Matching algorithm with efficient market-based redispatch bid structures and the change in CO_2 emission caused by redispatch

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Abstract

Electrification of the industry, large-scale battery systems and sustainable mobility and housing results in higher electricity use. This has increased congestion, i.e. the shortage of transport capacity, in the electricity grid. A method to solve this network congestion is by market-based redispatch where market participants adjust consumption or production at each side of a congestion problem. In the Netherlands this is done by: i) the Grid Operator Platform for Congestion Solutions (GOPACS) via power exchange markets, and ii) by the grid operator TenneT that receives bids from producers and consumers with a connection over 60MW. Using only one platform could be more efficient. However, it is not known what an efficient bid structure is for market-based redispatch and how to combine bids with a different structure for a redispatch solution. The aim of this research is to develop a new bid structure and a method to create efficient congestion solutions with this new bid structure by allowing it to also use GOPACS orders. Existing bid structures were investigated and case studies were considered to identify important attributes of a bid structure for redispatch, while taking limitations of electricity production assets into account. Based on the attributes, a new bid structure was proposed and a corresponding algorithm developed that can find a redispatch solution within this new structure and within the GOPACS bidding structure, allowing both systems to be integrated. As a second step, the potential climate benefits of reducing congestion were explored. For this, the change in CO_2 emissions resulting from redispatch of different electricity sources was estimated for bids in the GOPACS system over one year, with redispatch resulting in emission decrease.

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1 Introduction

Electrification of the industry, large-scale battery systems and sustainable mobility and housing results in higher electricity use. This has increased congestion, i.e. the shortage of transport capacity, in the electricity grid [1]. A more technical definition of congestion is the situation in which forecasted or realised power flows violate the thermal limits of a grid element [2]. Due to this increase in congestion not all the demand for new connections to the grid can be met. New solar energy, companies or housing cannot, at least temporary, be connected to the grid [3]. Expanding the electricity grid takes time and cannot keep up with the increasing electricity transportation demand [4]. Unresolved congestion could cause power outages. Therefore, measures need to be taken to mitigate congestion, which is called congestion management [5]. These measures use the flexibility of the market. Flexibility describes the degree to which a power system can adjust the electricity demand or generation within the boundaries of the transmission and distribution network. Sources of flexibility are flexible generation (e.g. dispatchable power plants, generator output curtailment), flexible demand (e.g. demand side management), reinforcement of the transmission and distribution facilities, and energy storage systems [6].

In the Netherlands one step that can be taken when there is structural or expected congestion is by capacity restrictions. This is an agreement with the system operator and the party connected to the grid where the connected party receives payment to not use the full amount of their agreed grid connection. Another option is to use market-based redispatch. With market-based redispatch market parties can offer to increase or decrease their electricity production (or consumption). These will be used to shift the location of production (or consumption) to decrease the power flow of the grid element that otherwise would be violating the safety limits. At the moment market-based redispatch is done in two different ways. One is using Reserve Power Other Purposes (ROP) bids done to TenneT directly. The other way is with Grid Operators Platform for Congestion Solution (GOPACS) that uses bids from electricity market platforms. GOPACS was launched in 2019 and is still in its starting phase. Not all market parties are connected to GOPACS since they offer their flexibility in production to TenneT with the ROP bids.

Using only one platform to solve congestion could make congestion management more efficient. The ROP bids and GOPACS orders could then be matched to find a solution, which increases the ability to solve congestion problems. Furthermore, the ROP bids can be used to solve congestion problems of Distribution system operators (DSOs). The DSOs that are also called Regional Network Operators are responsible for building, maintaining and operating the regional networks with lower voltage (¡110 kV) levels that connect to households [7]. GOPACS uses bids done on existing market platforms and are called orders. The GOPACS orders are flexible in volume, while the ROP bids are flexible in time. However, to use the ROP bids in the current GOPACS algorithm they need to have the same bid structure as the GOPACS orders. This requires a conversion where the flexibility in time gets lost, which might be much needed to solve congestion problems in the future. More generally, it is not yet known what bid structure is efficient in solving congestion in a market-based approach, such as GOPACS, and how to create a redispatch solution with bids of a different structure.

In terms of sustainability, congestion is a limiting factor in the energy transition. For example the new solar and wind production cannot always be connected immediately to the electricity grid. Congestion management might make it possible to connect more wind and solar electricity production by making more efficient use of the existing electricity infrastructure. Monforti-Ferrario and Blanco [8] have done a study on the change in emissions of both greenhouse gasses and air pollutants caused by redispatch in Germany. They concluded that redispatch does not necessarily imply an increase in emissions associated with power production in a country. However, the study does not show the full picture of the consequences of the German redispatch actions for other counties emissions due to a lack of consistent data. The change in emissions of greenhouse gases by market-based redispatch done by GOPACS in the Netherlands is not known yet.

An important aspect to point out is that in the European Union (EU) market-based redispatch must done in a non-discriminatory way [9]. Therefore, specifically favouring a certain redispatch solution, for instance one that results in lower CO_2 emissions, is not allowed.

1.1 Research objective and research questions

The research objective of this project is to develop a new bid structure and a method to create efficient congestion solutions with this new bid structure by allowing it to also use GOPACS orders. Furthermore, this research aims to create insight into the environmental impact of market-based redispatch in the Netherlands by quantifying the change in CO_2 emissions of redispatch. This leads to the following research questions:

1. What attributes of a bid are important to solve congestion efficiently?
    - What attributes make the matching of buy orders and sell orders efficient?
    - How can the technical limitations of electricity production be taken into account by the bid structure to maximize the bids the market parties can offer?
2. How can a buy and sell orders with different flexibility in time and/or volume be matched? What are methods that are able to match buy and sell orders together with this different flexibility in time and/or volume? Or how can the current algorithm be adapted to include different flexibility attributes?
3. How does congestion management via redispatch affect greenhouse gas emissions from electricity production?

2 Theoretical framework

This chapter describes context of the Dutch electricity sector in Section 2.1, in particular the flexibility of the electricity sector. Section 2.2 congestion management through redispatch will be explained. Section 2.3 discusses the GOPACS platform and the algorithm it uses. Section 2.4 discusses the ROP bids. Lastly, in Section 2.5 some mathematical preliminaries are stated.

2.1 The Dutch electricity sector

In the Dutch electricity sector, TenneT is the Transmission System Operator (TSO) that is responsible for building, maintaining and operating the high voltage grid ($\geq$ 110kV). It is responsible for connecting electricity producers and consumers, maintaining the balance of supply and demand and resolving large scale disruptions [10]. The Distribution System Operators (DSOs), i.e. Liander, Enexis, Stedin, Westland Infra, Coteq Netbeheer, RENDO Netwerken and Endinet, that are responsible for building, maintaining and operating the regional networks with lower voltage levels that connect to households[11]. Any actor other than the TSO and DSOs are considered market players. The electricity market has three fundamental freedoms:

- Freedom to dispatch: Generators and consumers have the right to produce or consume the amount of electricity that they choose, within the limit of their connection and the contractual limits of their connection agreement.
- Freedom of transaction: Market parties can enter into any form of contractual agreements regarding to their demand and supply.
- Freedom of connection: All demand and supply resources can connect into the grid on a non-discriminatory manner.

An important characteristic of the electricity grid is that the supply and demand always need to be balanced. Therefore, market parties also have a balance responsibility besides the three freedoms. This responsibility means market parties have to make sure to match their supply and demand of electricity. The electricity market works like any other market, so sellers can offer their electricity on a market platform and buyers can purchase it to be delivered in a specific time frame [10].

2.1.1 Flexibility of the market

Flexibility is quite a general term. In this section the meaning of flexibility of the power system, market parties and attributes used in this thesis are explained.

Flexibility of the electricity system can be described as the ability of the power system to adjust to demand and supply to maintain balance on the grid within the limits of the transmission and distribution system [12]. This flexibility can be characterised by spatiality, time and resource. Spatiality refers to the fact that the location of the grid connection of a resource is relevant. For example, with congestion management the flexibility needed is location-based. The time characteristic considers when and how long the flexibility is available. Some important time aspects are activation time, the time needed that a flexibility resource becomes available for use; The Ramping rate, indicating how fast a flexibility resource can change its electricity production or consumption; And the duration of the available flexibility. The resource characteristic of flexibility can be subdivided into four categories, supply side, demand side, grid side and storage [13]. Demand side includes demand side management and demand side response. Grid side means reinforcement of the distribution and transmission facilities[6]. Forms of storage are hydro storage and battery energy storage systems [14]. Regarding the supply side flexibility we can consider renewable electricity production (e.g. wind and solar-pv) and conventional electricity production (e.g. gas and coal power plants).

To understand the flexibility of a conventional electricity producing asset we consider the framework of operational processes shown in Figure 1 [15]. The operational processes describe the variation in speed and load of gas and steam power plants over time. The first state that it considers is no speed no load (NSNL) meaning that the power plant is off, also referred to as a cold asset. The following state is full speed no load (FSNL), which is the value when the generator is synchronized to the grid frequency. At full speed the turbine can start generating power. Next is the house load (HL), the capacity generation at which the own consumption of the power plant is covered. The house load represents a minimum load. Last there is full load (FL) that represents the maximum load.

In Figure 1 the processes 1-4 describe the start of a power plant. Process 5 in Figure 1 shows the ramp-up and ramp-down rate, which is the process of rapidly increasing or decreasing the load. The ramp rates depend on the technology of the power plant. Process 7 in Figure 1 is shutdown, which is the process of reducing the load and speed of the turbine to zero. After the power plant is shutdown there is a minimal period that it should be out of operation, called the minimal downtime. The minimal downtime is an economic limit since it is in the interest of operators to reduce the excessive thermal stress on the power plant caused by start-ups and shut-downs [15].

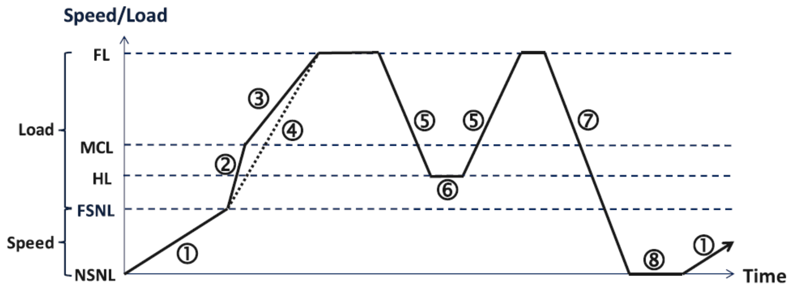


Figure 1: *Framework of operational processes that describe the variation in speed and load of gas and steam power plants over time. On the y axis considers the following states; no speed no load (NSNL), full speed no load (FSNL), house load (HL), minimal complaint load (MCL) and full load (FL)[15].*

For market parties we can define flexibility as the ability to change production or consumption. Market parties can offer their flexibility to a TSO for power balancing, frequency control and congestion management. Such an offer, also named a bid, if often characterised by the following attributes. The duration, rate of change, response time, location and the amount of power that we call the volume [16].

2.2 Congestion management

The situation in which forecasted or realised power flows violate the thermal limits of a grid element is called congestion [2]. Measures need to be taken to prevent congestion, which is called congestion management [5]. An overview of congestion management methods is shown in Figure 2 and more information about these methods see Gumpu et al. (2019) [17]. This thesis will focus on market-based redispatch. This method uses flexibility from the market parties to shift the electricity generation to another location to decrease the needed transport of the electricity.

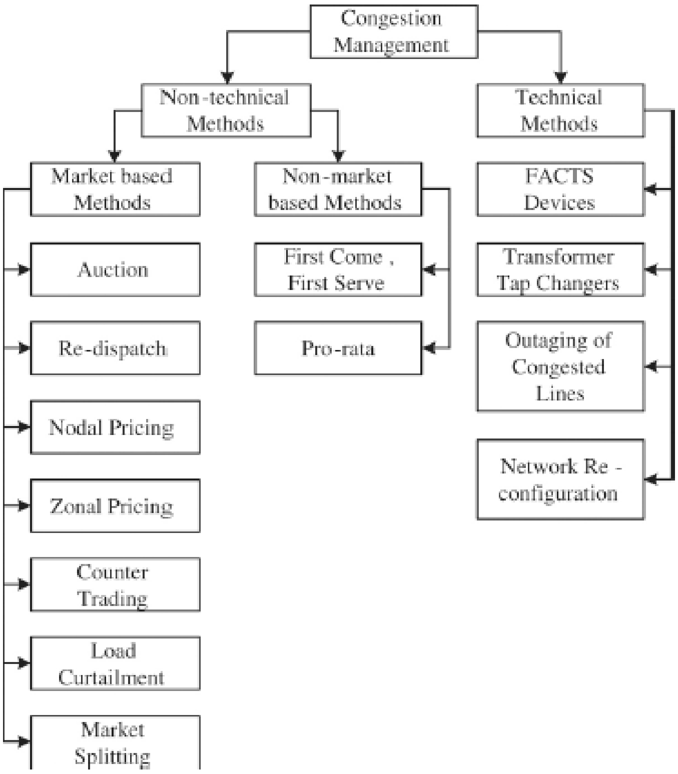


Figure 2: *Classification of congestion management methods [from: [18]]*

A simple two node congestion example is shown in Figure 3 (a) that will be used to explain redispatch. Nodes A and B are connected with a line that has a safety constraint P_{max} = 80 MW. At node A, 100MW is generated and at node B, 100MW is consumed. This means that 100MW is transported over the line that connects the nodes. Thus, there is a congestion problem of 20MW, that is the amount that exceeds the safety limit. Figure 3 (b) and 3 (c) show two different re-dispatch options to solve the congestion problem of Figure 3 (a). In (b) redispatch is done by decreasing generation at node A by 20MW and increase the generation at node B with 20MW to maintain the balance (e.g. match supply and demand). This change in generation results in a flow of 80MW over the line that connects nodes A and B, solving the congestion. In (c) redispatch is done by decreasing the consumption at node B by 20MW and decreasing the generation in node A to maintain the balance. Again, this results in a flow of 80MW over the line connecting nodes A and B, thus solving the congestion problem.

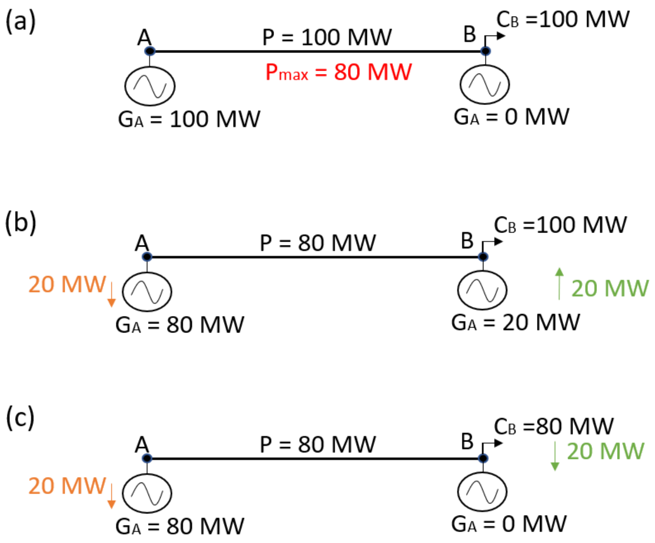


Figure 3: *An illustrative example of a network with two nodes A and B connected with a line that has a safety constraint* P_{max} *=80MW. Figure (a) is an example of a congestion problem of 20MW. Figure (b) is a redispatch solution to the problem of Figure (a) by changing the generation location. Figure (c) is a redispatch solution to the problem of Figure (a) by changing the consumption.*

However, the electricity network often is more complicated and has a more meshed structure. The way the power flows in a meshed electricity network can be determined by two physics laws. Kirchhoff's first law states that at any node in an electrical circuit the sum of the current flowing into the node is equal to the current flowing out of the node. Ohm's law states that the current is proportional to the voltage and inversely proportional to the line's impedance. Therefore, the power flows neither only via the shortest path nor via any single path from the generation location to the consumption location [5].

To show how redispatch changes in a meshed grid a 3 node example is shown in Figure 4. Figure 4 (a) shows a network with three nodes A, B and C that are connected with lines 1,2 and 3 of equal impedance. At node A 90MW is generated and at node C 90 MW is consumed. This results in a power flow of 60MW over line 1 and a flow of 30MW over both line 2 and line 3. There is a safety constrain of 51MW on line 1. Therefore, there is a congestion problem of 9 MW. However, a similar action as in the example in Figure 3 (b) of decreasing the generation in node A by 9MW and increasing the generation in node C by 9MW does not solve the congestion problem completely. This is shown in Figure 4 (b). The change of 9MW in generation from A to C only results in a power flow decrease of 6MW on line 1 that still violates the safety constraint. The effectivity of a change in electricity in-feed can be quantified in the following way. By shifting the generation of 1 MW from A to C has an impact on line 1 of $\frac{2}{3}$MW hence it has an effectivity of $\frac{2}{3}$.

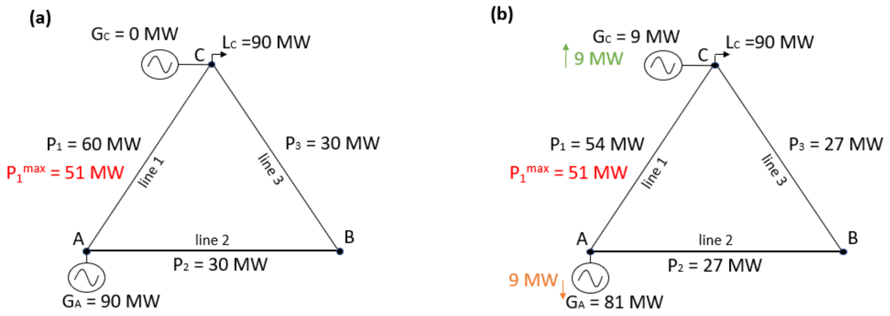


Figure 4: *An illustrative example adapted from [5] of a network with three nodes A, B and C connected with lines 1,2 and 3 of equal impedance. There is a safety constraint on line 1 of* $P_1^{max} = 51$ *MW. Figure (a) shows a congestion problem of 9 MW. Figure (b) shows that decreasing generation at A and increasing generation in C with 9 MW does not solve the congestion problem.*

In general, the amount of MW required for a redispatch action depends on where in the grid the generation gets increased and the location where the generation gets decreased.

2.3 GOPACS

In the Netherlands the Dutch grid operators have started the Grid Operators Platform for Congestion Solution (GOPACS) that uses the flexibility of the market for redispatch. Participating parties trade electricity by placing buy orders and sell orders on an existing electricity market platform. GOPACS calculates if orders that are unmatched by the regular market solve the congestion situation and if it does not aggravate congestion elsewhere in the electricity grid. A match is made between the orders that solve congestion and the grid operators pay the price difference, which is also called the spread price. In this match the volume and time of the buy and sell orders need to be the same to not disrupt the balance of the grid [19]. For the time the units that are used are the Imbalance Settlement Periods (ISPs). A day is considered to consists out of 96 ISPs that are each 15 minutes long [20].

2.3.1 GOPACS orders

The bids GOPACS uses originate from power exchange platforms and are called orders. A buy order is a bid that decreases the electricity in-feed, meaning a decrease in production or an increase in consumption. If the price of the buy order is positive then that is the amount of money that will be paid to the grid operator to reduce electricity in-feed of the market party. This happens since reducing the electricity in-feed saves fuel cost. Therefore, the market party with the buy order can make a profit by paying to reduce their electricity in-feed. If the price is negative than that is the amount of money that the grid operator needs to pay to reduce the electricity in-feed. A sell order is a bid that increases the electricity in-feed, meaning an increase in production or a decrease in consumption. The price of the sell order is the amount of money the grid operator needs to pay to the market party to increase their electricity in-feed.

The attributes that relate to flexibility of these GOPACS buy and sell orders are shown in Table 1. The GOPACS orders are flexible in volume, but not flexible in time. There is however an option for the bids to have a fixed volume called all-or-none. If the volume is flexible there is the option to have a minimal usage fraction for sell orders and a maximal usage fraction for buy orders to respect a minimal stable load.

Table 1: *Table containing attributes of Power Exchange (PX) bids that relate to the flexibility [21]*

Attribute	Explanation	Example
Starting time	Must start at time of an ISP	ISP 5
End time	Must end at time of an ISP with a min duration of 1 ISP, otherwise multiple of an hour	ISP 8
Volume	in MW	50 MW
All-or-none	If a bid is all-or-none than only the exact volume can be activated, otherwise the volume can be partially activated	Yes / No
Minimal/maximal usage fraction	For a buy order: the activation fraction can either be between 0 and the maximal usage fraction or be 1. For a sell order: the activation fraction can either be 0 or be between the minimal usage fraction and 1.	0.7

2.3.2 GOPACS algorithm

The GOPACS algorithm used to determines how to choose buy and sell orders to solve a congestion problem is based on GOPACS initial algorithm including enhancements based on the Thesis done by Leoni Winschermann [22]. The algorithm is a linear program meaning it is an optimization problem to in this case minimize a linear objective function with linear equality/inequality constraints [23]. The objective function is to minimize the spread price with the constraints that the activated buy and sell order volumes are equal and the problem volumes are solved. The linear program is solved using a mixed integer program meaning that the activated fraction can either be a real value or an integer value [24]. The use mixed integers allows for orders that are all-or-none and for orders that have a minimum/maximum usage fraction.

For every order i we have a decision variable X_i with $0 \leq X_i \leq 1$. If i is all-or-none X_i will be an integer, so either $X_i = 0$ or $X_i = 1$. It is also possible to add constraints such that X_i respects the minimal or maximal usage fraction. The decision variable represents the activated volume fraction of an order. If $X_i = 0$ then order i is not activated and if $X_i > 0$ the order is activated with a fraction X_i of the volume. For example if the volume of the order i is 100MW and $X_i = 0.7$ the $0.7 * 100MW = 70MW$ will be activated and used to solve a congestion problem.

The algorithm will minimize the price:

$$\sum_{s \in S} P_s V_s X_s - \sum_{b \in B} P_b V_b X_b. \tag{2.1}$$

Here P_i is the price of order i in €/MW, V_i is the volume of order i in MW and X_i is the activation fraction of order i with $0 \leq X_i \leq 1$. Therefore, $P_i V_i X_i$ is the price of the activated fraction of order i. Equation 2.1 will be minimized with the following constraints.

$$\sum_s X_s r_{s,t} - \sum_b X_b r_{b,t} = 0 \ \ \forall t \ \ (\textit{balance constraint per ISP}), \tag{2.2}$$

$$\sum_s X_s r_{s,t} \epsilon_s(k) - \sum_b X_b r_{b,t} \epsilon_b(k) \leq -R_k, t \ \ \forall t \ \ (\textit{remedy constrain per ISP}). \tag{2.3}$$

The balancing constraint 2.2 ensures that the activated volume of the buy and the sell orders is the same to not disrupt the balance of the grid. Here $r_{i,t}$ is a matrix containing the volume of the orders where the rows represent the orders and the columns model the time units (ISPs). With

$$r_{i,t} = \begin{cases} V_i & if \ \ order \ corresponds \ to \ ISP \ t \\ 0 & otherwise \end{cases} \tag{2.4}$$

The remedy constraints 2.3 ensures that the congestion problems will be solved. This constraint needs to be added for every congested grid element k. Here $\epsilon_{i,t}(k)$ is the effectivity that order i has at time t on grid element k. $R_{k,t}$ is the volume in MW that needs to be decreased on grid element k at time t [22].

2.4 ROP bids

Besides GOPACS, the Dutch transmission system operator (TSO) TenneT also uses bids that are directly submitted to TenneT to solve congestion. Producers and consumers with a connection of more than 60MW are obliged by the Dutch electricity code to provide power production that could be increased or decreased or consumption that could be reduced for the next day to the TSO [25]. These bids are called Reserve Power Other Purposes (ROP) and have a different structure, which includes a preparation time, delivery period, and a time period indicating when the bid can be activated [26] However, they do not include the possibility to active only a part of the volume of the bid. Therefore, the biggest difference between the GOPACS orders and the ROP bids is that PX bids are flexible in volume and ROP bids are flexible in time.

2.5 Integer programming preliminaries

This section describes some methods that can be used with integer programming. These methods are used in Section 4.2 to write a certain constraints as linear equations using binary decision variables such that they can be used in an integer program. Section 2.5.1 explains what a binary indicator variable is and how to define it. Section 2.5.2 explains how to write to linear constraints where either one of them must hold into two separate linear constraints. Finally, Section 2.5.3 explains how to write linear conditional constraint into two separate linear constraints.

2.5.1 Binary indicator variable

If x is an activation fraction, so $0 \leq x \leq 1$ than we can define a binary indicator variable y that indicates if order is activated or not. If $y = 0$ then the orders corresponding to x is not activated. If $y = 1$ then the order corresponding to x is activated, thus $x > 0$. This is done by first defining a binary decision variable y and then adding the constraint $x \leq y$ and $x > y$. Then

$$y = \begin{cases} 0 & if \quad x = 0 \\ 1 & if \quad x > 0 \end{cases} \tag{2.5}$$

2.5.2 Either-or constraints

Suppose we have two linear constraints

$$\sum_{j \in J_1} a_j x_j \leq c_1, \tag{2.6}$$

$$\sum_{j \in J_2} b_j x_j \leq c_2, \tag{2.7}$$

where a and b are vectors and x_j are decision variables with $x_j > 0 \, \forall j$. With the condition that at least one of these constraints must hold. Writing 2.6 and 2.7 as two independent constraints to use them in a linear program can be done by introducing a binary variable y. If we take sufficiently large M_1 and M_2 such that

$$\sum_{j \in J_1} a_j x_j \leq c_1 + M_1,$$

$$\sum_{j \in J_2} b_j x_j \leq c_2 + M_2,$$

always hold. The constraint can be written as follows

$$\sum_{j \in J_1} a_j x_j \leq c_1 + M_1 y, \tag{2.8}$$

$$\sum_{j \in J_2} b_j x_j \leq c_2 + M_2(1-y), \tag{2.9}$$

There are two possibilities. If $y = 0$ then constraint 2.6 is imposed and 2.7 is weakened to the from $\sum_{j \in J_2} b_j x_j \leq c_2 + M_2$ that always will be satisfied. If $y = 1$ then constraint 2.7 is imposed and constraint 2.6 is weakened to $\sum_{j \in J_2} b_j x_j \leq c_2 + M_2$ that always will be satisfied [27].

2.5.3 Conditional constraints

We have conditional constraints

$$\sum_{j \in J_1} a_j x_j \leq c_1, \tag{2.10}$$

$$\sum_{j \in J_2} b_j x_j \leq c_2. \tag{2.11}$$

Meaning that, if 2.10 is satisfied, then 2.11 must also be satisfied. This can be written as two independent constraints in two steps. First, we can see that these conditional constraints are equivalent to

$$\sum_{j \in J} a_{1,j} x_j > b_1 \quad or,$$

$$\sum_{j \in J} a_{2,j} X_j \leq b_2.$$

Since "2.10 $\Rightarrow$ 2.11" is equivalent to " $\neg$(2.10 $\wedge$ $\neg$2.11)" that is equivalent to "($\neg$2.10 $\vee$ 2.11)". Now the same approach as with the either-or constraints can be used [27].

3 Methods

Section 3.1 describes the method used to a find a concept of new bid structure. Section 3.2 describes the method to create congestion solutions with this bid structure the concept bid structure. Section 3.3 describes the method to calculating the CO_2 emissions caused by redispatch by GOPACS.

3.1 Bid structure

For the concept of the new bid structure there are different perspectives to consider. Firstly, an understanding of the existing structures and their attributes is needed. Therefore, the attributes of ROP, GOPACS orders, the UK balancing mechanism and the ENSTO-E[28] have been compared. An overview of the attributes has been made and they have been classified in the categories time flexibility, volume flexibility and linking. Secondly, it is important that the flexibility of the market can be captured in the bid structure as not to lose the flexibility such that it cannot be used for a congestion solution. Therefore, the market parties must be able and willing to offer their flexibility. Taking their limitations and limitations of electricity production into account will provide the ability for the market parties to offer more flexibility. To create an understanding of how a bid structure will enable a market party to offer their available flexibility some example structures have been considered. Examples of a cold and warm conventional unit were used to see what effects the use of the example bid structures have on the flexibility.

Furthermore, it is important that the bid structure can be used to efficiently create a congestion solution. To get an understanding of what contributes to an efficient congestion solution case studies have been done. The approach of the case studies is described in Section 3.1.1. With the knowledge obtained from the research that is described above, a concept of a new bid structure has been chosen to be investigated further. An adaptation of the GOPACS algorithm that can use this bid structure has been developed. In particular, this method is also able to use GOPACS orders. The approach used for the development of this method is described in Section 3.2.

3.1.1 Case studies of problem and bid scenarios

To get an understanding of what attributes are important in solving congestion problems efficiently some case studies have been done. In these case studies, a simplified version of the GOPACS algorithm has been used to find congestion solutions. This version does not support usage fractions which indicates what part of the volume of a bid can be used. The congestion problems used in the case study are based on historical congestion problems and only one congestion problem is considered at a time. Furthermore, a radial grid is assumed meaning that all the buy orders have an effectivity of one. The ROP bids and GOPACS orders used in the case study are also based on historical data. A minimal duration of 4 hours is assumed which is a common minimal run time for a combined cycle gas turbine. Moreover, the current GOPACS algorithm is not able to use ROP bids. Therefore, the ROP bids are converted into the GOPACS orders structure which results in a loss of flexibility. Furthermore, the GOPACS orders are often placed in reaction to the announcement of a congestion problem. Therefore, the historical GOPACS orders might not represent the complete flexibility of the market. The price of the bids are not known. Therefore, the same value has been taken for all the GOPACS buy orders, all the GOPACS sell orders, all the ROP decrease and all the ROP increase bids.

With the historical data and the assumptions named above congestion problem scenarios and bid scenarios were created. For the congestion problems four types where considered: Block TSO, volatile TSO, block DSO and volatile DSO. The main difference between TSO and DSO problems is the volume. DSO problems are around 1-10's of MW while the TSO problems are around an order of magnitude larger. A block problem has a constant volume for the whole duration while a volatile problem has a changing volume. The following seven bid scenarios were created:

1. Standard: A scenario based on the historical data and assumptions named above. All the other scenarios are adaptations from the standard scenario.
2. Only all-or-none: In this scenario all the bids are taken to be all-or-none, so the bids are not partially available in volume.
3. Less bids: This scenario contains less bids than in the standard scenario.
4. Only big volume: This scenario contains only the bids that have a volume over 50MW.
5. Shorter duration ROP bids: In this scenario the duration of the ROP bids are shorted from 4 to 2 hours. The number of bids are kept the same and the starting period of the bids is spread out over time.
6. All partial volume: This is scenario there are no all-or-none bids.

3.2 Algorithm development

With the knowledge obtained from the case studies, a concept of a new bid structure was chosen to further investigate. This structure is flexible in volume, and flexible in time. The current GOPACS orders are only flexible in volume. To find a method to match buy and sell orders which are flexible in time and volume the approach of adapting the GOPACS algorithm is used since the GOPACS algorithm is already able to use flexible volume. To do this, the background information on integer programming, as described in Section 2.5, has been consulted. The algorithm is implemented in Python with a PuLP solver and simple use cases were used to verify no unexpected behaviour is observed.

3.3 Computation of CO_2 emissions of Redispatch

To investigate the change in CO_2 emissions caused by redispatch from GOPACS a similar approach as the one applied by Monforti-Ferrario and Blanco [8] was used. Historic data from GOPACS over the period from 01-01-2022 up to and including 14-11-2022 of the Redispatch done by GOPACS for TenneT congestion problems was used.

The buy orders (decrease production or increase consumption) and sell orders (increase production or decrease consumption) used for the redispatch actions were classified into five categories: International, Natural gas, Consumption, Wind and Sun. A buy or sell order which changed the electricity in-feed on the grid connection 'BritNed' is categorised as 'International'. There are no orders on other international grid connections. All conventional power plants used for redispatch by GOPACS are combined cycle gas turbine (CCGT) plants and are categorised as 'Natural gas'. The other orders are assumed to be a change consumption, which is mainly horticulture, and are categorised as 'Consumption'.

The CO_2 emissions have been computed for the both the buy orders and the sell orders as

$$E_{m,c} = P_{m,c} * EF_c, \tag{3.1}$$

where $E_{m,c}$ are CO_2 emissions in kg in month m for electricity production category c, $P_{m,c}$ is the amount of electricity produced in MWh in month m for category c, $EF_{m,c}$ is the emission factor in kg CO_2/MWh. Besides the absolute CO_2 emissions the average emissions per unit of power produced are also calculated. The change is emissions is calculated as

$$saved\ \ emissions = \sum_C (\sum_{sell} EF_c * P_c - \sum_{buy} EF_c * P_c), \tag{3.2}$$

where C is the set of categories.

For the emission factors of the International category the average grid mix emissions of the UK have been used, since the source of the electricity is unknown. National Grid ESO has historical data on the carbon intensity in kg CO_2/MWh in the UK over the period of the collected redispatch data [29], which has an average value of 188.9 kg CO_2/MWh. The emission factors the National Grid ESO used are shown in Table 2 [30]. These emission factors only consider the direct CO_2 emissions. Therefore, we also consider only the direct emissions of the other categories. Thus, no Life Cycle approach is applied. Therefore, the emission factors for sources with no direct emissions (e.g. solar and wind) are set to zero. For consumption we assume the buy or sell order does not have any impact on the consumption at any other time and its emission factor is also set to zero. For the emission factor for natural gas the same value as used by the National Grid ESO is taken, 394 kg CO_2/MWh. This corresponds to an efficiency of 51.5% using the emission factor of 56.4 kg CO_2/GJ for natural gas in the Netherlands [31].

Table 2: *The emission factors used by the National Grid ESO to calculate the carbon intensity of the UK grid [from [32]].*

Source	kg CO_2/MWh
biomass	120
coal	937
dutch import	474
french import	53
gas CC	394
gas open cycle	651
hydro	0
Irish import	458
nuclear	0
oil	935
other	300
pumped storage	0
solar	0
wind	0

The emission factors are uncertain. Therefore, a minimum and maximum estimate for the emissions factors have been used to represent the uncertainty. The source of electricity of the international category is unknown. Therefore, the emission factor for this category is estimated by the average emission factor of the UK grid mix over the time period of the collected redispatch data. To get a better estimate of the uncertainty the minimal and maximal carbon intensity of the UK grid over the considered time period are used. This resulted in a minimal emission factor is 39 kg CO_2/MWh and a maximal emission factor is 323 kg CO_2/MWh. However, the source could be from renewable energy which would have an emission factor of zero or more emission intense power plant like coal and have an emission factor around 937 kg CO_2/MWh. The emission factor for CCGT power plants depends on the efficiency the power plant, which depends on the operational load [15]. The minimal value for the emission factor of 365.5 kg CO_2/MWh and a maximal value of 388.3 kg CO_2/MWh is used, which were the results of the study based by Gonzalez-Salazar et al. [15].

4 Results and Discussion

In Section 4.1 flexibility attributes for bid structures and case studies for efficient congestion solutions are considered. In Section 4.2 a concept bid structure is proposed along with a method to find congestion solutions using the proposed bid structure. In Section 4.3 the change in CO_2 emissions caused by dispatched are considered.

4.1 Attributes important in solving congestion management efficiently

4.1.1 Attributes related to the flexibility of bids

We can categorise the flexibility of a bid in volume and in time. Furthermore, the linking of bids can also be used to create some flexibility in time of volume. An overview of the different attributes regarding flexibility in the categories time and volume as well as linking is shown in Table 3. This overview is based on attributes of existing structures, which has some overlap, however different terms are used. In the overview shown in 3 the terms of the ROP bids and ENTSO-E bid are used. The attributes related to flexibility of the ROP, ENTSO-E and UK balancing mechanism bid structures are shown in Appendix B in Table 27, Table 28 and Table 29. The structure of the GOPACS orders was already shown in Table 1.

Table 3: *Overview of identified flexibility attributes of a bid structure*

Flexibility in	Attribute	Options
Time	Preparation time	
	Start time and duration	1. Fixed start time, Fixed end time 2. Validity period
	Minimal duration	
	Maximal duration	
	Resting duration	
Volume	Quantity	1. Volume for the whole bid 2. Volume at a given time period
	Partial volume	
	Minimal quantity	
Linking	Inclusive bids	
	Exclusive bids	

The attributes related to time are the preparation time and start time and duration. The preparation time is the delay between the acceptance of a bid and the actual activation of the bid. This delay could be used to take the start-up of a power plant into account. The ROP, ENTSO-E and UK balancing model bids all have this attribute. Regarding the start time and duration there are two possibilities. The first option is to have a fixed start time and fixed end time and therefore also a fixed duration. This is the case for the GOPACS orders. However, there is the convention to start and end the bids at the whole hour such that the buy and sell orders conveniently can be matched in time. The second option is to have a validity period. This is the time period in which the bid can be activated. The validity period could be used in combination with the following attributes. A minimal duration which is the minimal duration a bid needs to be activated and could be used to respect the minimal run time of a conventional power plant. Similarly, maximal duration can be an attribute. Lastly, resting duration which is the delay between the end of an activation and the start of the next activation. This could be used to respect the minimal down time. The ROP, ENTSO-E and UK balancing model bids all have a form of the validity period with a minimal duration. Only the UK balancing model bid also has a maximal duration and resting duration bid.

The attributes related to volume are the quantity, minimal quantity and partial volume. For the quantity there are two options. The first option is that the volume is fixed for the entire bid which is the case for the GOPACS order. The second option is to have a volume at a given time period (e.g. ISP). Therefore, the volume of the bid can vary over time. Either of these options can be combined with the option to be partial in volume or all-or-none. All-or-none could be useful if the electricity production of consumption only has to modes, on or off. An example of this is a single wind turbine or lights in a greenhouse[22]. In the case of partial volume it is also possible to have a minimal quantity attribute which could be used to respect the minimal load of a power plant.

The linking of bids could also be used to create more flexibility in a structure. The bids could be inclusively linked meaning if one of the bids gets activated the other bid must also be activated. The bids could also be exclusively linked meaning if one of the bids gets activated the other bid cannot be activated. This could be used to have more flexibility for example if there is a fixed volume. Then two bids can be done that are exclusively linked. One bid with the minimal volume, the minimal load of the power plant, and one bid with the maximal volume of the power plant. Since the bids are exclusively linked only one of them can be chosen. Therefore, the option for two different values of the volume are created in combination with the fixed volume. Similarly, the linking could be used in combination with a fixed time. Two exclusively linked bids, one with the minimal duration and one with more than the minimal duration could be done to create multiple options for the duration. Also, it could be used to have bids at different starting times.

4.1.2 Case study of the solutions for congestion problems

The problems used in the case study are shown in Figures 5, 6, 7 and 8. These problems are based on historic congestion problems, thus only reflect the current congestion situations. The TenneT block problem is a congestion problem of 100 MW with a duration of three hours. The TenneT volatile problem is a congestion problem with different volumes ranging between 50 to 200 MW with a duration of 3 hours. The congestion problems of the DSO have a much smaller volume. This DSO block problem has a volume of 1.7MW and has a duration of 4 hours. The DSO volatile problem has a volume between 0 to 10.4 MW with a duration of seven hours and 45 minutes.

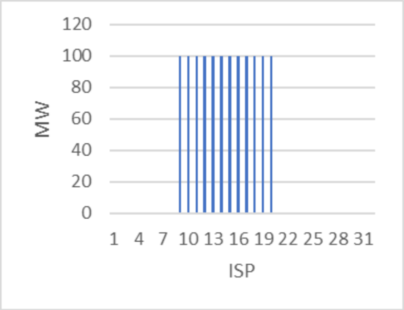


Figure 5: *TSO block congestion problem problem with a volume of 100 MW.*

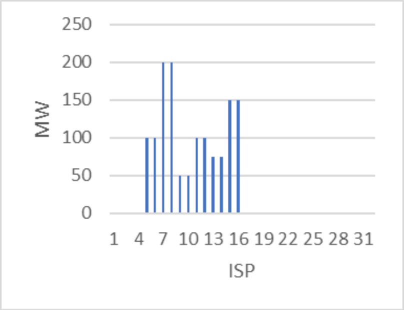


Figure 6: *TSO volatile congestion problem with a volume ranging between 50 MW and 200 MW.*

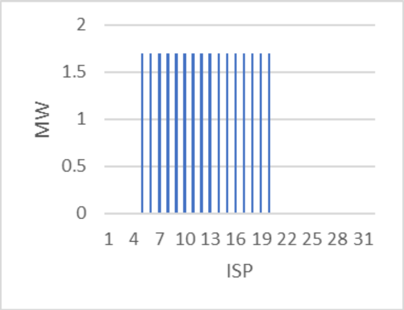


Figure 7: *DSO block congestion problem with a volume of 1.7 MW.*

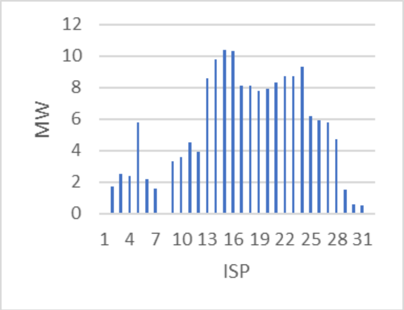


Figure 8: *DSO volatile congestion problem with a volume ranging between 0 and 10.4 MW*

The detail about the solutions discussed below can be found in Appendix A.1.

Scenario 1 In the bid scenario 1 is the standard scenario and is based on historical data. The solutions are shown in Figures 9, 10, 11 and 12. The solution for the TSO block problem shown in Figure 9 has a longer duration than the problem. The solution starts in ISP 1 while the problems starts in ISP 9 and the solution ends at ISP 32 while the problems ends in ISP 21. We can say that the solution oversolves in time. This is because the solution uses the ROP bids that have a duration of 16 ISP and the start and end time of the ROP bids and the congestion problem are not the same. The ROP bids are used despite their longer duration compared to the GOPACS orders since the GOPACS orders do not offer enough volume to solve the congestion problem. The solution to the TSO volatile problem shown in Figure 10 also oversolves in time. However, there is only oversolving at the beginning of the congestion problem. There is no oversolving in time at the end of the congestion problem since in the end time of the TSO volatile problems is the same as the end time of a ROP bid. Again, the ROP bids are used since the GOPACS bids do not offer enough volume for the congestion solution. Furthermore, the solution has a bigger volume than the congestion problems during most ISPs. We can say that the solution oversolves in volume. This oversolving in volume happens because t the bids have a fixed volume for the whole duration of the bid. Therefore, the volume of solution is the maximal volume of the congestion problem for the entire duration of the bids.

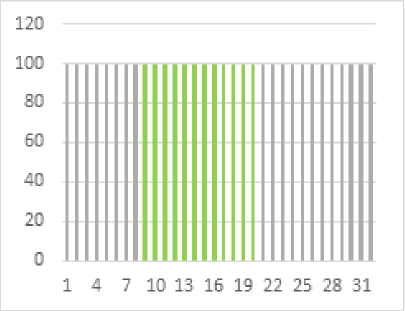


Figure 9: *Solution to the TSO block problem using bids of scenario 1. In green the solved congestion problem and in grey the oversolving of the solution.*

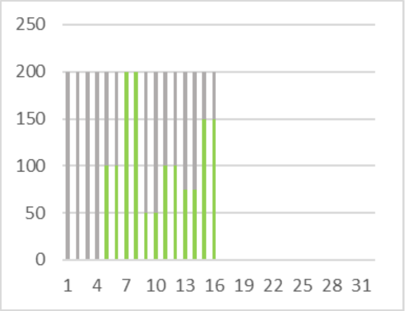


Figure 10: *Solution to the TSO volatile congestion problem using bids of scenario 1. In green the solved congestion problem and in grey the oversolving of the solution.*

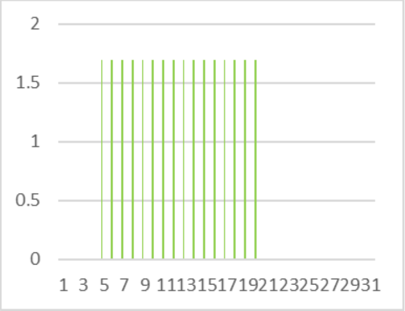


Figure 11: *Solution to the DSO congestion problem using bids of scenario 1. In green the solved congestion problem.*

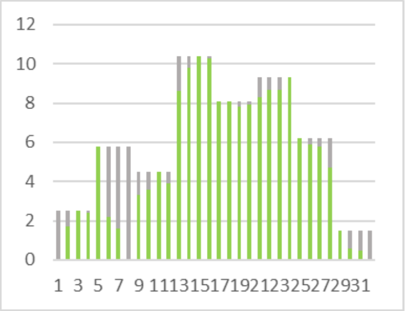


Figure 12: *Solution to the DSO volatile problem using bids of scenario 1. In green the solved congestion problem and in grey the oversolving of the solution.*

The DSO block problem is solved exactly, shown in Figure 11. The solutions uses bids which are partially available in volume to match the volume of the solution exactly to the volume of the congestion problem. Furthermore, the bids used in the solution where the GOPACS orders with a duration of 1 hour which matched up with the start and end time of the congestion problem. The solution of the DSO volatile problem shown in Figure 12. Similarly to the TSO congestion problem there is oversolving in volume as well as time. This time the volume of the solution is the maximum of the congestion problem in each hour which is the duration of the GOPACS orders. The oversolving in time is caused by the difference in the start time of the bids and the congestion problem.

This shows the oversolving in time depends on the duration of the bids and whether the start and end time match up with the start and end time of the bids. For bids with a duration of 1 hour the worst case scenario is that 1,5 hours gets oversolving in time. In general, for bids with a duration of n hours the worst case scenario there is oversolving of $n - 0.5$ hours. Furthermore, in case of a volatile congestion problem the volume of the solution is maximum volume in the duration of the bids. Therefore, a shorter duration of the bids will likely result in less oversolving in volume.

Scenario 2 Scenario 2 is similar to scenario 1 except that all the bids are all-or-none. The solution to the TSO block problems is the same as in scenario 1 since this solution already only used all-or-none bids. The solution for the TSO volatile problem is the same in volume as in scenario 1 however, it uses different bids which are more expensive. For the DSO problems there is a lot of oversolving in volume shown in Figure 13 and Figure 14. The volume of the solution cannot be adjusted to the volume of the problem since the bids are all-or-none. Moreover, not all bids can be used since they do not have a matching counter action, meaning a bid that decreases the electricity in-feed, a buy order, needs to be matched with a bid that increases the electricity in-feed, a sell order, to maintain the balance. For the solution of the DSO problems the bids with a longer duration must be used since the bids with shorter duration do not have a counter action. Therefore, the solutions also oversolves in time.

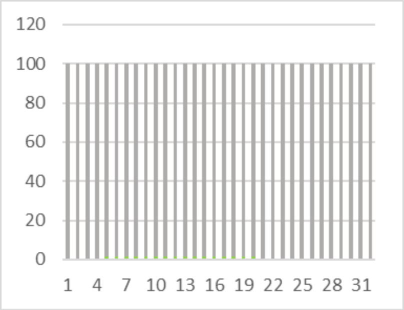


Figure 13: *Solution to the DSO block problem using bids of scenario 2. In green the solved congestion problem and in grey the oversolving of the solution.*

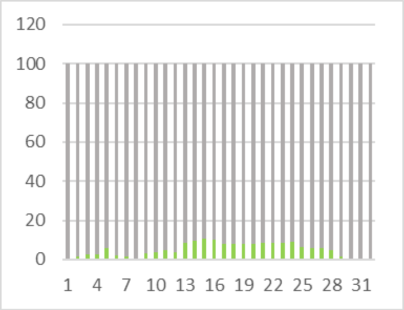


Figure 14: *Solution to the DSO volatile congestion problem using bids of scenario 2. In green the solved congestion problem and in grey the oversolving of the solution.*

Scenario 3 Scenario 3 contains less bids than scenario 1. The difference in the solutions for the TSO problems is that there is (more) oversolving in volume which is shown in Figure 15 and Figure 16. This because the available buy orders are very large in volume and all-or-none. For the solutions for the DSO block problem can still be solved exactly which is shown in Figure 17. However the solution is more expense than in scenario 1 since a cheaper bid used in scenario 1 was not available in scenario 3. The solution of the DSO volatile problem is shown in Figure 18 and is solved efficiently for the first half, however for the second half the was oversolving in volume. In the second half of the problem there was not enough volume of the GOPACS orders, therefore the ROP bids which are all-or-none and large in volume needed to be used. Thus, having less bids causes the need to use more bids which are larger in volume, all-or-none and/or have a longer duration which causes oversolving. Scenario 4 was very similar to scenario 3 since less bids also meant less bids of smaller volume.

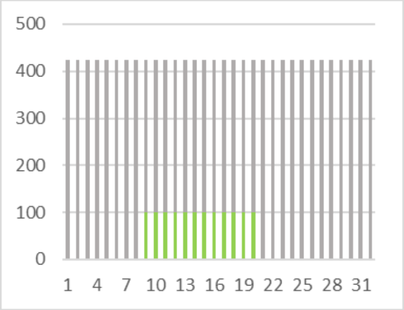


Figure 15: *Solution to the TSO block problem using bids of scenario 3. In green the solved congestion problem and in grey the oversolving of the solution.*

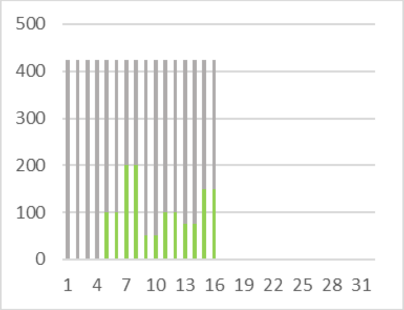


Figure 16: *Solution to the TSO volatile congestion problem using bids of scenario 3. In green the solved congestion problem and in grey the oversolving of the solution.*

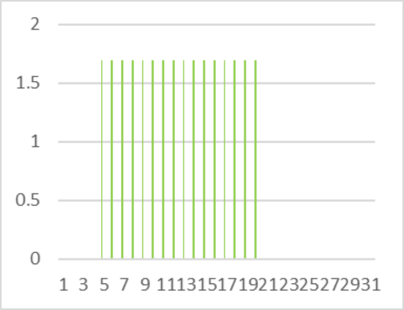


Figure 17: *Solution to the DSO congestion problem using bids of scenario 3. In green the solved congestion problem and in grey the oversolving of the solution.*

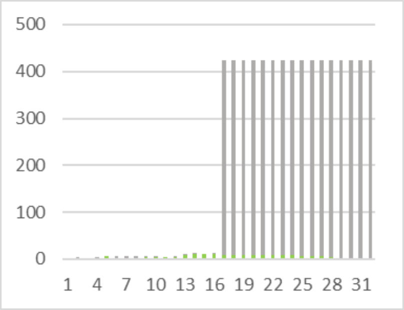


Figure 18: *Solution to the DSO volatile problem using bids of scenario 3. In green the solved congestion problem and in grey the oversolving of the solution.*

Scenario 5 In scenario 5 the ROP bids had a shorter duration, 2 hours instead of 4 hours. This decreases the available volume since the number of bids stayed the same. The solutions for the TSO problems in scenario 5 shown in Figure 19 and Figure 20 are only partial solutions, not the whole congestion problems are solved. There is not enough volume available to solve the congestion problems completely. The DSO problems are solved in the same way as in scenario 1 since this solution does not use any ROP bids and is therefore not affected by the shorter duration of these bids.

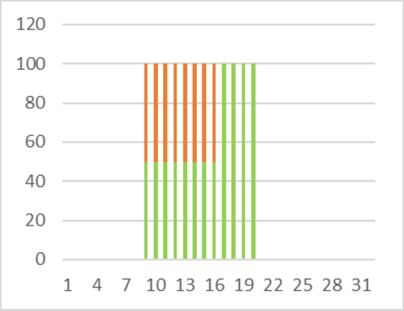


Figure 19: *Solution to the TSO block problem using bids of scenario 5. In green the solved congestion problem, in orange the unsolved part of the congestion problem and in grey the oversolving of the solution.*

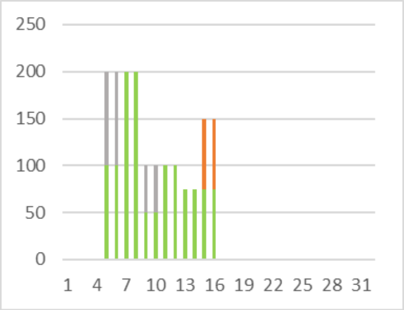


Figure 20: *Solution to the TSO volatile congestion problem using bids of scenario 5. In green the solved congestion problem, in orange the unsolved part of the congestion problem and in grey the oversolving of the solution.*

Scenario 6 In scenario 6 all the bids have a partial volume, meaning the bids are not all-or-none. For the TSO problems there is less oversolving compared to bid scenario 1 which is shown in Figure 21 and Figure 21. There still is oversolving in time due to the long duration of the ROP bids, however the volume of the solution outside of the congestion problem is smaller. For the DSO problems the solution is the same as in scenario 1 since it already consisted out of bids which were not all-or-none.

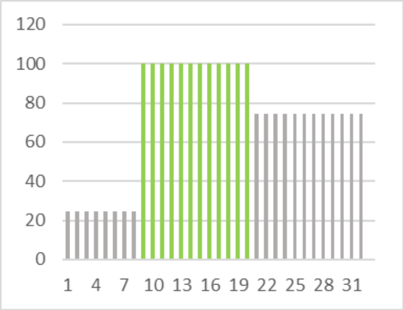


Figure 21: *Solution to the TSO block problem using bids of scenario 6. In green the solved congestion problem and in grey the oversolving of the solution.*

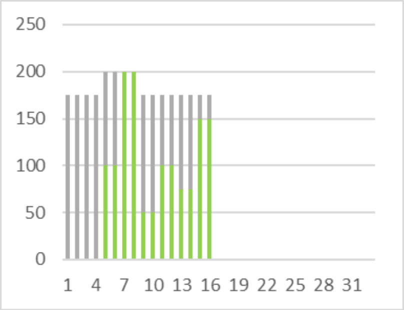


Figure 22: *Solution to the TSO volatile congestion problem using bids of scenario 6. In green the solved congestion problem and in grey the oversolving of the solution.*

In summary, we have the following conclusions. Firstly, a longer duration of a bids can cause more oversolving in time. This depends on how the duration of the bid compares to the duration of the congestion problem as well as how the start and end time of the bid compares to the start and end time of the congestion problem. Furthermore, in the case of a volatile problem the maximum value of the problem within the duration of the bid will be solved. Therefore, a shorter duration could also reduce the oversolving in volume. Secondly, All-or-none bids can cause more oversolving in volume since the bids cannot be adjusted to match the volume of the congestion problem. Especially if the bids have a large volume compared to the congestion problem. Moreover, the matching of a buy and sell order becomes more difficult since the (sum of) buy order(s) needs to have exactly the same volume as the (sum of) sell order(s). This results in a decrease of bids that can be used and the possibilities to use them for a congestion solution. Thirdly, having a few bids could result in not or only finding a partial solution. Moreover, it could also cause more oversolving in time or volume since there are less choice to find an optimal solution.

Thus, for a bid structure to contribute to an efficient solution it first of all needs to be able to capture as much of the flexibility of the market parties as possible such that there are enough bids for a redispatch solution. Secondly, the buy and sell orders can be more easily matched if they are partial in volume. Moreover, if the bids are flexible in volume the redispatch solution can be adjusted to the volume of the congestion problem reducing the amount of oversolving in volume. To reduce the amount of oversolving in time the bids should be flexible in time such that the start and end of the redispatch solution can be matched with the start and end of the congestion problem. An alternative could be to provide the market with detail information of the start and end time of the congestion problem such that the market can make bids suited to the congestion problem. The flexibility in time and flexibility in volume would also likely make a solution for a volatile congestion problem more efficient.

4.2 Adapted algorithm

In this section a concept of a new bid structure is chosen with the knowledge of the previous sections to further investigate. This bid structure is shown in Table 4. The structure is flexible in volume and flexible in time. Furthermore, it contains attributes to take limitations of electricity production into account. An algorithm has been developed that is able to use bid with this new structure as well as GOPACS orders. This algorithm is an adaptation for the current GOPACS algorithm. The main idea of the new structure is to keep the flexibility of volume as in the GOPACS orders and to have more flexibility in time. The implementation of the flexibility is achieved by adapting the current GOPACS algorithm by having a decision variable per ISP per bid instead of a decision variable per bid. Furthermore, constraints need to be added to make sure that flexibility in time is used by the algorithm as intended.

Some of the attributes are can already be used by the current algorithm. The preparation time can be implemented into the algorithm by filtering the bids out if the preparation time is longer than the time left before the first (possible) activation. However, the start time of an activation is flexible. Therefore, the bid could also be adapted such that the volume is zero at the ISPs where there is not enough preparation time left. The minimal and maximal duration can be implemented by adding constraints which is explained in Section 4.2.3. The attribute divisible can be implemented by making the decision variable an integer as is done in the current GOPACS algorithm or by setting the minimal volume to be the same as the volume. The volume now can have a different value per ISP instead of one value for the whole bid. This is implemented by having a decision variable per ISP per bid instead of a decision variable per bid. The minimal volume is equivalent to a usage fraction which is already used in the current GOPACS algorithm. However, the difference is that the minimal volume is per ISP per bid instead of only per bid. Similarly, to the volume this is implemented with the decision variables per ISP per bid. There is one indirect implication of using a bid which is flexible in time, which is that once a bid is activated and later inactivated the bid cannot be activated again. This gives the opportunity to the market parties to update their bids once one of their offered bids has been activated. Therefore, it is useful to solve multiple congestion problems that occur at a similar time, since solving one would result in the loss of a bids which were only partly used. Constraints are added to the linear program to make sure a bid only gets activated once. This constraints is explained in Section 4.2.2.

Table 4: *Table containing attributes of the proposed bid structure that relate to the flexibility*

Attribute	Explanation	Example
Preparation time	Time (number of ISPs) between the acceptance of a bid and the activation of the bid	4 ISPs
Minimal duration	Minimal duration a bid has to activated	16 ISPs
Maximal duration	Maximal duration a bid can be activated	32 ISPs
Divisible	Similar to all-or-none. It indicates whether the volume of a bid can be partially activated. Contrary to all-or-none if divisible is true than the bid can be partially activated	True / False
Volume	The volume in MW of the bid at a certain time period (ISP). If the bid is divisible then this value is the maximum volume	in Table 5
Minimal volume	the minimal volume in MW per ISP of the bid. Comparable to usage fraction of PX bids	in Table 5

Table 5: *Example of a bid that offers the volume per ISP*

ISP	(maximal) volume in MW	minimal volume in MW
1	100	50
2	100	50
3	150	50
4	150	50
5	200	100
...		
96	100	50

4.2.1 The adapted algorithm

We adapt the GOPACS algorithm such that there is a decision variable for every bid at every ISP. The decision variables become $X_{i,t}$ instead of X_i. We now consider the volume of an order i at time t: $V_{i,t}$. This changes the $r_{i,t}$ matrix. The rows still represent the orders and the columns model the time units. The entries become

$$r_{i,t} = \begin{cases} V_{i,t} & if \;\; order\ i\ corresponds\ to\ ISP\ t \\ 0 & otherwise \end{cases} \tag{4.1}$$

We keep notation of the r-matrix such that the notation stays similar to the case for the GOPACS orders.

The new linear program becomes, minimize the spreadprice

$$\sum_t (\sum_s P_s V_{s,t} X_{s,t} - \sum_b P_b V_{s,t} X_{s,t}), \tag{4.2}$$

with the following constraints

$$\sum_s X_{s,t} r_{s,t} - \sum_b X_{b,t} r_{b,t} = 0 \;\; \forall t \quad (balance) \tag{4.3}$$

$$\sum_s X_{s,t} r_{s,t} \epsilon_s(k) - \sum_b X_{b,t} r_{b,t} \epsilon_s(k) \leq -R_{k,t} \;\; \forall t \quad (remedy) \tag{4.4}$$

and the constraints for described in Section 4.2.2 and Section 4.2.3. The remedy constraint can be added for every problem k. It is also possible to have a price that depends on the time interval $P_{i,t}$.

4.2.2 Constraints such that the activation is not zero in between

Suppose we have a bid at ISP 1 up to and including n with a non-zero volume and a minimal duration d_{min}. We define the binary decision variable $Y_{i,1}, ..., Y_{i,n}$ indicating whether the bid i is activated in the corresponding ISP as explained in Section 2.5.1.

If an order has been activated and becomes zero after that activation then the bid cannot be activated again. Thus, the indicator variable needs to stay zero. Therefore, the activation fraction will also become zero. So, if $Y_{i,t-1} = 1$ and $Y_{i,t} = 0$ then $Y_{i,t+1} = Y_{i,t+2} = ... = Y_{i,n} = 0$. This can also be written as

$$If \;\; Y_{i,t} - Y_{i,t-1} \leq -1 \;\; then \;\; \sum_{k=t+1}^{n} Y_{i,k} \leq 0 \tag{4.5}$$

This is equivalent to

$$Y_{i,t} - Y_{i,t-1} > -1 \;\; or \;\; \sum_{k=t+1}^{n} Y_{i,k} \leq 0 \tag{4.6}$$

This can be written as two separate constrains by defining a binary decision variable $Z_{i,t}$.

$$\begin{aligned} Y_{i,t} - Y_{i,t-1} &> -1 - Z_{i,t} \\ \sum_{k=t+1}^{n} Y_{i,k} &\leq n(1 - Z_{i,t}) \end{aligned} \tag{4.7}$$

Thus, to exclude the possibility that activated bid does not have an activation fraction of zero in between its activation when using decision variables per ISP the following decision variables and constrains need to be added. For all $t \in \{2, .., n-1\}$ we add

- an extra binary variable $Z_{i,t}$
- the constrains in 4.7

Then for a congestion problem of duration n this adds $n - 1$ extra binary variables and $2n - 2$ extra constrains for every order i.

Instead of only being able to activate a bid a consecutive number of ISPs it is also possible to add constrains such that the bid can be activated again after a certain resting period, say d_r. This can be done by replacing the constraints in equation 4.7 by

$$Y_{i,t} - Y_{i,t-1} > -1 - Z_{i,t} \tag{4.8}$$

$$\sum_{k=t+1}^{n} Y_{i,k} \leq (d_r - 1)(1 - Z_{i,t}) \tag{4.9}$$

4.2.3 Constraints: Minimal and maximal duration

Again, suppose we have a bid at ISP 1 up to and including n with a non-zero volume and a minimal duration d_{min}. We define the binary decision variable $Y_{i,1}, ..., Y_{i,n}$ indicating whether the bid i is activated in the corresponding ISP as explained in Section 2.5.1.

The minimal duration is the minimal consecutive number of ISPs a bid needs to be activated. Thus, if a bid is activated for the first time in an ISP then the following ISPs the bids need to be activated as well for the minimal duration d_{min}. Assuming a bid cannot be zero in between an activation, which is ensured with the "no zero in between" constraint, an activation can only happens once. Therefore, a bid gets activated for the first time if $Y_{i,t-1} = 0$ and $Y_{i,t} = 1$ for $t \geq 2$. The case $t = 0$ can be treated separately. Also, the activation cannot start if there are less ISPs left than the minimal duration d_{min}, which will also be treated separately. Thus, we need to ensure that if $Y_{i,t-1} = 0$ and $Y_{i,t} = 1$ then $Y_{i,t+1} = Y_{i,t+2} = ... = Y_{i,t+d_{min}-1}$ for $t \in \{2, .., n - d_{min} + 1\}$ together with some constraints for the edge cases $t = 1$ and $t \geq n - d_{min} + 2$. To use this constraint in the algorithm we need to write it in the form of linear (in)qualities.

$$If \;\; Y_{i,t-1} = 0 \;\; and \;\; Y_{i,t} = 1 \Rightarrow Y_{i,t+1} = Y_{i,t+2} = ... = Y_{i,t+d_{min}-1}, \tag{4.10}$$

can be written as

$$If \;\; Y_{i,t-1} - Y_{i,t} < 0 \;\; then \;\; \sum_{k=t+1}^{t+d_{min}-1} Y_{i,k} \geq d_{min} - 1. \tag{4.11}$$

This is equivalent to

$$Y_{i,t-1} - Y_{i,t} \geq 0 \;\; or \;\; \sum_{k=t+1}^{t+d_{min}-1} Y_{i,k} \geq d_{min} - 1. \tag{4.12}$$

Equation 4.12 can be written as two separate constrains by defining a binary decision variable W_i.

$$\begin{gathered} Y_{i,t-1} - Y_{i,t} \geq -W_{i,t}, \\ \sum_{k=t+1}^{t+d_{min}-1} Y_{i,k} \geq (d_{min} - 1)W_{i,t}. \end{gathered} \tag{4.13}$$

Equations 4.13 needs to hold for all $t \in \{2, .., n - d_{min} + 1\}$.

For the case that $t = 0$, the bids gets activated for the first time if $Y_{i,1} = 1$. To ensure that in this case the duration of the activation has a duration of d_{min} we have if $Y_{i,t} = 1$ then $Y_{i,t+1} = Y_{i,t+2} = ... = Y_{i,d_{min}}$. This is equivalent to

$$\begin{aligned} Y_{i,1} &\leq W_{i,1}, \\ \sum_{k=2}^{d_{min}} Y_{i,k} &\geq (d_{min} - 1)W_{i,1}. \end{aligned} \tag{4.14}$$

To ensure that the activation cannot start if there is not enough time left to have a duration of d_{min} we consider the following. The last possible moment the activation can start is in ISP $n - d_{min} + 1$. Therefore, if the bid is not activated in this ISP, $Y_{i,n-d_{min}+1} = 0$, the ISP that follow also cannot be activated, $Y_{i,n-d_{min}+2} = ... = Y_{i,n} = 0$. This is equivalent to

$$\begin{aligned} Y_{i,n-d_{min}+1} &\geq W_{i,n-d_{min}+2}, \\ \sum_{k=n-d_{min}+2}^{n} Y_{i,k} &\leq (d_{min} - 1)W_{i,n-d_{min}+2} \end{aligned} \tag{4.15}$$

Then to respect the minimal duration when using separate decision variables per ISP the following extra decision variables and constrains needs to be added. For all we add

- an extra binary variable $W_{i,t}$ for $t \in \{1, ..., n - d_{min} + 2\}$,
- the constraints in equation 4.13 for $t \in \{2, ..., n - d_{min} + 1\}$,
- the constraints in equation 4.14,
- the constraints in equation 4.15.

Thus, for a congestion problem of duration n this adds $n - d_{min} + 2$ extra binary variables and $2(n - d_{min} + 2)$ extra constrains for every non-zero bid during the duration of the problem with a minimal duration of d_{min}.

Something similar can be done for the attribute maximal duration.

4.2.4 Other possible constraints

The developed algorithm described above could result in a volatile volume activation of bids. Meaning the activation could jump between the minimal and maximal volume over time. This could potentially be an issue for market parties. Changing the production of the power plant might be difficult and goes at a certain rate, the ramp rate. Therefore, there is a difference in the possible production change and the change in volume ask by the activated bid resulting in an unbalance on the grid. With the fixed volume for the whole bid this issue only occurs twice, at the start and end of a bid. If the activation of a bid is volatile in volume this issue occurs more. Therefore, it could be considered to limit a volatile activation of a bid. One way to do this would be to limit the change in volume by a certain amount, δ. So if a bid is activated at times $t - 1$ and t then we should have the constraint

$$|V_{i,t}X_{i,t} - V_{i,t-1}X_{i,t-1}| < \delta.$$

Other possible methods could consider using the ramp-rate, which would then have to be included in the bid structure. Or limiting the number of times the volume can change. However, then the fact that the volume in the bid can change also has to be considered.

For batteries it might be useful to add the constraint for a maximal power in MWh that can be used for congestion management. Suppose P_{max} is the maximal power in MWh that the bid i offers and $V_{i,t}$ is the volume in MW offered at time t. Then the following constrained can be added assuming that the time unit of the activation fraction X_i, t is 1 ISP

$$\sum_t \frac{V_{i,t}}{4} X_{i,t} \leq P_{max}. \tag{4.16}$$

The attributes of linking were not considered in the concept bid structure. However, the linking of bids could also be added to the algorithm. Firstly, we consider inclusive bids. Suppose bid i is inclusively linked to bid j, meaning bid i can only if activated if bid j is activated. Suppose Y_i and Y_j are binary indicator variables of the bids i and j, indicating whether the bids are activated or not. This could also be done at every time period, an ISP, instead of the whole bid. If bid i is exclusively linked to bid j then we want $Y_i = 1$ only if $Y_j = 1$. This is equivalent to the constraint

$$Y_j \geq Y_i. \tag{4.17}$$

Secondly, we consider exclusive bids. Suppose bid i is exclusively linked to bid j, meaning bid i can only be activated if bid j is activated and vice versa. Suppose we have the binary indicator variables Y_i and Y_j of the bids i and j. Then we have the constraint

$$Y_i + Y_j \leq 1, \tag{4.18}$$

such that at most one of the bids can be activated. Again, this could also be considered at every time period instead of the whole bid. Furthermore, it is also possible to have multiple exclusively linked bids [22], say bids $1, ..., n$. Suppose Y_1,...,Y_n are the binary indicator variables for the bids $1, ..., n$ respectively, then we have the constraint

$$Y_1 + ... + Y_n \leq 1, \tag{4.19}$$

such that at most one of these bids can be activated.

4.2.5 Analysis of method

The algorithm is implemented in python with a PuLP solver and in this section we test some simple cases to verify that no unexpected behaviour occurs. We test if the minimal duration, not zero in between, the minimal volume are satisfied. Furthermore, we show that the solution will fit the congestion problem in time if the bid starts at a different time than the congestion problem. In these simple cases we consider a time interval of 4 ISPs which has a congestion problem, one buy order and one sell order which both have a minimal duration and a minimal volume. The buy orders has an efficiency of 1 and the sell order has an efficiency of 0. Therefore, the redispatch solution requires the exact volume of the congestion problem.

The first case is to test if the minimal duration is respected. We consider a congestion problem with a shorter duration than the minimal duration of the bids. The duration of the congestion problem is 2 ISPs while the minimal duration of the bids is 4 ISPs. The bids used have the same volume as the congestion problem with a minimal volume that is the same as the maximal volume which is 20MW. Therefore, the most efficient solutions would for the buy and sell orders to have the same volume as the congestion problem over the duration of the congestion problem. However, this should not be allowed due to the minimal duration. Table 6 shows the congestion problem and the bids. Table 7 shows the output of the algorithm where the activation of the bids has indeed the duration of the minimal duration of 4 ISPs.

Table 6: *Input to test if the minimal duration is respected. The minimal volume is taken as the same volume as the maximal volume.*

	ISP 1 (MW)	ISP 2 (MW)	ISP 3 (MW)	ISP 4 (MW)	minimal duration	efficiency
problem	20	20	0	0		
buy	20	20	20	20	4 ISPs	1
sell	20	20	20	20	4 ISPs	0

Table 7: *Output of test to see if the minimal duration is respected.*

	ISP 1	ISP 2	ISP 3	ISP 4
buy	20	20	20	20
sell	20	20	20	20

Now we test if the activated volume does not become zero during an activation. We take the same approach as before. However, we now consider a congestion problem which is zero in ISP 3 while it is 20MW in ISP 1,2 and 4. The bid situation is the same as before. This input is shown in Table 8 and the most efficient solution would have an activation of the bids such that they are zero if the congestion problem is zero. However, this is not allowed with the non-zero in between constraint. Table 9 shows that the activation volume of the bids is indeed not zero during the activation.

Table 8: *Input to test if an activation volume will not become zero during an activation. The minimal volume is taken as the same volume as the maximal volume.*

	ISP 1 (MW)	ISP 2 (MW)	ISP 3 (MW)	ISP 4 (MW)	minimal duration	efficiency
problem	20	20	0	20		
buy	20	20	20	20	4 ISPs	1
sell	20	20	20	20	4 ISPs	0

Table 9: *Output of the test to see if the activated volume will not become zero during an activation.*

	ISP 1	ISP 2	ISP 3	ISP 4
buy	20	20	20	20
sell	20	20	20	20

To test if the solution can start and end at the same time as the congestion problem even if the bids start at a different time we consider a congestion problem that start at ISP 2 and ends at ISP3 with a minimal duration for the bids of 2 ISPs. This is shown in Table 10. The results in Table 11 shown that the activation of the bids indeed matches with the congestion problem.

Table 10: *Input to test if the solution can start and end at a different time of the bids. The minimal volume is taken as the same volume as the maximal volume.*

	ISP 1 (MW)	ISP 2 (MW)	ISP 3 (MW)	ISP 4 (MW)	minimal duration	efficiency
problem	0	20	20	0		
buy	20	20	20	20	2 ISPs	1
sell	20	20	20	20	2 ISPs	0

Table 11: *Output of the test to see if the activation will be adjusted to the congestion problem even if the bids start and end at a different times.*

	ISP 1	ISP 2	ISP 3	ISP 4
buy	0	20	20	0
sell	0	20	20	0

To test if the minimal volume is respected we consider a congestion problem with a volume which is smaller than the minimal volume of a buy and sell orders. Therefore, the most efficient solution would require an activation of a volume less than the minimal volume. The congestion problem and bids used are shown in Table 12. The output is shown in Table 13 shows that indeed the activation is at least the minimal volume.

Table 12: *Input to test if at least the minimal volume will be activated.*

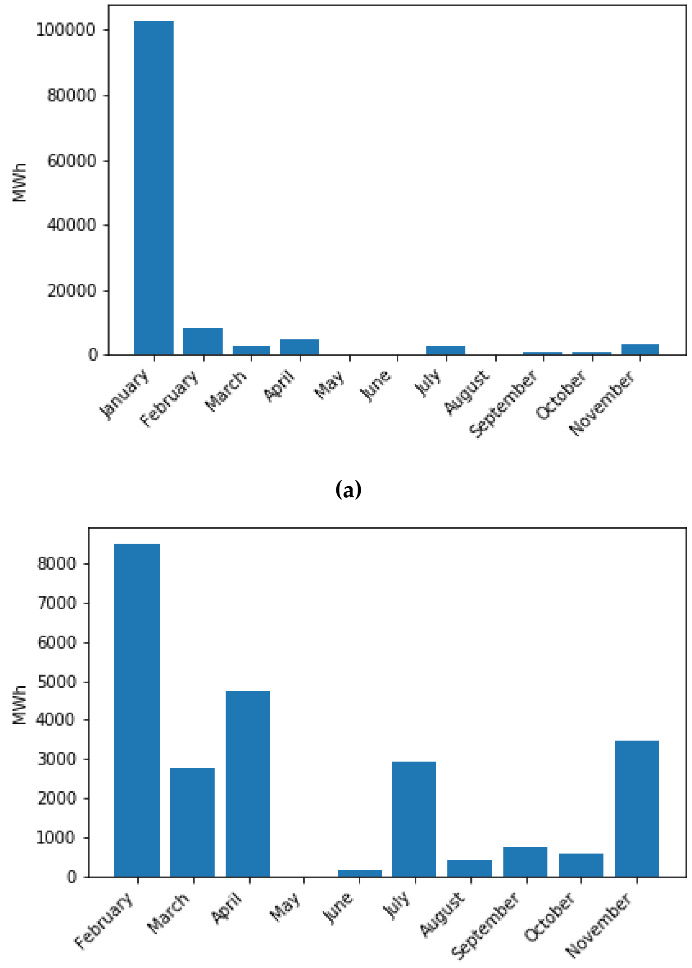
	ISP 1 (MW)	ISP 2 (MW)	ISP 3 (MW)	ISP 4 (MW)	minimal duration	efficiency
problem	20	20	20	20		
buy max. volume	40	40	40	40	4 ISPs	1
min. volume	30	30	30	30		
sell max. volume	40	40	40	40	4 ISPs	0
min. volume	30	30	30	30		

Table 13: *Output of the test to see if the minimal volume is respected.*

	ISP 1	ISP 2	ISP 3	ISP 4
buy	30	30	30	30
sell	30	30	30	30

4.3 CO_2 emissions of market-based redispatch

In this section the change in CO_2 emissions due to redispatch are discussed. The total amount of redispatch is described first, followed by the share of each electricity production option in the buy and sell orders (both per MWh and in absolute terms). Furthermore, the price of the buy and sell orders is considered since redispatch by GOPACS is based on cost-optimization. Lastly, the CO_2 for the buy and sell orders is considered per MWh and the overall change in CO_2 emissions.



(a)

(b)

Figure 23: *Bar diagram showing the volume of redispatch by GOPACS for TenneT congestion problems in MWh. The data for November only goes up to the 14th. In Figure 23a the volume for the months January up to and including November are shown. In Figure 23b January is not included.*

Figure 23 shows the volume in MWh of redispatch per month done by GOPACS for the TenneT congestion problems over the period of the collected data. There was 127159

MWh of redispatch in total with a significant difference for the different months. In January the amount of redispatch is more than one order of magnitude bigger compared to most months. In May there was no redispatch. There could be several reasons for these differences. The amount of congestion depends on the choices made by the market which depend among other things on the demand and available electricity production. Certain circumstances will require more transmission over certain transmission lines. For example if there will be a lot of production in one side of the Netherlands (e.g. the North) and a lot of consumption on the other side of the Netherlands (e.g. the South). Furthermore, international electricity trade could have an impact congestion as well. Another aspect that could increase the amount of congestion is maintenance. Due to maintenance there will be less transmission capacity available and therefore congestion will happen earlier. Furthermore, this data only includes the transmission congestion problems solved by GOPACS. TenneT also uses the ROP bids to solve congestion. Therefore, this data does not show the whole picture.

Figure 24 shows the share of the categories International, Natural Gas and Consumption for the sell orders, the increase in production or decrease in consumption, for each month. Most of the sell orders fall into the International category which has a share of 96.3% over the period from the collected data. Natural gas has a share of 2.7% and consumption a share of 1.0%. There are two month that deviate from this. In June all of the sell orders where a decrease in consumption, but there was only redispatch of 181.5 MWh. In October there was a high share of natural gas and almost no international sell order. The overall high share in international sell orders indicates that there is not enough competitive or well located capacity to increase production or decrease consumption in the Netherlands on the GOPACS platform.

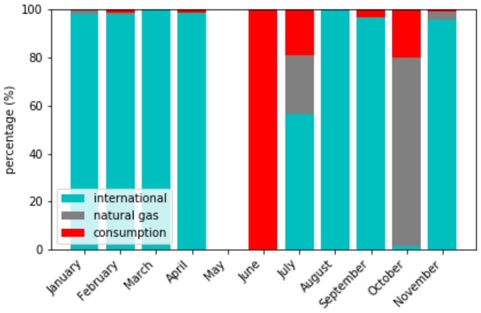


Figure 24: *The percentage of International, Natural Gas and Consumption of the sell orders.*

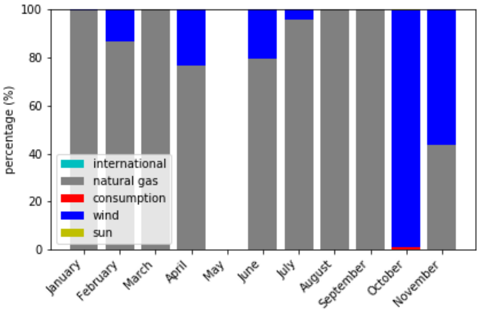


Figure 25: *The percentage of International, Natural Gas, Consumption, Wind and Solar of the buy orders.*

Figure 25 shows the share of the categories International, Natural Gas, Consumption, Wind and Solar for the buy orders, the decrease in production or increase in consumption, for each month. Most of the buy orders fall into the category Natural Gas which has a share of 95.5% over the period of the collected data. Wind has a share of 4.5% and the other categories have a share of less than one percent. In October and November there is a higher share of wind buy orders.

The redispatch solution is based on cost optimization. Therefore, the price of the buy and sell orders influences which buy and sell orders will be chosen for redispatch. The location is also important since this determines if the order can contribute to a redispatch solution. A combination of buy and sell with a lower efficiency will require a bigger volume to solve the congestion solution which will increase the price of the solution. The buy and sell orders offered will depend on what is sold on the electricity market. The sell orders, an increase in electricity production, will exist of production capacity that is not sold on the market yet. This will likely be the more expensive forms of electricity production. Wind and solar electricity that have no marginal cost will likely be already sold on the electricity market. Therefore, wind and solar will likely not have any additional capacity left to offer for a sell order. The buy orders, a decrease in electricity production, are already sold on the electricity market and have influenced the congestion situation. An electricity producing asset that uses a fuel will likely be cheaper buy order since decreasing electricity production results in fuel savings. The location of the electricity production is important and determines of a buy or sell order can contribute to a congestion solution.

In the EU market-based redispatch such as GOPACS has to be done in a non-discriminatory way. However, considering the average prices of the categories of the sell and buy orders named above we can consider what would change if the redispatch solution could prefer the buy and sell orders that would result in lower CO_2 emissions. Here we assume all the buy and sell orders in the different categories have around the same efficiency for the congestion problem. Therefore, changing the category of buy and sell orders would not require additional volume to solve the congestion problem. For the sell orders there are only the categories international, natural gas and consumption. International is the cheapest and consumption the most expensive option. Assuming the consumption does not change at another moment as a result of the sell order it should be preferred regarding the CO_2 emissions. With the estimate of the emission of the international category by the average grid mix of the UK the international category should be preferred second and before the natural gas category. Therefore, the share of consumption category would increase for the sell orders depending on the available flexibility to decrease consumption. For the buy orders is natural gas the cheapest option which is the main share of the buy orders and has the highest emissions. Wind is the most expensive option, however has the second biggest share indicating that there is probably not a lot of volume offered by the remaining categories. Thus, the share of the categories would not change a lot by preferring buy orders with high emissions. If the grid is further decarbonised the increased amount of renewables might increase the amount of congestion, due to their location (e.g. at sea). This would likely result in more renewable energy buy orders, however their might also be more renewable energy sell orders available.

The ROP bids TenneT receives are the flexibility from producers and consumers with a connection of more than 60 MW. Most of the power plants with a capacity of more than 60MW in the Netherlands use natural gas as their fuel, there also some coal and biomass power plants and a nuclear power plant [33]. However, nuclear power plant are inflexible in their power generation and therefore not suitable for redispatch. For gas and coal the flexibility of production depends on the type of power plant [15]. Furthermore, big wind parks are also part of the ROP bids. Using the ROP bids in GOPACS will increase the total volume of the bids to use by GOPACS making GOPACS more able to solve more and bigger congestion problems. Congestion is expected to increase in the future [34]. Therefore, the ability of GOPACS to solve more congestion might be much needed. Furthermore, the share of the categories for the buy and sell orders could change. For the sell orders their might be ROP bids that can compete with the international orders. This could decrease the share of international orders and increase the natural gas, coal or wind orders. The buy orders already mostly exist of natural gas and wind orders. Thus, a change in the buy orders due to the ROP bids could mainly be an increase in coal buy orders.

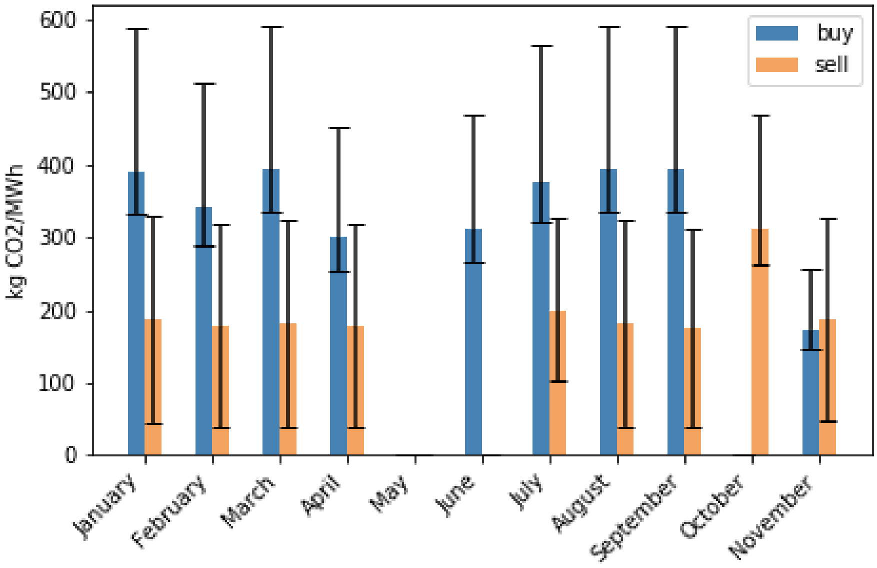


Figure 26: *Bar diagram showing the CO_2 emissions in kg/MWh of the buy orders in blue and of the sell orders in orange.*

Figure 26 shows the CO_2 emissions in kg/MWh for the buy and sell orders. The majority of the emissions of the sell orders comes for international orders, since they make up 96.3% of the sell orders. The majority of the emissions of the buy orders comes from the natural gas orders, since they make up 95.5% of the buy orders. The emission factor for the international orders is the average value for the UK electricity grid that has a value of 188.9 kg CO_2/MWh, while the emission factor of natural gas is 394 kg CO_2/MWh. For most of the months the emissions from the buy orders is higher than the emissions from the sell orders except for October and November. The emissions per unit of electricity from the buy orders in October and November are lower compared to other months since the share of wind is larger in October and November. The emissions from the sell orders are more or less the same except for June and October. In June all the sell orders are a decrease in consumption and therefore there are no emissions associated with the sell orders of June. In October there was a higher share of natural gas sell order which resulted in higher emissions per unit of electricity compared to the other months. With the main estimate for the emissions decreased around 122-313 kg CO_2/MWh for the months January to September except for May. For October and November the emissions increased with 311 and 15 kg CO_2/MWh due to the higher share of wind in the buy orders. However, the emissions are uncertain which is shown by the error bars in Figure 26.

Considering the absolute emissions the main estimate is that 24000 tonnes of CO_2 emissions are saved due to the redispatch in the period of the collected data. If we consider the electricity production CO_2 emissions from 2019 [35] this would be a 0.07% decrease of the total CO_2 emissions of electricity production in the Netherlands. However, with the uncertainties considered this could range between -1000 and 65000 tonnes of CO_2 emissions. This translates to a saving of 190 kg CO_2/MWh with a range of -8 to 517 kg CO_2/MWh. The uncertainty for the buy orders is mostly caused by the uncertainty in the emissions factor of natural gas. This uncertainty comes from the fact that the efficiency of a CCGT depends on the operational condition. The efficiency is higher for full load compared to minimum load. The emissions are higher for a cold start compared to a hot start[36]. Furthermore, the CCGT power plant efficiency also depends on the ambient temperature, pressure and humidity [37]. A case study in Italy by Jarre et al. showed that an average efficiency of the CCGT power plants is around 50% [36], which matches with the emission factor that was used in this study. Though, there was a range the power plants ranged between 363.5–426.9 kg CO_2/MWh For the sell orders the uncertainty mostly comes from the uncertainty of the International category and the fact that the method of electricity production is unknown. Making a better estimate of the emissions saved by redispatch would require more research and data of the production of the electricity for the buy and sell orders.

A case study done on redispatch data from Germany also showed that the CO_2 emissions from the increase in production have been smaller than the emissions from the decrease of production. This resulted in an overall decrease in emissions [8]. However, their study did not take into account the emissions related to the increase in production outside of Germany.

We can also consider the redispatch without the international orders, since there is no accurate estimate for its emission factor and the international orders make up the majority of the sell orders. The changes the total volume of the buy and sell orders. Without the international orders the the there is 4743.2 MWh of sell orders, while there is 127157.8 MWh of buy orders. The buy orders are almost the same as with the international order, there is only 1.2 MW of international buy orders. In Figure 27 shows the share of natural gas and consumption for the sell orders if we do not consider the international orders. There is quite a difference for the different months. In January, July, October and November there is a bigger share of natural gas. In February, April, June and September there is a bigger share in consumption. For June this was already the case when including the international orders. In March and August there are no sell orders anymore.

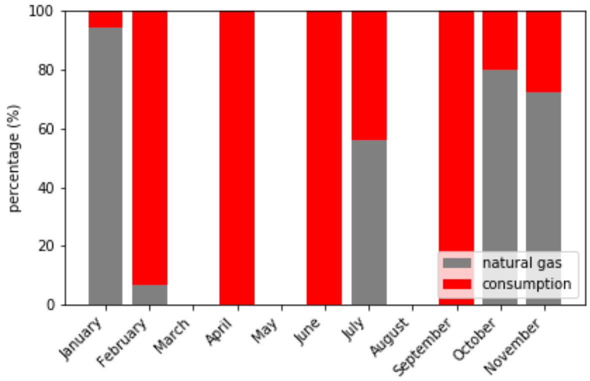


Figure 27: *Percentage of natural gas and consumption for the sell orders.*

Figure 28 shows the CO_2 emissions per MWh when including and excluding international orders. For the emissions without the International orders there is again quite a difference between the different months. The months with have a higher share of natural gas orders also have similar or higher emissions per MWh compared to the emissions that includes the international orders. In the other months there are almost no emissions when the international orders are not included.

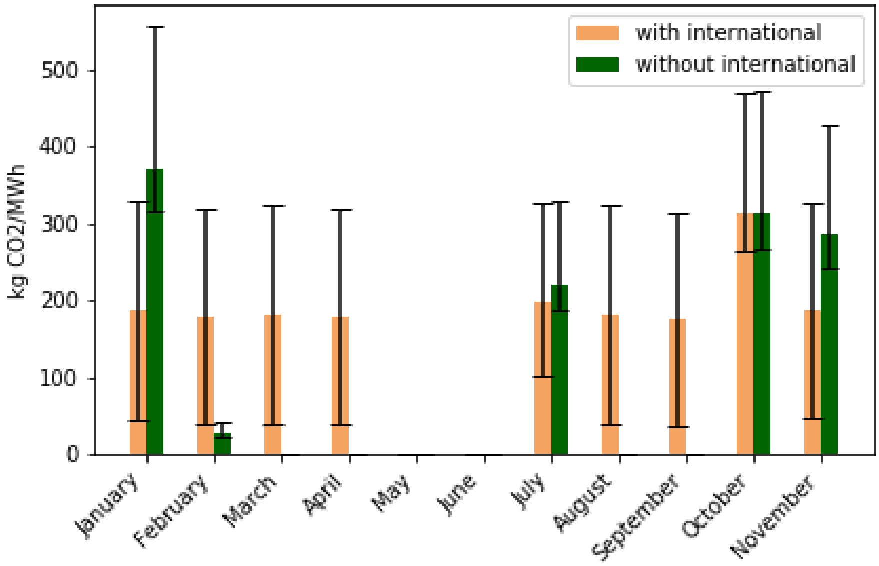


Figure 28: *Bar diagram showing the CO_2 emissions in kg/MWh of the sell orders when including international orders in orange and without international orders in green.*

In Figure 29 the CO_2 emissions for the buy and sell orders per MWh are shown when international orders are excluded. The emissions of the buy orders are similar to the case of with the International emissions, since there were almost no international buy orders. For most months the buy orders have higher CO_2 emissions per MWh compared to the sell orders, except in October and November. It is important to note that the amount MWh for the buy and sell orders is not the same when the international orders are excluded. For the absolute emissions this results in a main estimate of a decrease of 46485 tonnes of CO_2 emissions with a range of 38520-70619 tonnes of CO_2 emission due to the uncertainty. The translates to a decrease of 365 kg CO_2 per MWh of redispatch with a range of 302-555 kg CO_2/MWh.

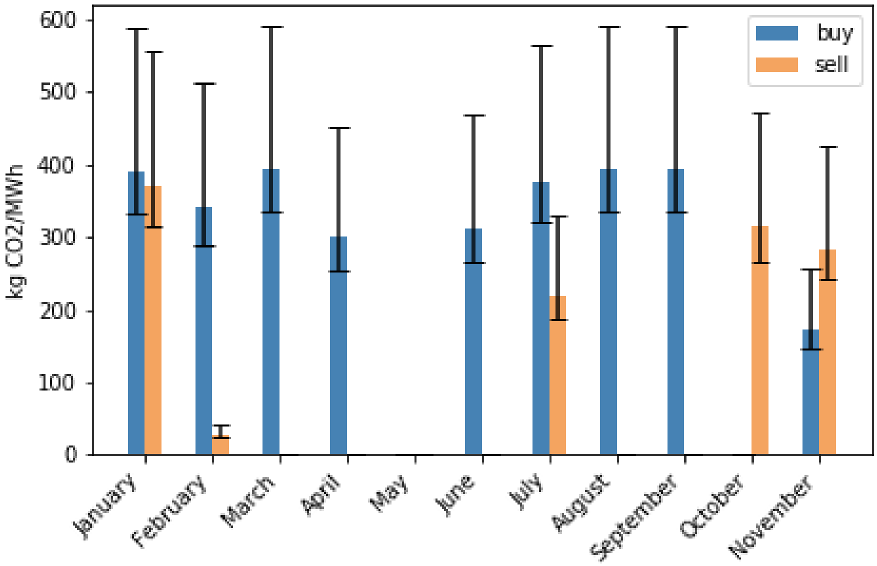


Figure 29: *Bar diagram showing the CO_2 emissions in kg/MWh of the buy orders in blue and of the sell orders in orange without International emissions.*

4.4 Limitations and Uncertainties

For the case study of the congestion problems the focus was on the volume of the congestion problem while the method is based on cost-optimization. It is possible that a solution with a higher volume is cheaper creating less intuitive results. Furthermore, a radial grid was assumed meaning the efficiency is not relevant. However, the transmission grid has a more meshed structure. Therefore, the efficiencies are relevant and influence the congestion solution. This influence on the congestion solution by different efficiencies could be further investigated. Furthermore, the historic data used to create the bid scenarios was not complete. The congestion problems and bid scenarios were not taken from the same moments. However, the congestion problems and the flexibility of the market are related. There could be seasonal dependencies. Moreover, the historic data does not represent the possible future congestion situation and market flexibility. The amount of congestion is expected to increase. Furthermore, the amount of renewable electricity production is expected to increase which would change the flexibility of the market[12].

For development of a bid structure the perspective and interest of the market is not considered. However, to fully understand how to capture as much flexibility from the market their interests should also be considered. Moreover, the change in bid structure will also have an impact on the market parties. They have to develop methods and the IT infrastructure to offer their flexibility in this new bid structure. Market parties also require some flexibility for themselves to balance their own assets when for example the wind electricity is different from what was predicted. Therefore, choices need to be made on how to use the new bid structure.

For the developed algorithm the run time was not considered. It is unknown what the impact of the adaptation in the algorithm has on the run time, especially on a large scale of congestion problems and bids. It requires further investigation to known if the developed algorithm is a practical method for finding congestion solutions.

In this study only the direct CO_2 emissions from redispatch are calculated. Future research could also consider a Life Cycle approach and include the indirect emissions. Furthermore, the assumption was made that a decrease in consumption did not change the consumption at any other period in time. However, it is possible that it would result in an increase of consumption at another moment. There are likely emissions associated with this increase. In this study only the change in emissions by redispatch done by GOPACS in done. Redispatch is also done by TenneT with ROP bids and therefore also has an impact on the emission change of redispatch in the Netherlands. Furthermore, redispatch is not the only method on congestion management used in the Netherlands. The other method that is used is curtailment. To get a more complete overview of the impact on CO_2 emissions the change in emissions by curtailment should also be quantified. The difficulty here is that the change in the market situation and the composition of the different methods of electricity production caused by curtailment is unknown. Then the environmental impact of congestion should also be considered from a bigger perspective. Renewable energy might have an impact on congestion. For example, a high amount of wind energy on sea might require a lot of transportation to more inland areas where the electricity is needed. Conversely, congestion also has an impact on renewable electricity production by curtailment or redispatch. Furthermore, congestion management like curtailment or redispatch could also increase the amount of renewable electricity production that can be connected to the electricity grid since with congestion management the electricity grid can be used more efficiently. Thus, impact on CO_2 emission by redispatch is only a small part of the total emission impact by congestion. Therefore, to get a better understanding of the environmental impact of congestion the other aspects named above should be investigated.

5 Conclusions

5.1 Bid structure and developed algorithm

This research aimed to identify what makes a good bid structure for market-based redispatch from a system operator perspective. I found that there are two important aspects to take into account when deciding what would be a good bid structure. Firstly, it is important that market parties can offer their flexibility with the structure and would also be willing to offer it. This means that the structure should take technical limitations of electricity producing assets into account and other limitations market parties could have. To limit the risk of not having enough offered flexibility to solve the congestion problems as well as increasing the possibilities to create an efficient solution. The flexibility might be much needed for future congestion problems. Secondly, the structure should make it possible to create an efficient congestion solution. This means that the buy and sell orders can easily be matched in time and volume. This mostly requires flexibility of the bid in volume. Flexibility in time is useful for creating an efficient solution as well as capturing the flexibility of the market.

I proposed a bid structure based on the conclusions above and developed a linear algorithm to decide what bids with such a structure to activate for redispatch. Moreover, the algorithm is able to use GOPACS orders in combination with bids of this new structure that is flexible in time. The implemented algorithm seems to work for the cases studied. The next step would be to try more complex congestion problems and bids to see if the algorithm is able to solve this and within a reasonable run time.

5.2 Redispatch emission change

This research aimed to create more insight into the environmental impact congestion by quantifying the change in CO_2 emissions due to market-based redispatch done by GOPACS. However, GOPACS is only a part of the redispatch done for congestion management. The redispatch done by GOPACS from 01-01-2022 up to and including 14-11-2022 amounted to around 0.1 TWh. The decreased electricity production as a result from this redispatch mostly came from CCGT power plants which has a share of 95.5% followed by wind with a share of 4.5 %. The increase of electricity production mostly came from the UK with a share of 96.3% followed by CCGT power plants with a share of 2.7%. Moreover, instead of an increase in production there was also a decrease of consumption with a share of 1%. The emission factors for electricity production are uncertain due to the variability in efficiency of CCGT power plant and the unknown sources of electricity production of the UK bids. For most of the months the emissions decreased around 122-313 kg CO_2/MWh except for October and November where the emissions increased with 311 and 15 CO_2/MWh. This resulted in an estimate of decrease 24000 tonnes of CO_2 due to redispatch done by GOPACS from 01-01-2022 up to and including 14-11-2022. Considering the electricity production CO_2 emissions from 2019, this would be a 0.07% decrease of the total CO_2 emissions of electricity production in the Netherlands. If we exclude the emissions of International orders, then the redispatch would result in a decrease of 46000 tonnes of CO_2. Thus, congestion management with market-based redispatch could result in CO_2 emission reduction, though large uncertainties remain.

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A Case study: congestion solutions

A.1 Results of the case study

The tables below show the solutions to the different problems with the different bid scenarios.

Table 14: *Solution to bid the TSO block problem for bid scenario 1.*

Order number	buy/sell	all-or-none	activated fraction	volume (MW)	Start ISP	duration (in ISP)
52	buy	yes	1	100	0	16
58	buy	yes	1	100	16	16
4	sell	no	1	100	0	4
8	sell	no	1	100	4	4
15	sell	no	1	100	8	4
22	sell	no	1	100	12	4
28	sell	no	1	100	16	4
34	sell	no	1	100	20	4
41	sell	no	1	100	24	4
47	sell	no	1	100	28	4

The solution to the TSO block problem with bid scenario 2 is the same as in Table 14, except that the orders are all all-or-none. The solution to the TSO block problem with bid scenario 4 is also the same as in Table 14.

Table 15: *Solution to bid the TSO block problem for bid scenario 3.*

Order number	buy/sell	all-or-none	activated fraction	volume (MW)	Start ISP	duration [ISP]
25	buy	yes	1	425	0	16
30	buy	yes	1	425	16	16
28	sell	yes	1	400	0	16
34	sell	yes	1	400	16	16
13	sell	no	0.5	50	16	4
19	sell	no	0.5	50	24	4
1	sell	no	0.25	100	0	4
4	sell	no	0.25	100	4	4
7	sell	no	0.25	100	8	4
10	sell	no	0.25	100	12	4
16	sell	no	0.25	100	20	4
23	sell	no	0.25	100	28	4

Table 16: *Solution to bid the TSO block problem for bid scenario 5.*

Order number	buy/sell	all-or-none	activated fraction	volume (MW)	Start ISP	duration [ISP]
12	buy	no	1	9	8	4
13	buy	no	1	9	8	4
14	buy	no	1	7.5	12	4
19	buy	no	1	9	12	4
20	buy	no	1	9	12	4
21	buy	no	1	7.5	12	4
58	buy	no	1	100	16	4
28	sell	no	1	100	16	4
15	sell	no	0.5	100	8	4
22	sell	no	0.5	100	12	4
11	buy	no	0.49	50	8	4
18	buy	no	0.49	50	12	4

Table 17: *Solution to bid the TSO block problem for bid scenario 6.*

Order number	buy/sell	all-or-none	activated fraction	volume (MW)	Start ISP	duration [ISP]
11	buy	no	1	50	8	4
12	buy	no	1	9	8	4
13	buy	no	1	9	8	4
14	buy	no	1	7.5	8	4
18	buy	no	1	50	12	4
19	buy	no	1	9	12	4
20	buy	no	1	9	12	4
21	buy	no	1	7.5	12	4
25	buy	no	1	9	16	4
26	buy	no	1	9	16	4
27	buy	no	1	7.5	16	4
15	sell	no	1	100	8	4
22	sell	no	1	100	12	4
28	sell	no	1	100	16	4
34	sell	no	0.745	100	20	4
41	sell	no	0.745	100	24	4
47	sell	no	0.745	100	28	4
3	sell	no	0.245	100	0	4
8	sell	no	0.245	100	4	4
60	buy	no	0.18	425	16	16
51	buy	no	0.06	425	0	16

Table 18: *Solution to bid the TSO volatile problem for bid scenario 1.*

Order number	buy/sell	all-or-none	activated fraction	volume (MW)	Start ISP	duration [ISP]
49	buy	yes	1	100	0	16
52	buy	yes	1	100	0	16
3	sell	no	1	100	0	4
4	sell	no	1	100	0	4
8	sell	no	1	100	4	4
9	sell	no	1	50	4	4
15	sell	no	1	100	8	4
16	sell	no	1	50	8	4
22	sell	no	1	100	12	4
23	sell	no	1	50	12	4
10	sell	no	0.5	100	4	4
17	sell	no	0.5	100	8	4
24	sell	no	0.5	100	12	4

The solution to the TSO volatile problem with bid scenario 4 is the same as in Table 18.

Table 19: *Solution to bid the TSO volatile problem for bid scenario 2.*

Order number	buy/sell	all-or-none	activated fraction	volume (MW)	Start ISP	duration [ISP]
49	buy	yes	1	100	0	16
52	buy	yes	1	100	0	16
3	sell	yes	1	100	0	4
4	sell	yes	1	100	0	4
8	sell	yes	1	100	4	4
10	sell	yes	1	100	4	4
15	sell	yes	1	100	8	4
17	sell	yes	1	100	8	4
22	sell	yes	1	100	12	4
24	sell	yes	1	100	12	4

Table 20: *Solution to bid the TSO volatile problem for bid scenario 3.*

Order number	buy/sell	all-or-none	activated fraction	volume (MW)	Start ISP	duration [ISP]
25	buy	yes	1	425	0	16
28	sell	yes	1	425	0	16
1	sell	no	0.25	100	0	4
4	sell	no	0.25	100	4	4
7	sell	no	0.25	100	8	4
10	sell	no	0.25	100	12	4

Table 21: *Solution to bid the TSO volatile problem for bid scenario 5.*

Order number	buy/sell	all-or-none	activated fraction	volume (MW)	Start ISP	duration [ISP]
12	buy	yes	1	9	8	4
13	buy	yes	1	9	8	4
14	buy	no	1	7.5	8	4
19	buy	no	1	9	12	4
20	buy	no	1	9	12	4
21	buy	no	1	7.5	12	4
54	buy	yes	1	200	4	4
8	sell	no	1	100	4	4
9	sell	no	1	50	4	4
18	buy	no	0.99	100	12	4
22	sell	no	0.75	100	12	4
10	sell	no	0.5	100	4	4
15	sell	no	0.5	100	8	4
11	buy	no	0.49	50	8	4

Table 22: *Solution to bid the DSO block problem for bid scenario 1.*

Order number	buy/sell	all-or-none	activated fraction	volume (MW)	Start ISP	duration [ISP]
7	buy	no	0.23	7.5	4	4
14	buy	no	0.23	7.5	8	4
21	buy	no	0.23	7.5	12	4
27	buy	no	0.23	7.5	16	4
8	sell	no	0.02	100	4	4
15	sell	no	0.02	100	8	4
22	sell	no	0.02	100	12	4
28	sell	no	0.02	100	16	4

The solution to the DSO block problem with bid scenario 3, bid scenario 5 and bid scenario 6 is the same as in Table 22.

Table 23: *Solution to bid the DSO block problem for bid scenario 2.*

Order number	buy/sell	all-or-none	activated fraction	volume (MW)	Start ISP	duration [ISP]
52	buy	yes	1	100	0	16
58	buy	yes	1	100	16	16
3	sell	yes	1	100	0	4
8	sell	yes	1	100	4	4
15	sell	yes	1	100	8	4
22	sell	yes	1	100	12	4
28	sell	yes	1	100	16	4
34	sell	yes	1	100	20	4
41	sell	yes	1	100	24	4
47	sell	yes	1	100	28	4

The solution to the DSO block problem with bid scenario 4 is the same as in Table 23.

Table 24: *Solution to bid the DSO volatile problem for bid scenario 1.*

Order number	buy/sell	all-or-none	activated fraction	volume (MW)	Start ISP	duration [ISP]
21	buy	no	1	7.5	12	4
27	buy	no	1	7.5	16	4
33	buy	no	1	7.5	20	4
40	buy	no	0.83	7.5	24	4
7	buy	no	0.77	7.5	4	4
14	buy	no	0.6	7.5	8	4
2	buy	no	0.33	7.5	0	4
20	buy	no	0.32	9	12	4
32	buy	no	0.2	9	20	4
22	sell	no	0.1	100	12	4
34	sell	no	0.09	100	20	4
28	sell	no	0.08	100	16	4
26	buy	no	0.07	9	16	4
41	sell	no	0.06	100	24	4
8	sell	no	0.6	100	4	4
15	sell	no	0.05	100	8	4
4	sell	no	0.03	100	0	4
45	buy	no	0.02	100	28	4
47	sell	no	0.02	100	28	4

The solution to the TSO block problem with bid scenario 5 and bid scenario 6 is the same as in Table 24.

Table 25: *Solution to bid the DSO volatile problem for bid scenario 2.*

Order number	buy/sell	all-or-none	activated fraction	volume (MW)	Start ISP	duration [ISP]
52	buy	yes	1	100	0	16
58	buy	yes	1	100	16	16
3	sell	yes	1	100	0	4
8	sell	yes	1	100	4	4
15	sell	yes	1	100	8	4
22	sell	yes	1	100	12	4
28	sell	yes	1	100	16	4
34	sell	yes	1	100	20	4
41	sell	yes	1	100	24	4
47	sell	yes	1	100	28	4

The solution to the DSO volatile problem with bid scenario 4 is the same as in Table 25.

Table 26: *Solution to bid the DSO volatile problem for bid scenario 3.*

Order number	buy/sell	all-or-none	activated fraction	volume (MW)	Start ISP	duration [ISP]
9	buy	no	1	9	12	4
30	buy	yes	1	425	16	16
34	sell	yes	1	400	16	16
3	buy	no	0.77	7.5	4	4
6	buy	no	0.5	9	8	4
13	sell	no	0.5	50	16	4
19	sell	no	0.5	50	24	4
0	buy	no	0.33	7.5	0	4
16	sell	no	0.25	100	20	4
23	sell	no	0.25	100	28	4
10	sell	no	0.1	100	12	4
4	sell	no	0.06	100	4	4
7	sell	no	0.05	100	8	4
8	buy	no	0.03	50	12	4
1	sell	no	0.03	100	0	4

B Flexibility attributes of existing bid structures

Table 27: *Table containing attributes related to flexibility of the current ROP bids structure.*

Attribute	Explanation
Preperation time	Minimum number of ISPs between moment of accepting the bid and activation of bid.
Delivery period	Minimal consecutive number of ISPs a bid has to be activated.
Volume	amount of MW. A positive value to increase the electricity in-feed and a negative value to decrease the electricity in-feed.
Bid rows	The time periods a bid can be activated
Regelobject	Linkage of two bids. When one of the two bids is activated the other cannot be activated anymore.

Table 28: *Table containing attributes related to the flexibility of the ENTSO-E reserve bid [28].*

Attribute	Explanation
Divisible	Indication whether or not each element of the bid may be partially accepted or not.
Block bid	Indication that the values in the period are considered as a whole. The bid cannot be changed or subdivided.
Step increment quantity	The minimum increment that can be applied for an increase in an activation of a bid.
Activation constraint duration	The delay between moment of accepting the bid and activation of bid.
Resting constraint duration	Delay to be respected between the end of activation and the start of the next activation.
Minimum constraint duration	The minimum duration that a bid has to be activated.
Maximum constraint duration	The minimum duration that a bid has to be activated.
Multipart Bid	The bids linked together must all be accepted.
Exclusive Bid	Only one of the bids linked together can be activated.
Quantity	The quantity is either the maximum quantity, if there is a minimal quantity, or the quantity that can be activeted at a given time position (e.g. an ISP).
Minimum quantity	The minimum quantity that can be activated at a given time position (e.g. an ISP).

Table 29: *Table containing attributes related to the flexibility of the UK balancing mechanism [38][39].*

Attribute	Explanation
Max export/import limit	The maximal volume in MW of exporting/importing at associated times.
Run-down/up rate	The rate of running up/down in MW/minute, also called the ramp-rate.
Notice to deliver bids	The delay between moment of accepting the bid and activation of bid.
Minimum zero time	The minimal duration the activation needs to be zero before returning to importing or exporting.
Stable export/import limit	Positive/negative volume in MW expressing the minimum stable export/import operating level.
Maximum delivery volume	Maximum power in MWh that can be activated.
Maximum delivery period	The maximum period over which the maximum delivery volume applies.