IMPACT OF REFERENCE ELECTRICITY MARKET SELECTION FOR REAL-TIME ELECTRICITY TARIFFS ON EMISSIONS ASSOCIATED WITH OPERATIONS: A CASE STUDY OF AN INLAND PORT TERMINAL

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ABSTRACT

As the energy transition progresses, small- and medium-scale industrial prosumers in Germany are increasingly faced with the challenge of balancing economic and ecological concerns in their energy procurement strategies. This paper examines the correlation between reference market selection for real-time electricity tariffs and the emissions associated with the electricity procurement (associated emissions). Specifically, it investigates whether intraday (ID) auction market has advantages over the day-ahead (DA) auction market with respect to the associated emissions of an inland port terminals operation, when selected as reference market for real-time electricity tariffs.
Utilizing time-series analysis, the correlations between the carbon intensity of the grid electricity mix and the prices of each of the two considered markets are explored by means of the Spearman correlation coefficient. The energy system model of a fully electrified inland port terminal equipped with flexibility-providing energy technologies is used to simulate a financially optimized operation using in two separate scenarios the prices of the DA and the ID. The emissions associated with the operation of the port terminal is compared between the scenarios. The approach is then extended with a multi-objective optimization to include both electricity price and carbon intensity into the decision-making process of the operation planning. All calculations are performed for two exemplary years.
The results show no advantage in associated emissions for the ID market over the DA market, even when carbon intensity is factored into the optimization. On the contrary, the DA scenario consistently showed lower or equal associated emissions. While only one energy system is considered in this study, there is no reason to assume that alternative energy systems would exhibit deviating behavior.

1 INTRODUCTION

As small- and medium-scale industrial prosumers simultaneously strive for a balance between economic viability and ecological responsibility, the strategies for energy procurement are becoming increasingly complex. Where, traditionally, electricity supply contracts with a fixed energy price per kilowatt-hour are common for small- and medium-scale companies in Germany, tariffs with dynamic prices are growing in prevalence. The prices of these tariffs are tethered to the dynamic prices of a reference market and therefore also called "real-time electricity tariffs" (Förster et al., 2024) or "real-time-pricing" (Grimm et al., 2021). Common reference electricity markets nowadays are the futures trading market or the day-ahead auction market but tariffs with the intraday auction market as reference are conceivable to be available soon as its increased volatility attracts the interest of consumers that are able to shift their load in time (Koch et al., 2021).

Historically, the choice of electricity tariffs has largely been driven by the pursuit of low electricity prices. In the context of the energy transition the environmental impact associated with the procurement of electricity, specifically the carbon emissions, is gaining interest in this decision-making process.

https://doi.org/10.52202/077185-0162

And although “green” electricity contracts that pledge net carbon neutrality are widely available, environmentally conscious enterprises are beginning to question what emissions can actually be attributed to the generation of the electricity procured by them (“associated emissions”).

Renewable energies like wind and solar are fluctuating, intermittent and, importantly, usually lower in operational costs than non-renewable energies. For the divestment of electricity from these fluctuating, intermittent renewable sources the focus is shifting towards markets with high temporal resolution and low lead times (Kuppelwieser & Wozabal, 2023). In previous studies, it has been shown, that low prices at short-term markets such as the day-ahead auction market (DA) correlate positively with low average carbon emissions of the grid electricity (Förster et al., 2024; Koch et al., 2021). However, to the best of the authors knowledge, it has not been investigated if the correlation between market prices and carbon intensities increases with increasing temporal resolution and delayed lead times of the market. Therefore, this is the first research question of this paper, which will be answered based on the market prices of the day-ahead auction market (DA) and the intraday auction market (ID).

(Koch et al., 2021) showed, that dynamic electricity tariffs based on the DA can contribute to an emission reduction when load is shifted to times of low market prices. Similar results were obtained by (Förster et al., 2024), who conducted the research with special focus to Germany in the crisis years 2020-2022 and by (Stoll et al., 2014) who conducted it with focus on Great Britain, Ontario and Sweden, considering both real-time-pricing and time-of-use tariffs. Following these findings and building onto the considerations of the first research question, we investigate if lower associated emissions can be achieved in a purely financially optimized operation of an inland port terminal when ID prices are assumed for real-time electricity tariffs, compared to a comparable operation under assumption of DA prices. This represents the second research question, which has not been investigated yet.

In the context of associated emissions and real-time electricity tariffs, (Stoll et al., 2014) propose the idea to stipulate the disclosure of hourly values for the average carbon emissions of the grid electricity together with the prices, to provide a possibility and incentive to the consumers to adjust their electricity procurement to times of low associated emissions. Therefore, a multi-objective optimization approach is employed for each market scenario to incorporate the carbon intensity directly into the decision-making process together with the respective markets’ prices. The results for these two multi-objective optimizations are compared to see whether the ID market has benefits over the DA market in terms of the emissions associated with the inland port terminals operation when the carbon intensity is directly incorporated in the decision-making process. This is the third research question of this paper.

In summary, the three research questions are:

1. Does the correlation between market prices and carbon intensities increase with increasing temporal resolution and delayed lead times of the market?
2. Can lower associated emissions be achieved in a purely financially optimized operation of an inland port terminal when ID prices are assumed for real-time electricity tariffs compared to comparable operation under assumption of DA prices?
3. Does the ID market exhibit benefits over the DA market in terms of emissions associated with operation of the inland port when the carbon intensity is directly incorporated into the decision-making process via multi-objective optimization?

While the first research question will be answered based on time-series analysis alone, the second and third research question can best be answered with a definition of the underlying energy system. In contrast to (Stoll et al., 2014) and inspired by (Förster et al., 2024), the energy system of a fully-electrified inland port terminal is used as object of investigation. Flexibility towards the grid electricity procurement is offered primarily by a battery storage system and secondarily by hydrogen conversion units.

https://doi.org/10.52202/077185-0162

The remainder of this paper is structured as follows: the methodology used to investigate the relationship between electricity reference market selection for real-time electricity tariffs and the associated emissions is presented in chapter 2. The results are presented in chapter 3 before the conclusion, discussion and the outlook on future work is given in chapter 4.

2 METHODOLOGY

In this chapter, the methodology used to answer the three research questions laid out above is described. Chapter 2.1 provides a broad overview of the general approach before the energy system and its model are described in chapter 2.2. Following this, the relevant timeseries used in this study are described in chapter 2.3, before the multi-objective optimization approach is described in detail in chapter 2.4.

2.1 General approach

As pointed out in chapter 1, the first research question can be answered based on time-series analysis alone. To this end, the electricity prices of the EPEXs "Day-Ahead Auction Market" (DA) and the "Intraday Auction Market" (ID) are evaluated on their correlation with the carbon intensity timeseries (the calculation of which is described in chapter 2.3). The two markets are selected due to their utilization of merit-order based market clearing prices instead of bid prices, making them ideal for the comparison of this work. Following the assumption of (Stoll et al., 2014), Spearman's rank correlation coefficient is used instead of the more common Pearson correlation coefficient, as a non-linear but monotonic relationship between the price and carbon intensity of the grid electricity is assumed. The results on this analysis are presented in chapter 3.1.

To answer the second research question, the capability of a system to shift its load needs to be defined. Instead of parametrizing the time span of possible load shift in advance, like it is done in (Koch et al., 2021), inspiration is taken from (Förster et al., 2024) where refrigeration of frozen foods in cold stores is taken as an exemplary commercial flexibility potential. In this work, the battery storage system (BS) of a fully electrified inland port terminal is considered as primary flexibility option. The secondary flexibility option is the avoidance of grid electricity procurement through usage of hydrogen conversion units. To model the BS operation under optimal conditions, the energy system of the inland port terminal is modelled as a mixed-integer linear optimization problem (cf. chapter 2.2). The optimization objective is the minimization of energy procurement costs (EPC), which is the sum of all electricity and hydrogen procurement costs. The model is used in two scenarios, once with the DA prices (DA scenario) and once with the ID prices (ID scenario). The results of the two scenarios with respect to the attainable EPC and associated emissions are displayed and discussed in chapter 3.2.

For the third research question, the previously mono-objective models are revised into multi-objective models (cf. chapter 2.4), which consider the market prices of the respective scenario (DA or ID) and the carbon intensity of each timestep, in the decision-making process. Increasing interest in the carbon intensity minimization is simulated.

To reduce the risk of evaluating properties that are exclusively inherent to the price and carbon intensity timeseries of one specific year, data for an additional year is. With it, all relevant calculations are performed for both years as a sensitivity analysis.

2.2 Energy system and model description

As previously pointed out, the energy system used as investigation object in this paper is a currently built, fully electrified inland port container terminal in Germany. It is a trimodal terminal and as such a link for logistics via rail, road, and river. On the demand side 6 cranes, 5 shore-to-ship power stations, an office, a social building and all other electrical appliances (such as lighting, traffic control, etc.) are subsumed under "electric demand". The buildings also have a demand for space heating and drinking hot water, represented by "thermal demand". On the supply side, a photovoltaic (PV) power plant with fixed feed-in, two hydrogen-based combined-heat-and-power engines (CHP) and two hydrogen-based

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fuel cells (FC) complement the grid supply. The thermal demand can be covered by the hydrogen CHPs and two air-water heat pumps (HP). A battery storage (BS) system is installed to increase the consumption of PV within the terminal. This BS is the main source of flexibility towards the grid, which is needed for the here presented study. The layout of the energy system is depicted in Figure 1.

Despite the complex combination of energy technologies in the energy system, the results taken from the optimization of this energy system are expected to be transferrable to other energy system models with a similar amount of flexibility. The reason for this is that the BS can represent any component or group of components in other energy systems with a similar amount of flexibility towards the grid.

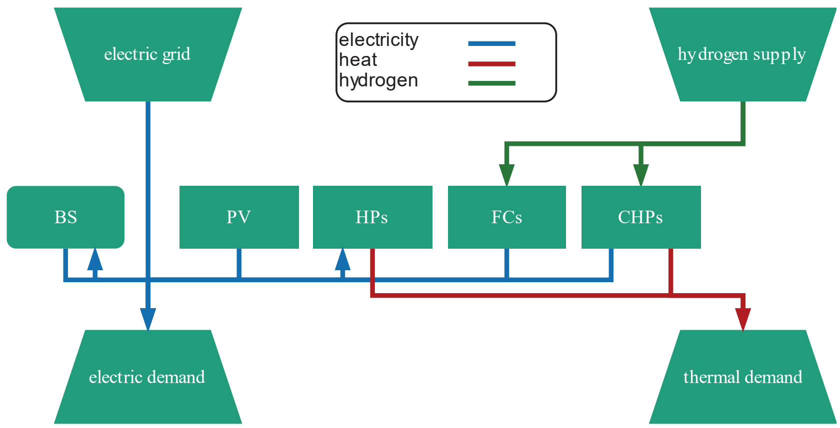

Figure 1: Layout of the inland ports energy system used in this study

The depicted energy system is modeled as a MILP with the software package *oemof.solph* (Krien et al., 2020) and the resulting model is solved with the solver *gurobi* (Gurobi Optimization LLC, n.d.). All energy system components are modelled with the standard *oemof.solph* components; the reader is referred to the publicly accessible documentation. The optimization model is set-up on a 15-Minute time resolution. To simulate the limited *a priori* knowledge about future prices, all calculations are carried out with a limited foresight of 24 hours, starting at 00:00 and ending at 24:00 to reflect the market conditions inherent to the DA and ID. While the gate closures are at 12am and 3pm for the DA and ID, respectively, in both markets the trades are performed for the 24 hours (or the 96 15-Minute intervals in case of the ID) of the next day. Restrictions on this mechanism imposed to accommodate for weekends and national holidays are neglected in this study, as they are not expected to affect the results in a meaningful way. The two market scenarios are modelled as independent models. They share all characteristics, including the carbon intensity timeseries, except the price timeseries for grid electricity procurement.

2.3 Timeseries description

The subject of this paper is the comparison of two reference markets for real-time electricity tariffs, represented by their prices, and their influence on the emissions associated with electricity procurement from the grid. This chapter focusses on the description of the relevant timeseries and their origin.

All data used in this paper is corresponding to the year 2020, if not otherwise stated. This is attributed to the availability of operational data for the inland port terminal for that particular year. The timeseries for the DA and ID prices are provided by EPEX spot. The DA price timeseries is resampled from hourly resolution to 15-Minute resolution via a forward fill method. This is done to ensure conformity with the carbon intensity timeseries and operability with the optimization model, which also uses quarter-hourly resolution (cf. chapter 2.2). The price of hydrogen procurement is assumed at a constant value of 6.85 €/kg, calculated from the EEX Green HYDRIX index (*EEX HYDRIX Index*, n.d.). Pure market prices are assumed in this study without additional taxes, surcharges, or other cost factors.

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The carbon intensity of the grid electricity is calculated as the average carbon intensity of the gross electricity production in the market zone Germany/Luxembourg for every 15-Minute timestep. To this end, data on the actual generation per production type and 15-Minute timestep for this market zone was taken from (entsoe, n.d.). In combination with the specific emission factors per MWh and production type taken from (Agora Energiewende, 2023), the carbon intensity in kg/kWh is calculated.

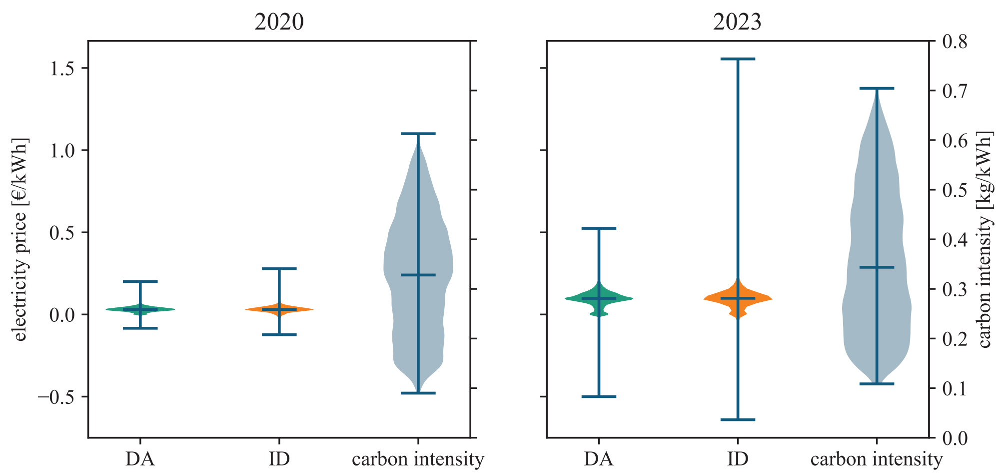

Figure 2: Violin plots of price and carbon intensity timeseries

For the sensitivity analysis, data of the year 2023 is used. This applies to the DA and ID price timeseries as well as the actual generation per production type and the specific emission factors, as these are also subject to change due to decommissioning and replacement. All data sources listed above provided the data for both years. As 2020 is a leap-year and as such is 24 hours longer than 2023, additional editing is necessary. Therefore, all 2023 timeseries are appended by the 96 timesteps of the initial day (January 1st, 2023) to ensure operability with the optimization model. The influence of the inaccuracy is expected to be negligible for the results of this paper.

The value-distribution for the price and carbon intensity timeseries are depicted in Figure 2 and explicit statistical values are provided in Table 1. For 2020, the majority of the DA prices are evenly distributed within a narrow range, apart from outliers. The ID prices show slightly more pronounced outliers than the DA, but a similar distribution for the majority of the values. Compared to 2020, the majority of the prices have increased for both markets in 2023, but more extreme minima and maxima can also be seen. The carbon intensity values have overall increased slightly from 2020 to 2023, leading to higher mean, median, minimum and maximum values (cf. Table 1).

Table 1: Statistical description of the price and carbon intensity timeseries for 2020 and 2023

	2020			**2023**		
	DA *[€/kWh]*	ID *[€/kWh]*	Carbon intensity *[kg/kWh]*	DA *[€/kWh]*	ID *[€/kWh]*	Carbon intensity *[kg/kWh]*
Mean	0.0304	0.0304	0.3280	0.0949	0.0959	0.3587
Median	0.0309	0.0309	0.3319	0.0979	0.0987	0.3436
Std. dev.	0.0175	0.0210	0.1155	0.0477	0.0544	0.1420
Min	-0.0839	-0.1230	0.0898	-0.5000	-0.6405	0.1085
Max	0.2000	0.2782	0.6128	0.5242	1.5553	0.7042

2.4 Weighted-sum multi-objective optimization

To answer the third research question, the mono-objective optimization model described in chapter 2.2 is amended by the objective to reduce the associated emissions directly. The underlying assumption here is that in the future, the carbon intensity of each timestep could be disclosed together with the

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prices to incentivize consumers to move the grid procurement of shiftable loads to less carbon-intensive timesteps (cf. (Stoll et al., 2014)). To this end, the two objectives “EPC minimization” (financial objective) and “associated emissions minimization” (ecological objective) are used in a weighted-sum approach (Marler & Arora, 2010). The method is explained briefly below.

In the following let $\{0, \ldots, T\}$ be the set of all timesteps $t \in \{0, \ldots, T\}$, and $x_{i,t}$ the optimization variables with $i \in \{0, \ldots, n\}$ optimization variables $x_{i,t}$ in the feasible set X. The weighted-sum approach projects multiple objectives onto a single objective function (OF) by weighing and summing the objective function coefficients (OFC) $c_{i,t}$ of the multiple objectives. A single OF would have the form:

$$z^g = \min_{x \in X} \sum_{t=0}^{T} \sum_{i=0}^{n} (c_{i,t}^g \cdot x_{i,t}) \qquad (1)$$

where the index $g \in \{f, e\}$ can indicate either the financial (f) or the ecological (e) objective. The weighted-sum approach re-adjusts the OFC $c_{i,t}^g$ for every optimization variable with exogenously defined weights w^g . The OF for the multi-objective optimization can thus in our case be described by:

$$z^{MO} = \min_{x \in X} \sum_{t=0}^{T} \sum_{i=0}^{n} [(w^f \cdot c_{i,t}^f + w^e \cdot c_{i,t}^e) \cdot x_{i,t}] \qquad (2)$$

where $w^g \geq 0$ represents the weight of the financial (f) or the ecological (e) objective. To represent growing interest in the ecological objective, 11 multi-objective optimization calculations (indexed by m) are carried out with an equidistant increase of the ecological objective weight w_m^e between them. The weights are selected such that:

$$w_m^f + w_m^e = 1 \quad \forall\, m \in \{1, \ldots, 11\} \qquad (3)$$

holds. Which means that the financial objective weight w_m^f must decrease with increasing weight on the ecological objective w_m^e. For a more succinct equation, the OFC can be defined as:

$$c_{m,i,t}^{MO} = w_m^f \cdot c_{i,t}^f + w_m^e \cdot c_{i,t}^e \;\; \forall\, \mathrm{m} \in \{1, .., 11\}, \forall\, \mathrm{t} \in \{1, \ldots, \mathrm{T}\}, \forall\, \mathrm{i} \in \{1, \ldots, \mathrm{n}\} \qquad (4)$$

such that:

$$z_m^{MO} = \min_{x \in X} \sum_{t=0}^{T} \sum_{i=0}^{n} (c_{m,i,t}^{MO} \cdot x_{i,t}) \quad \forall \mathrm{m} \in \{1, .., 11\} \qquad (5)$$

The only relevant OFCs in this study are the electricity procurement costs, the hydrogen procurement costs, and the carbon intensity factors associated with procurement of electricity from the grid. All other OFCs are set to 0.

3 RESULTS

3.1 Time-series analysis for grid prices and carbon intensity

The first research question of this paper is whether the correlation between market prices and carbon intensity increases with increasing temporal resolution and delayed lead times of the market. To answer this question, the DA and ID prices are compared based on their correlation with the carbon intensity timeseries.

Figure 3 displays the price and carbon intensity of each timestep for both market scenarios and both considered years. From visual inspection we can see that the lowest carbon intensities tend to coincide with the lowest prices for both, though the data varies much stronger over the price than the carbon intensity. This is the case for the DA and ID in both years. Figure 3 also shows that the highest carbon intensities do not coincide with the highest prices, which is amplified in the 2023 data. This is plausible, as cost intensive peak load power plants are often gas power plants, which have lower carbon intensities than, for example, lignite power plants with lower operating costs. In literature, this is referred to as the merit order dilemma of emissions (cf. (Fleschutz et al., 2021)). As the price for natural gas in Germany

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increased drastically within 2022 and stayed high for 2023 in consequence of the Russian war on Ukraine, the amplification of this effect in the 2023 data is plausible.

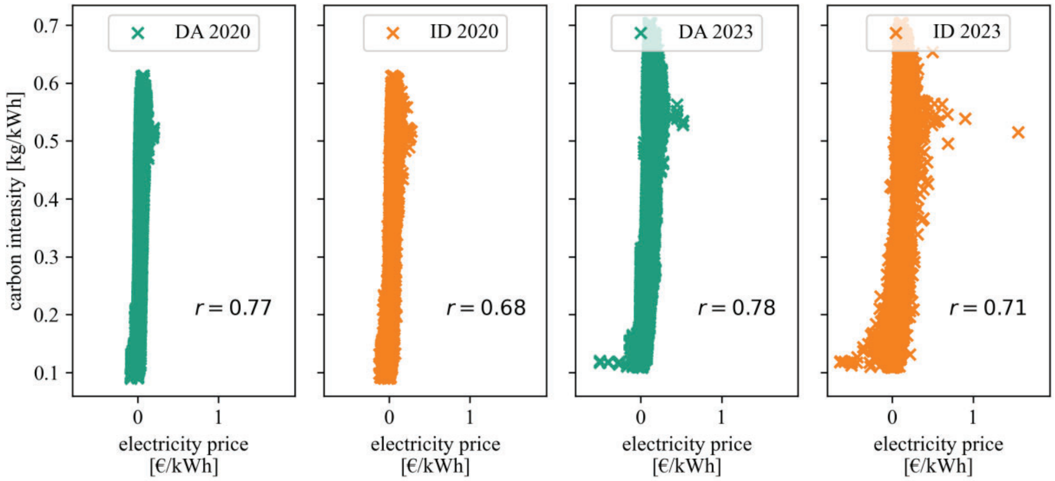

Figure 3: Correlation of price and carbon intensities of relevant timeseries

Following (Stoll et al., 2014) argument, Spearman's ranked correlation coefficient r is used to calculate the correlation between the carbon intensity and price timeseries. The coefficient is given in Figure 3 for every relevant timeseries combination. The DA prices display higher correlation with the carbon intensity than the ID prices in both years. Based on these findings, the first research question - whether the correlation between market prices and carbon intensity increases with increasing temporal resolution and delayed lead times of the market - cannot be affirmed or at least is not supported by the available data.

However, the correlation coefficient considers all timesteps of the timeseries, including those leading to the merit order dilemma of emissions mentioned above. It is expected that these timesteps influence the correlation coefficient negatively and it is also expected that the negative impact is stronger in the ID scenario, as high-cost low-carbon-intensity gas power plants are more active in the ID due to higher attainable prices (cf. Figure 3). Given sufficient flexibility within the energy system, an EPC minimizing optimization will avoid high prices for grid electricity procurement, including the timesteps where the merit order dilemma of emissions comes into play. Therefore, despite the results not supporting the first research question, the experimental investigation is continued.

3.2 Mono-objective optimization for financial costs

The second research question of this paper is whether a purely financially motivated operation optimization decreases the associated emissions when the ID prices are considered as real-time electricity tariff, compared to the DA prices. As object of investigation, an energy system representing an inland port terminal is used. The results are expected to be transferable to other energy systems with a BS or similar flexibility options (cf. chapter 2.2). The results of the initial mono-objective optimization, minimizing only the EPC considering the timeseries of 2020, are depicted in Figure 4.

Comparing the results based on the EPC, lower values are achieved in the ID scenario than in the DA scenario in both investigated years. The optimization leverages the at times lower market prices of the ID efficiently, which reduces the total EPC by 20% compared to the DA in 2020 and 10% in 2023. Between 2020 and 2023, the EPC roughly triple in both market scenarios, which is in line with the roughly tripled mean prices reported in Table 1.

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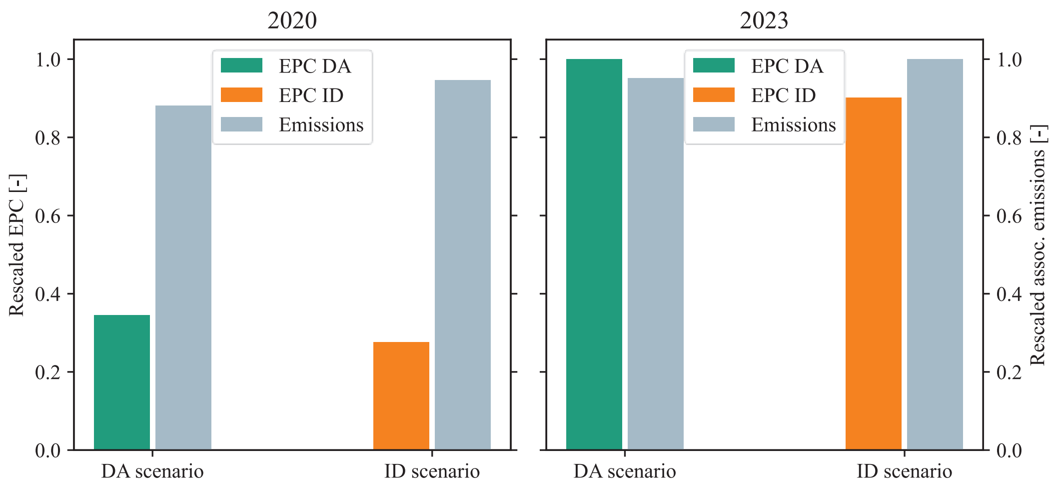

Figure 4: Rescaled results of the single-objective optimization[1]

Figure 4 also shows that the associated emissions in the ID scenario are 7% higher than in the DA scenario for 2020. This difference decreases to 5% for 2023. Still, the results confirm the findings of the correlation analysis (cf. chapter 3.1) and reveal that also the second research question - whether a purely financially motivated operation optimization decreases the associated emissions when the ID prices are considered as real-time electricity tariff compared to the DA prices - cannot be answered affirmatively.

3.3 Multi-objective optimization for EPC and associated emissions

The third and last research question is whether real-time electricity tariffs based on the ID prices have benefits over the those based on DA prices in terms of the associated emissions, when the carbon intensity of the grid electricity is directly incorporated into the decision-making process.

This incorporation is done with a weighted-sum approach (cf. chapter 2.4). This idea originally hinges on the assumption that the correlation with the carbon intensity is higher for the ID prices than the DA prices, which could not be affirmed (cf. chapter 3.1). Additionally, it could not be confirmed that a purely financially motivated operations optimization will lead to lower associated emissions if the ID prices are used as real-time electricity tariff, compared to the DA prices (cf. chapter 3.2). As the DA and ID scenario will share the same carbon intensity timeseries in the multi-objective optimization, it might not be obvious why their (weighted) incorporation is expected to yield different results than the mono-objective optimization. The reason lies within the dynamic of the carbon intensity and price timeseries and the ability of the system to shift the timesteps of electricity procurement. With favorable weights and OFCs, it is possible that an increase in the weight of the ecological objective leads to a shift of electricity procurement in the ID scenario, but not in the DA scenario and therefore reduces the associated emissions stronger in the ID scenario than in the DA scenario. For this reason, the investigation is being continued.

Figure 5 a) displays the Pareto front for the DA and ID scenario in 2020 on the left. Four overlapping markers in the lower right corner, one for each of the two second highest ecological weightings ($w_9^e = 0.8$ and $w_{10}^e = 0.9$) of the DA and ID scenario are depicted again in the lower magnification for better visibility. The upper magnification is meant to give a more detailed look onto the cluster of results in the upper left corner.

[1] Values are rescaled due to an NDA; the same scaling factor was used for 2020 and 2023.

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From visual inspection we find that it is possible to reduce the associated emissions by incorporating the carbon intensity into the optimization with increasing weight. This is a relevant result regarding the inland port terminal used as object of investigation in this study: it is possible to reduce the emissions associated with the procurement of grid electricity. As this is the only source of carbon emissions on site, this shows that it is possible to reduce the overall emissions of the inland ports' terminal. However, these emissions reductions come at the cost of EPC, which increase with increasing weight on the ecological objective. This means that it is cheap to avoid some emissions but expensive to avoid all. Here, the ID scenario is again at an advantage: for low weights on the ecological objective, the EPC of the ID scenario is up to 20% lower than in the DA scenario (cf. Figure 5 c)). For $w_m^e \geq 0.6$, the procurement of hydrogen replaces grid electricity procurement (cf. Figure 5 d)) in the examined energy system, eliminating all differences between the scenarios in terms of their associated emissions and EPC due to the same assumed costs and carbon intensities (cf. chapter 2.3).

From Figure 5 a) and b) no advantage for the ID scenario over the DA scenario can be seen with respect to the associated emissions at the same objective weighting. On the contrary: the associated emissions in the ID scenario are at least as high as the associated emissions in the DA scenario for the same weighting. As all displayed values in Figure 5 b) are greater or equal to zero[2], it is clear that switching to the ID as reference market will not decrease the associated emissions, irrespective of the weighting.

The results for the calculation with data from 2023 is depicted in Figure 6, which is structured in the same way as Figure 5. Despite the different values, the relevant findings pointed out above are also valid for the 2023 data. Therefore, also the third research question cannot be answered affirmatively: even when considering the carbon intensity of the procured electricity directly, using the ID as reference market for real-time electricity tariffs does not exhibit an advantage over the DA with respect to the associated emissions.

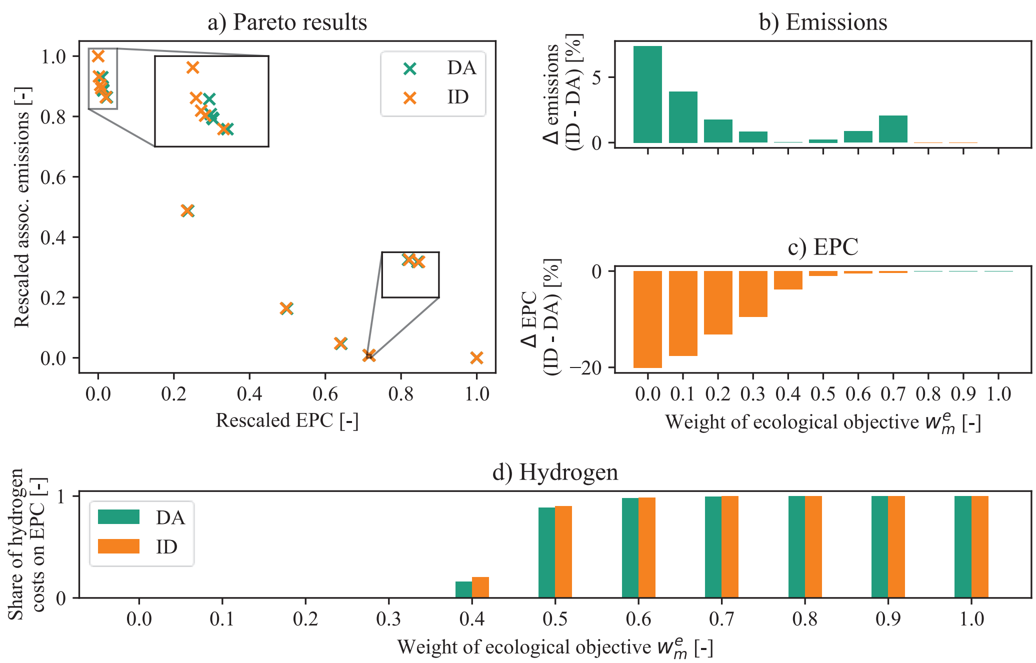

Figure 5: Results of the multi-objective optimization using data from 2020[3]

[2] At $w_m^e = 0.9$, a slight positive value can be seen, but this falls into the MIP-Gap and is therefore insignificant.
[3] Values for plot a) are rescaled due to an NDA; different scaling factors were used for 2020 and 2023.

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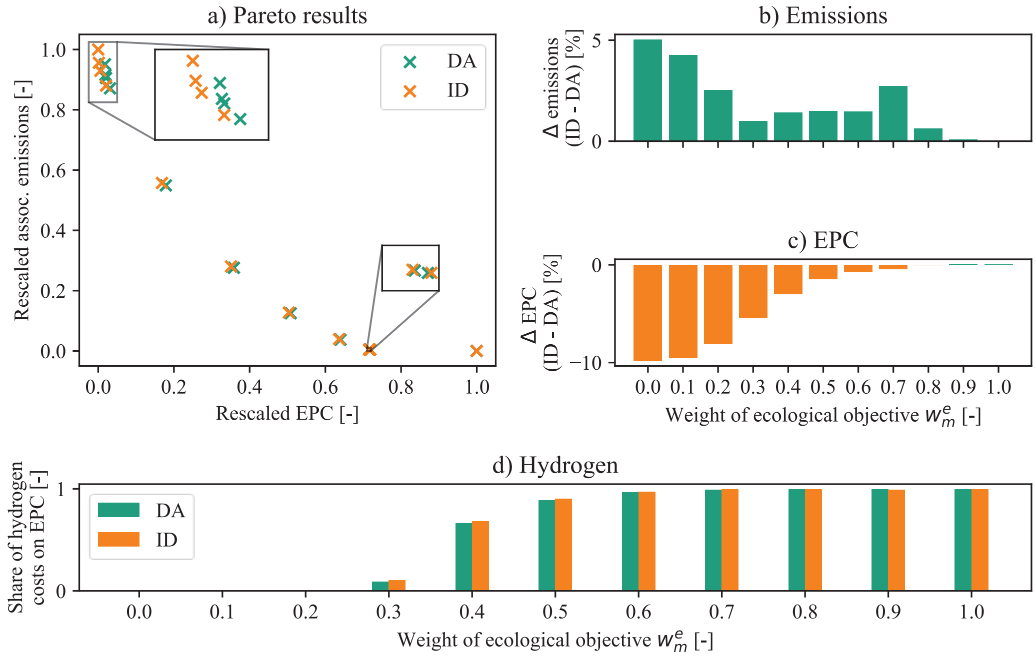

Figure 6: Results of the sensitivity analysis with data from 2023[3]

4 CONCLUSION, DISCUSSION AND OUTLOOK

From the results presented in chapter 3, no advantage for the ID can be derived with respect to the associated emissions, compared to the DA when either one is used as reference market for real-time electricity tariffs. While this result was indicated by the correlation analysis presented in chapter 3.1, neither the financially motivated optimization of an exemplary energy system, nor the incorporation of the carbon intensity of the grid electricity into the optimization could alter this finding. These outcomes also did not change when a second year was considered as data basis. The negative answers to the research questions of this study are nonetheless considered a successful outcome for practical application: it could be shown that already available real-time electricity tariffs based on the DA are better suited to reduce the associated emissions of an inland port terminal in a purely financially and combined financially and ecologically motivated optimization, than not yet available real-time electricity tariffs based on the ID can.

Additional interesting results were obtained in this study, that will be briefly reviewed here. In chapter 3.1 it was shown that the timeseries used in this study are subject to the merit order dilemma of emissions. It describes that power plants with high carbon intensities are sometimes cheaper in operating costs than power plants with low carbon intensities, leading to increased run times of the former and thus increased emissions due to the merit order of electricity markets. This dilemma affects the correlation between electricity prices and carbon intensities negatively. (Fleschutz et al., 2021) showed that increasing the price of carbon increases the correlation between carbon intensity and the marginal cost of fossil fuels, which can solve the dilemma.

From the results in chapter 3.2 an advantage of the ID scenario over the DA scenario could be identified with respect to the EPC of the energy system; in this study, the ID scenario could reach up to 20% lower EPC compared to the DA scenario. This is also depicted in Figure 5 c). These results should be treated with caution, as only pure market prices were considered. It should be kept in mind that an energy supply company offering real-time electricity tariffs will put a surcharge on the market prices to hedge

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against risks such as prognosis deviations in the demand of customers. This surcharge usually increases with more short-term gate closures of the reference market, as only markets with even later gate-closures (and therefore higher risk of high prices) can be used to balance the deviations. As exact values for the surcharge are highly individual, they could nullify the cost benefits gained by using the ID as reference market.

The findings of this study are subject to certain limitations that are laid out in the following. In chapter 3.3 the results of the multi-objective optimization were presented, which reflects an increased interest in ecological ambitions. For higher weights on the ecological objective, a displacement of grid electricity procurement by hydrogen procurement occurred. While this shows the optimal behavior of the inland port terminals energy system, it does veil the effects that high weights on the ecological objective could have with respect to the grid electricity procurement. However, it is expected that no significant differences between the DA and ID scenario would be visible if there were no hydrogen procurement option, as both scenarios utilize the same carbon intensity timeseries. Nonetheless, in future works an energy system should be used as object of investigation that has a certain amount of flexibility but not the possibility to evade grid electricity procurement altogether.

The idea of including the carbon intensity into the optimization is based on the suggestion of (Stoll et al., 2014) to disclose these values for the grid electricity as an incentive for end users to defer shiftable loads to timesteps of low carbon intensity. While progress towards lower overall emissions in the electricity sector can be expected from this approach, it could also be taken further: the disclosed carbon intensity could be specific to the corresponding electricity market and inform not only on the average carbon intensity, but also on the carbon intensity of the marginal power plant, as presented in (Fleschutz et al., 2021). The value would thus represent the electricity traded at that market to the corresponding price and indicate the amount of carbon emissions that every consumer could avoid by reducing their demand by one kWh. With this approach, an even higher correlation between the price and carbon intensity is expected to be achievable, making the most financially operation option also the most ecological one.

NOMENCLATURE

BS	Battery Storage	
CHP	Combined Heat and Power	
DA	Day-Ahead Auction Market	
FC	Fuel Cell	
HP	Heat pump	
ID	Intraday Auction Market	
EPC	Electricity Procurement Cost	$(€/(kWh \cdot a))$
OF	Objective Function	
OFC	Objective Function Coefficient	
PV	Photovoltaic	
w	weight on the objective	(-)
x	optimization variable	(-)
c	objective function coefficient	(variable)
z	objective function value	(variable)

Sub- and superscript

t	timestep
i	optimization variable
m	index of the multi-objective calculations
g	general objective
f	financial objective
e	ecological objective

https://doi.org/10.52202/077185-0162

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ACKNOWLEDGEMENT

The author gratefully acknowledges the financial support by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), promotional reference 03EN3046C.

https://doi.org/10.52202/077185-0162