

# Auxiliary flexibility in an integrated green steel plant participating in Day-ahead and Intra-day electricity markets

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## ABSTRACT

In the pursuit of decarbonisation, process industries are turning to electrification as a solution to avoid fossil fuels for heating and processing raw material. Transitioning to renewable electricity couples the processes to varying electricity availability and requires more consideration for production timing and scheduling to support grid stability and avoid high electricity prices. However, practical challenges limit the capability for unforeseen rescheduling for large processes. This paper explores the idea of auxiliary flexibility in an electrified steel production process, where only the auxiliary systems can react to changing conditions. We model an H<sub>2</sub>-DRI-EAF inspired process with controllable Air-Separation unit, water electrolysis, pressurized hydrogen storage, gas liquefaction units, and a battery energy storage system to react to a production related demand delay. First, we compare hourly and 15-minute DA pricing and observe that without fast flexibility the cost difference is marginal, while fast-reacting flexibility (electrolyser ramping and batteries) enables a small additional benefit from 15-minute pricing, around 0.3% on average and up to 1% at maximum. Second, without a demand delay, allowing DA+ID decisions provides significant additional cost reduction via intraday arbitrage, yielding up to about 3% lower total costs compared to DA-only operation under perfect price knowledge. Third, when introducing 15–45-minute demand delays close to delivery, the model shows little to no cost increase on average compared to no delay. This highlights that price-taker models yield optimistic results in small markets, where open positions over 100 MW would realistically influence the market price significantly.

**Keywords:** Process Operations, Energy Management, Optimization, Scheduling

## INTRODUCTION

The global transition from fossil fuels places process industries under pressure to decarbonize their operations. Electrification presents an key pathway for decarbonization for many processes but the increasing share of supply side volatility complicates operations [1]. At the same time, electrification intensifies the coupling between processes and grid conditions. This growing interdependence makes large industrial loads candidates for contributing to grid stability through demand-side management (DSM).

As of September 2025, the European day-ahead energy markets moved to a 15-minute market time unit (MTU), from a one-hour MTU, to improve supply-demand

balance [2]. The shorter MTU requires more accurate control over consumption timing and -volume. Research on industrial DSM has focused on established power-intensive processes, such as air-separation units (ASU) [3], steel industries [4], and chlor-alkali electrolysis [5], using hourly electricity pricing. The 15-minute markets present potential for increased value of short-duration storage for electricity, raw materials, intermediate and final products and operational flexibility, compared to hourly markets.

Green steel represents one of the harder challenges for industrial decarbonization, as currently steel production accounts for around 7% of global emissions. Alternate production routes to replace the blast furnace and basic oxygen furnace (BF-BOF) process have been

presented, with different configurations of a hydrogen-based shaft furnace and electric-arc furnace (H<sub>2</sub>-DRI-EAF) are recognized as most promising future pathways [6]. However, reacting to 15-minute price change frequency is likely unrealistic for such large plants with quality-sensitive products.

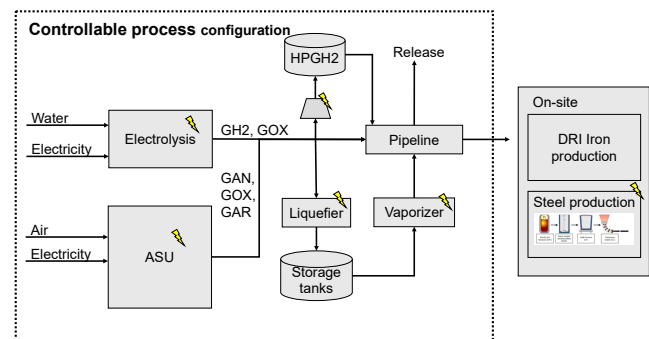
Both iron- and steel-making processes consume large amounts of gases and are typically equipped with ASUs to meet this demand. Scheduling ASUs for providing DSM has been studied from multiple angles [7]. Similarly, hydrogen production via water electrolysis has received significant attention as a source of power system flexibility [8], where certain types of electrolyzers can change load levels without excessive wear. For green steel production both hydrogen and ASUs present continuous processes that can dynamically adjust their load without disrupting the steel plant operations itself.

A practical challenge in electricity market participation is that day-ahead bids are submitted before the market clearing price is known, while scheduling decisions can be adjusted once prices are revealed. Simultaneous optimization of market bidding and process schedules has therefore been proposed [9], [10] to minimize imbalances and electricity costs. In 15-minute markets this becomes increasingly challenging, as predicting consumption and prices with higher accuracy is more difficult. Additionally, the ability of large processes to react to price changes is also likely limited. This means that changes in production schedules that occur after the day-ahead market position is locked in make auxiliary load adjustments potentially a practical tool for managing market position imbalances.

In this paper, we evaluate the demand-side flexibility of a green steel inspired process through its auxiliary units in 15-minute electricity markets. We model controllable electrolyzers, an ASU, gas liquefaction units, and a battery energy storage system (BESS) within an integrated process. We take the electricity, hydrogen, argon, and oxygen consumption of the steel production process as exogenous demands and examine the flexibility generated by optimizing the auxiliary units under 15-minute day-ahead (DA) and intraday (ID) electricity markets. Specifically, we address three questions: (1) How does the transition from hourly to 15-minute DA pricing affect operational costs and the value of flexibility? (2) What is the potential cost reduction from participating in the ID market with a fixed day-ahead position? (3) Can auxiliary flexibility mitigate the settlement imbalance cost caused by short-term production delays? We use a deterministic scheduling approach based on the state-task-network (STN) framework, with a two-stage decision process where the first stage performs day-ahead scheduling and the second stage determines the intraday recourse to minimize the total electricity costs.

## THE GREEN STEEL PROCESS

We model the gas and electricity demands based on an integrated H<sub>2</sub>-DRI-EAF process configuration, which is regarded as one of the viable routes for green steel production. In the process, raw iron ore is reduced in a shaft furnace with hydrogen forming direct-reduced iron (DRI). The DRI is then fed to a steel production process with electric arc furnaces (EAF), argon-oxygen decarburization (AOD) unit and continuous casting (CC). We consider the integrated steel production to work as an uncontrollable electricity and gas demand for controllable air separation units providing the process with nitrogen, argon and oxygen. Similarly, the water electrolysis unit that provides hydrogen for the DRI process is accounted as a controllable unit. Figure 1 shows the basic process configuration.



**Figure 1.** The modelled process configuration.

The process model is based on the STN framework presented in [11]. Each state represents a material in some specific state, and they can be converted to other states through tasks. The processes (tasks) are modeled with convex region surrogate models, allowing us to capture a wide range of process operating points and subsequent consumption of materials and electricity, while retaining convexity.

To account for short-term operational flexibility, we assume that gaseous product pipelines provide storage capacity (line-packing), corresponding to 15-minutes of average consumption [12]. Additionally, gaseous products can be converted to liquid products with a liquefaction step to be stored and again later vaporized for consumption. The gaseous hydrogen from electrolysis can be stored in a high-pressure storage unit, which requires compression. Gaseous products can be vented out of the system at any time.

For the iron and steel production processes, we consider a medium-sized integrated plant with an annual production rate of 1 Mton of steel, and base the demands for oxygen, and hydrogen from [6] and the argon and nitrogen consumption as described in [13]. We utilize the 24-heat steel plant schedule from [14], determining the demands for electricity, argon, oxygen, and nitrogen. We

assume EAF consumption is raised to full power in two steps: first at 70%, second at 90%.

The flexible ASU, liquefiers and vaporizers are parametrized based on [12] and extended such that gaseous nitrogen to oxygen ratio is 1.5:1 and argon about 5% of oxygen production. The electrolyser is modeled based on the model presented by [15], and hydrogen compression energy consumption calculated assuming adiabatic compression. We assume that of all hydrogen demand, we can produce 10% with variable load electrolysers giving us a controllable electrolyser capacity of 48.7 MW. We assume the remaining hydrogen demand is met through steady-state external supply or inflexible baseload production, isolating the impact of flexible capacity on the local energy system. The BESS is modeled separately on top of the STN model. We use a simplified model with a constant charge and discharge efficiency of 95%. For simplicity, no degradation effects are considered.

We model the BESS according to equations (1-4).

$$SOC_t = SOC_{t=1} + SOC_{t-1} + \eta^{BESS} \cdot p_t^{CH} - \frac{P_t^{DC}}{\eta^{BESS}} \quad (1)$$

$$0 \leq SOC_t \leq SOC^{max} \quad (2)$$

$$p_t^{CH} \leq P^{max} \alpha_t \quad (3)$$

$$p_t^{DC} \leq P^{max}(1 - \alpha_t) \quad (4)$$

Here  $SOC_t$  depicts the state of charge,  $p_t^{CH}$  and  $p_t^{DC}$  the charge and discharge energies, respectively, for each timestep  $t$ , and  $\eta^{BESS}$  the charge and discharge efficiency. To limit the rate of discharge from the battery,  $P^{max}$  is used to set the maximum energy draw per time-step and  $\alpha_t$  as an on/off binary variable to limit simultaneous charging and discharging.

## MARKET PARTICIPATION MODEL

We consider two market participations for electricity procurement from the day-ahead (DA) and continuous intra-day (ID) markets. First, we procure the required energy from DA market based on demand forecast for the next day, without considering possible ID prices. This fixes a physical position that is carried over to the next stage where a possible demand forecast error is balanced by further procurement from the ID market, and where the final operational decisions are made. We utilize the real DA and ID power prices from Finland in October 2025 from Entso-e [16] and Nord-Pool continuous intra-day market [17], assuming a perfect knowledge of both prices in advance. For the hourly prices we take the average of each 15-minute price within an hour, forming a static price for each hour. It is assumed that the process can act as a price taker. We acknowledge that this assumption is a very generous one, considering the large demand of a steel plant in Finland, especially in the

continuous ID market, where the average 15-minute transaction volume is in the range 150 MW for the studied period.

We use this approach to compare the effects of the transition from hourly to quarter-hourly (15-minute) DA markets to assess ability of a large process to react to faster changing prices. Additionally, we analyze the balancing capability of a plant in the case of demand forecast error. It is assumed that the steel plant acts as a balance responsible party towards the grid operator, therefore it must ensure an energy balance at each 15-minute time step, reflecting the practice in Finland. A balance responsible is expected to make power procurement from the energy markets or other contracts such that the consumed or produced energy matches the market position for each balance period. However, energy procured from DA market based on forecasts can differ drastically in the balance settlement, if there are significant errors in the consumption or production forecast if no action is taken. An imbalance in the balance settlement is penalized by fees from the TSO. We model the forecast error as a shop floor delay of 15, 30 and 45 minutes by delaying demand accordingly and forcing a power balance in the ID stage. The demand delay is shown in Figure 2.

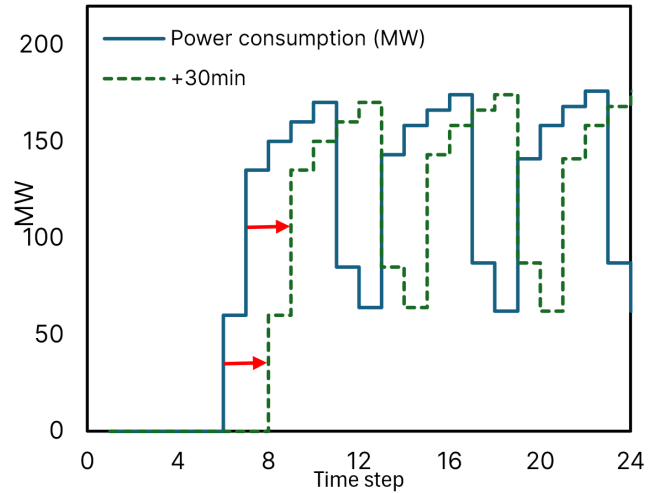


Figure 2. Demand delay for 30 minutes

$$\min \sum_{t \in T} C_t^{DA} (e_t^{buy} - e_t^{sell}) \quad (5)$$

$$s. t. e_t^{buy} - e_t^{sell} = E_t + p_t^{CH} - p_t^{DC} \quad (6)$$

The DA stage is governed with equations (5-6). Where  $C_t^{DA}$  is the DA electricity cost for each time step,  $e_t^{buy}$ ,  $e_t^{sell}$  are the electricity purchase and selling variables respectively.  $E_t$  is the sum of energy consumption over all units. After solving the DA stage, we have a net electricity position, which we pass over to a second optimization stage where ID operation is solved, reacting to a possible demand delay. The ID stage is represented by equations (7-8).

$$\min \sum_{t \in T} C_t^{ID} (e_t^{buy} - e_t^{sell}) \quad (7)$$

$$s. t. e_t^{buy} - e_t^{sell} + \Phi^{DA} = E_t + p_t^{CH} - p_t^{DC} \quad (8)$$

Here ID prices are represented by  $C_t^{ID}$ , and the DA position  $\Phi^{DA}$  in equation 8. Additionally, simultaneous buying and selling is limited by a binary variable, similar to eq. 3 in both stages. The intraday stage yields a net adjustment (positive or negative) to the day-ahead outcome, which is summed to form the total electricity cost over the horizon.

## STUDIED CASES

We start by forming a base scenario where we set storage capacities to 0 and allow only steady state operation for the electrolyser and ASU. Similarly, we limit liquefaction and BESS capacity to 0. This gives us a baseline cost comparison between the quarterly and hourly DA prices and provides a sense of the costs a production delay might cause.

For further case studies we introduce flexibility into our system; for case 1 we allow flexible ASU operation. The control of an ASU is an intricate process, and changes in production setpoints are slow, so the introduction of ASU flexibility provides multi hour electricity consumption flexibility. The ASU is over-dimensioned by 10%, compared to the maximum oxygen demand of 20 000 Nm<sup>3</sup>/h.

In Case 2, we introduce liquefaction and vaporization units, which allow for liquefying oxygen and nitrogen for storage and later use through vaporization.

For Case 3, we allow electrolysis units to operate flexibly with storage by giving them the ability to reduce their production rate by 100% an hour, meaning a reduction of power consumption of 2.5 MW per time-step.

Finally for Case 4, we consider BESS sizing of 5, 10, 25 and 50 MWh, with a fixed charge/discharge rate of 5 MW for 5- and 10-MWh units and 10 MW for 25- and 50-MWh units. This configuration deliberately decouples the power and energy capacities (C-rates), allowing us to analyze different storage durations and how power and energy limit capacities limit the operation.

It is important to note that this study only focuses on the operational electricity cost savings enabled by these auxiliary units. The capital investment, maintenance, and other costs associated are considered out of the scope of this work.

All cases are run for 14 separate days, with identical demands and with four demand delays of 15, 30, and 45 minutes. The cases are listed in Table 1.

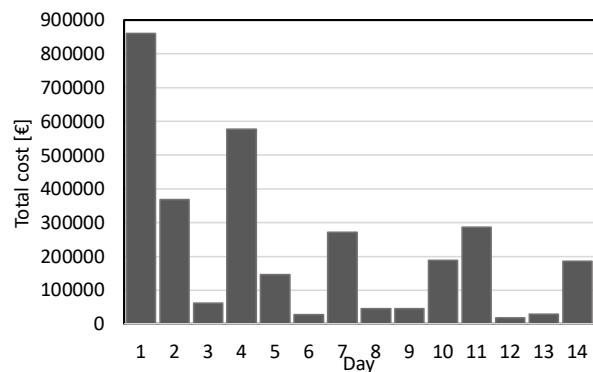
**Table 1:** Studied cases. SS: steady state, F: flexible

Case	ASU	Liquefaction	H2 storage	Electrolyser	BESS (MWh/MW)
Base	SS	no	no	SS	no
1	F	no	no	SS	no
2	F	yes	no	SS	no
3	F	yes	yes	F	no
4.1	F	yes	yes	F	5 /5
4.2	F	yes	yes	F	10 /5
4.3	F	yes	yes	F	25 /10
4.4	F	yes	yes	F	50 /10

## RESULTS

### 15-minute pricing

We first analyze the DA costs to assess how the more frequent pricing affects our results and whether our modeled system can benefit from it. Figure 3 shows the cost distribution across the days studied in the base, steady state system and shows a very large variability between days when consumption pattern is in fact equal each day. The cost variation is caused by the variation in DA prices. Though this kind of price risk is in reality reduced by utilizing longer term contracts to control price risk, here it illustrates well how drastically electricity prices can change day-to-day costs. Since the cost variance is high, it makes sense to compare relative cost reduction. Figure 4 illustrates the relative cost difference between the mean pricings for each case and day with error bars showing the deviation between days.

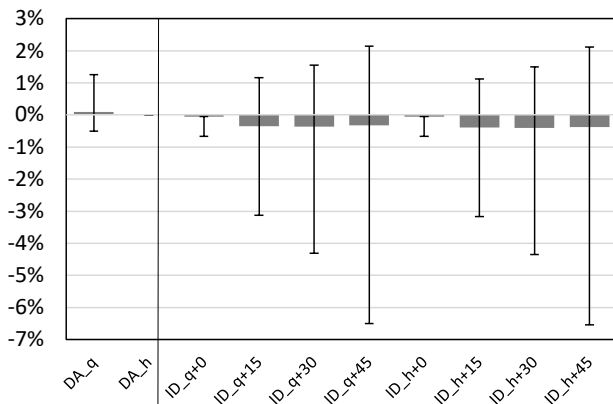


**Figure 3.** Absolute total cost for studied days in baseline case for 15-min pricing

We use DA to refer to only DA cost, q and h to refer to DA pricing granularity quarterly (15-min) and hourly respectively, and ID refers to DA+ID cost with a specified DA granularity and delay in minutes.

A comparison of the differences of the hourly and 15-minutes pricing scenarios for DA stage is shown in

Table 2. The cases are compared to base case, so we observe additional cost differences with the added components. With steady state operation, 15-minute pricing causes 0.09% more costs on average. This is likely caused by the chance of how pricing peaks hit consumption peaks with minimum and maximum values showing differences between extreme days. This can be viewed as an insignificant error associated with the method generating the hourly dataset. As price peaks and valleys in 15-minute data are averaged into hourly data, it is by chance how they line up with the consumption peaks, since with a continuous consumption average total cost would be equal.



**Figure 4.** Relative cost difference in the baseline case. DA<sub>q</sub> is relative to DA<sub>h</sub>.

**Table 2:** Mean, minimum, and maximum cost difference of 15-min DA pricing to hourly pricing

Case	mean diff	min diff	max diff
Base	0.09%	-0.59%	1.17%
1	0.00%	0.00%	0.00%
2	0.00%	0.00%	0.00%
3	-0.20%	-0.72%	-0.02%
4.1	-0.30%	-1.00%	-0.04%
4.2	-0.29%	-0.99%	-0.04%
4.3	-0.38%	-1.28%	-0.05%
4.4	-0.37%	-1.23%	-0.06%

In Case 3, which has the capability to ramp the electrolyzers, the shorter pricing interval allows a 0.20% cost reduction on average. Adding a BESS increases the gap from Case 3 but doesn't grow with added capacity until Case 4.3. Case 4.4 benefits less from the shorter pricing interval, compared to Case 4.3, which is explained by the increased ability of the case with hourly pricing to utilize the BESS capacity. We can also note that slow reacting flexibility by the ASU and liquid storage don't allow the utilization of the shorter pricing interval. This suggests that with increasing fast reacting flexibility a cost decrease can be achieved with the shorter pricing time interval. However, this cost decrease is likely insignificant

in many industrial applications but might increase the viability for very fast reacting components such as BESS units.

**Table 3:** DA costs per studied case with difference to baseline and subsequent ID cost reduction.

Case	DA <sub>q</sub>	ID <sub>q+0</sub>	ID <sub>h+0</sub>	Diff to base
<b>Base</b>	222397	-0.05%	-0.05%	0.00%
<b>1</b>	221977	-0.19%	-0.19%	-0.19%
<b>2</b>	221977	-0.49%	-0.49%	-0.19%
<b>3</b>	219923	-1.66%	-1.68%	-1.11%
<b>4.1</b>	219179	-2.08%	-2.20%	-1.45%
<b>4.2</b>	218770	-2.17%	-2.30%	-1.63%
<b>4.3</b>	217282	-2.75%	-2.90%	-2.30%
<b>4.4</b>	216589	-3.00%	-3.13%	-2.61%

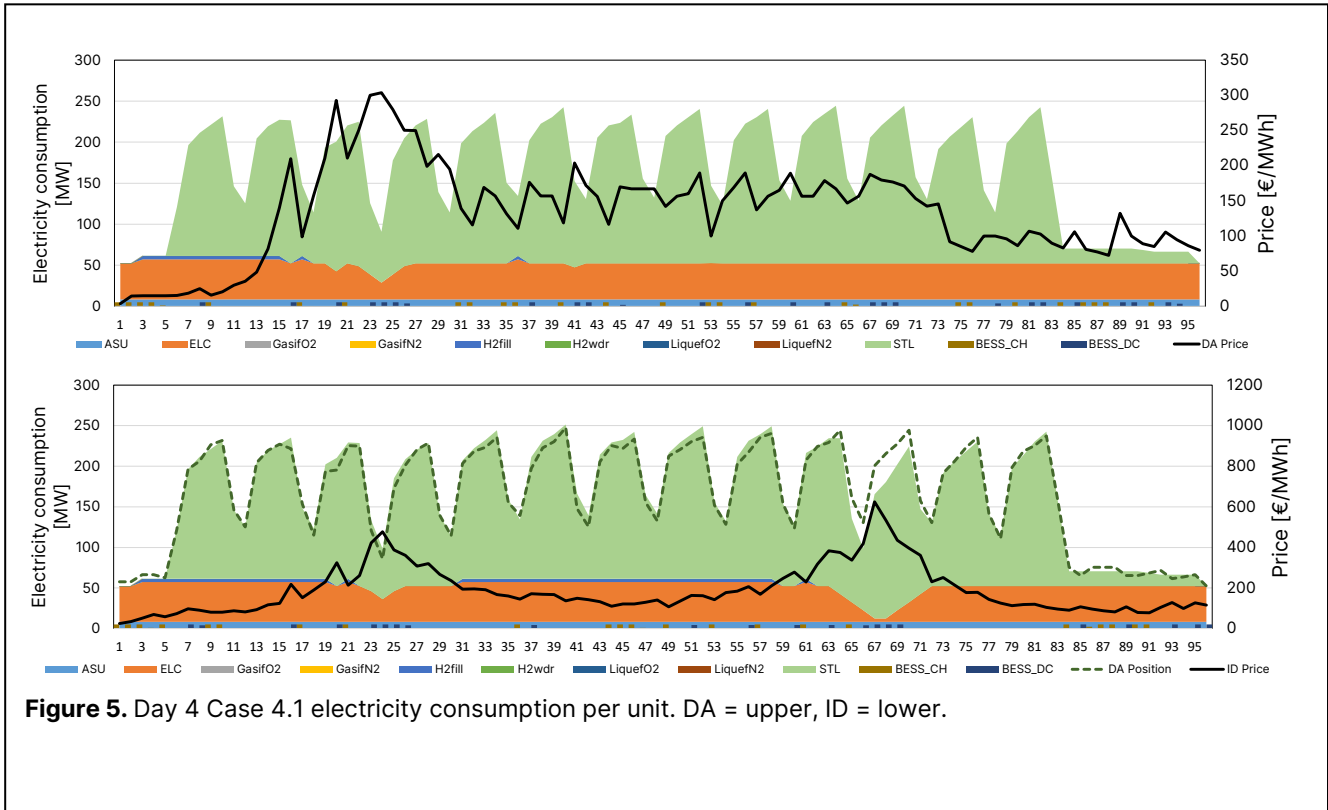
### Auxiliary Flexibility - Intraday Market participation

Next, we assess the capability of auxiliary systems to perform DSM activities to reduce electricity costs. First, without consideration of the demand delay. Table 3 shows that on average added flexibility can reduce costs by up to 2.61%. Furthermore, adding the ID stage where changing prices can be exploited against the DA position further reduces costs, up to about 3% of the DA cost.

We demonstrate this in figure 5 that shows how the electricity consumption and subsequent DA and ID prices affect the operating decisions of the production units for day 4 in Case 4.1. Here, DA operation reduces costs by 1.2%, compared to the baseline and then a further 1.49% with the ID operation. During the first price peak of the DA stage, the electrolyser reduces production significantly but is considerably limited due to insufficient time to fill the hydrogen storage. The ID prices on this day did not follow the trend of the DA prices and allowed continuous hydrogen production to deviate from the DA schedule and later utilize stored hydrogen to sell the position during the peak of the ID price on that day. The figure also visualizes the question of auxiliary flexibility for such a production process. It shows how massive the electricity consumption of the electric arc furnaces is compared to the ASU consumption, of about 10%, and other units even smaller. The majority of the shiftable demand is provided by the electrolyser units, which also shows the enormous electricity consumption of hydrogen production through electrolysis, as this only represents 10% of total hydrogen production required for DRI.

### Managing Settlement Imbalances

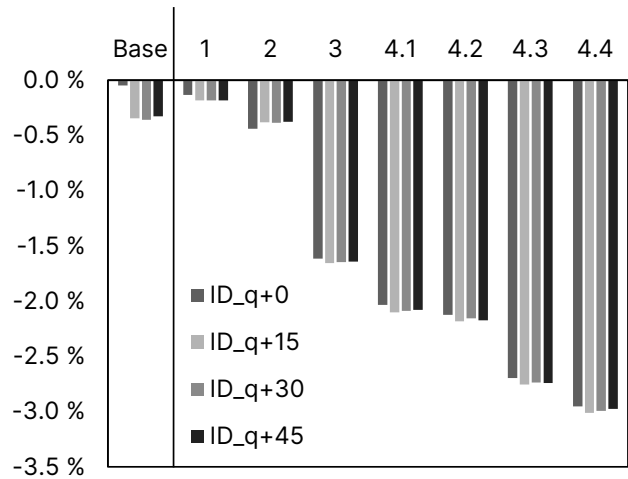
Figure 6 illustrates the relative cost difference between the ID costs with no demand delay and with 15-, 30-, and 45-minute demand delay. The cases 1-4 are shown as additional difference compared to the baseline difference. Against expectation, the delay causes in



**Figure 5.** Day 4 Case 4.1 electricity consumption per unit. DA = upper, ID = lower.

these cases reduced costs on average, compared to the base case. On individual days, Figure 4 shows large variance with growing delay, as in some cases we see up to a 2% cost increase, for some a 7% cost decrease in the baseline case. In the baseline scenario this is caused just by how the shifted consumption peaks happen to hit the ID price each day as the shift causes a symmetric open position. For cases with flexibility, we see even more variation between days caused by the frequent negative prices in the ID market allowing the system to ramp consumption on those time points, even with no practical use. For the studied time-period, this creates on average a positive impact on the total costs. With a constant price, the additional cost caused by such a delay would amount to zero.

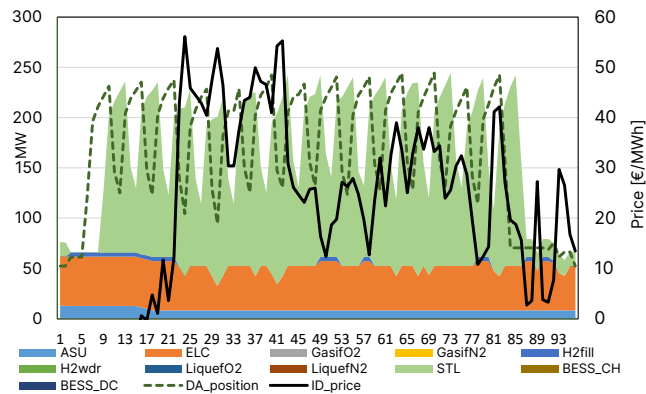
This behavior is unrealistic and highlights the limitation that comes with the price-taker assumption. The shifted demand frequently causes over 100 MW buy or sell bids in the ID market, which is close to the average 15-minute trading volume. This means that such a transaction volume would likely affect the price significantly against our favor causing large costs from a demand shift, incentivizing the auxiliary flexibility even more. We also assume that the imbalance position is corrected exclusively from the continuous market, whereas there are other ID markets available to handle such cascading delays.



**Figure 6.** Average relative cost difference to DA<sub>q</sub> costs. Cases 1-4 are additive to Base.

Looking at individual days, we observe that the ASU and the liquefiers are not utilized to fill the shifted position and are only turned on to increase the consumption during negative prices, which are frequent in the continuous ID market, or down during price peaks. We see in Cases 1 and 2 only little additional cost decrease compared to the base case. Similarly, while Cases 3-4 can further lower total costs, they seem to react to changes in prices rather than to the shifted demand, indicating that such a demand shift doesn't impose additional costs

that incentivize the system to correct the imbalance. This is illustrated in Figure 7, showing the ID operation of day 14 in Case 3, where the system only avoids the price spikes. Figure 7 also illustrates how a small demand delay introduces large open positions for almost 200 MW in the beginning and ends of the steel process operation period, which could occur similarly even if we perform optimal scheduling for the process for the DA markets.



**Figure 7.** Day 14 Case 3 production profile

Our approach is very optimistic in the sense that we only consider the price-taker role in both markets. We also have perfect, risk-free, knowledge of upcoming prices. While the model shows a 3% saving (approx. 10 k€ on average cost), this benefit is dwarfed by the market risks illustrated in Figure 3. With a price volatility reaching 500%, optimizing an average day yields negligible benefits if the system remains exposed to daily costs of up to 800 k€. Therefore, future development should consider focusing on finding multi-day flexibility, as the ability to avoid consumption on high-priced days is likely more valuable than improving efficiency during them.

## CONCLUSIONS

In this work, a green steel inspired process configuration was analyzed in the view of auxiliary flexibility for demand-side management. We considered a system with controllable electricity consumption for an ASU, nitrogen and oxygen liquefiers, electrolyser and gaseous hydrogen storage, and various BESS sizes, which we studied under different combinations.

We first quantified the relative differences that hourly and 15-minute DA pricing cause on the system total cost, and whether the more frequent pricing interval could be exploited by a flexible system to reduce operational costs. It is noted that slowly reacting flexibility cannot utilize the more frequent pricing. For components that are able to react to changing prices, we see only a small decrease in total costs (around 0.3% on average and 1% at maximum). This suggests that the 15-minute pricing might increase the viability of BESS units, with

more arbitrage opportunities.

Second, we looked at how arbitrage in the ID markets can be used to decrease costs with a naive DA+ID market strategy and showed that the additional arbitrage opportunity is able to provide us with up to 3% of additional cost decrease on average.

Finally, we analyzed how a delay in the steel process between the acquired DA position and delivery can be mitigated with flexibility provided by the auxiliary units. We see that with the current setup; the demand delay causes neither additional costs nor profits on average compared with a case with no delay. This exposes the limitation in assuming a price-taker scenario as we see no cost increase on average with the delay even though it creates frequent open positions in the range of 100 MW on a market that likely has limited liquidity.

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