Integrating User Requirements in Uni-directional Congestion Mitigation Algorithms for Smart Grids

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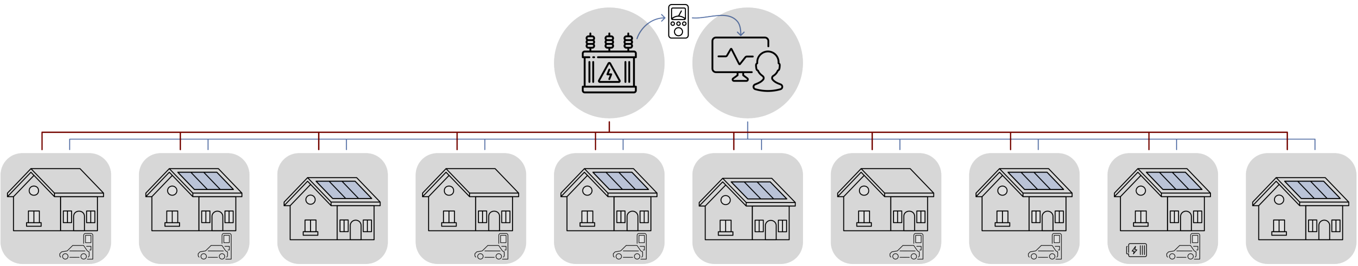

Fig. 1. Depiction of the Simulated Entities.

The adoption of variably generated renewable energy sources and the shift to electric transport and heating is imposing new demands on the power grid. Congestion occurs when the local demand for energy transportation exceeds the physical limitations of the grid. The flexibility of many electrical devices allows mechanisms to be deployed that mitigate congestion. To prevent power outages, a mechanism is needed that intervenes by controlling flexible devices when congestion occurs. For such mechanisms, uni-directional control algorithms provide regulatory and privacy advantages over bi-directional approaches, which require data to be published by the connected devices. However, uni-directional control algorithms do not yet consider the requirements of individual users as bi-directional approaches do. This paper presents and examines the effectiveness of a novel uni-directional congestion mitigating measure that considers individual user requirements using uni-directional auctions, such that priority is given to users with a higher need for grid capacity. Various algorithms are evaluated in a simulated low-voltage grid of ten households, uni-directional auctions are 94.3% as effective as their bi-directional counterpart at mitigating congestion, and 87.6% as effective at meeting user requirements.

Additional Key Words and Phrases: Energy Transition, Energy Security, Smart Grid, Congestion Mitigation, User Centric Uni-directional Control

1 INTRODUCTION

Congestion on the power grid, which can negatively impact energy security, is a thermal overload of the power grid's hardware components. Congestion occurs when too much power is being transported over the physical infrastructure. The electrification of heating and transport increases the risk of local congestion [5, 13]. Additionally, transporting high proportions of variably generated renewable energy over a power grid requires adjusting demand, such that it matches the variable supply, in order to keep the alternating current frequency on the grid consistent [7].

Demand flexibility is the ability for devices to adjust their electricity consumption based on external factors such as pricing or the state of the power grid. Active control mechanisms can be used to control flexible devices, such as electric vehicles (EV) and battery energy storage systems (BESS), in order to mitigate congestion [12]. However, demand flexibility can also be used to maintain a global balance in supply and demand. This can worsen local congestion issues [1, 8].

GridShield is a uni-directional active control mechanism that intervenes when the demand for energy transport exceeds the local grid capacity [9]. GridShield consists of two types of components: a single transmitter and multiple receivers. The GridShield transmitter is placed at the transformer station, which is the physical connector that links the local power grid to the rest of the system. Each receiver is located near EV supply equipment (EVSE) and can directly control its behaviour. The measured power at the transformer station is a strong indicator for congestion in its section of the grid [11]. In case the measured power is greater than the rated capacity, the transmitter broadcasts to all connected devices an instruction to reduce the maximum power that can be taken from the grid. Van Sambeek et al. [11] have shown that GridShield intervenes before potential power outages occur in both simulations and real-world tests. They conclude that, "Due to its unidirectional design, it is deemed compatible with Dutch and EU privacy laws [...]".

When GridShield intervenes the maximum power for all devices is decreased equally although one device might have a stronger need for energy, to serve its user's requirements, than others. One user might for instance want their EV to charge 10kWh in one hour, while another may be able to wait for an extra hour to receive the same amount of energy. GridShield would in this case still assign the same capacity to both EVs.

Double-sided auctions are a bi-directional active control mechanism which can be used to control a cluster of devices such that a target power for the entire cluster is maintained [3, 6]. The coordinating entity, or auctioneer, can request bid functions from all connected devices. Each device then publishes such a bid function, in which it indicates how much energy it would use for all possible energy prices. A bid function expresses for each device how great its need for power, and thus grid capacity, is. Knowing all bid functions, the auctioneer is able to determine a price for which

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the total power complies with the physical limitations of the grid. Double-sided auctions are device agnostic and thus deemed future proof, but because each device needs to submit its bid function it requires bi-directional communication.

This paper explores a novel approach named uni-directional auctions, which is a uni-directional congestion mitigation measure that considers user requirements even though connected devices do not need to publish data such as their bid functions. In uni-directional auctions the auctioneer sets a price based on the live measurements at the transformer station rather than inspecting the bid functions of the connected devices. Uni-directional auctions improve over GridShield by expanding the scope to any generic device-type and by yielding priority to devices for which the user has a higher desire for grid capacity. Compared to double-sided auctions, uni-directional auctions enhance privacy by eliminating the need for devices to disclose their bid functions. Consequently, the uni-directional auctioneer does not require any data reception capabilities, other than its local measurements, which greatly reduces security risks. Additionally, new flexible devices can be added to the system more easily as their public keys do not need to be known by the auctioneer.

The feasibility of uni-directional auctions is evaluated and compared against other solutions using a simulation of ten households. The following research questions are addressed:

- **Research Question:** How can electricity consuming, storing and producing devices coordinate their behaviour in order to collectively operate within the physical limitations of the power grid while adhering to respective users requirements using uni-directional communication?

We answer the above research question using the following sub-questions:

- *Sub-question 1:* How can measurements of the physical state of the power grid inform a uni-directional control algorithm that considers user requirements?
- *Sub-question 2:* What metrics are effective in evaluating the performance of a congestion mitigation algorithm?

Section 2 explores requirements to which an active control congestion mitigation mechanism should comply. Both quantitative and qualitative measures are defined. In Section 3 we evaluate GridShield and double-sided auctions in depth. Section 4 presents uni-directional auctions and lays out how an auctions based approach can be applied as a congestion mitigation measure. Section 5 describes how the various congestion mitigation measures are tested, while Section 6 presents the results. Finally, Section 7 interprets the findings and answers the research questions.

2 REQUIREMENTS

An active control mechanism for congestion mitigation needs to meet several requirements to be effective and practical. Both quantitative and qualitative metrics are established. The quantitative requirements quantify the performance of a mechanism in two key areas: the ability to guard the power limits of the system and the ability to comply with user requirements. The quantitative requirements help in evaluating the applicability of control mechanisms in real scenarios.

2.1 Quantitative Requirements

We define the following quantitative requirements and their respective metrics:

2.1.1 Congestion Mitigation. The system must respond quickly to changes in grid conditions to prevent overload and potential failures. We measure the extent to which both the positive and negative power limits of the local grid are violated.

$P_{\text{trafo, t}}$ is the power at the transformer station at time t. The positive power limit is denoted as $P^{(\text{max})}_{\text{trafo}}$ and the negative power limit as $P^{(\text{min})}_{\text{trafo}}$. We utilise the euclidean norm of the power limit violations, $||P_{\text{viol}}||_2$, in order to quantify thermal buildup of the hardware components of the grid [11] during T moments in time:

$$||P_{\text{viol}}||_2 = \sqrt{\sum_{t=1}^{T} \max(0, \max(P_{\text{trafo},t} - P^{(\text{max})}, P^{(\text{min})} - P_{\text{trafo},t})^2}.$$

2.1.2 Priority Differentiation. The system should meet as many individual user requirements as possible. We quantify the impact of congestion mitigation measures on the user experience by comparing the available grid capacity with the capacity that is needed to meet the user requirements. We do this in a different manner for each evaluated device-type, because users have different demands of each type. PHEVs, EVs, PV systems and BESSs are considered in this work. No specific metric is constructed for BESSs, as they specifically serve the purpose of improving on congestion mitigation performance and the priority differentiation metrics of other device-types.

- For PHEVs and EVs we calculate the unmet energy demand for each charging session, referred to as the energy not served (ENS). For each session s in a set of sessions S, a target energy $E_s^{(\text{target})}$ is defined. $E_s^{(\text{target})}$ is compared with the actual amount of energy charged:

$$E_{\text{EV\_ENS}} = \sum_{s=1}^{S} (E_s^{(\text{target})} - E_s^{(\text{charged})}).$$

- Flexible PV systems can be curtailed, which is the intentional reduction or shutting down of power generation. For PV systems we consider the energy that could have been generated from solar radiation, but was not due to the control mechanisms. This number is referred to as the total curtailed energy: $E_{\text{curtailed}}$.

2.2 Qualitative Requirements

The following qualitative requirements are established:

- **Privacy:** a congestion mitigation measure must minimize the need for sharing sensitive information about user's energy consumption patterns.
- **Feasibility:** a congestion mitigation measure must be easy to implement and require minimal changes to existing infrastructure.
- **Device Independence:** a congestion mitigation measure must be applicable to all energy consuming, storing and producing devices.

- **Non-Disruptiveness:** a congestion mitigation measure must disrupt the normal operation and behaviour of flexible devices as little as possible.

Privacy and *feasibility* are essential for a given congestion mitigation measure to be applicable in a practical environment with real users. *Device independence* grants a control mechanism the ability to (more effectively) spread the burden by leveraging more flexibility in the system. *Non-disruptiveness* is crucial for two reasons. Firstly, a congestion mitigation measure should alter the behaviour of devices as seldom as possible in order to minimize the impact on user experience. Secondly, in the European Union, the networking companies who are responsible for the stability of the power grid are forbidden to intervene in the electricity markets [2]. A congestion mitigation measure should thus only intervene when strictly necessary for the stability of the grid, such that all connected users can participate in the internal market. This also allows the balancing of supply and demand to co-exist with congestion mitigation.

3 EXISTING ACTIVE CONTROL MECHANISMS

In this section we discuss control mechanisms that have already been presented in literature.

3.1 GridShield

GridShield was designed to use the available grid capacity more effectively by controlling the maximum charge rate of EVSEs [9, 11]. GridShield measures the power at the transformer that connects the concerning EVSEs, P_{trafo}.

If $P_{\text{trafo}} > P^{(\text{max})}_{\text{trafo}}$ the GridShield transmitter publishes ϕ where $0 \leq \phi < 1$. EVSEs set their new maximum charge rate as follows: $P^{(\text{GS-max})}_{\text{EVSE}} = \phi \cdot P^{(\text{max})}_{\text{EVSE}}$. The parameter ϕ is chosen using a control algorithm such that $\phi = 1$ if no congestion occurs and is reduced up to a minimum of $\phi = 0$ if congestion does occur [9].

3.2 Double-sided Auctions

Double-sided auctions are a bi-directional active control mechanism that can be used to control a cluster of devices such that a target power for the entire cluster is maintained [3] [6]. The coordinating auctioneer requests bid functions from all devices. Each device replies with a bid function, in which it expresses its need (and indirectly the users need) for energy. A bid function is a monotonically decreasing function $b(p)$ that relates a price p to a power value P. For instance, a high value P at a high price p indicates that a device will consume a high amount of power even if this is expensive. Another device that would like to consume great amounts of power, but has less of an urgent need to do so, can lower P for high prices, but keep P high for lower prices.

Given the aggregate of all bid functions, the auctioneer is able to determine a price for which the total power complies with the physical limitations of the grid. A hierarchical control structure may be implemented such that aggregators forward an aggregate bid function of their respective clusters to a higher level auctioneer, which would allow the entire power grid to be covered by an auctioneer. Such coverage can allow for the balancing of the global supply and demand. In this paper no aggregators are considered as we specifically study congestion mitigating properties. Figure 2 shows an example of bid functions by various devices and their aggregate function. Points of interest are marked on the aggregate function where $P = P^{(\text{min})}_{\text{trafo}}$, $P = P^{(\text{max})}_{\text{trafo}}$ and $p = 0$. Table 1 compares GridShield and double-sided auctions on the qualitative requirements defined in Section 2.2.

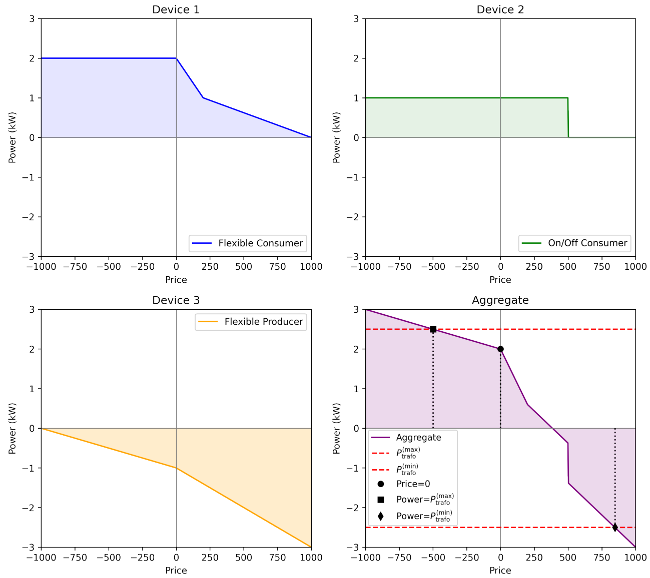

Fig. 2. Bid functions of devices and their aggregate function.

4 CONTRIBUTION

In this section, we introduce uni-directional auctions, a novel active control mechanism that employs similar priority differentiation as double-sided auctions but utilizes uni-directional communication. Additionally, we present a specific implementation of uni-directional auctions designed for congestion mitigation, ensuring non-disruptiveness. This is achieved through deliberate design choices in the control algorithm and the selection of bid functions.

Section 4.1 presents the general concept of uni-directional auctions. Section 4.2 presents a design for bid functions specifically tailored to congestion mitigation. Finally, Section 4.3 presents a control algorithm for uni-directional auctions that, when combined with the concepts presented in Section 4.2, only intervenes when there is a risk of congestion. Table 2 provides an overview of uni-directional auctions with respect to the qualitative requirements defined in Section 2.2.

4.1 Uni-directional Auctions

In uni-directional auctions, each device produces its bid function $b(p)$ as it would in double-sided auctions, but does not publish it to the auctioneer. The auctioneer constantly measures the power at the transformer station and alters the price p according to a control algorithm, such that the measured power shifts as close as possible towards the desired power $P^{(\text{target})}$. The updated value p is published to all devices over a uni-directional communication link. Each device

Qualitative Requirements	GridShield	Double-sided Auctions
Privacy	No privacy-sensitive data is published by the devices.	Requires bid functions to be published, potentially exposing privacy-sensitive data.
Feasibility	Easy to implement; only one way communication is needed and devices simply multiply their regular maximum power by ϕ where $0 \leq \phi \leq 1$.	Each device needs to create a bid function and abide by it. Two way communication is needed between the auctioneer and each device.
Device Independence	Originally EV specific, though implementations can be made to include any device-type.	Completely device independent.
Non-Disruptiveness	Only intervenes when strictly necessary.	Continuous control of total power. Sections 4.2 & 4.3 show that this can be implemented such that the alteration of default behaviour is only limited to situations when congestion occurs.

Table 1. Qualitative Evaluation of GridShield and Double-sided Auctions

Qualitative Requirements	Uni-directional Auctions
Privacy	No privacy-sensitive data is published by the devices.
Feasibility	Easy to implement; only one way communication is needed. Each device needs to create a bid function and abide by it.
Device Independence	Completely device independent.
Non-Disruptiveness	Continuous control of total power. Sections 4.2 & 4.3 show that this can be implemented such that the alteration of default behaviour is only limited to situations when congestion occurs.

Table 2. Qualitative Evaluation of Uni-directional Auctions

consumes the amount of power it determined in its, privately held, bid function $b(p)$. The auctioneer here has a function similar to the transmitter in GridShield. The auctioneer (or transmitter in the case of GridShield) alters the price p (or ϕ for GridShield) based on a control algorithm that is informed by measurements at the transformer station.

4.2 Bid Functions for Congestion Mitigation

The GridShield transmitter only defines a maximum power limit for devices. If there is no risk of congestion, the GridShield transmitter simply grants all devices their usual maximum power and thus these devices behave as they would without congestion mitigation related control. Both uni-directional and double-sided auctions are different in that the price, given some $b(p)$, defines the exact power at which a device should operate. In order for uni-directional and double-sided auctions to be used solely as a congestion mitigation measure, a scheme should be used in which devices do behave as they would prefer to, *unless* there is a risk of congestion. This can be done by selecting all bid functions such that at some price p_0 devices operate on the power that they would prefer to operate on. Given the bid functions with a distinct p_0, the goal simply becomes to keep p equal or as close as possible to p_0. The price p can still be altered if the aggregate power at price p_0 does not respect the systems constraints. An increase in p reduced P and a decrease in p increases P.

4.3 Congestion Mitigation Control Algorithms for Uni-directional and Double-sided Auctions

Algorithm 1 chooses a price p in order to ensure non-disruptiveness, taking the aggregate bid function $b_{\text{agg}}(p)$ as an input. The maximum and minimum power limits of the system, $P^{(\text{max})}_{\text{trafo}}$ and $P^{(\text{min})}_{\text{trafo}}$, are also defined. The inverse of the aggregate bid function, $b^{-1}_{\text{agg}}(P)$, can be used to find the price p at which $P = P^{(\text{target})}$. As devices do not have infinite flexibility, the bid functions are defined with a minimum $p^{(\text{min})}$ and maximum $p^{(\text{max})}$. A situation may arise where either of these extremes is not enough to ensure $P^{(\text{min})}_{\text{trafo}} \leq P \leq P^{(\text{max})}_{\text{trafo}}$. In this case there is simply not enough flexibility in the system and no feasible solutions exists.

Algorithm 1 Bi-directional Auctioneer: choose p

```
if $b_{\text{agg}}(p_0) < P^{(\text{min})}_{\text{trafo}}$ then
    $p \leftarrow \max(p^{(\text{min})}, b^{-1}_{\text{agg}}(P^{(\text{min})}_{\text{trafo}}))$    ▷ $P^{(\text{min})}_{\text{trafo}}$ is violated
else if $b_{\text{agg}}(p_0) > P^{(\text{max})}_{\text{trafo}}$ then
    $p \leftarrow \min(p^{(\text{max})}, b^{-1}_{\text{agg}}(P^{(\text{max})}_{\text{trafo}}))$    ▷ $P^{(\text{max})}_{\text{trafo}}$ is violated
else
    $p \leftarrow p_0$    ▷ neither limit is violated
end if
```

If $b_{\text{agg}}(p)$ is not known, a more intricate algorithm is needed to achieve similar behaviour. For uni-directional auctions, the inputs of the control algorithm are the measured power at the transformer station P_{trafo} and the current price p. $P^{(\text{min})}_{\text{trafo}}$ and $P^{(\text{max})}_{\text{trafo}}$ are also known. Algorithm 2 presents pseudo-code for the control algorithm of the auctioneer in uni-directional auctions. Using only the known measurements and constants the system knows whether the price should be increased, decreased or remain the same, but it does not know how great the changes to p should be. The algorithm *probes* for the desired price p rather than using $b_{\text{agg}}(p)$ to determine what exact value p should be.

Algorithm 2 Uni-directional Auctioneer: choose p *(conceptual)*

```
if $P_{\text{trafo}} > P^{(\text{max})}_{\text{trafo}}$ then
    increase $p$                                  ▷ goal: $P_{\text{trafo}} = P^{(\text{max})}_{\text{trafo}}$
else if $P_{\text{trafo}} < P^{(\text{min})}_{\text{trafo}}$ then
    decrease $p$                                  ▷ goal: $P_{\text{trafo}} = P^{(\text{min})}_{\text{trafo}}$
else
    if $p > p_0$ then
        decrease $p$                              ▷ until $p = p_0$
    else if $p < p_0$ then
        increase $p$                              ▷ until $p = p_0$
    end if
end if
```

Algorithm 3 is an implementation where we define the adjustments to p to be proportional to the error either between P_{trafo} and $P^{(\text{max})}_{\text{trafo}}$ or between P_{trafo} and $P^{(\text{min})}_{\text{trafo}}$. The parameters a, x and y are introduced. a is an offset that shifts $P^{(\text{min})}_{\text{trafo}}$ and $P^{(\text{max})}_{\text{trafo}}$ to create a safety band between the considered power limits and the actual physical power limits of the grid. y defines how large the shift of p is towards p_0 when $P^{(\text{min})}_{\text{trafo}} \leq P \leq P^{(\text{max})}_{\text{trafo}}$. Similarly, x defines how large the shift of p is away from p_0 when $P < P^{(\text{min})}_{\text{trafo}}$ or $P > P^{(\text{max})}_{\text{trafo}}$. We choose to use $\frac{P_{\text{trafo}} - limit}{limit}$, where *limit* is either the upper or lower limit, as opposed to $P_{\text{trafo}} - limit$, because the former version does not require different parameters if the system has a different capacity. As long as the proportions of device-types and the flexible capacity of those devices stays the same the parameters remain effective.

Algorithm 3 Uni-direction Auctions: choose p

```
upper_limit ← $P^{(\text{max})}_{\text{trafo}} - a$
lower_limit ← $P^{(\text{min})}_{\text{trafo}} + a$
if $P_{\text{trafo}} >$ upper_limit then
    $p \leftarrow min(p^{(\text{max})}, p + (x \cdot \frac{P_{\text{trafo}} - \text{upper\_limit}}{\text{upper\_limit}}))$        ▷ increase $p$
else if $P_{\text{trafo}} <$ lower_limit then
    $p \leftarrow max(p^{(\text{min})}, p - (x \cdot \frac{P_{\text{trafo}} - \text{lower\_limit}}{\text{lower\_limit}}))$        ▷ decrease $p$
else
    if $p > p_0$ then
        $p \leftarrow \max(p_0, p - (y \cdot \frac{P_{\text{trafo}} - \text{upper\_limit}}{\text{upper\_limit}}))$        ▷ decrease $p$
    else if $p < p_0$ then
        $p \leftarrow \min(p_0, p + (y \cdot \frac{P_{\text{trafo}} - \text{lower\_limit}}{\text{lower\_limit}}))$        ▷ increase $p$
    end if
end if
```

5 METHODOLOGY

To evaluate the different active control congestion mitigation measures we utilize a simulated environment using artificial load profiles for ten households generated using the tools presented in [4]. Seven households have PV production, half of the houses have an EV while two households have a PHEV. One households contains a BESS. A full year is simulated, with a resolution of one minute. For each EV charge sessions are defined with a start time, end time and target energy, which is used to calculate the energy not served $E_{\text{EV\_ENS}}$. A base case is simulated where no congestion mitigation takes place. Additionally double-sided auctions and uni-directional auctions are evaluated. This paper specifically evaluates the feasibility of uni-directional auctions. Uni-directional auctions, given a perfect control algorithm, are to behave exactly as double-sided auctions do as the double-sided auctioneer already knows, given $b_{\text{agg}}(p)$, what the optimal price p is. The comparison between uni-directional auctions and double-sided auctions is thus crucial. GridShield as presented in [9, 11] does not consider devices other than EVs and provides no protection of the negative power limit. Thus we do not evaluate our method by comparing it to GridShield, as the comparison would be unfair and would not contribute meaningfully to assessing the feasibility of uni-directional auctions.

5.1 Simulations

5.1.1 Base Case: No Congestion Mitigation. As a base case, we run a simulation where devices consume the power that they would without any control.

5.1.2 Double-sided Auctions. The auctions implementation [10] is used to simulate the auctioneer and its interaction with all devices. The price p is determined using Algorithm 1.

5.1.3 Uni-directional Auctions. The auctions implementation [10] is also used for the implementation of uni-directional auctions, but the auctioneer cannot access bid functions of any of the devices. Algorithm 3 is used to set the price p. Parameter a is set to 10% of the respective power limits. A parameter sweep is done for variables x and y where:

$$x, y \in \{0.5, 1, 2, 3, 4, 5, 7, 10, 15, 25, 50, 100, 200, 300, 500\}.$$

5.2 Bid functions

Bid functions are chosen according to the constraints laid out in Section 4.2. Concretely, $p_0 = 0$, $p_{(\text{max})} = 1000$ and $p_{(\text{min})} = -1000$. The same bid functions are used for both double-sided auctions and uni-directional auctions. Figure 3 shows the bid functions of the used device-types in the simulated environment: EV, PV, BESS and a baseload. The baseload encompasses all non-flexible devices in a household, which are assumed to be uncontrollable by the simulated congestion mitigation measures.

We define bid functions by setting points and interpolating a curve between these points. Figure 3 marks these points for the EV, PV and BESS bid functions:

- **EV**: the volume under the bid curve is reduced if there is a low need for energy in order to fulfill the users requirement: $A = (p = -1000, P = P^{(\text{max})}_{\text{EV}})$, $B = (p = 0, P = P^{(\text{max})}_{\text{EV}})$, $C = (p = 500, P = \frac{\text{energy left to charge}}{\text{time left}})$, $D = (p = 1000, P = 0)$.
- **PV**: $P^{(\text{min})}_{\text{PV}}$ is the total power the PV installation can generate at the present solar irradiance. $A = (p = -1000, P = P^{(\text{max})}_{\text{PV}} = 0)$, $B = (p = -500, P = P^{(\text{min})}_{\text{PV}})$, $C = (p = 1000, P = P^{(\text{min})}_{\text{PV}})$.

- **BESS** the state of charge (SoC) of the BESS is reflected in the bid function such that, at $p = 0$, the BESS tends to SoC = 0.5:
  $A = (p = -1000, P = P_{\text{Batt}}^{(\max)})$,
  $B = (p = \max(-1000, -1200 + (1 - \text{soc}) * 2000), P = 0)$,
  $C = (p = \min(1000, 1200 - \text{soc} * 2000), P = 0)$,
  $D = (p = 1000, P = P_{\text{Batt}}^{(\min)})$.
- **Baseload** all other devices are assumed to not be controlled by the active control mechanism. The bid function for each households baseload is constant where $P = P_{\text{baseload}}$.

The EV bid function is defined such that at $p = -1000$ to $p = 0$ it consumes its maximum power. At $p = 500$, P is the exact amount of power at which the EV needs to consistently charge in order for the the exact target charge to be reached at the end of the charging session. The PV bid function is defined such that at $p = -1000$ no energy is produced while at $p = -500$ to $p = 1000$ all available solar energy is delivered. The BESS bid function is designed to shift such that, if the state of charge (SoC) is low, the BESS slowly charges at $p = 0$. Similarly, if the SoC is high, the BESS slowly discharges at $p = 0$. At either extremes the bid function is chosen such that the BESS will charge or discharge, unless the SoC is under a critical limit. The blue BESS bid function in Figure 3, labeled “SoC=5%”, is an example of where the SoC is under such a critical limit: the BESS won’t discharge.

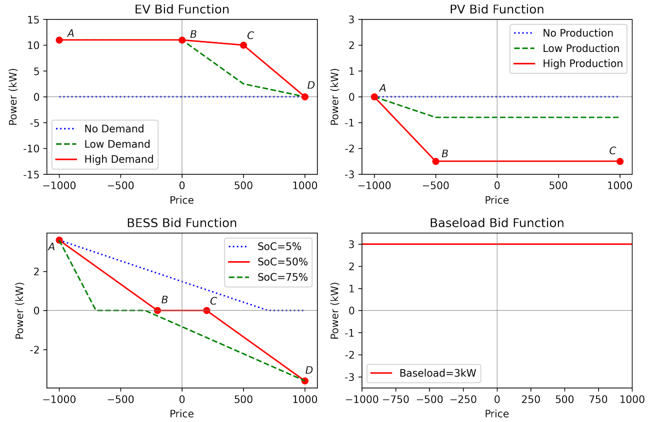

Fig. 3. Bid functions of devices as used in simulated environment.

6 RESULTS

In this section, we present the results of our simulations. The quantitative metrics defined in Section 2.1 are used to evaluate the performance of the tested control schemes. In this section, we often normalize $||P_{\text{viol}}||_2$, $E_{\text{EV\_ENS}}$ and $E_{\text{curtailed}}$, denoted as $||P_{\text{viol}}||_{2,\text{norm}}$, $E_{\text{EV\_ENS,norm}}$ and $E_{\text{curtailed,norm}}$ respectively.

Figure 4 plots all results where the x axis are the energy not served and energy curtailed performance metrics and the y axis is the euclidean norm of the power limit violations. We observe that no uni-directional auctions simulation reaches on the x axis, $||P_{\text{viol}}||_{2,\text{norm}}$, close to double-sided auctions. Likely due to the uni-directional auctioneer’s inability to predict devices suddenly turning on or off, creating brief power spikes above and below the power limits.

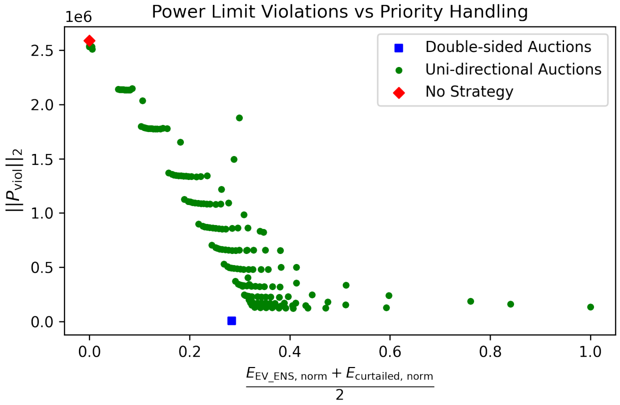

Fig. 4. Scatter Plot of All Simulated Congestion Mitigation Schemes

Figure 5 specifically focuses on uni-directional auctions, coloring the individual simulation results by the parameter x. A clear pattern is visible where a greater x generally performs better in protecting the power limits. Figure 6 provides a similar visualization, but now colors by the value of y. Here, a high value for y performs better on the user requirement measures. The euclidean distance in the 3 normalized dimensions between all results is calculated. Uni-directional auctions with parameters $x = 300$ and $y = 100$ are the closest data point to double-sided auctions in the 3 normalized dimensions. We use these parameters for uni-directional auctions in Table 3, Figure 7 and Figure 8. Table 3 compares the results of the three evaluated approaches numerically, where $E_{\text{EV\_ENS}}$ and $E_{\text{curtailed}}$ are both denoted in Wh. Figure 7 shows the load demand curve, which is the sorted power over time, for all three tested mechanisms. Figure 8 plots the sorted price for double-sided auctions and uni-directional auctions.

The metric $||P_{\text{viol}}||_2$ is found to be reduced by 99.8% using double-sided auctions and by 94.1% using uni-directional auctions compared to no congestion mitigation. Uni-directional auctions performs 87.6% as well as double-sided auctions in solar energy curtailed $E_{\text{curtailed, norm}}$.

Control Mechanism	$\lvert P_{\text{viol}}\rvert 2$	$E_{\text{EV\_ENS}}$	$E_{\text{curtailed}}$
No congestion mitigation	2.59×10^6	0	0
Double-sided Auctions	6.14×10^3	0	9.35×10^6
Uni-directional Auctions	1.53×10^5	1.73×10^0	1.07×10^7

Table 3. Comparison of Simulated Congestion Mitigation Measures

7 CONCLUSION

Recent and ongoing changes to the consumption and production behaviour of grid connected devices present new challenges that require solutions to ensure security in the supply of energy. One significant challenge in this regard is grid congestion. Active control mechanisms such as GridShield and double-sided auctions can

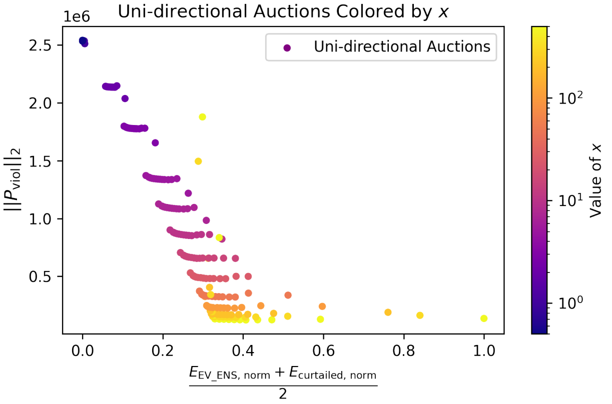

Fig. 5. Power Limit Violations vs Priority Handling for Uni-directional Auctions colored by Parameter x

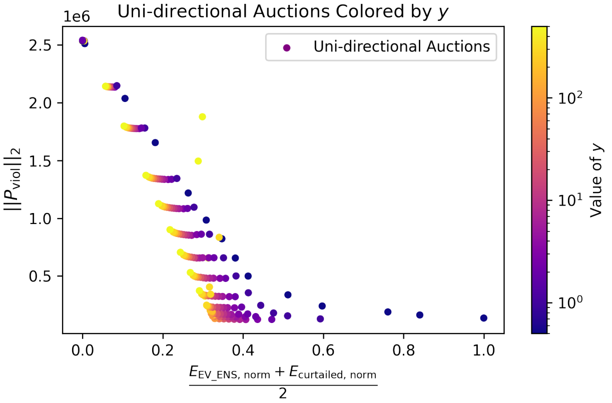

Fig. 6. Power Limit Violations vs Priority Handling for Uni-directional Auctions colored by Parameter y

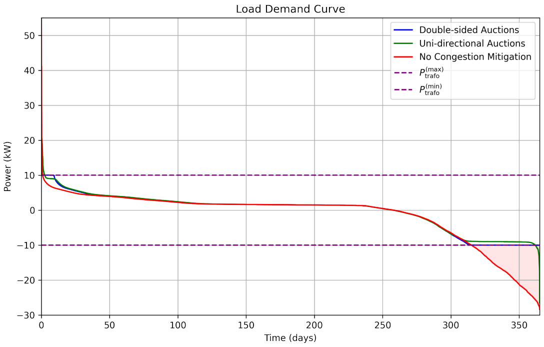

Fig. 7. Sorted Power over Time

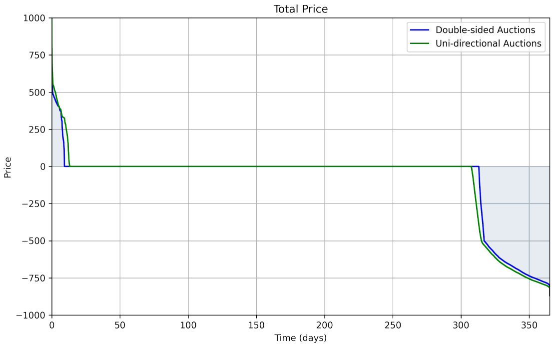

Fig. 8. Sorted Price over Time

address these congestion issues. Mechanisms like double-sided auctions utilize bi-directional communication which requires complex communication networks and the publishing of privacy sensitive data. Existing uni-directional control mechanisms such as GridShield do not differentiate between the urgency of devices, but have more potential for real-world application.

This paper has introduced uni-directional auctions, a novel uni-directional active control mechanism that yields priority to devices with a greater need for energy transportation. Uni-directional auctions combine the privacy benefits of GridShield with the priority differentiation of double-sided auctions. We have shown that uni-directional auctions, when used in combination with the control algorithm presented in Section 4.3, is 87.6% as effective as double-sided auctions in meeting the user requirements while achieving 94.3% of the performance in protecting the power grid.

In order to answer the research question we first consider our sub-questions.

Sub-question 1: *How can measurements of the physical state of the power grid inform a uni-directional control algorithm that considers user requirements?.*

Sub-question 2: *What metrics are effective in evaluating the performance of a congestion mitigation algorithm?*

- *Sub-question 1:* The total power at the transformer station accurately indicates how much capacity is free on the grid. We have shown that this information can be propagated as a price to connected flexible devices. Each of these devices can specify a bid function which is shaped by its user's requirements. The individual bid functions in combination with the price define how much capacity is assigned to each device. The entity which determines the price has no need to know what happens at the level of the individual devices, as its only goal is to find the price for which the *total* power respects the physical limitations of the grid. This means that uni-directional communication suffices to consider the requirements of individual users.
- *Sub-question 2:* Two types of quantitative metrics, when combined, accurately capture the performance of a congestion mitigation measure. Previous research has found that the

euclidean norm of the positive and negative power limit violations is a strong measure of the stress on the grid's hardware components [11]. The second type of metric quantifies the (un)met user requirements. We found that different device-types serve distinct purposes, but that the negative impact of control mechanisms can be generalized as each device requires a specific amount of transportation capacity from the grid to serve its user's needs. The amount of desired and/ or locally produced energy for which no transportation is available is an accurate measure of a congestion mitigation algorithm's ability to meet user requirements.

We can now address the research question: *How can electricity consuming, storing and producing devices coordinate their behaviour in order to collectively operate within the physical limitations of the power grid while adhering to respective users requirements using uni-directional communication?*

- **Research Question:** Electricity consuming, storing and producing devices can coordinate their behaviour in order to collectively operate within the physical limitations of the power grid while adhering to their respective user requirements, using a uni-directional auctioneer. The auctioneer broadcasts a price determined by a control algorithm that considers the measured power at the transformer station. Each flexible device knows how urgent its need for grid capacity is as it knows the requirements of its user. Because the auctioneer only needs to broadcast a price, and receives feedback using the measured power at the transformer station, the auctioneer needs no additional input and uni-directional communication suffices. When the physical limits of the grid are violated, the auctioneer adjusts the price and broadcasts it to the connected devices. The devices with the least urgent need for energy transportation provide the most flexibility, such that priority is yielded to the devices with a higher urgency to serve their user's requirements.

In conclusion, uni-directional auctions are a promising approach to mitigating grid congestion that preserves privacy, complies with EU regulations and effectively yields priority to the devices with the greatest urgency to serve its users. Further research can explore real-world implementations, possibly utilizing existing (experimental) uni-directional infrastructure, of uni-directional auctions in order to learn whether similar congestion mitigating performance can be achieved in the real-world. Future work can also explore more variations of the control algorithm used by the auctioneer, which determines the price, in order to improve uni-directional auctions' performance even further. Integral and differential factors can be considered while dynamically altering the parameters can be introduced to possibly create a stronger resilience to alterations of the makeup of the available flexibility.

A AI USAGE

During the preparation of this work the author used Codium and Github Copilot in order to automate the presentation of data, commenting and writing of code. The spellchecker provided by Overleaf was used in order to avoid spelling mistakes. The author reviewed and edited the content as needed and takes full responsibility for the content of the work.

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