-Ampere
MW - Megawatt
MWh - Megawatt-hour
Netbeheer Nederland - Grid operator organization for the Netherlands
Nordpool / EPEX spot - Dutch electricity (day-ahead) market providers
PV - Photovoltaic
RES - Renewable Energy Systems
TSO - Transmission System Operator (TenneT for the Netherlands)
TWh - Terawatt-hour

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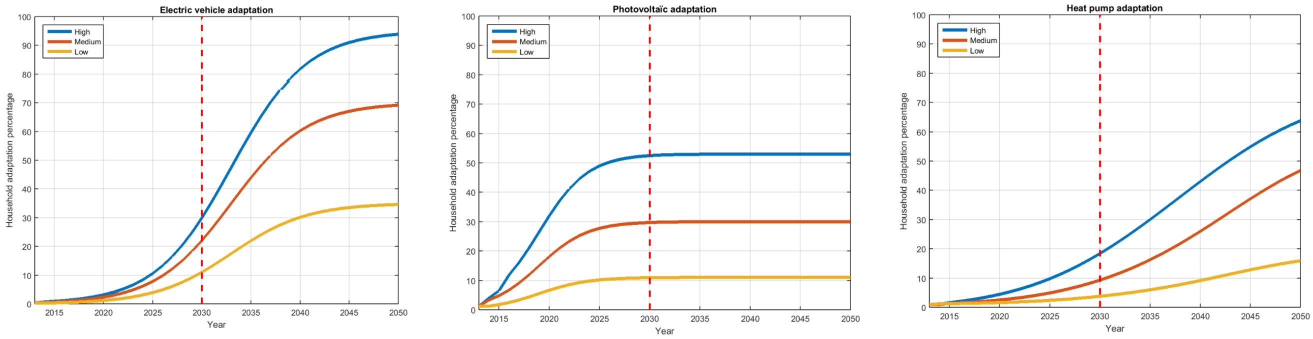
1 Introduction

In the rapidly changing world of electricity usage, sustainability takes precedence, and electricity generation by renewable energy sources continues to grow at a rapid rate [13]. One of the reasons for the growth is to achieve net zero emissions in 2050 to limit global warming to 1.5 °C [14]. Simultaneously, the electrification of society around the world is increasing the demand for electricity, with demand growth for space heating and cooling (heat pumps), electric vehicle adoption, and hydrogen production [15]. Both increase the capacity demand of electricity grids for the transportation of electricity and increase the volatility of both the utilization of the electricity grids and the electricity prices [16][17]. A consequence of these developments is that capacity limits in the grid are reached, leading to transport congestion, that the electricity grid physically cannot transport enough electricity from one area to the other. In the Netherlands, this is a pressing issue in certain areas, with enterprises, schools, and houses unable to get a grid connection in various places in the country as a result [18]. These issues will only become more pressing as the transport demands of the Dutch electricity grid are only increasing.

1.1 Electrification trends

To visualize the rapid increase in the growth rate of electrification in the Netherlands, for three different scenarios- heat pumps, electric vehicles (EVs), and Photo-Voltaic (PV) installations are shown in Figure 1. In the figures, three different adoption growth scenarios are shown where with current adoption the scenario 'high' is followed. This is underlined by the capacity growth of the total electricity generation in the Netherlands. The generation capacity was 33 Gigawatt (GW) in 2015, but due to the installment of new renewable energy systems has grown to 56 GW in 2023 [4].



(a) Electric vehicle adaptation (b) PV installation adaptation (c) Heat pump adaptation

Figure 1: Three graphs with three scenarios for household adaptation of EVs, PV installations, and heat pumps. The trendline models ended at 2030 as shown with the red dotted line [1]

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Heat pumps: One growth market in the Netherlands is heat pumps. Heat pumps can be used for heating of buildings and/or for cooling. The projection is that heat pumps will take over gas-heated homes in adoption, which is solidified by regulations that gas-fired standalone central heating systems cannot be sold anymore starting from 2026 [19].

The growth for heat pump system installment on a year-to-year basis was 57% in 2022. In 2022 the installed amount of heat pumps was 110,000 systems [20], which with 8.1 million households [3] amounts to 1.35% of the total amount of households in the Netherlands. According to Dutch New Energy research, the total installed heat pump systems amount to 350,000 (as of 2021) [2]. Using the growth rate and installed amount of 2022, the total amount of installed heat pumps has increased to 460,000 at the end of 2022, corresponding to a share of 5.7% of households. Comparing the installment growth of heat pumps with the adoption trend shown in Figure 1, it corresponds to the high growth scenario [1]. In Figure 2, the growth of the installed heat pumps over the last 13 years is shown.

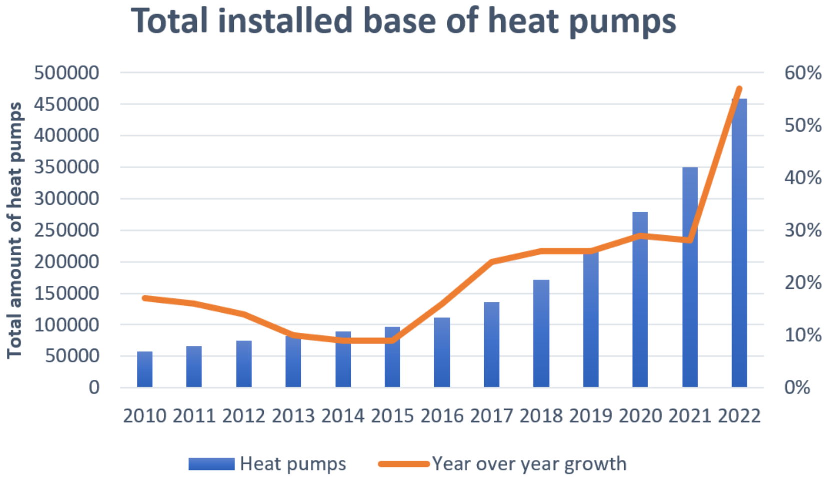


Figure 2: Heat pump installed base and growth, with on the left axis the amount of total installed heat pumps in the Netherlands and on the right axis the growth year over year growth [2].

Electric Vehicles: Other electricity transport demand growth comes from the increasing amount of electric vehicles (EVs). EVs draw a lot of power intermittently from the grid to charge their large batteries. This results in high power draw during the charging times of the EV. The EV market in the Netherlands is a growth market, with the ambition to have 50% of the new car sales to be EVs by 2025 and 100% by 2030 [21].

The total amount of personal vehicles in the Netherlands amounts to 8,917 million in 2023 [22]. From this, 341,326 are EVs [21] indicating that 3.8% of the current amount of vehicles is electric. Combining the ambition for 50 and 100% EV sales and that in 2015 a total of 125,000 cars have been sold [22], shows a trend for a significant increase in EV adoption.

Solar photo-voltaic: Solar Photo-Voltaic (PV) field installment growth is exponential. In the past decade, the produced electricity has increased by a factor of 90 with an average yearly growth factor of 1.6. Resulting at the end of 2022 in a production of 17.6 Terrawatt-hour (TWh) over one year [11]. The data is visualized in Figure 3. The installed capacity in the grid of solar PV in Megawatt (MW) is shown in Figure 4, with an installed capacity growth estimated at nearly 4 GW per year to a projected installed capacity of 37.2 GW at the end of 2026 [23], which would amount to more than half of the total electricity generation capacity (as of 2023) in the Netherlands [4].

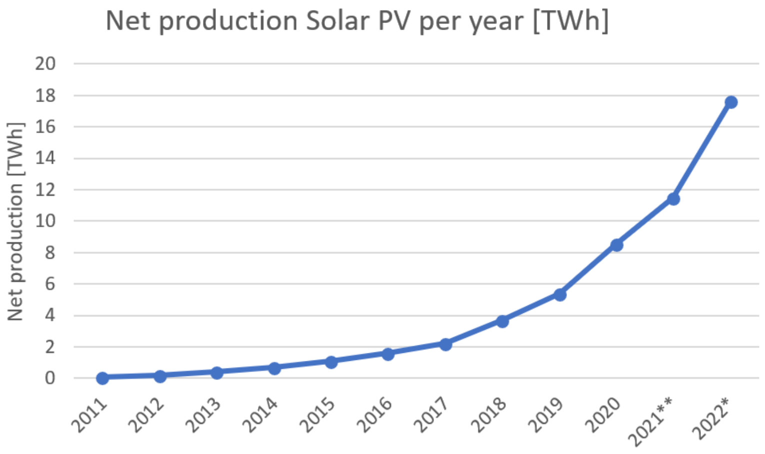


Figure 3: Net production of solar PV in the Netherlands over a 10-year period in TWh. The data for 2021 and 2022 are preliminary results [3].

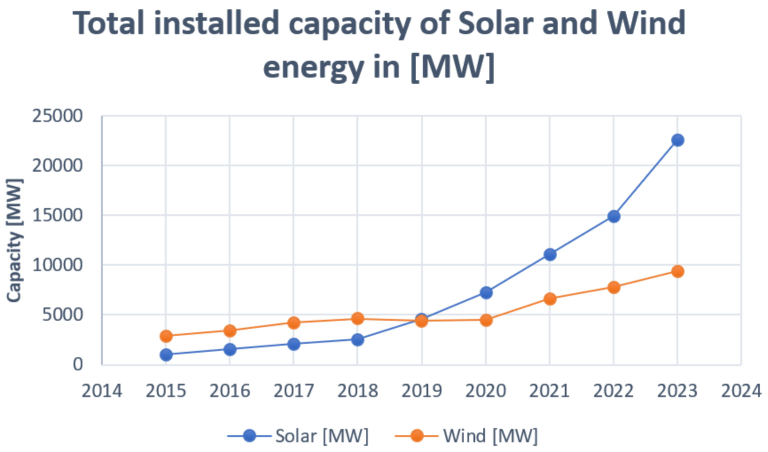


Figure 4: Total installed capacity of solar PV and wind turbines in the Netherlands 2015-2023 [4].

Wind turbines: The installation of wind turbine capacity has different phases, as shown in Figure 4. From 2015 to 2018 there was minor growth in wind turbine capacity, however, in the following two years, there was a decrease, due to small onshore wind turbines being dismantled. The growth stagnation resulted in the installed capacity of wind turbines being overtaken by solar PV in 2019.

Starting from 2020, the installed capacity of wind turbines has been growing again. According to information from the Rijksoverheid the plan is to have at least 4.5 gigawatts (GW) of installed capacity (off-shore) wind by the end of 2023 [24], which means an increase of 1.3 GW compared to the current installed capacity at the end of 2022. By the end of 2030 this capacity has to be about 21 GW [24]. Assuming the current installed capacity does not change, the total installed capacity of wind turbines will reach 27.2 GW by 2030 which would be nearly half of the total electricity generation capacity (as of 2023) in the Netherlands [4].

1.2 Electricity grid reinforcement

To facilitate the increase in demand for electricity transport, the grid is reinforced at different levels. The Dutch electricity grid layout is divided into three categories:

- The transmission high-voltage (HV) grid operated by the Transmission System Operator (TSO) TenneT consisting of 110 kilovolt (kV) to 380 kV lines,
- The distribution medium-voltage (MV) 10 kV to 50 kV grid operated by the Distributed System Operators (DSOs) in their respective areas,
- The low-voltage (LV), below 10 kV, grid operated by the DSOs for small businesses and residential households.

In Figure 5 the above-ground electricity grid is shown in the Netherlands. Apart from cables above the ground, underground cables are also present all over the country. There is no official free public data on underground electricity cables, however, there is a free tool published, showing the above-ground and underground cables in the Netherlands using unofficial data, here [25].

In all three categories, the grid is being reinforced by installing additional cables and increasing the number of substations, to increase the transport capacity of the grid. To give a sense of the scale of these operations, two examples of a DSO and TSO are given.

The first example is Liander, a Dutch DSO responsible for the electricity grid in the areas of Flevoland, Friesland, Noord-Holland, Gelderland, and a part in Zuid-Holland, scheduled to invest €3.592 billion in the years 2022-2024 to increase grid quality and solve capacity problems [26].

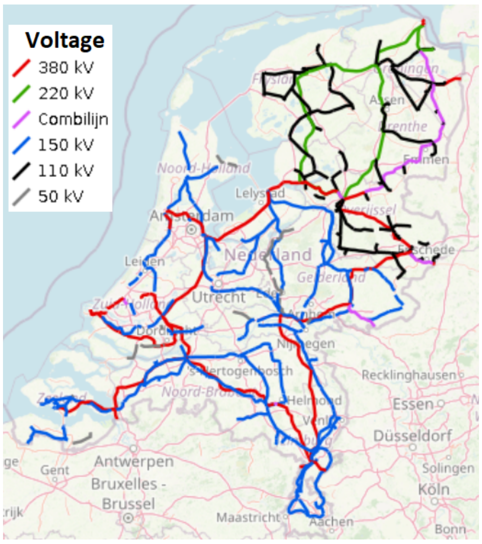


Figure 5: Above ground medium and high voltage grid in the Netherlands [5]

The other example is from Tennet, to increase the number of high voltage substations by 40. This increases the number of locations where electricity can enter or leave the HV grid. This could result in a reduction in loads, as electricity transport distance might be reduced, reducing the capacity requirements for electricity transport. In the years 2022 to 2032, TenneT is investing a total of € 13 billion in grid reinforcement and grid quality improvements [27].

But an issue not solved with grid reinforcement, is the growth of grid connection capacity demand outpacing the growth in grid capacity, as the grid reinforcements that are currently carried out are not sufficient. An example is from the province of Zeeland, where the applications for new electricity grid connection capacity totals 3.5 GW, significantly more significant than the current supply of electricity to the region, requiring the grid capacity to increase by a factor of 8 to meet transport demands [28].

1.3 Problem definition

The growth of electricity transport demands on the supply side (solar PV and wind energy) and growth in the demand side (an increase in EVs and heat pumps) is leading to multiple issues. In addition to the transport demand growth outpacing the growth in available grid capacity, there are two other problems. One is the lower predictability of renewable energy generation resulting in a higher imbalance on the market [17]. The other problem is synchronization, for example, simultaneous supply of electricity from solar PV is currently resulting in substation malfunctions and outages in LV areas in local neighborhoods [29]. In these cases, the electricity flow from the LV to the MV grid overloads the substation due to grid congestion, where the electricity transport demands exceed the physical capabilities. To avoid grid congestion occurring more frequently, grid capacity availability for new or expansion of existing connections is limited, resulting in a shortage of capacity for grid connections.

To summarize, the increase in grid connection capacity shortage is caused by the following:

- Higher total volume of electricity transport, due to electrification with the supply and demand growth,
- Synchronisation of electricity loads, for example, all heat pumps in a neighborhood turn on simultaneously due to shifts in temperature,
- Intermittent electricity generation, for example with solar PV there is no generation at night.

The resulting capacity shortage in the electricity grid in the Netherlands is a serious problem as electrification is required to reduce the consumption of fossil fuels (gas, coal) and to increase energy production from renewable sources. To illustrate the severity of the capacity problem currently in the Netherlands and the speed of the developments, two maps are shown in Figure 6 and 7. Figure 6 shows that in more than half of the country (as of April 2023) no extra grid connection capacity was available, while a few months (as of August 2023) later more areas have no remaining grid connection capacity, as shown in Figure 7.

Aside from sustainability goals, the capacity shortage also causes problems for the developments in the economy, as businesses cannot build new or extend activities, and the deficiency causes social problems as new residential buildings are not built because there is no available grid connection capacity for new schools and hospitals [18].

Lastly, according to Netbeheer Nederland (Grid Operators Netherlands), in July 2023 the waiting list for grid connections for electricity demand was 6000, and for the supply of electricity 8000. The waiting list has grown significantly as in May 2023 the total number on the waiting list was 5600 [30].

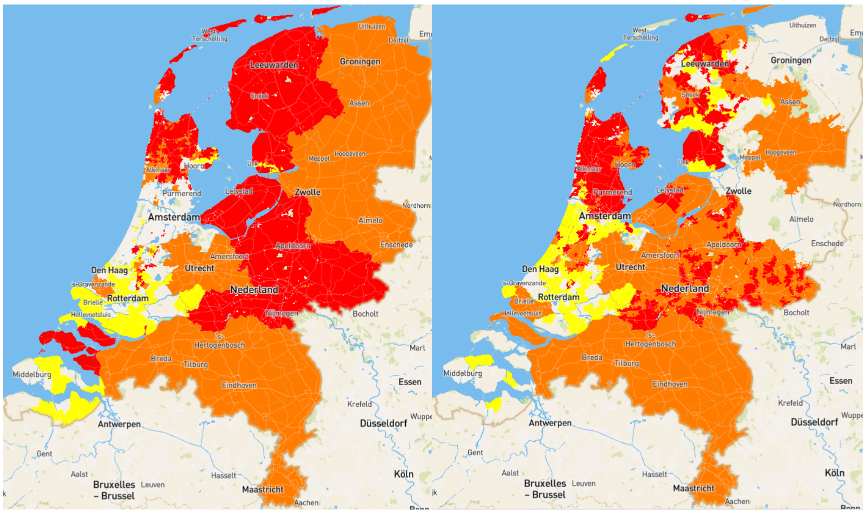


Figure 6: Grid capacity availability of the Netherlands for April 2023, left the supply and right the demand side. The coloring shows the availability of capacity, transparent is available, yellow is limited, orange is preliminary no availability, and red is no availability [6]

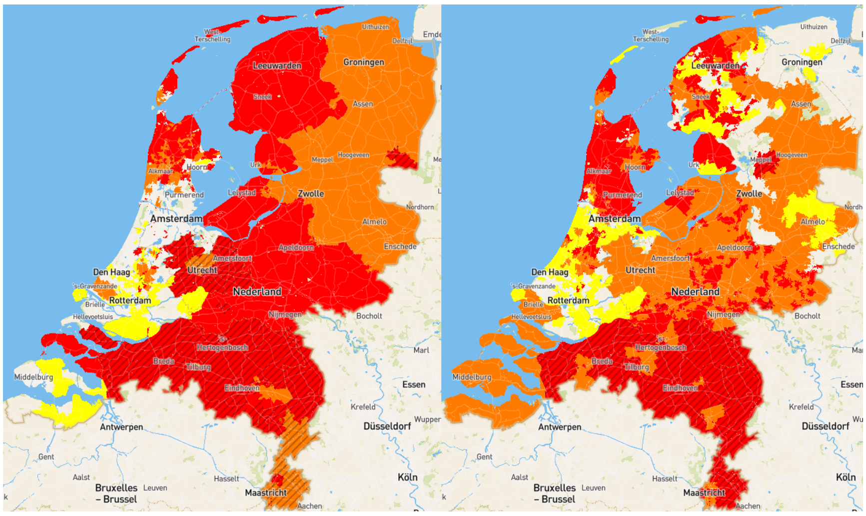


Figure 7: Grid capacity availability of the Netherlands for August 2023, left the supply and right the demand side. The coloring shows the availability of capacity, transparent is available, yellow is limited, orange is preliminary no availability, and red is no availability [6]

1.4 Research lay-out

To investigate what is currently being done against the congestion and capacity shortage the following research question was answered, also taking into consideration novel approaches if the current set of solutions does not suffice:

- **What is the current state of solving the capacity shortage and congestion in the electricity grid in the Netherlands and how could novel approaches help solve these problems?**

The first part of the research delves into the current state of solving the congestion and capacity shortage. The main solution currently, is to increase the grid capacity by grid reinforcement. This is, however, a solution with high costs per grid connection and not enough to keep up with the growth of electrification of society [31].

Therefore research has been carried out to evaluate the alternative solutions that are currently implemented on various scales in the Netherlands. Which is detailed in Chapter 2. The method used was literature research while discussing what impact the different solutions have. The conclusion from that research is that the current solutions are not sufficient, as the capacity shortage is still growing and will keep growing with the impact of the current solution set.

This leads to the second objective of the research, where a novel approach is proposed in Chapter 3 named the Rush Hour tariff. The tariff is explained in this chapter, what the goal is, how it could be implemented in the market, what the advantages are, and on what testing criteria the tariff will be evaluated.

The proposed tariff was tested on data of the day-ahead electricity market, to evaluate the performance of a theoretical implementation. In Chapter 4 the methodology of the scenario tests is explained including what data has been used. Additionally, the technical implementation of the tariff and the descriptions of the scenarios were given in this chapter. The outcomes of the scenarios are presented in Chapter 5.

These results are used in Chapter 6 to evaluate the performance of the Rush Hour Tariff, based on the testing criteria defined in Chapter 3. Then the methodology is discussed in Chapter 7 and lastly, the conclusion of the two research questions is given in Chapter 8, including recommendations for future research on the prospects and implementation of the Rush Hour Tariff.

2 Literature research and interpretation

This chapter presents a literature review on the current state of the Dutch electricity grid, including context on the current situation and solution developments.

First, the code decision on congestion management of the electricity grid code is addressed, published in 2022 by The Autoriteit Consument en Markt (ACM) which translates to the Authority for Consumers and Markets. This document updates the terminology about electricity transport, capacity shortage, and grid congestion. The code decision was specifically created to address congestion occurrences and states the process of when Tennet or the DSOs are not obliged to hand out grid connection capacity, as theoretical limits in the network were being reached. The code decision document also lists options for different contract forms, like the grid connection capacity limiting contract. The code decision document is used to create definitions for capacity shortage and congestion used for this research.

Additionally, the current congestion management research process is discussed, as given in the code decision document about grid reinforcement, capacity limiting contracts, and the N-1 to N-0 rule.

Subsequently, this chapter delves into the congestion market named GOPACS, providing insights into the Dutch electricity market and its participants. Finally, alternative solutions are explored, discussing their potential impact and any associated constraints.

2.1 Regulatory update

In November 2022, the Authoriteit Consument & Markt (ACM) published a code decision on congestion management for the electricity grid code which contains regulations on congestion occurrences, stating the process for the TSO and DSOs on how to react, when an area can be designated as having no available grid connection capacity and the process on how to solve the congestion.

In the upcoming sections, several passages are extracted from the code decision, accompanied by interpretations. The complete document is available at the following source [32].

- **Terminology of electricity transport capacity:** The terminology of the transport capacity can be used to define the capacity shortage in (a part) of the network.
  - ***Existing transport capacity:*** *The maximum capacity the grid can handle, taking into consideration the applicable grid design criteria and operational safety limitations;*
  - ***Required transport capacity:*** *The transport capacity required to fulfill the demand for transport of all contracted grid connections in a (sub)node, as stated in article 2.3 of the regulations investment plan and quality electricity and gas;*
  - ***Available transport capacity:*** *The part of the existing transport capacity that is not used to fulfill the required transport capacity. The available transport capacity is equal to the difference between the existing transport capacity and the required transport capacity*

  The capacity shortage (see also Figure 7) is a result of contracted grid connection capacity exceeding the existing transport capacity, resulting in potentially having the scenario that the required transport capacity demands exceed the existing transport capacity. The higher the contracted grid connection capacity in an area is, the more likely congestion would occur.

- **[Clarification: 4.1 Changed circumstances point 28]:** *The electricity demand has grown fast in recent years amongst others as a consequence of the developments of data centers, and the increasing demand for electric vehicles and heat pumps. Simultaneously there is an increase in the supply of renewable electricity, especially by projects where electricity is generated by solar and wind power. Such projects have a relatively short implementation period in comparison to the implementation period for grid reinforcement. In recent* *years the shortage in the electricity grid has increased, because grid reinforcement is not executed at the same pace as the growth in transport demand of electricity on those grids.*

This part is mainly a reinforcement of the arguments given in Chapter 1, that grid reinforcement as the sole solution is not sufficient to solve the the capacity shortage.

- [**Article 9.10 section 2.d**] *The grid operator does not have to apply congestion management for the demand of electricity, where the required transport capacity is larger than the technical limit of the existing transport capacity. The technical limit consists of 110% of the existing transport capacity, increased by the available flexible loads, to a maximum of 150% of the existing transport capacity*

  This section states that the possible contracted grid connection capacity is increased to 110-150% of the existing transport capacity. Once the contracted grid connections exceed the 110% - 150% existing transport capacity in the grid (depending on the availability of flexible loads), the grid operator is no longer required to assign capacity to existing grid connections willing to upgrade to higher loads or to assign new grid connections in the transport area.

  Therefore if the amount of flexible loads in a (sub)grid can be increased, the technical limit could be increased to 150% or further if in cooperation with the ACM is found that there is enough headroom in the practical required transport capacity.

- [**Clarification: 4.3 Rules for designation of transport capacity point 58: From article 9.10, third paragraph, section e, of the amended Network Code**]:*A grid operator is not required to apply the market-based congestion management regime if the limiting element causing congestion is located in low-voltage networks. When congestion occurs in low-voltage networks, there is typically a small number of connected entities within the congestion area. As a result, the number of affected entities and potential flexibility providers in that specific congestion area is limited. Additionally, the necessary reinforcement and/or expansion of the network is minor and, given sufficient execution capacity, can be carried out swiftly. In such cases, the ACM considers it inefficient to establish congestion management before the network reinforcement is completed. This is further elaborated in subsection 4.11 of this explanatory note accompanying the decision.*

  This part clarifies article 9.10, which states that low-voltage networks are exempt from congestion management. This is important for the GOPACS congestion market explained later in this chapter.

- [**Observation 10 'Financial Threshold' Point 96**]:*The annual profiles were not statistically justified average profiles for those different situations. An average annual transmission of 78% of the available transmission capacity does not occur in almost any grid area, according to Netbeheer Nederland The actual average annual transmission mostly varies from around 14% to 50% of the available transmission capacity.*

  This section contains the view of Vereniging Energie, Milieu en Water, Netbeheer Nederland, Enexis Netbeheer B.V., and Vereniging Energie-Nederland on the height of the financial compensation of congestion. The interesting part of the submitted view is the discussion on the allocation of the electricity grid, which has a yearly average of 34% with a common range of 14% to 50%. These numbers will be used as a reference to calculate the grid utilization.

2.2 Capacity shortage and congestion

In the following paragraphs, the definitions of capacity shortage and congestion are given. The explanation is backed up by illustrations, visualizing the capacity shortage and congestion problems.

Capacity shortage

When there is a shortage of grid connection capacity, a company cannot get a contract for grid connection capacity, or upgrade a grid connection when there is no available transport capacity. This means that practically there could be space for a new company to be connected, however theoretically if all grid connections use electricity simultaneously, the TSO or DSO in question cannot guarantee that electricity can be delivered. An illustrative example is given in Figure 8 where in node A three contracts together exceed the existing transport capacity of 100 Megavolt-amperes (MVA) in the grid and therefore the grid connection with the contract colored in red cannot receive electricity. In this example, the minimal 110% technical limit increase of the existing capacity is not taken into account.

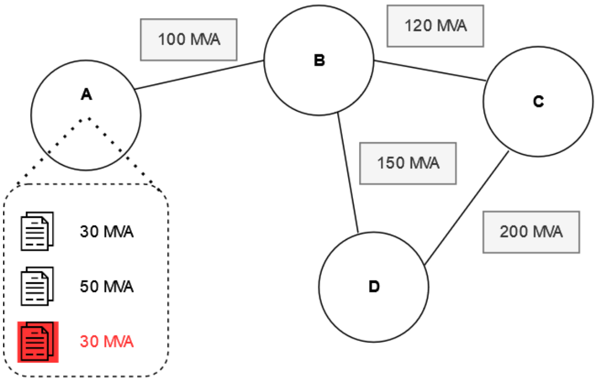


Figure 8: Illustrative example of contracts at a node exceeding the existing transport capacity from node A to node B. Grid connection capacities are denoted in MVA, in node A this exceeds the 100 MVA connection that goes from node A to node B. This means that the last 30 MVA grid connection cannot receive a contract for the desired capacity.

Congestion

Congestion is a two-fold operational problem, where the existing transport capacity cannot transport the electricity from one area to the other, resulting in a double imbalance situation. With an oversupply of electricity in one area and a shortage in another area. Figure 9 illustrates where congestion occurs as a transport bottleneck between nodes A and B. In the figure, the technical limit of 110% has already been applied, but this does not increase the existing transport capacity. This implies that if 110 MVA of transport capacity is required, it physically cannot be transported and therefore causes congestion. This causes nodes C and D to not receive enough electricity due to the shortage of electricity at node B. With node A stuck with an oversupply of electricity.

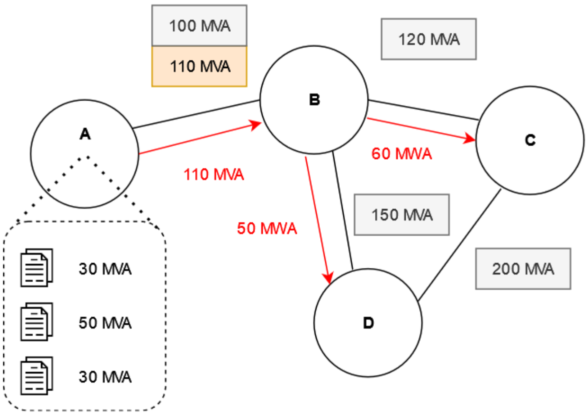


Figure 9: Illustrative example of congestion after applying the technical 110% rule. Transport demands of 60 MVA at node C and 50 MVA at node D cannot be met due to the 100 MVA limit from node A to B. This results in grid congestion where there is an oversupply of electricity at node A and a shortage of electricity in nodes C and D

2.3 Current congestion mitigation process

When, in an area in the Netherlands, the available capacity of the grid is zero, the TSO or DSO must reinforce the network by investing in realizing new cables and/or substations. This reinforcement can take several years to realize and according to the ACM code decision document the DSOs and TSO, who govern the area, in the meantime, have to investigate different mitigation possibilities to prevent physical congestion in their networks. The process of this can be seen in Figure 10. In the following paragraphs, the different parts of the process are explained with the corresponding constraints.

For DSOs, according to the code decision document of the ACM [32], congestion management research does not need to take place for LV grids. This means that if there are congestion and/or capacity problems in an LV area, no measures need to be taken for that area specifically. This means that the behavior of the feed-in of RES will result in a cut-off when the voltage goes above the regulation threshold.

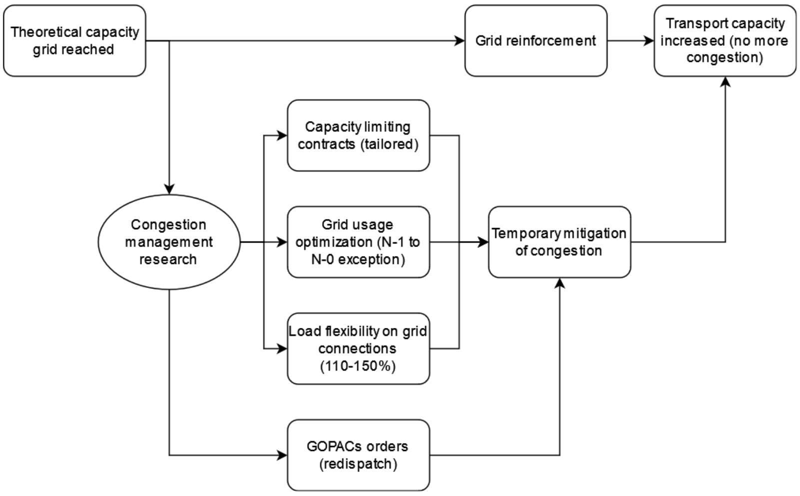


Figure 10: Process of when the theoretical capacity is reached or congestion occurs in an area and how the TSO and DSOs solve this

Grid reinforcement

Grid reinforcement is the main driver to solve grid congestion and the grid connection capacity shortage. Apart from electrification outgrowing reinforcement, there are several other problems.

In Figure 11 several issues are stated with their consequences. The nitrogen deposition problem in the Netherlands will be a cause for delay in the construction of the new parts of the grid [33] with Tennet stating that without a construction exemption for nitrogen emissions (as a result of the construction work) during construction, the construction projects for high-voltage grid transport could have delays lasting multiple years [34].

The second issue is the labor constraints, according to Hans-Peter Oskam, director of the energy transition and policy at Netbeheer Nederland, there is a need for 18.000 workers in the coming seven to eight years which means doubling the current workforce [35].

Grid usage optimization

TenneT has started to use the reserve capacity of the high-voltage grid in Emmen. This works by transporting sustainable generated electricity over the reserve capacity (supply) on the transmission lines and when there is a disturbance on the grid, the supply is cut off from the grid to prevent overloading the grid. Grid utilization is on average only 25-35% in the Netherlands, with higher utilization during peak moments. A way to mitigate the congestion problems is to utilize the existing network closer to 100% [36].

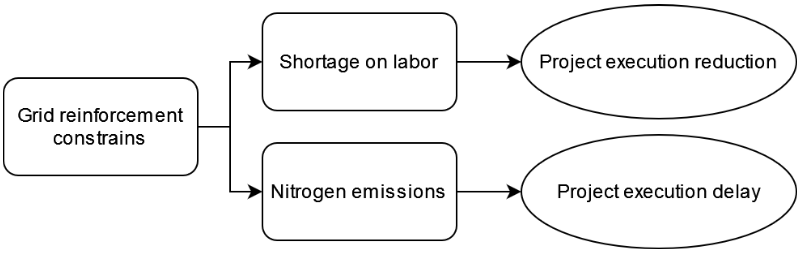


Figure 11: Grid reinforcement constraints

Another way of optimizing grid usage is for DSOs to apply for a so-called N-1 to N-0 exception. Normally in an area where electricity is supplied through two transformers and one transformer has an outage (maintenance or malfunction), the area can still be supplied through the other transformer. The N-1 to N-0 exception means that in such an area, the capacities of both transformers are added, and double the capacity becomes available but during maintenance or malfunction of a transformer, there is no fallback, and electricity outage could be a result.

This is therefore a trade-off between stability and capacity of the grid. Additionally, the application of the exception does not lead to an exception of congestion management for the DSO, and the theoretical grid capacity of 110-150% is kept in place [32].

Peak availability constrained contracts

A policy solution is the application of grid connection capacity contracts with constraints added for peak availability of the grid connection capacity. This results in a contract where the TSO or DSOs can enforce a reduction of grid connection capacity in periods where there is no available transport capacity to avoid congestion. For electricity grid users such a contract could be beneficial, depending on the financial compensation, by shifting their loads to different hours and/or by installing buffers (large batteries).

This solution decreases the potential maximum simultaneous demand for electricity transport and therefore decreases the chances for congestion to occur. However, the effect of the contracts is based on the number of enterprises willing to sign these tailor-made contracts and there are not many enterprises that are willing to go for such a contract. Enexis has not been able to get one enterprise to sign a contract, with Alliander and Stedin being able to only make deals with 10 enterprises over several months (as of June 2023) [37].

This means that by far not enough enterprises are not willing to voluntarily accept a peak availability-constrained contract, for this policy solution to be of significant effect.

Yet, the grid operators continue to pursue alternative transport right contracts and Netbeheer Nederland (grid operators Netherlands) recently published two proposition papers, one about non-firm Access To Transmission (ATO) and one about energy hubs [38].

The non-firm ATO goes further than a capacity-limited contract. Instead of certain moments of capacity reduction, the non-firm ATO is based on having no guarantee of electricity transmission and that therefore only reserve capacity in the grid (existing - required transport capacity) can be accessed. This means that the 'leftover' transport capacity can be used and if there is none, then there is no electricity transmission possible during those periods.

As the level of interest from enterprises in the capacity-limiting contract is minimal, the probability is high that there will be similarly limited interest in a contract offering further reduced security for grid capacity. Nevertheless, non-firm ATOs could present a potential solution for enterprises currently having no grid connection availability.

2.4 Congestion market process

As stated in the code decision document, once congestion management research is carried out, the TSO and DSOs have the option to mitigate congestion with the GOPACS congestion market. To have an understanding of how this market works alongside other markets, some background information is given on the Dutch electricity markets. Subsequently, the GOPACS market is explained.

The Dutch electricity market consists of different markets as shown in Figure 13. The wholesale market (day-ahead market), imbalance market, and congestion market are explained in the following paragraphs. More information on market roles can be found here [8].

Day-ahead market

The day ahead is the market where Balancing Responsible Parties (BRPs) buy and sell their electricity one day before actual delivery occurs. The BRPs denote their their electricity sales in a bid ladder, for demand and supply. This electricity is then settled according to a marginal price principle, where every market participant whose orders are accepted pays the same price. The market price is calculated from the intersection between the supply and demand curve (more on this in Chapter 4). The market works in hour blocks during a 24-hour period, where BRPs buy or sell their demand and supply of electricity per hour. The day-ahead market in the Netherlands closes at 12.00 CET, on one day before delivery.

There are two day-ahead markets available in the Netherlands, one provided by EPEX Spot [39] and another by Nordpool [40]. Nordpool is active in the Nordic region and provides the ability to balance out day-ahead market prices if there is interconnect availability. This means that if there is a surplus of electricity in Norway and a deficit in the Netherlands, electricity in Norway is bought for lower prices and sold in the Netherlands for higher prices. The limit of volume is the physical limit of the interconnect cables. The effect of interconnect flows is further explained in the methodology chapter where an example is given.

An example of an hour block from Nordpool is shown in Figure 12 where the sale and purchase (supply and demand) lines cross at a price around €150 per MWh. This means that the volume traded in that hour is dependent on the bid ladders and the resulting intersection of the price curves. In this example, the volume is roughly 3150 MWh of electricity.

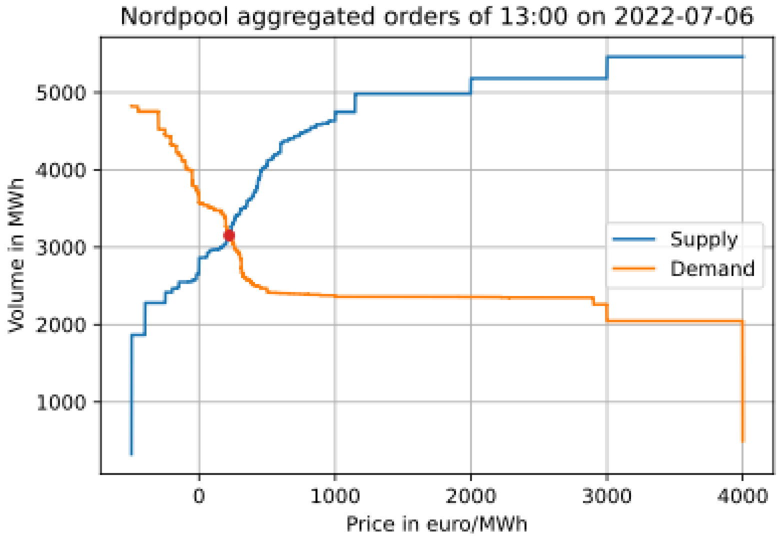


Figure 12: Day-ahead market hour block at 2022-07-06 at 13:00 [7]

Intraday market

Trading is theoretically possible till 5 minutes before the actual electricity delivery takes place on the intraday market. The intraday market is a market where order matching is required and it is a continuous auction, however, trading liquidity starts to dry up 1 hour before the delivery moment as the interconnect (cables to other countries) trading closes.

Intraday trading is useful for smaller orders, for example when the weather forecast becomes more precise as the time horizon of the forecast shortens and position adjustments need to be made.

Imbalance settlement and market

If the prognosis of the position is off (for example, too much electricity sold or too much electricity was bought) then this imbalance is corrected on the imbalance market, at a cost. This market works with 15-minute blocks where grid imbalances are settled with a pricing mechanism. The imbalance is measured in real time over the 15-minute interval and settled for the respective time unit after the period has ended. Tennet (the TSO) has contracts with reserve capacity suppliers and reserve consumers that balance the oversupply or shortage of electricity and are paid for their services. On the imbalance market, BRPs can also trade to balance their portfolio, either receiving a reward for balancing the electricity grid or costs if their forecast was off and the BRP resulted in being part of the imbalance of electricity on the grid.

Congestion market

In 2018 a new market was introduced, the congestion market GOPACS. As a market-based solution for solving the congestion. The GOPACS market is a market where order matching is done between grids operated by DSOs. These orders are only opened when there is congestion in transporting electricity from one part of the grid to another part of the grid.

Congestion Service Providers (CSP) are contracted by TenneT and the DSOs to be able to deliver congestion services. These providers are enabled to trade on the congestion market (GOPACS) [8]. Independent parties with a certain capacity and/or BRPs can register with TenneT to take on the role of a CSP. An overview of the roles of the electricity market is shown in Figure 13, which shows how the role of the CSP is added to the existing market.

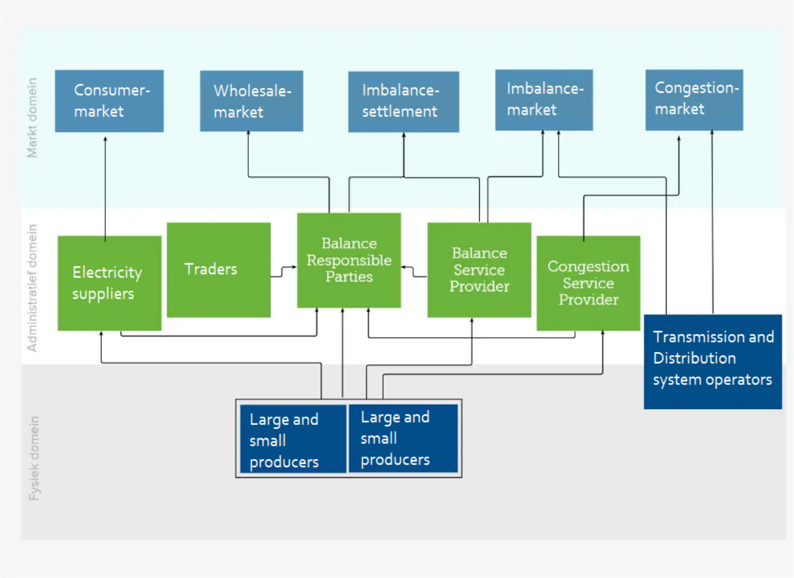


Figure 13: Market roles in the Dutch electricity market according to TenneT [8]

In an area where there is too much supply of electricity, an order of a CSP needs to be matched to another area where there is a shortage. This situation is illustrated in Figure 14. The CSP can then reduce the electricity consumption in the area with a shortage with an equivalent amount of electricity supply reduction in the area with too much supply. This reduces the electricity transport demands, reducing and/or solving the congestion.

In Figure 15 the volume traded on the GOPACS market is shown, in the yearly graph it looks like steady growth in volume traded on the market. However, in the monthly graph shown in Figure 16, the volume traded data is more seasonal, with especially large volumes traded during the winter months, which could be related to higher wind

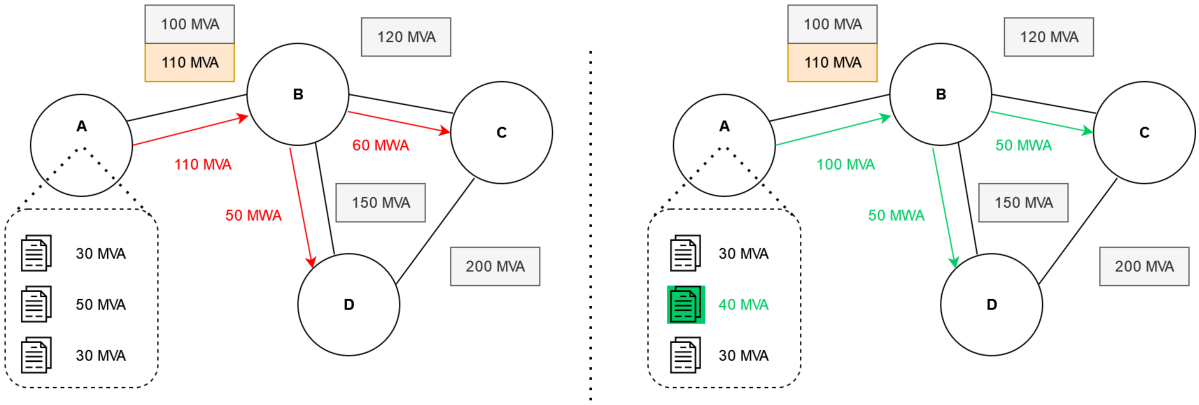


Figure 14: Two illustrations showing the situation on the left with congestion in the grid, the capacity shown in the red arrows cannot be transported over the 100 MVA line (existing transport capacity). This could be solved with a GOPACS order, where in this case shown on the right a CSP matched an order reducing electricity production in node A while decreasing electricity consumption in node C, balancing the electricity production and consumption and solving the congestion

electricity generation, causing congestion. Another reason for this is that, as stated in the ACM document, LV networks are exempt from congestion measures for DSOs. This results in TenneT being the main trader on the GOPACS market as large off-shore wind turbine parks are connected to the off-shore grid operated by TenneT [41].

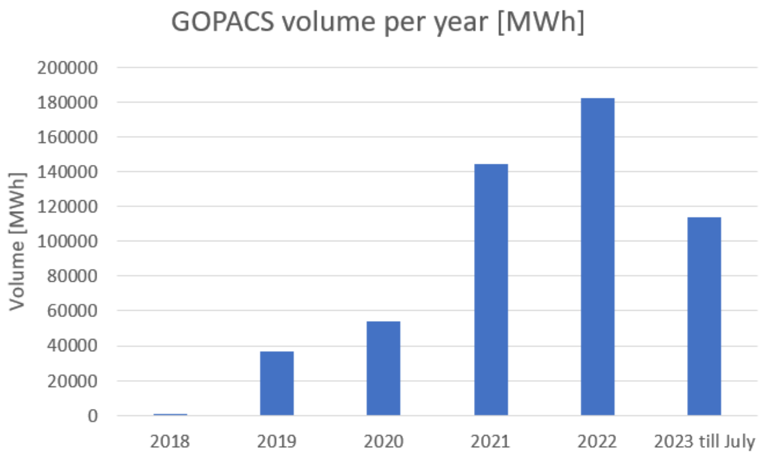


Figure 15: GOPACS yearly volume in MWh with 2023 till July [9]

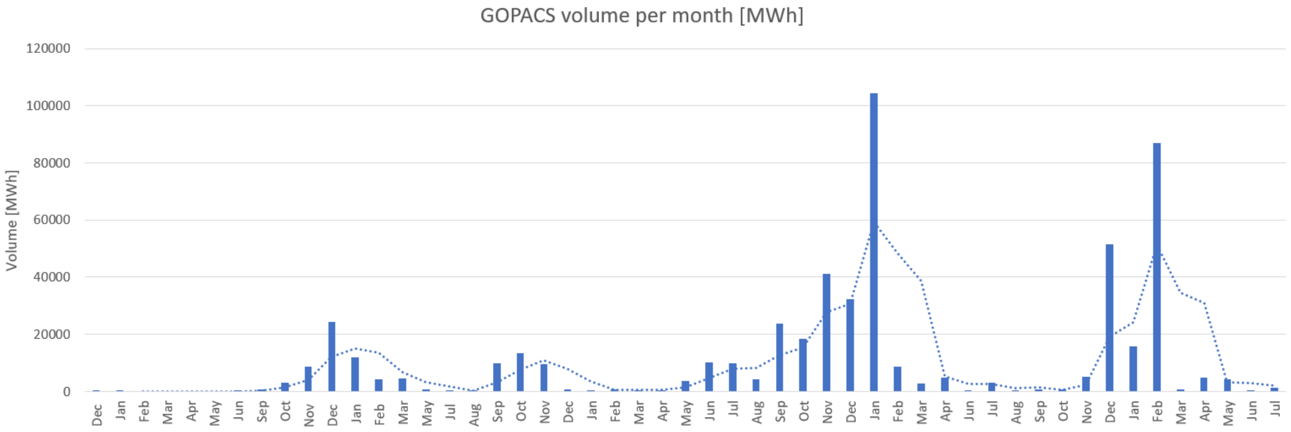


Figure 16: GOPACS monthly volume in MWh per month from December 2018 till July 2023 with the dotted line the trendline averaging the past 3 months [9]

2.5 Conventional solutions

Curtailment

Options for capacity-limiting contracts or assets that can be used by CSPs for GOPACS orders are curtailment solutions to cut off-grid loads. In the following paragraphs, some details are given on curtailment technologies that are part of the energy transition. Curtailment can be used to create more flexible grid loads, where financial compensation is given when a capacity-limited contract is signed. These kind of contracts are explained later in this chapter.

Solar PV

Solar PV fields have a close to zero operational cost, the power generation of solar PV fields can be shut off and turned on without incurring costs. The downside, however, is the reduction of renewable energy generation and losses of revenue. However, depending on the number of curtailment occurrences and duration of the curtailment, revenue losses are not of significance.

Wind power

Wind farms like solar PV fields can be curtailed. Wind turbines, however, need around 30 seconds to start and shut off their operation. Curtailment of wind turbines is more beneficial than solar PV fields, as wind turbines do have operational costs (lifespan reduction due to operation). This means that curtailment of wind turbines can be taken up for consideration when electricity prices go below zero. If it is only due to congestion problems, revenue from electricity generation is still lost.

Heat pump control

As a temporary solution to the congestion problem in the medium voltage grid in Buiksloterham-Zuid/Overhoeks (a neighborhood in Amsterdam), the proposal is made to shut off heat pumps of residential buildings for a certain period during grid congestion. This brings immediate carbon emission savings and residents are not hindered, as building regulations resulted in residential buildings providing enough comfort during the period when heat pump operation is disabled [42].

While this could reduce congestion, it does not scale very well, as prolonged shut-off times of heat pumps could result in reduced living standards. Therefore, a thorough analysis is required of heat pump control, to not interfere with residential comfort [42].

Contract reserve capacity

Another way of alleviating the congestion is to contract power plants for reserve capacity. Coal power plants that have been planned for shutdown, can be kept operational for reserve capacity. This can be done to mitigate congestion problems with fluctuating loads due to Renewable Energy Systems (RES). Keeping coal plants only in use for reserve capacity reduces carbon dioxide emissions in comparison to keeping the day-to-day operation and supplying electricity to the grid. This solution is carried out in Germany [43].

However, for the Dutch market, the main focus is to have market-based solutions. This means that using such plants for reserve capacity is possible, but execution would be through GOPACS orders rather than contracting the reserve capacity solely for congestion.

2.6 Various other solutions

Local Marginal Pricing

In the United Kingdom, one of the explored solutions is to create multiple sub-networks where different prices are possible, called Local Marginal Pricing (LMP). This means that per area, there is a day-ahead market clearing resulting in possible different prices per area. This results in a price steering mechanism that mitigates the problems of congestion. The drawback of LMP is that it is a reactive solution, only when congestion occurs the price will differ, as with enough transport capacity the price would be equal throughout the country. This means that it will not increase the headroom in the existing transport capacity but will affect the double-sided imbalance problem created by congestion [44].

Energy Hubs

As stated previously, there is a difference between the theoretical capacity limits that are contracted to the DSOs and the practical simultaneous usage of this electricity capacity. enterprises that therefore do not have the simultaneous use of electricity can therefore create a so-called energy hub. This means that instead of individual enterprises, the hub as a whole has a capacity connection to the grid and the enterprises themselves divide it amongst how the electricity demand and supply are organized.

According to the Financieel Dagblad (Dutch Financial Times), some enterprises are willing to adopt this, as the alternative is having no grid connection (upgrade) at all. However, the DSOs are reluctant due to policy constraints and the unknown effects on the network. There are pilot cases with one on Schiphol landpark with positive results, as they have not had to use their backup gas generator in case they had a shortage of electricity. However rolling this energy hub system out can take years longer as DSOs assess the pilot cases, learn from them, and mitigate possible risks [45].

Because this policy solution is only in effect in pilot cases, it is unknown what effect it will have on the capacity and congestion problems.

Volume Discount Regulation

For large electricity users, there is a regulation that gives a discount on electricity transport costs if the electricity usage is constant over time. This is called the volumecorrectieregeling (VCR), which translates to Volume Correction Regulation, for large electricity users. The idea behind the VCR was that the constant use of electricity was more cost-effective for transportation.

However, the ACM requested a consultation by Royal HaskoningDHV, who concluded that the VCR does not support the energy transition where loads are flexible and aligned with renewable energy generation. The regulation will be ended in 2024, potentially leading to an increase in demand for capacity-limited contracts, though currently, the demand effects are unknown [46].

Batteries as buffers

Batteries for storage of electricity are a logical implementation to buffer electricity of wind and solar generation, so it can consume electricity (charge) in periods with an oversupply and supply electricity (discharge) during periods with a shortage. Using battery energy storage systems (BESS) is therefore required for the energy transition according to TenneT with a capacity of around 9 GWh by 2030 [47].

However, in the Netherlands, the problem is high grid connection capacity tariffs. According to an interview in the Dutch newspaper Trouw with the director of the energy transition of Eneco Ron Wit, a battery project with 50 [MW] and 200 [MWh] capacity is realized in Belgium and not the Netherlands due to high grid connection costs. In the article, Ron states that the grid connection tariffs would result in costs of around €90 million, which according to Wit is higher than the initial investment. He states that for batteries to be financially attractive, the grid connection costs in the Netherlands need to be lowered by 80-90% to make the Netherlands competitive with Germany and Belgium [48].

2.7 Conclusion and future outlook

As described in the introduction chapter, the current rate of electrification is growing and outpacing grid reinforcement. The capacity shortage is increasing and congestion is occurring more frequently. Aside from grid reinforcement being outpaced, it is also constrained by labor shortages and nitrogen emission regulations slowing grid reinforcement further.

Congestion-mitigating solutions do not result in the scale of reduction required to solve the congestion in the grid. Only a handful of enterprises are willing to sign grid capacity limiting contracts, the virtual energy hub solution is only in the pilot phase and large battery buffer systems are being installed in neighboring countries as a result of high grid connection costs in the Netherlands.

This results in Netbeheer Nederland (Gridmanagement Netherlands) stating that if voluntary capacity limiting contracts do not have the impact required, mandatory capacity reduction is an option [49]. Mandatory capacity reduction however will bring a lot of new problems, namely that large consumers or production facilities need to adjust their consumption or production in a short period, resulting in a negative economic and social impact.

To avoid such a situation, new approaches should be investigated to determine if alternatives are available to mitigate the mandatory capacity reductions and/or mitigate the congestion problems.

These new approaches could utilize the fact that while there is a capacity shortage, the average grid utilization is 34% as stated in the ACM code decision document. Last year, most grids reached their capacity limit only at 1% of the time according to the Landelijk Actieprogramma Netcongestie (National Action program for grid congestion) [50]. Therefore while capacity demands grow, there is still a significant amount of operational capacity available for the transport of electricity. Optimizing grid utilization could increase the possibility of increasing the technical limit of 110-150% for the existing transport capacity and reduce the capacity shortage.

This utilization fact is the basis of the novel approach outlined in the subsequent chapter: the Rush Hour tariff.

3 Rush Hour Tariff

In road traffic, the highest demand for highway capacity is during the rush hours. During rush hour, traffic jams can occur when too many cars are on the highway simultaneously, causing road congestion. To reduce these traffic jams, more highways are built or existing ones are broadened to compensate for the rush hour traffic demands. This creates the situation where highways are constructed according to rush hour peak demands. Yet an alternative to solve the road traffic jams could be to implement a tariff, making it more expensive to travel during the rush hour, resulting in a reduction of road car traffic during rush hours and possibly lowering the requirement for the number of highways required. This reasoning can be applied to the electricity grid and additionally, in comparison to road traffic, congestion in the electricity grid is more critical as electricity cannot be buffered in the grid, as cars on the highway.

Therefore to damp the operational required transport capacity during peak hours in the Netherlands, a novel solution in the form of a tariff was created. The tariff is named the Rush Hour Tariff (as an analogy to the rush hour in traffic), which has the goal of reducing the amount of electricity transported in the grid during peak hours. The tariff is explained in the following steps: The goal and definition of the tariff; the proposed implementation and influences on the different electricity markets; the testing criteria to determine the performance of the tariff and the social justification of the Rush Hour tariff.

3.1 Tariff goal

The average utilization of the grid is 34% [32]. This means that while there is a capacity shortage for grid connections and congestion is occurring incidentally, half of the time less than a third of the maximum capacity of the grid is utilised. Additionally, if congestion occurs, it typically only lasts for hours [9].

This operational headroom could be realized with load shifting, shifting electricity loads to different hours which could be done by installing buffers in the grid. The financial incentive therefore needs to punish non-flexible loads, so that making loads flexible and/or installing buffers becomes economically viable.

As a result, a grid with more flexible loads and buffers has lower peak usage and less congestion. This gives the possibility for DSOs to raise the technical limit on grid capacity of 110-150% higher (see Chapter 2), increasing the available transport capacity and reducing the waiting list of 8000 enterprises for grid connections.

3.2 Implementation of the Rush hour tariff

The proposed Rush Hour tariff is a tariff charging a variable fee on demand and/or supply bids on individual hour blocks on the day-ahead market, where the grid utilization is higher than a predetermined threshold (for example 45%). As a result of applying the tariff, the resulting volume traded on the hour block on the day-ahead market lowers, consequently lowering the amount of electricity transported during that hour.

Tariff market implementation

The day-ahead price is the electricity price without any taxes or transport costs included. The price is calculated with an algorithm called EUPHEMIA. In Figure 17 a schematic is shown of the steps that are taken for the day-ahead price calculation. The first step is order aggregation of the Dutch day-ahead market. The second step is to include the interconnect flows to equalize the market price in the European market, this is done with an implicit auction and order matching of European day-ahead markets. After this, the EUPHEMIA algorithm is used to determine the best social welfare price for electricity. Two examples of what is taken into account by the EUPHEMIA algorithm are the ramp-up and downtime of substations, and complex orders of the day-ahead market. The detailed working of EUPHEMIA is left out of the scope of this research and more information about EUPHEMIA can be found here [51].

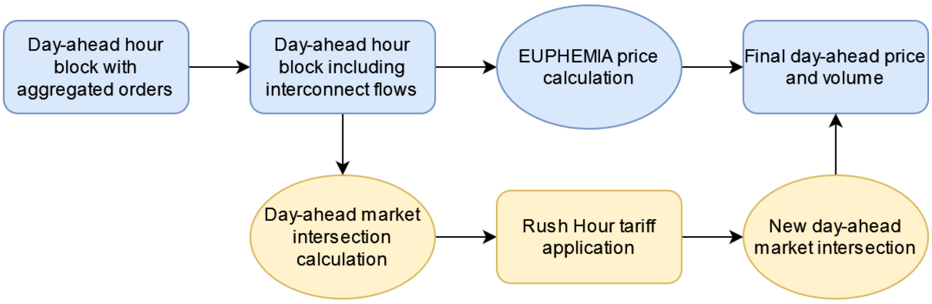


Figure 17: Process of day-ahead market price calculation shown in blue, with the process used for this research with tariff implementation in yellow

The tariff could be implemented in a Dutch-specific adoption of the EUPHEMIA algorithm. For this research however, the approach taken is shown in Figure 17 where day-ahead price calculation with the application of the rush hour tariff is done without the use of EUPHEMIA.

Day-ahead market implementation benefits

There are multiple reasons for the choice of the day-ahead market for tariff implementation:

- The day-ahead market clearing occurs a day before actual transport takes place, making the day-ahead market a good proxy for determining the grid loads for the following day.
- GOPACS orders could be mitigated, if a lower volume traded in an hour block results in mitigation of congestion in an area
- Most electricity trading takes place on the day-ahead market, meaning if the tariff is applied on the day-ahead market most if not all transported electricity, is taxed by the tariff
- The day-ahead market price calculation is done after aggregating all orders. This results in the possibility of calculating a new price/volume point after the application of the tariff without participants having to change their orders. This means the tariff operates in existing market limits so that it can be implemented without any change required in market participants' bids.
- Application on the day-ahead market does not result in imbalances in the grid (electricity shortage or oversupply). A new price/volume intersection is calculated after the application of the tariff, matching supply with demand.

Tariff effect on other Dutch electricity markets

If a tariff model is implemented in the day-ahead market, it also influences the other electricity markets. While technical implementation is left out of scope for this research, two considerations are given here:

- For intraday trading, tariff application could be predetermined from the day-ahead market, resulting in similar tariffs per traded electricity units whether it is traded on the day-ahead market or the intraday market.
- For the effect on the imbalance market, a sketch is given in Figure 18 to show if implemented correctly, the imbalance in the grid could be decreased with the use of the tariff.

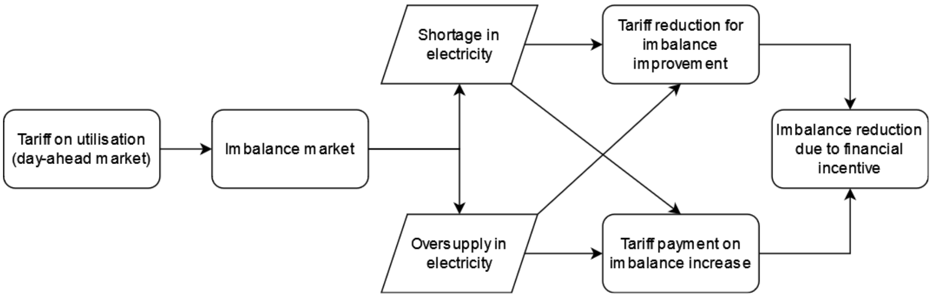


Figure 18: Tariff influence on imbalance market

3.3 Testing criteria

In the following items the testing criteria are listed on which the principle will be tested:

- **Volume reduction:** The main testing criteria of the tariff is whether it can realize a utilization reduction. This is dependent on the price elasticity in the market. More price elasticity means a higher tariff price is required to achieve the utilization reduction.
- **Robustness:** Tariff application should not create an unstable market. Therefore results need to be reviewed in robustness of the application of the tariff, to assess in what scenarios the tariff is stable and when the application of the tariff has volatile effects on the resulting price. The robustness is dependent on the price elasticity, less price elasticity results in a higher robustness.
- **Price behavior :** Different forms of implementation will have different effects on the resulting price on the day-ahead market. The tariff could push the clearing price in a certain direction. It needs to be assessed what price effect is desired and what is not.
- **Transparency and complexity:** To understand what is going on with electricity usage, production, and transport usage of the grid, transparency is required. The current situation does provide that with open orders on the website of the TSO and/or DSOs (with GOPACS). The tariff implementation should be evaluated for the effect it has on price discovery and visible and invisible market costs.

  Another part of the transparency is the complexity. If the algorithms that apply the tariff become too complex, it will become difficult to follow the steps that the algorithm is performing, indirectly reducing the transparency.
- **Financial incentive goal:** The tariff gives a financial incentive on the day-ahead market. Is this financial incentive present by electricity grid users or does it result in added costs for intermediary parties (for example BRPs)? Important is to assess what effect the financial incentive has directly and indirectly.

What is out of the scope of this research is the market feedback, the change in the placement of bid orders after the tariff has been implemented for a certain period. It also does not include the effects of change in the behavior of electricity users, due to a change in electricity costs after tariff application.

3.4 Social justification of Rush Hour tariff

Currently with the reinforcement of the grid, the costs are paid by the TSO and DSOs. This means that every grid user pays for the energy transition, while not everyone can participate. Households with no solar PV panels, no EV, and no heat pump do not benefit from a reinforcement of the grid but they do still pay for it (by their grid connection costs or by taxes). This creates inequality, as for residents living in apartments it could be impossible to participate.

By enabling the Rush Hour tariff, the costs of network usage shift more to those that use the grid during peak hours. Also as the tariff charges per energy unit [MWh] of electricity, electricity grid users pay proportionally to their use of the grid. This results in better equality for electricity grid usage costs. Additionally, those that are not able to participate in the energy transition, do get an incentive to increase grid stability by load-shifting and/or installing buffers like batteries and could indirectly benefit.

4 Methodology

This chapter explains the methodology used for the implementation of the Rush Hour tariff to assess its performance.

First, in this chapter, the data limits and changes on all data sets are given. Then the day-ahead market bid curves and hour blocks are explained from the given Nordpool exchange data, to give insight into what the bid curves consist of and what influences the resulting electricity price.

Secondly, calculations of different input data are given, what scenarios are created to test the tariff on, and what the expected results are of tariff application. At the end of the chapter, the algorithm of the tariff is presented which is used on the data to generate the results.

4.1 Data used

There are two data sources used for this research. The first source is day-ahead market data, including aggregated bid curve data on demand and supply, made available for this research by Nordpool [7]. The other data are actual grid load numbers and day-ahead prices taken from ENTSO-E [4].

Data limits

The tariff implementation and effects taken into consideration are limited to the day-ahead electricity market of the Netherlands. The period is 2022-07-02 till 2023-07-31. The reason is that only for that period day-ahead market data with interconnect flows from Nordpool was available. Data from over 8 years ago does not provide insights due to the changed characteristics of the electricity grid transport, for example, changes due to the increase in solar PV capacity as shown in Chapter 1.

Daylight saving time changes

For daylight saving time shifts two changes to all the data sets are made. For the hour shift ahead, an extra hour is introduced which is interpolated from the neighboring two hours, and for the hour shift back in October the two hours are averaged and reduced to one. This means that the total amount of hours stays the same and that Central Eastern Time (CET) timestamps can be used to compare different hour blocks at different moments throughout the year.

4.2 Day-ahead market bid-curves

The information in the bid curves on the day-ahead market includes the characteristics of electricity demand and supply bids from BRPs. This is important because price elasticity affects the performance of the tariff. The price elasticity results from marginal electricity generation costs, for example, shown in Figure 19. In this figure, different sources of electricity and their supply stack volume are given which shows the price inelasticity for mainly renewable energy and price elasticity for fossil power plants. Price inelasticity in this case means that the demand offered stays equal regardless of price changes. The reason for this is the low operating costs and subsidies on renewable energy generation. Therefore in different price regions of the day-ahead market, application of the Rush Hour tariff will have different effects depending on the price elasticity.

Interconnect flow

Nordpool has two datasets that were made available for this research, one from the period of 2021-10-22 till 2023-07-31 with the interconnect orders and another with the period of 2022-07-02 till 2023-07-31 without the interconnect orders.

The day-ahead market is an aggregated order market with 24 markets (one market per hour) per day. This results in a step-wise graph as shown in Figure 20. In this example, it can be seen that the interconnect volume has a

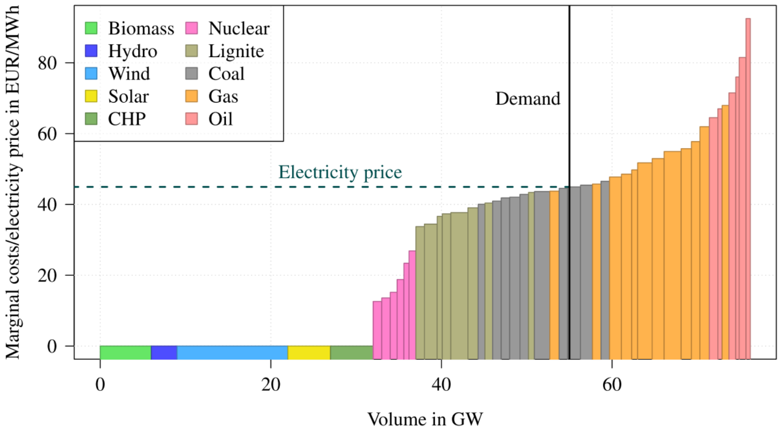


Figure 19: Supply stack model showing marginal costs and inelastic demand for different power plants. This is an illustrative example of the German electricity market in 2020 [10]

large influence on price discovery. Without the interconnect flows the price would be 577,9 euro/MWh and with the interconnect this is lowered to 37,5 euro/MWh. The difference in volume between the different price points is 6537.8 - 4769.1 = 1768.7 [MWh].

This shows that with a lower price in the surrounding countries around the Netherlands, electricity flows to the Netherlands through the interconnect cables, lowering the price by a factor of 15. This example shows that the interconnect influence cannot be ignored with tariff implementation. Other investigated bid curves without the interconnect show that there are a significant amount of occurrences where the market would not have closed if there were no interconnect flows, meaning that the bid and supply curve never intersect in the price range of -500 to 4000 euro/MWh. The interconnect capacities can be seen in table 1, showing that roughly one-third of the transmission capacity in the Netherlands could be transported over the interconnect cables.

Connection to country from the Netherlands	**Capacity export [MW]**	**Capacity import [MW]**
Belgium	1700	2400
Germany	4250	4250
Denmark	700	700
United Kingdom	1000	1000
Norway	700	700

Table 1: Interconnect capacity from the Netherlands to other countries in 2021 [12]

Another interesting thing to note from Figure 20, is that there is a also volume shift on the demand side of the curve, shown in Figure 21, in which electricity is being exported on the interconnect where probably the price was higher than in the Netherlands. This means that the grid in the Netherlands was partly used as a pass-through to let electricity flow from one country abroad to another country abroad through the Netherlands.

Day-ahead market orders

For this research, it is assumed that orders on the bid-curves of the day-ahead market are single-hour block orders. In reality, there are other order types such as minimum income orders which could cover multiple-hour blocks that ensure covering the production costs of electricity for that order, or normally linked order blocks that only execute if all blocks would be executed [51]. For this research, every hour block is evaluated individually.

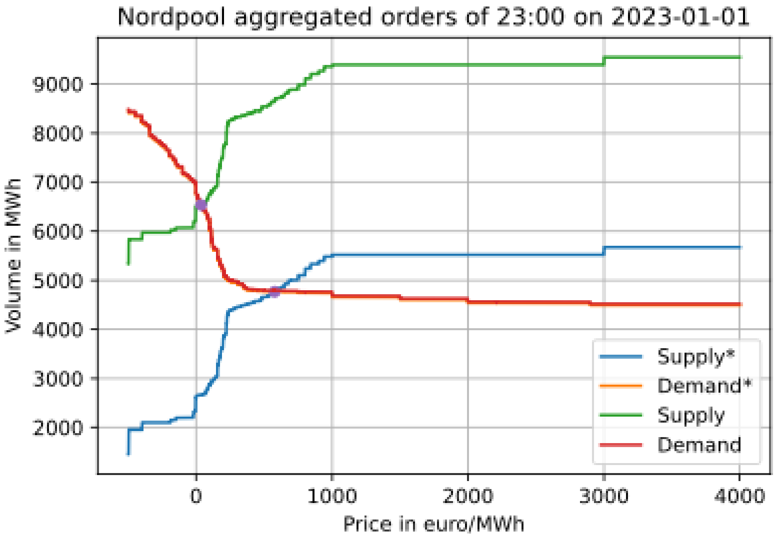


Figure 20: Day-ahead price curves from Nordpool data on 2023-01-01 23:00 with Supply/Demand the curves with interconnect volume and Supply*/Demand* denoting the curves without interconnect volume.

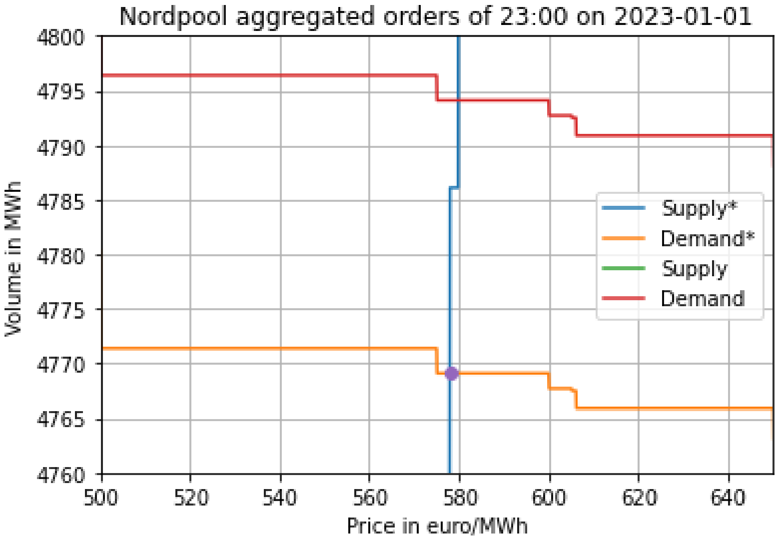


Figure 21: The zoomed-in graph of the day-ahead hour block of 2023-01-01, showing the difference in Demand (with interconnect volume) and Demand* (without interconnect volume) curves.

Day-ahead price calculation

The price calculation from the Nordpool market data is done with linear interpolation of the aggregated step curves of the day-ahead market hour blocks including the interconnect volume. When the steps of the curve overlap, the middle point of the overlap is used as the resulting intersection.

As the algorithm EUPHEMIA influences the final price, the calculated price can deviate from the listed price on ENTSO-E. For the considered period the error of the price calculations can be seen in Figure 22. The graph shows that from hour index 5114 to 5138 there are significantly larger deviations in price calculation for an unknown reason. These large deviations occur on one date specifically, on 2023-01-31. Decided is to exclude this date from the data set. The resulting price calculation deviations are shown in Figure 23. The data shows that 69,1% has an error smaller than 0.1 EUR/MWh which is the smallest order bid, and 89% has an error smaller than 1 EUR/MWh. 5% of the hour blocks have an error larger than 2 euro, however, of that 5%, there are only 31 occurrences where the relative difference is larger than 5% which is 0,3% of the total.

This is less accurate than [52] has achieved with their linear interpolation of day-ahead market data. Possible causes for this are limits in the accuracy of Nordpool data; market differences between Germany and the Netherlands; or the volatility of recent years in the electricity market with higher electricity prices causing larger absolute differences but smaller relative differences in prices calculated. However, to test the performance of the Rush Hour tariff, the results are accurate enough.

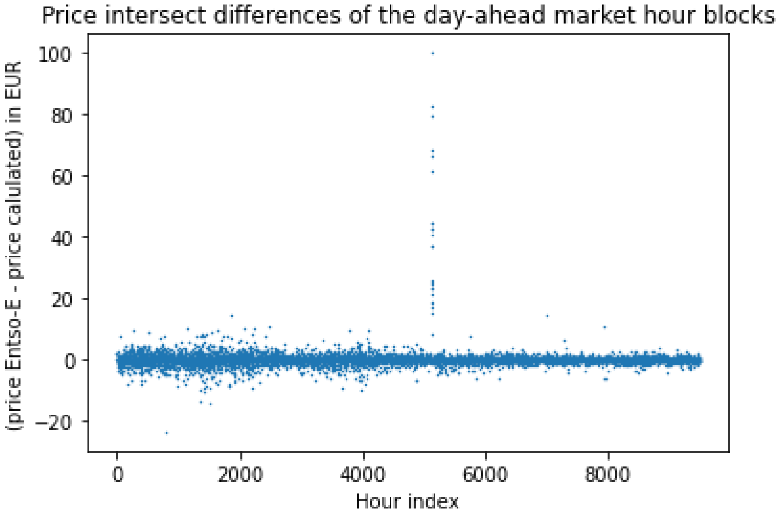


Figure 22: Price differences between ENTSO-E day-ahead market prices and calculated prices from Nordpool data

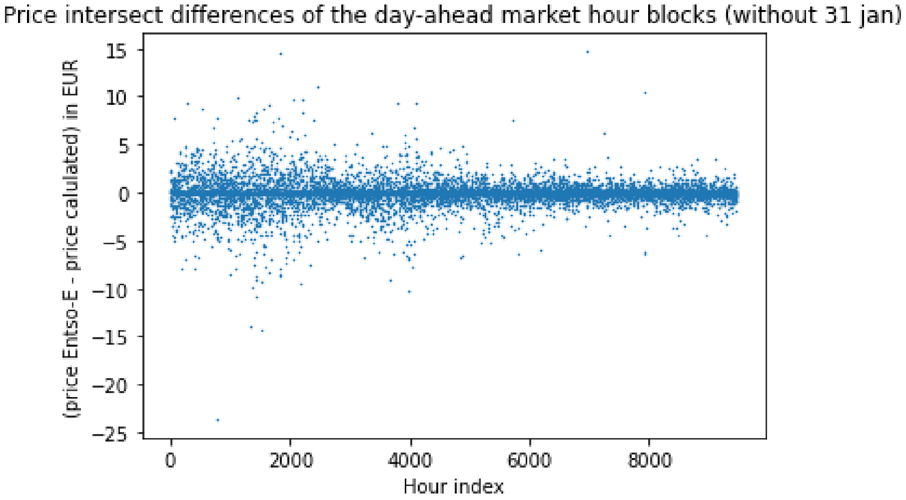


Figure 23: Price calculation differences without 2023-01-31

Another change that was made was for the hour block of 14:00 on 2023-07-02, where the price could not be calculated from the Nordpool data. This was caused by the bid and supply curve not intersecting. The resulting day-ahead market price was -500, which is the same price as the neighboring blocks and therefore the price and volume on the 14:00 hour block are interpolated from the two neighboring hours.

4.3 Grid utilization

For calculation of the grid utilization, two data sets are available: a day-ahead forecast total load per time unit; and the actual load per time unit. The forecast load is for example based on meteorological data according to the definition page of ENTSO-E. The actual load numbers represented in MW [4]:

$$Actual\ load\ [MW] = Net\ generated\ electricity - (export - import) - absorbed\ energy \tag{1}$$

Where *net generated electricity* is the generated electricity minus self-consumption in [MW], *export* and *import* are the interconnect flows in [MW], and *absorbed energy* is the transmission and distribution losses in [MW]. For both the forecast load and actual load, the time unit is 15 minutes. To get hourly data, 4 timestamps are summed and divided by 4 to get hourly data.

The forecast load seems more applicable to use for grid utilization calculation as it does not include intraday trading and imbalance volume, however, anomalies were found when comparing the hourly forecast volume data to the calculated volume data from the Nordpool data. An example is that the forecast load on the grid in the Netherlands from the ENTSO-E data was 475 MW for 2023-06-10 13:00, where the actual load during that hour is 11500 MW which is over a factor of 20 different. There were multiple cases where the forecast load was significantly low. Therefore the decision was made to use the actual load data which also includes intraday trading and imbalance settlements.

The grid utilization average of 34% is used with the assumption that the average grid load of 11700 MWh per hour from the actual load values from ENTSO-E is representative of the grid load.

Using this, the maximum actual grid load from ENTSO-E of 18003 MW corresponds to a grid utilization of 0.52 with the minimal grid load of 3237 MW corresponding to a utilization of 0.09. This falls fairly closely to the statement given in the ACM code decision document (see Chapter 2), with numbers of 14% and 50% grid utilization. In Figure 24 a probability distribution plot is shown of the grid utilization.

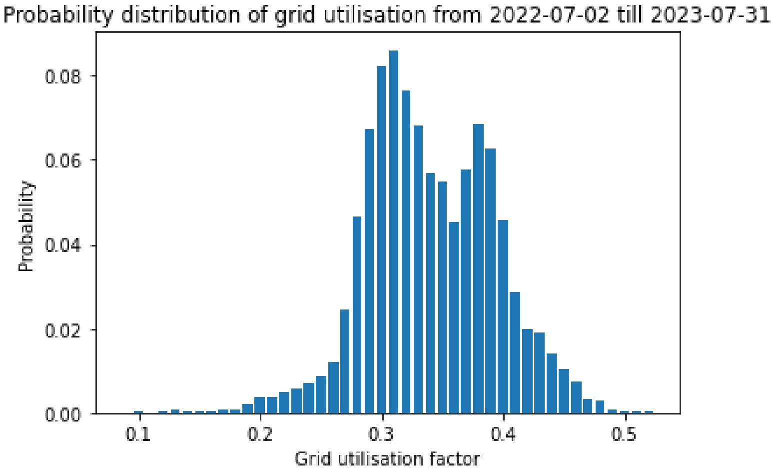


Figure 24: Probability distribution of the grid utilization factor of the Dutch electricity grid from 2022-07-02 till 2023-07-31 with 2023-01-31 omitted.

4.4 Scenario setup

To determine the influence of the tariff on the final price and the revenue gained by applying the tariff, there are three applications tested. One on the demand curve, one on the supply curve, and one on both. For these three applications, three scenarios for the utilization limit are made, 5%, 10%, and 20% utilization reduction. This means that with the utilization of 0.52 maximum, a 10% reduction gives 0.468 as the grid utilization factor limit. Every hour that goes above the utilization of 0.468 then has the tariff applied to it so that after the application of the tariff algorithm the utilization factor is reduced to 0.468. The three scenarios can be seen in table 2.

Grid utilization reduction from maximum utilization of 0.52	**Resulting utilization factor goal**	**utilization factor reduction**	**Maximum target volume reduction**
5%	**0.494**	**0.026**	894 [MWh]
10%	**0.468**	**0.052**	1789 [MWh]
15%	**0.442**	**0.078**	2684 [MWh]

Table 2: The three grid utilization reduction scenarios

The effects of the different applications are shown in table 3. As stated in the table, when the tariff is applied on the supply and demand side, the clearing price is dependent on the elasticity of either curve. This dependency is visualized in Figure 25, where is shown that when the supply curve is more horizontal, meaning a less elastic price, a larger price shift is required to get the desired volume reduction.

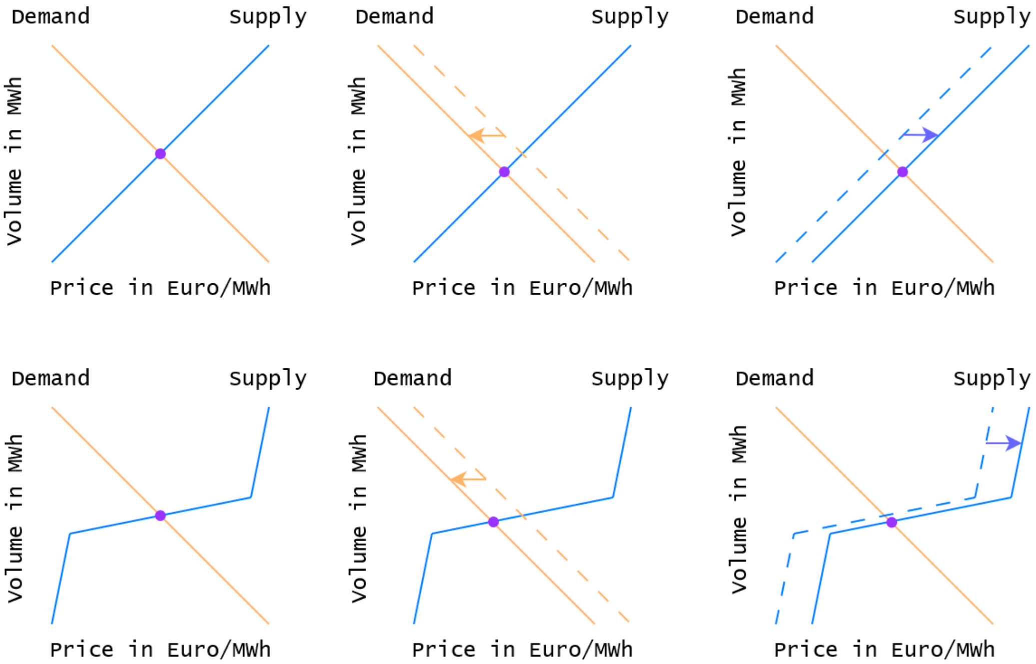


Figure 25: Illustrations showing the effect of the application of the tariff on the day-ahead market supply and demand curves, showing a demand shift, a supply shift, and the same shifts in the situation where the supply curve is less price elastic. This illustrates the results of the application of the tariff and that a less elastic supply or demand curve, results in less volume reduction with the same price movement.

The limit of the tariff is set on a price increase of 1500 euro/MWh. This could be reached if the price is perfectly inelastic, meaning that if this is reached either the volume reduction could not be reached or not be reached in the range of 1500 euro/MWh price increase. However, it is debatable whether a price increase of 1500 euro/MWh or higher is desired to reach the lower grid utilization. The choice for 1500 euro/MWh is to show the limits of the algorithm, to show in what range of utilization % the results become unstable. To show a more realistic application, afterward for the best-performing tariff application (demand or supply application, or applied on both), the scenarios are calculated again with the maximum tariff of 100 euro/MWh.

	Tariff causing a Supply shift	**Tariff causing a Demand shift**	**Tariff causing a Supply and Demand shift**
Supply curve result	Payment for tariff	Lower clearing price	Payment for tariff
Demand curve result	Higher clearing price	Payment for tariff	Payment for tariff
Market result	**Higher clearing price** **Lower volume**	**Lower clearing price** **Lower volume**	**Clearing price dependent on supply and demand elasticity** **Lower volume**

Table 3: Effects of curve shifts on the day-ahead market after tariff application

4.5 Target volume

The day-ahead market intersection from the Nordpool data, does not have the same value for volume as the national level due to the market share that Nordpool has. To give an approximation of the tariff influence on the national scale, an approximation is made.

The approximation is done by dividing the volume from the Nordpool data by the actual load volume from ENTSO-E for each individual hour. This results in an average factor of 0.46 of Nordpool/ENTSO-E volume which seems to correlate with the assumption that Nordpool/EPEX spot has a 40/60 % market share. In some cases, however, the factor was greater than 1, most likely caused by interconnect influence as the ENTSO-E data subtracts the export of electricity on the interconnects from the load value. This factor greater than 1 was present in 51-hour blocks.

To give insight into the import and export volumes on the interconnect, monthly interconnect flow values are given in Figure 26. The figure shows that during the data period used for this research, only two months have more import than export of electricity in the Netherlands. This means that the load data used from ENTSO-E shows lower values every other month due to a higher export than import and this has an influence on the utilization calculation of the electricity grid and the correlation factor of Nordpool/ENTSO-E volume.

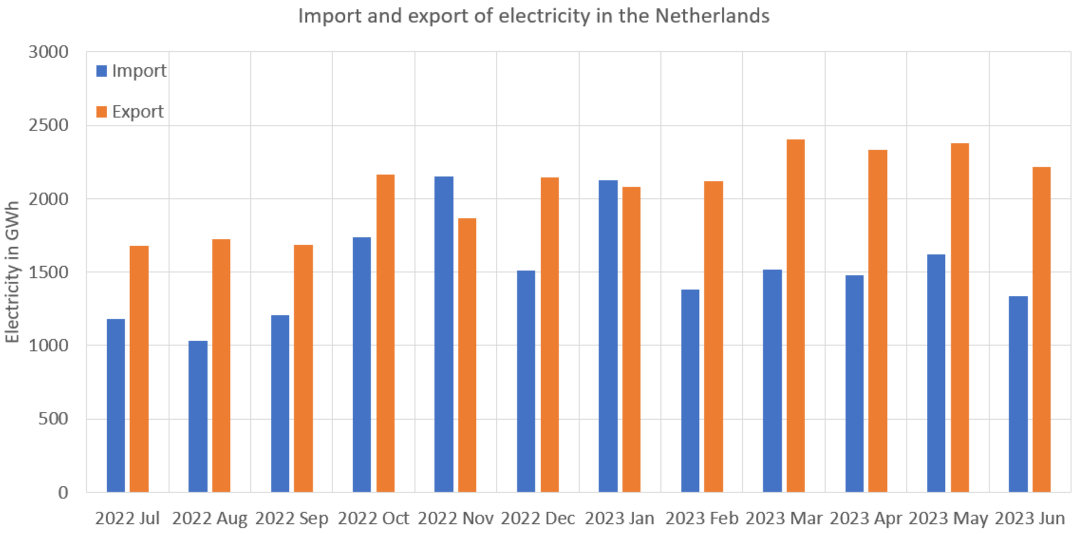


Figure 26: Electricity import (blue) and export (orange) in GWh on interconnect cable flows of the Netherlands from July 2022 till June 2023 [11]

Despite interconnect influence, the Nordpool/ENTSO-E volume factor was used to correlate the Nordpool market volume to the national volume. This was done to calculate what change in Nordpool volume is required, to reach the desired grid load in MW. The formula for target volume becomes:

$$Target\ Volume_{Nordpool}\ [MWh] = \ Nordpool\ volume\ -\ volume\ reduction * (\mathit{Nordpool/ENTSO\text{-}E\ volume}) \tag{2}$$

With $Target\ Volume_{Nordpool}$ the Nordpool day-ahead market volume reduction for the respective hour in [MWh], $Nordpool\ volume$ the day-ahead market volume of Nordpool on the respective hour in [MWh] and the volume reduction in [MWh] comes from the grid utilization target scenarios. For example, 1% of grid utilization represents 344.1 [MWh] during one hour (average grid load of 34% is 11700 [MW]), so for an hour block where the utilization has to be reduced by 4% the volume reduction becomes:

$$Volume\ reduction\ [MWh] = \ 344.11\ [MWh]\ *\ 4\ =\ 1377[MWh] \tag{3}$$

4.6 Tariff revenue

Application of the tariff generates revenue. For the tariff application with maximum price changes of 1500 euro/MWh, revenue calculations are unrealistic, therefore only for the price modifier cap of 100 euro/MWh application, the revenue of the tariff is calculated. The revenue per hour of tariff application is calculated as follows:

$$Tariff\ revenue = Price\ modifier\ \ * Volume_{Nordpool}\ /(\mathit{average\ Nordpool/ENTSO\text{-}E\ volume}) \tag{4}$$

Where $Tariffrevenue$ is the resulting revenue for the tariff application in euro, $Price\ modifier$ is the resulting tariff application in euro/MWh, $Volume_{Nordpool}$ is the resulting day-ahead market volume in [MWh] and $\mathit{average\ Nordpool/ENTSO\text{-}E}$ is the average volume difference in the total considered period from the Nordpool day-ahead market volume and the ENTSO-E actual grid load, which is 0.46.

4.7 Tariff algorithm

To apply the tariff in the different scenarios on the Nordpool day-ahead market, an algorithm was created. The algorithm shifts the demand and/or supply curve on the price axis and calculates a new intersection. As the curves shift outwards the resulting intersection has a lower volume. This is done until either the price limit or the target volume reduction is reached. The revenue from the tariff can then be calculated from the price modification on supply and/or demand curves times the resulting volume on the new intersection. The variables used are as follows:

- $Target\ Volume_{Nordpool}$ - The volume threshold target required to be reached to achieve the required utilization reduction in [MWh]
- $Volume_{Nordpool}$ - The Nordpool day-ahead intersection volume after each iteration [MWh]
- $Price_{Nordpool}$ - The Nordpool day-ahead intersection price after each iteration in euro/MWh
- $Price\ modifier$ - The price modifier of the tariff in euro/MWh, here set at 1500 euro/MWh
- $Application\ tariff\ Demand/Supply$ - Boolean, whether the tariff is applied on the demand and/or supply curve
- $Demand/Supply\ curve$ - The aggregated bid curves (volume and price)
- $Demand/Supply\ Price$ - The price of the aggregated bid curves in euro/MWh
- $New\ intersection$ - The new day-ahead market intersection point containing the new price and volume.
- $Compute\ intersection$ - Calculation of the intersection of the $Demand$ and $Supply$ curve, in this case done with linear interpolation
- $Volume_{Nordpool}$ - The volume after the new intersection calculation [MWh]
- $Price_{Nordpool}$ - The price after the new intersection calculation in euro/MWh

Three variables are the output of the algorithm $Volume_{Nordpool}$ and $Price_{Nordpool}$ for the resulting day-ahead market price, and $Price\ modifier$ for the resulting tariff application price.

Algorithm 1 Rush Hour tariff

```
while $Volume_{Nordpool} \geq Target\ Volume_{Nordpool}$ do
    if $Price\ modifier \leq 1500$ then
        if $Application\ tariff\ Demand\ == True$ then
            $Demand\ curve \leftarrow Demand_{Price} - 1$
        end if
        if $Application\ tariff\ Supply\ == True$ then
            $Supply\ curve \leftarrow Supply_{Price} + 1$
        end if
        $New\ intersection(price,\ volume) = Compute\ intersection:\ (Supply\ curve,\ Demand\ curve)$
        $Volume_{Nordpool} \leftarrow New\ intersection(volume)$
        $Price_{Nordpool} \leftarrow New\ intersection(price)$
    end if
    $Price\ modifier \leftarrow Price\ modifier + 1$
end while
```

5 Results

In this chapter, the results are presented of the application of the tariff algorithm on the prepared data. First, the three utilization reduction scenarios are given, with the three thresholds (5,10,15%) reduction targets. Subsequently, the 100 euro/MWh price cap tariff results are shown, where additionally the net costs for the demand and supply sides are given.

5.1 Scenario one

The first scenario with a reduction in utilization for the 5% highest utilization moments, results in the application of the tariff in 7 hours of the total 9456. In Figure 27 the results of the calculations are shown, where it can be seen that the application of the tariff on the supply side results in a clearing price increase, a demand side application in a price decrease, and when both are applied it results in either a price increase or decrease. Interestingly for the demand and supply side application is that a higher day-ahead price results in a lower price after the tariff application and a lower day-ahead price in a higher price after the tariff application.

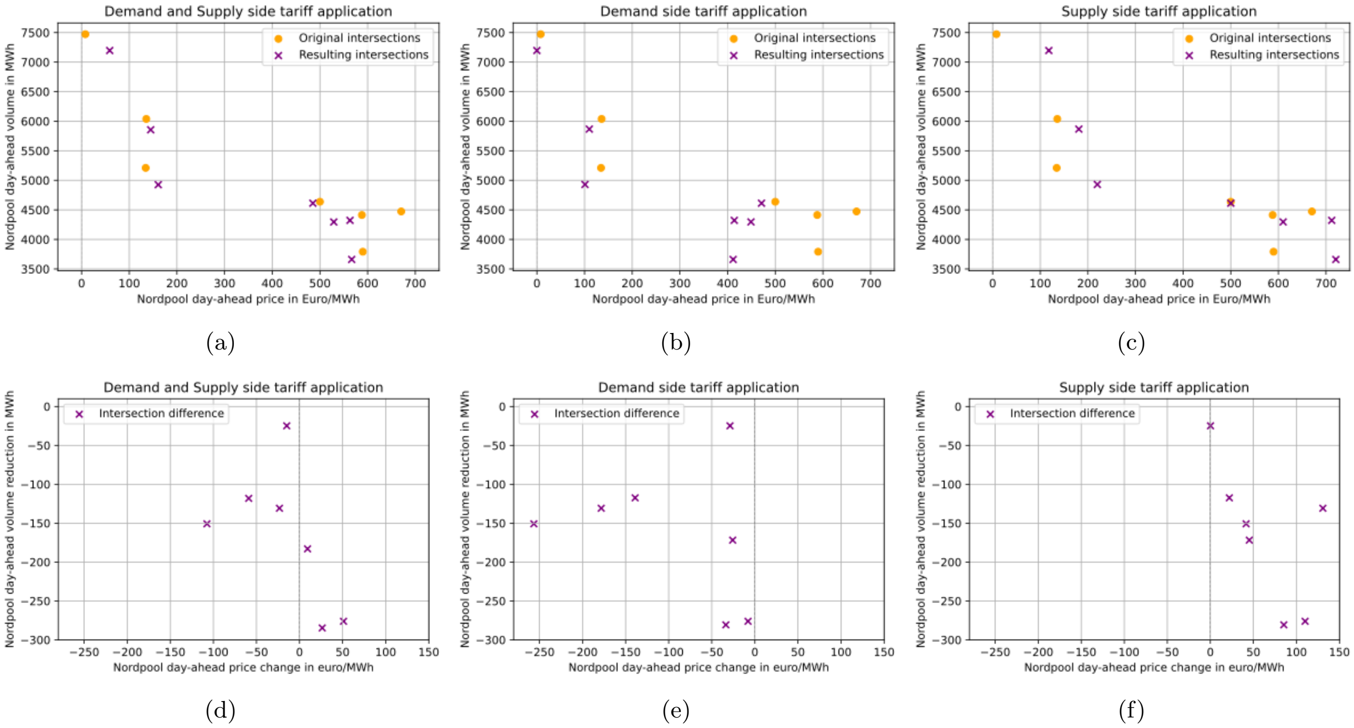
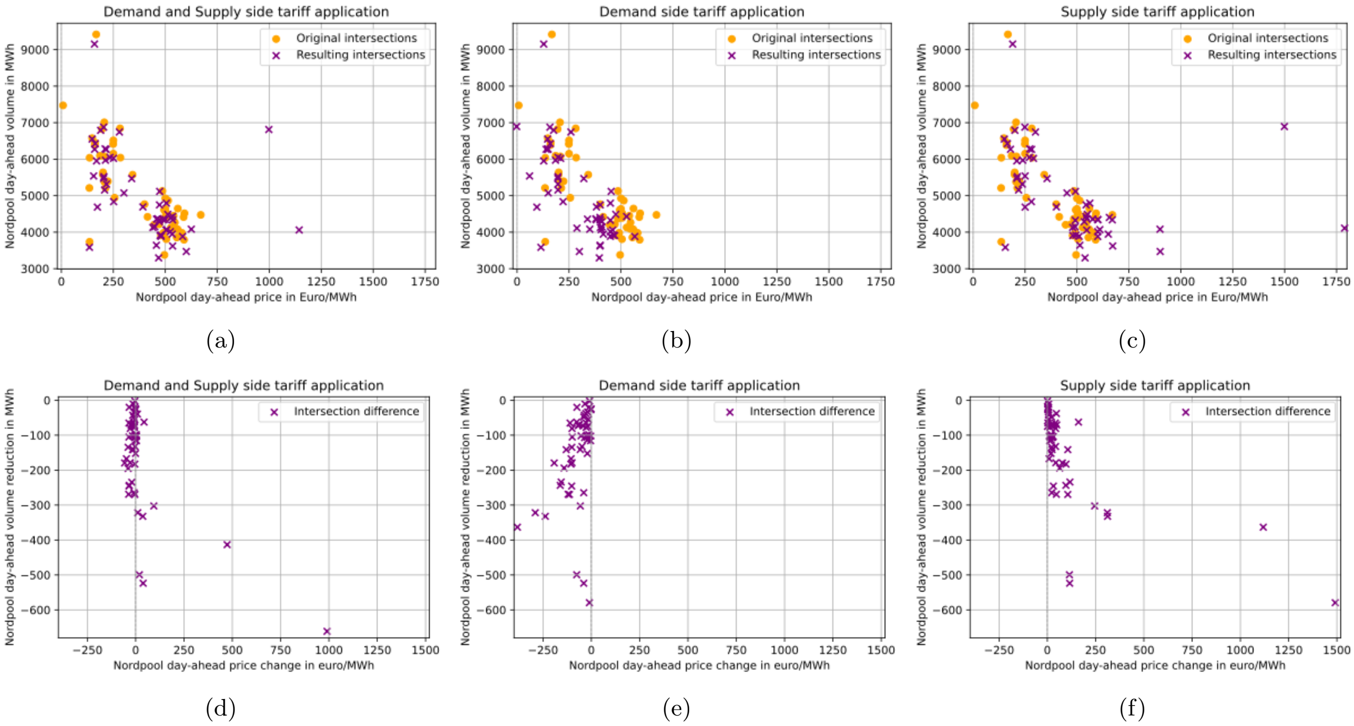


Figure 27: Results of the Rush Hour tariff application in the 5% maximum utilization reduction scenario on the prepared day-ahead market data.

5.2 Scenario two

For scenario two with the 10% maximum utilization reduction, the amount of hours where the tariff is applied has increased to 54 and the results are shown in Figure 28. Similar behavior as compared to scenario one. However, the application of the tariff, especially when a higher reduction of volume is required, the resulting price changes become extreme. The crossover point seems to be between 200 and 300 [MWh] of reduction.



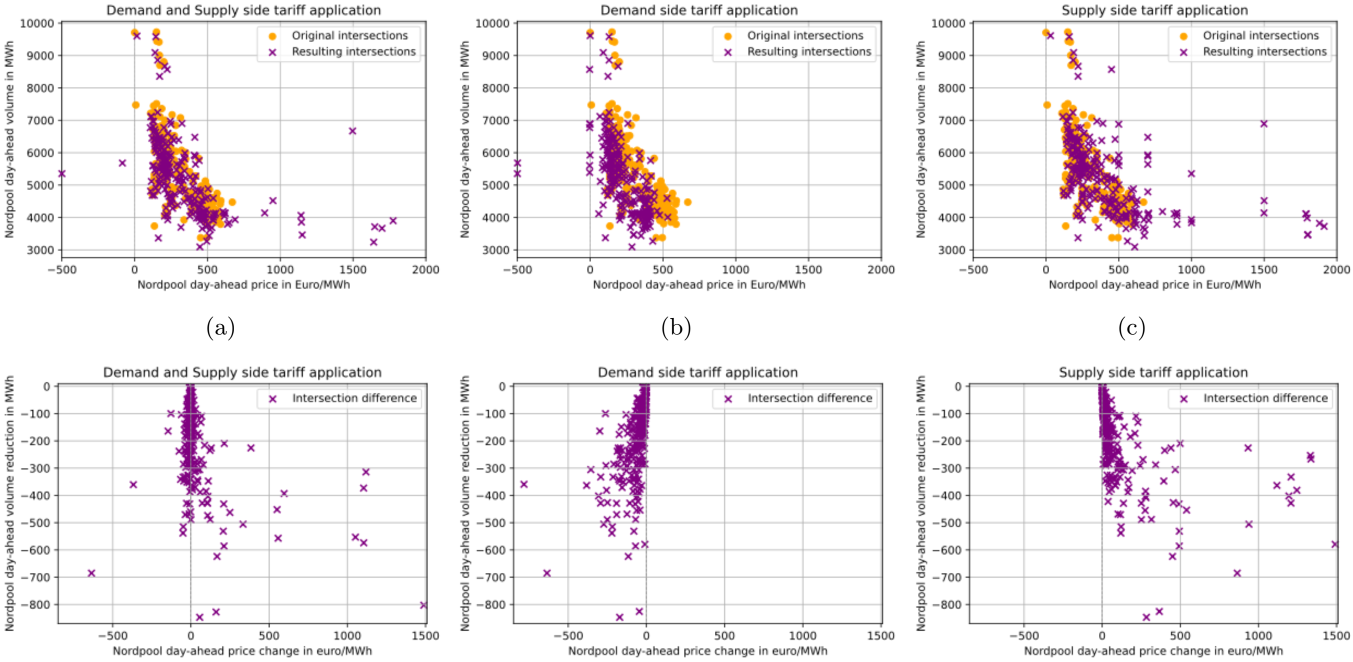
(a) (b) (c)

(d) (e) (f)

Figure 28: Results of the Rush Hour tariff application in the 10% maximum utilization reduction scenario on the prepared day-ahead market data.

5.3 Scenario three

For scenario three with the 15% maximum utilization reduction, the amount of hours where the tariff is applied has increased to 245 and the results are shown in Figure 29. The same price change behavior can be observed as in the previous two scenarios. However, the reduction target is to a lower volume in comparison to scenario two, which does result in more extreme behavior where in 9 hour blocks the Nordpool target volume could not even be reached. The crossover point again as in scenario two seems to be between 200 and 300 [MWh] reduction, resulting often in a price change larger than 100 euro/MWh in either direction. When the tariff is applied to the demand and supply, the results appear to be more stable until 400 [MWh] reduction with more erratic behavior starting to appear after 200 [MWh] reduction.



(a) (b) (c)

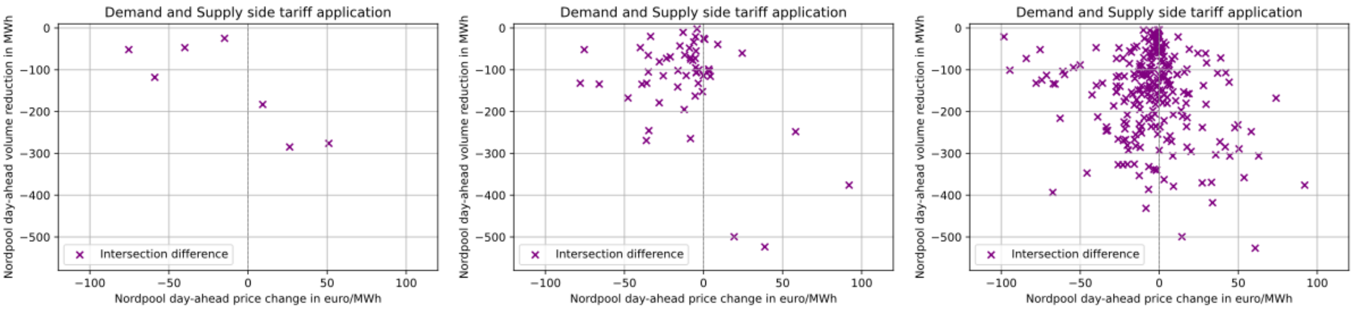
(d) (e) (f)

Figure 29: Results of the Rush Hour tariff application in the 15% maximum utilization reduction scenario on the prepared day-ahead market data.

5.4 Price modifier cap scenario

The results of the scenarios with a price cap on tariff application on both the demand and supply sides are given here. The price modifier is capped at a maximum shift of 100 euro/MWh. The results are shown in Figure 30, with extreme price movements now absent. The target volume is not reached in several cases, with data on the target misses shown in Table 4, with the number of misses out of the total hours in the second column, the percentage of reduction volume that was not reached in the third column and the spread of these reduction volume misses in the last column.

As the application of the tariff influences the price, the net costs for the demand and supply side are different as a result of the day-ahead market price change. If the price difference is negative, it results in less costs for the demand side but more for the supply side. The results for the scenarios of this are shown in Table 5 where the tariff revenue is shown alongside the net costs for the demand and supply side. The net cost differences are a zero-sum difference. This means that instead of an equal costs for the demand and supply side, costs for the supply side are higher and the demand costs are lower by the same difference.



(a) (b) (c)

Figure 30: Results of the Rush Hour tariff application in the 5%,10%,15% maximum utilization reduction scenario on the prepared day-ahead market data with the tariff price modifier capped at 100 euro/MWh.

Utilization reduction	Occurrence target volume reduction miss	Average miss target volume	Target volume miss spread in percentage
5%	2 out of 7	63%	63% - 64%
10%	13 out of 54	24%	1.3% - 86%
15%	68 out of 245	27%	2% - 91%

Table 4: Volume reduction target misses for scenarios with 100 euro/MWh price modifier cap after Rush Hour tariff application on both the supply and demand curves

Scenario utilization reduction	Tariff revenue	Net costs for demand side	Net costs for supply side
5%	€9.400.000	€4.200.000	€5.200.000
10%	€57.400.000	€23.200.000	€34.200.000
15%	€282.000.000	€129.500.000	€152.500.000

Table 5: Tariff revenue and net costs from Nordpool for scenarios with 100 euro/MWh price modifier cap after Rush Hour tariff application on both the supply and demand curves

6 Evaluation of the Rush Hour tariff

In this chapter, the principle of the rush hour tariff is evaluated according to the testing criteria given in Chapter 3. Per feedback criteria, a description is given of what the performance of the tariff is.

- **Volume reduction:** The tariff implementation in all three variants, resulted in the same volume reduction in their respective reduction scenarios. This means that the main goal of the tariff, the reduction in utilization, can be achieved in nearly all hour blocks. With the price cap of 100 euro/MWh, in 25-28% of the hour blocks the target is not reached as the tariff application was limited by price elasticity.
- **Robustness:** From the results it can be concluded that the implementation of the tariff needs to be capped on price modification of the supply and demand curves to prevent extreme price fluctuations. The 100 euro/MWh cap removes the extreme price fluctuations. Better estimations are required on what accepted price modifications are.

  Alternatively, a choice can be made for constant price implementation to reduce or remove resulting day-ahead market price changes.
- **Price behaviour:** The predicted market result behaviour (as described in table 3), was observed after tariff application. What the scenario results also show, however, is the amplitude of the price shifts, which are larger when the tariff is only implemented on either the supply or demand. The resulting price fluctuations are less when the tariff is applied simultaneously on the supply and demand curves.

  The price changes of the day-ahead market itself are something to take into consideration. Before tariff application on an hour, it is unknown how much either the demand or supply side will incur in tariff costs and subsequently the costs (or benefits) of a changing day-ahead market price. For the implementation of the tariff, severe restrictions should be put in place to not result in significant price changes on the market.
- **Incentive differences based on contract type:** The tariff implementation will influence BRP behavior based on the contracts they have with their customers. Different forms of contracts have different outcomes for the incentive of the tariff on BRPs and/or their customers.
  - **Constant price electricity contracts:** If the BRP has a set price contract with their customer, it would result in the BRP having to pay the tariff prices, because the set price in the contract does not change with the tariff implementation. This means that the result of the tariff is that the BRP (only for existing contracts) will have to pay for the tariff. Another result is that for customers with new contracts, the set price in the contract goes up. Therefore the incentive for more flexibility in loads or buffer implementation is not present in set-price electricity contracts.
  - **Variable price electricity contracts:** The contract form between set price and dynamic contracts are variable contracts. Variable contracts have an electricity price that changes after a certain amount of time during the duration of the contract period. This means that the same result is present for the pricing and tariff payments as stated in the set price contract section, with the difference that seasonal variations in grid usage might be included. This could result in customers reducing the grid usage in months where the tariff prices are high, but would not give an incentive for customers to become more flexible with their grid usage in an hourly period.
  - **Dynamic price electricity contracts:** Dynamic contracts are contracts where the customer of the BRP pays a different electricity price per hour, based on day-ahead markets. Therefore the price paid by customers of BRPs already are denoted in day-ahead market prices. With the inclusion of the tariff, BRPs just could forward the tariff payments to their customers, giving the customers the incentive to change their electricity grid usage behavior.

- **Transparency and complexity:** The tariff implementation does not have to result in higher complexity. The algorithm application is simple and with a capped tariff price modification, it does not result in significant price changes.

  In the occasion that the resulting day-ahead market price cannot change due to the application of the tariff, the complexity increases as the resulting tariff application algorithm will either tax the supply or the demand side higher depending on the price elasticity of the supply and demand curves.

  However, with a constant price requirement, the issue of double effects of the tariff is avoided, and transparency increases. This is due to the effect of the tariff resulting in a price change. As shown in the methodology chapter, the demand side application results in a lower price, meaning the demand is directly taxed and indirectly benefits from a lower price, while the supply side is indirectly affected due to a lower price.

  Another factor to take into consideration is the predictability of the day-ahead market price. As the bid curves are only known after the day-ahead market has closed, it means that bids cannot be adjusted for that day. The tariff therefore does introduce an extra variable, though if correct grid load forecast data is used, at least the hours when the tariff will be applied can be predicted.

Tariff revenue

The tariff generates revenue and the height of the revenue depends on the scenario of implementation. This revenue could be used for applications that reduce the congestion and or capacity shortage further. This means that the tariff could also be used as an instrument to generate revenue and cover the costs of solving the congestion in the grid.

7 Discussion

In this chapter, the discussion is given about the research into the current state and solutions to congestion and capacity shortage in the Dutch electricity grid, and then the discussion about the methodology of the Rush Hour tariff.

Current state and solutions

- **Policies for the low voltage grid:** The research carried out in Chapter 2 left solutions for residential households and policies for LV networks out of the scope, as congestion management research does not need to be carried out by DSOs for LV networks. However, 40 percent of newly installed solar PV was at residential buildings in 2022. This has a significant impact on electricity transport demand changes and possible policy changes for residential households have not been taken into consideration. However, the Rush Hour tariff also affects these households, providing an alternative approach to congestion in these areas.
- **Temporal validity:** The temporal validity of this research is short. On 2023-10-05 (one day before the final delivery of this report) a new article was released by Rijksoverheid stating that €416.6 million is reserved for installing batteries at large solar PV fields and that Tennet has proposed a new contract form leading up to a reduction of 65% in grid connection costs for batteries [53]. These are significant changes that can help mitigate the congestion in the grid and more solutions are likely to come out shortly.

Rush Hour tariff methodology

- **Grid utilization calculation:** The grid utilization calculation uses the load data from ENTSO-E. This data is influenced by net generation - (export-import). Therefore an oversupply of electricity results in a lower grid load and vice versa. This means that the hours where the tariff is deployed are hours in the grid where there is an electricity shortage in comparison with neighboring European countries. This corresponds with the interconnect volume data and the fact that the tariff was not applied in the summer months of 2022 or 2023 in the data set.

  While DSOs do not have to carry out congestion management in LV networks where congestion during the summer period mostly occurs due to solar PV at residential buildings, it could be interesting to investigate what effect this would have during summer period hours.
- **Grid load data:** As stated in the methodology, only Nordpool day-ahead market data was available, EPEX spot data was not. While it is highly likely that there is order book matching and that the main issue is the lack of data on the volume of the EPEX market. This results in the approximation made in this research, but for higher accuracy, it is recommended to include the EPEX spot data in further rush hour tariff research.
- **Market participant feedback:** Currently the goal of the tariff is only partly reached. The volume reduction is a direct result of the application of the tariff, but with the limitation of only investigating individual hour blocks, the feedback from market participants is not taken along. In reality, a lower volume in one hour could increase the volume in another, depending on the behavior of the market participants acting on the tariff implementation. This load-shifting behavior could result in shifting the utilization problem rather than solving it.
- **Interconnect tariff payments:** An issue with the current implementation of the tariff is that the question of who will pay for the tariff costs for electricity over the interconnects is not answered. This is a major bottleneck that needs to be solved, considering the influence of interconnect volume on the day-ahead market and the implications this has for cross-border trading in the Dutch market.
- **Price edge cases:** There are edge cases that were not encountered in the data set used, but in real applications could have severe consequences. One of them is when the day-ahead clearing price reaches the boundaries of

the price (-500 or 4000 euro/MWh), tariff application would not result in (further) volume reduction, but would result in tariff costs. Edge case rules should be made, as tariff application could otherwise lead to prices below -500 euro/MWh or higher than 4000 euro/MWh.

- **Day-ahead market order assumptions:** As stated in the methodology chapter, each hour block on the day-ahead market was viewed individually with the assumption that all orders were aggregated hourly orders. In reality, this is not the case, and implementing the tariff costs before or after EUPHEMIA calculations can create significant differences. Complex orders might be or not be executed after implementation of the tariff costs, which either results in applying the algorithm again to find a new clearing price, or to have market participants have varying results with complex orders.
- **Day-ahead market price calculation without EUPHEMIA:** For this research the EUPHEMIA algorithm was not taken into account. However, if the tariff were implemented after EUPHEMIA algorithm price and volume calculations, it would result in a different price and volume. This again influences the load on cables, and interconnect volumes amongst others. This could lead to an optimization problem, as for every iteration of the Rush Hour algorithm, the EUPHEMIA algorithm would need to be applied to calculate a new price.

8 Conclusion

In this research, the current state of the electricity grid was investigated along with testing an alternative approach to solve the congestion in the grid. This was done by answering the research question (also see Chapter 1):

- **What is the current state of solving the capacity shortage and congestion in the electricity grid in the Netherlands and how could novel approaches help solve these problems?**

The current state of the electricity grid in the Netherlands has trends showing a growth in both demand and supply of electricity transport capacity. The shortage of grid capacity is only growing as a result, with grid reinforcement not able to keep up. The shortage in grid connection capacity is increasing rapidly with 6000-8000 enterprises on the waiting list in the Netherlands (as of July 2023), where in three months 2400 were added.

To solve this, in 2022 a code decision was published by the ACM detailing procedures on definitions of the capacity limits in the grid for the TSO and DSOs when they are required to guarantee delivery of electricity, and what legal procedures are put in place for when an area can be designated as a congestion area.

Solutions that are currently implemented are met with low interest, as the demand for capacity-limiting contracts has reached around 50 enterprises nationwide for the past few months (as of July 2023). This is low in comparison to the 8000 enterprises on the waiting list. The GOPACS market is barely used by DSOs for congestion mitigation and does not offer a solution for LV networks. Netbeheer Nederland proposes to adopt non-firm ATOs and energy hubs, which could provide an opportunity for new grid connections for enterprises that otherwise would not have gotten grid connection capacity but are highly unlikely to garner the required demand from existing enterprises to reduce their grid capacity demands and therefore have an impact on the current capacity shortage and congestion in the grid.

Therefore a novel approach was proposed in this research, the Rush Hour tariff, aiming to reduce the amount of electricity transport demand during peak hours by a financial incentive. The approach used the fact that the grid has a 34% average utilization, increasing operational grid capacity if grid usage is optimized and reducing the grid capacity shortage. The Rush Hour tariff is applied on the day-ahead electricity market during peak utilization hours. The benefits of using the day-ahead market as a proxy were that trading takes place one day before electricity delivery and most of the trading takes place on this market. Other benefits of the proposed tariff implementation were that it does not cause grid imbalances and market participants do not have to make any changes to their bidding strategy.

The tariff tariff was tested on data from ENTSO-E and Nordpool day-ahead market data from 2022-07-02 till 2023-07-31. The day-ahead market data included data on demand and supply curves, which were used to apply the tariff. The actual grid usage load data from ENTSO-E was used to determine grid usage numbers per hour. Three scenarios were created with a 5%, 10%, and 15% threshold on grid utilization reduction and a separate application with the price modifier of the tariff capped at 100 euro/MWh. There were three different ways to apply the tariff, on the demand side, on the supply side, and both. All had the effect of lowering the resulting clearing volume but resulted in different clearing price changes.

The tariff application in each scenario became increasingly unstable the higher the volume reduction target was, and the different scenarios yielded different results in price and volume reduction. This was caused by the price elasticity of the curves near the intersection before the tariff application. The scenarios where both the demand and supply lines were shifted often showed a decrease in clearing price with higher day-ahead prices, and an increase in price with lower day-ahead prices, resulting from a difference in price elasticity depending on the day-ahead market price.

While the tariff implementation succeeded in a reduction in volume reduction in the investigated hour blocks, it comes with significant changes in the behavior of the market. While it is highly likely the Rush Hour tariff results in a reduction in grid utilization, further research is required in the following key areas to determine whether it helps solve the congestion and capacity shortage in the grid:

- **Locality:** Research into the effects of the tariff on local grid areas, determining if and by how much congestion is reduced in for example LV areas and how much influence the three different electricity price contracts (constant, variable, dynamic) for grid users have on this reduction.
- **Technical:** Research into the feasibility of implementation of the tariff (in the EUPHEMIA algorithm), optimizing the tariff algorithm to result in a good balance between volume reduction and price impact while using improved grid utilization data.
- **Socioeconomic:** Research into bid strategy changes of BRPs resulting from tariff costs; how other electricity markets (intraday, imbalance) are influenced by the tariff and what the final result on the electricity grid is; how the relation and balance behavior is influenced by tariff costs between BRPs and their customers (determining who pays for the tariff costs, BRPs or their customers); and results of the tariff implementation if and how grid users will change their behavior (load-shifting and/or installing buffers).
- **Regulatory:** Research into determining tariff policy for interconnect flows and the influence of the Rush Hour tariff on the European market and their market participants.

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