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Development of a Joint Penalty Signal for Building Energy Flexibility in Operation with Power Grids: Analysis and Case Study

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Abstract: Electricity generation from renewable energy reduces greenhouse gas emissions and, in the long term, the cost of electricity in power grids. However, there is currently no strong positive correlation between greenhouse gas intensity and electricity spot prices in Germany, despite increasing renewable energy penetration. Therefore, energy flexibility programs that rely on demand response may not be fully effective in reducing carbon emissions unless the energy market aligns consistently with carbon emission factors. To address this issue, we propose a model for joint signals consisting of power grid climate gas intensity and price signals that can achieve both environmental and economic benefits for building energy flexibility applications. Next, to assess the maximum possible flexibility hours from the grid side, we explore penalty signal threshold limits with daily and biweekly aggregation. Using a case study, we analyze energy flexibility with joint signals to explore their effect on greenhouse gas emissions and building operation cost. Our results suggest that joint signals can be more effective than a single type of signal in promoting energy flexibility.

Keywords: building energy flexibility; building–grid interaction; dynamic climate gas intensity; joint penalty signal; demand response

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1. Introduction

The European Commission addresses the climate crisis and intends to decrease the current greenhouse gas (GHG) emissions by at least 55% by 2030 compared to 1990 levels [1]. Looking further ahead, the Commission aims to achieve a further reduction of 55% in 2050 compared to 2030 [2]. Germany, which has high GHG emissions per capita compared to other EU countries and the global average, aims to reduce GHG emissions by 80–95% by 2050 compared to 1990 levels [3]. The country's target for 2040 is a minimum reduction of 88%, with the goal of achieving GHG neutrality by 2045 [4]. On this path, Germany defines limits for the annual climate gas emissions by sectors and an annual control mechanism. To achieve the climate action goals, dissemination of renewable energy systems and energy efficiency investments are positive measures, hence heating systems based on renewable energy sources will be funded. The integration of renewable energy systems (RES) into the power supply is critical on the path to these targets. RES have intermittent form, coming from the variations in solar radiation and wind strength, which can result in variable electricity generation and fluctuating energy supply [5,6]. These changes over time within the power grid create stability issues [7].

National (Transmission) grids are responsible for transmitting electricity over long distances from large power plants to various regions of a country [8]. On the other hand, local (distribution) power grids distribute electricity from the national grid to homes and businesses in a specific area. The national and local power grids are different in design, function, and operational requirements due to the differences in the scale of their operation and the distances they cover [9]. As a result, electricity prices can vary between these grids due to factors such as generation costs, transmission costs, distribution costs [10,11], and stability issues. Moreover, electricity prices are influenced by the generation mix of electricity sources, which can vary between national and local power grids. Nevertheless, due to the cost reduction of RES technologies and the increasing cost of electricity generation by nonrenewable sources, RES is expected to contribute more significantly to the power grid globally [12].

Increasing electricity production from RES exposes energy providers to challenges in balancing supply and demand efficiently and economically [5]. To ensure efficient allocation of renewable and conventional energy, markets that allow for the trading of new information are crucial [13]. Increasing the flexibility and responsiveness of short-term wholesale markets to accommodate the growing share of renewable energy is suggested by the European Commission [14]. This proposes empowering consumers to participate in electricity markets by providing them with smart meters and dynamic retail tariffs that reflect changing wholesale prices, enabling them to make informed decisions about energy consumption [15]. To address this issue, energy flexibility in buildings as part of demand response management can be used to optimize the load in the power grid [5] based on various external factors such as power grid demand, energy price signal and $CO_{2eq.}$ intensity.

Exploiting the potential of demand response has become an area of growing interest [16]. Demand response involves actions on the demand side by reacting to conditions in the power grid, providing an opportunity to reduce operating costs and GHG emissions [17]. However, the impact of demand–response programs on CO_2 emissions is often inaccurately assessed using dynamic power grid intensity [18]. The dynamic power grid intensity ($CO_{2eq.}$ intensity) refers to the amount of CO_2 emissions released in the generation of one unit of electricity per hour. The marginal emissions factor based on specific generators' CO_2 intensity provides a more accurate estimate of actual reductions rather than grid-average electricity [19]. The merit order dilemma, which refers to the preference for cheaper, more carbon-intensive technologies in the electricity generation process due to their low marginal costs, is often ignored [20]. Since accurately calculating marginal emissions at a given time is complex, identifying marginal generators and isolating their emissions can be challenging [21]. As a result, load shifting through demand–response programs cannot fully exploit the potential for carbon reduction unless the merit order of the energy market is correlated with carbon emission factors [20]. However, due to the mentioned complications, the $CO_{2eq.}$ intensity signal based on average electricity emission factors are used conventionally in the present applications. In other words, the electricity spot price from the energy market and the commonly used $CO_{2eq.}$ intensity value are not always positively correlated, which raises concerns about the optimizing method for both economic and environmental benefits in energy flexibility applications. Although energy storage can facilitate decarbonisation by boosting renewable energy integration in the long run, its effectiveness in reducing GHG emissions in the short term hinges on factors such as the storage technology used and its operational management [22].

The purpose of this paper is to develop a joint signal of price and $CO_{2eq.}$ intensity and use it as a penalty signal for energy flexibility applications in buildings that achieves both environmental and economic savings. Modelling such a signal is a critical issue in building–grid studies to avoid one type of prominent saving since these signals are not always positively correlated. In the literature, there are various studies discussing the price and $CO_{2eq.}$ intensity as a penalty signal to exploit the energy flexibility but, not much attention has been given to the joint influence of these signals and existing research with this focus is limited. One study [23] investigated the joint impact of both price and CO_2 signals in demand–response programmes using Markov–chain load models. Another study [24] conducted a tradeoff analysis between CO_2 emissions and electricity cost achieving both economic and environmental benefits by utilizing various schedules. [25] examined the combined impact of price and CO_2 emissions in demand response programmes and formulated an optimal control model to reduce energy cost and carbon emissions for five households in South Africa by mixed integer nonlinear programming. Similarly, [26] used mixed integer linear programming for an optimisation model to jointly minimize electricity costs and CO_2 emissions through an optimisation model for home energy management, achieving lower total cost, CO_2 emissions cost, and peak demand shaving. [27] used a mixed integer linear programming model with the ε-constraint method and Pareto curves to examine coordinated scheduling, which resulted in reduced cost and CO_2 emissions. A pilot study to evaluate the influence of real-time price visualisation on electricity consumption, electricity costs, and CO_2 emissions was performed [28]. Since there was a negative correlation between electricity price and $CO_{2eq.}$ intensity in the Swedish electricity market in the period studied, the load shifting results showed a reduction in electricity costs while CO_2 emissions raised.

In this context, this paper introduces two joint penalty signals—concurrence penalty signal and combined penalty signal—and analyses their effectiveness when applied with threshold levels that determine the start of energy flexibility. To achieve this goal, the paper addresses the following research questions:

1. What are the main drivers of the $CO_{2eq.}$ intensity in the German power grid?

The power grid $CO_{2eq.}$ intensity development is discussed in relation to the electricity spot price and energy flow.

2. How does the observation interval affect the definition of penalty signal thresholds?

The paper analyses the upper and lower thresholds for CO_{2eq} intensity and electricity spot price and evaluates the flexibility operation under different observation intervals, such as daily and biweekly, for the heating season. Daily and biweekly observation times refer to the time intervals at which the penalty signals are monitored and used to determine the energy flexibility thresholds.

3. What is the impact of joint penalty signals?

The penalty-unaware status of a case building is compared to different penalty-aware cases using four penalty signals, $CO_{2eq.}$ intensity, electricity spot price (before tax), and two joint signals (concurrence and combined). Their effect on building performance metrics is discussed.

After this introduction (Section 1), this paper is structured as follows: Section 2 shows the calculation methodology of power grid $CO_{2eq.}$ intensity, the threshold calculation of penalty signals and the methods to form the concurrence and combined penalty signals based on $CO_{2eq.}$ intensity and price signals. Section 3 presents the factors influencing the power grid $CO_{2eq.}$ intensity and its relationship with price signal. Additionally, the impact of the different observation intervals on the definition of the penalty signal thresholds is presented. In Section 4, the calculated thresholds are applied in a case study with the described penalty signals, and the result of the simulation results are illustrated. Section 5 discusses the implications of these findings and the analysis. Section 6 concludes the study.

2. Methodology

2.1. Dynamic $CO_{2eq.}$ Intensity Calculation

The dynamic $CO_{2eq}.$ intensity calculation data was collected from ENTSO-e [29], which provides free access to electricity production data and the energy flow information between countries with a time step of 15 or 60 min. The CO_2 emission factors for electricity production technologies are accessible from various resources. In Germany, the grid electricity is generated by 17 different technologies as shown in Table 1.

The production data and the energy flow between countries were obtained for the years 2017–2021, with the interconnected countries for energy flow varying by year. Table 2 presents the yearly average CO_2 emission coefficients of the connected countries. These data were only used as input for the emission calculation resulting from energy trade.

Table 1. Climate gas emissions of various electricity generation technologies in Germany. Climate gases are expressed in CO_2 equivalents (Data source: [30].)

Electricity Production Technology	CO_2 Coefficient ($gCO_{2eq.}$/kWh)
Biomass	70
Fossil brown coal/lignite	1054
Fossil coal-derived gas	433
Fossil gas	433
Fossil hard coal	873
Fossil oil	841
Geothermal	183
Hydro pumped storage-aggregated	14
Hydro run-of-river and poundage	3
Hydro water reservoir	14
Solar	67
Waste	342
Wind offshore	6
Wind onshore	10
Nuclear	68
Other	45
Other renewable	45

Table 2. The $CO_{2eq.}$ intensity of interconnected countries between 2017 and 2021 [31–35].

Country	$CO_{2eq.}$ Intensity ($gCO_{2eq.}$/kWh)				
	2017	2018	2019	2020	2021
Austria	103	100	92	82	82
Belgium	-	-	174	161	140
Czech Republic	472	465	433	437	403
Denmark	179	193	123	109	155
France	69	58	56	51	58
Germany	413	404	344	311	349
Luxembourg	64	65	73	59	55
Netherlands	460	440	392	328	325
Norway	-	-	-	32	27
Poland	778	784	719	710	736
Sweden	10	11	10	9	10
Switzerland	35	35	35	35	35

The $CO_{2eq.}$ intensity in the power grid was influenced by five main factors, including the CO_2 emission coefficient of production technologies (Table 1), the share of technologies in use (from ENTSO-e platform with 60 min data resolution), the CO_2 emission coefficient of imported electricity based on countries (Table 2), and the amount of exported and imported electricity (ENTSO-e). Total CO_2 emissions coming from the production technologies were calculated using the electricity production amount and CO_2 emission coefficients from Table 1 by Equation (1). The average CO_2 emission coefficient of the import countries was used with the amount of imported electricity to calculate the total CO_2 emissions coming from the imported electricity in Equation (2). Total CO_2 emissions coming from the production technologies were reduced by considering the exported electricity to neighbouring countries. In Equation (3), the share of exported electricity in the total electricity production was found and the reduction amount was calculated in Equation (4). The next step focused on the total load in the power grid, presenting the approximate amount of electricity to be consumed by the users. The existing load in the power grid included the produced electricity and the electricity exchange coming from energy transaction Equation (5). Finally, the grid $CO_{2eq.}$ intensity (Equation (7)) was found by the ratio of total CO_2 emissions in the power grid (Equation (6)) to total load in the power grid.

$$PT_{CO_2\ emission} = \sum_{i=1}^{I} \sum_{h=1}^{H} PT_{i,h} \times CO_{2,i} \quad (1)$$

$$Import_{CO_2\ emission} = \sum_{j=1}^{J} \sum_{h=1}^{H} IE_{j,h} \times CO_{2eq,j} \quad (2)$$

$$EE_{\text{Ratio}} = \frac{\sum_{k=1}^{K} \sum_{h=1}^{H} EE_{k,h}}{\sum_{i=1}^{I} \sum_{h=1}^{H} PT_{i,h}} \quad (3)$$

$$Export_{CO_2\ emission} = PT_{CO_2\ emission} \times EE_{\text{Ratio}} \quad (4)$$

$$Load_{Grid} = \sum_{i=1}^{I} \sum_{h=1}^{H} PT_{i,h} + \sum_{j=1}^{J} \sum_{h=1}^{H} IE_{j,h} - \sum_{j=1}^{J} \sum_{h=1}^{H} EE_{i,h} \quad (5)$$

$$Grid_{CO_2\ emission} = PT_{CO_2\ emission} + Import_{CO_2\ emission} - Export_{CO_2\ emission} \quad (6)$$

$$Grid_{CO_2\ intesity=} \frac{Grid_{CO_2\ emission}}{Load_{Grid}} \quad (7)$$

2.2. Threshold Calculation

Thresholds, which represent the boundary points for applying energy flexibility, were dynamically determined based on the observation time and the penalty signal, which in this study are $CO_{2eq.}$ intensity and electricity spot price. In some studies, the observation time is chosen to be "daily" [36,37] or "biweekly" [38]. These observation periods are time intervals at which the penalty signals are monitored and used to determine the energy flexibility thresholds. This implies that 8760 data points per year are taken and aggregated into daily and biweekly intervals.

In the meantime, to approximate the optimal solution, different studies have discussed penalty signal thresholds, which represent the level at when energy flexibility is requested from a building energy system based on this aggregated data. Ref. [39] introduced two adjustable parameters to define the top and bottom threshold for grid interaction signals. In [40], various upper and lower thresholds were used to calculate the number of hours for the set-point adjustment. The thresholds were determined with 25th and 75th percentiles in [36].

In this study, the thresholds as responding to penalty signals were defined by the upper 25% quartile (downward flexibility) and the lower 25% quartile (upward flexibility) using hourly values. Whisker plots were used to assign the penalty signals into quartile groups by percentile analysis. Subsequently, this research compared the results of both aggregation intervals based on the grid status for heating season.

2.3. Development of Penalty Signals and the Simulation Cases

For every aggregation interval, five cases were simulated by a building energy simulation tool to quantify the total CO_2 emissions of the building energy supply, cost, and load profile according to the specified penalty signals. (Table 3).

In the first case (Case Emission), the $CO_{2eq.}$ intensity was exploited as a penalty signal. In the second case (Case Price), price signal was applied. In the third case (Case Concurrence), if the $CO_{2eq.}$ intensity and price signal reflected the same behaviour at the same moment, such as either upward or downward interaction, this synchronised status was used as a signal (Figure 1).

Table 3. The simulation cases based on the penalty signals.

Cases	Penalty Signal
Emission	$CO_{2eq.}$ intensity
Price	Electricity spot price
Concurrence	Simultaneous
Combined	Combined
Reference	Penalty unaware case—Thermostatic valve control

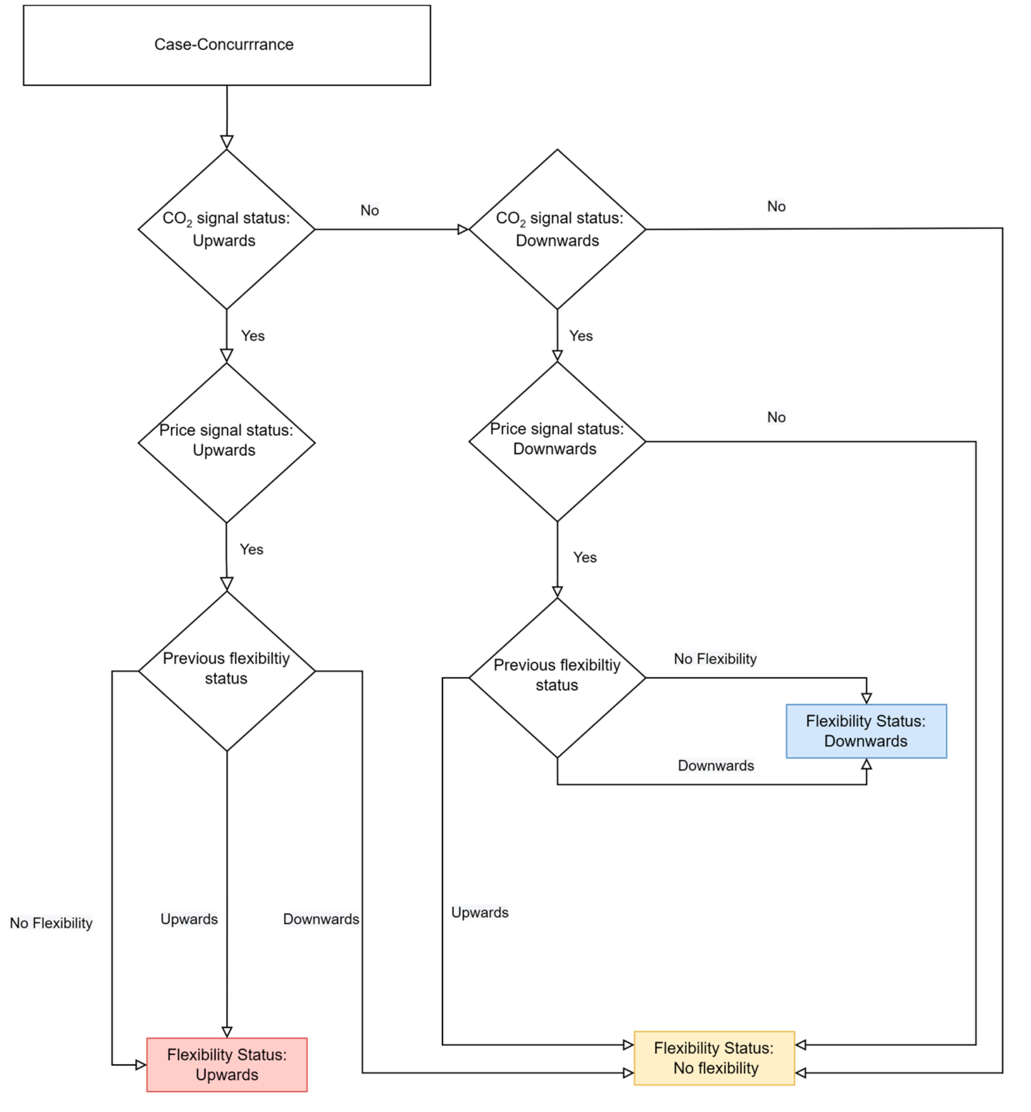


Figure 1. Development of concurrence signal based on the $CO_{2eq.}$ intensity and price signal.

In the fourth case (Case Combined), the combination of $CO_{2eq.}$ intensity and price signals were driven for power grid interaction, such that if one of these signals offered interaction, it was taken into account to develop the combined status. The strategy to form this status was as follows: (1) If both signals offered the same type of power grid interaction state (upwards (+1), downwards (−1), or no interaction (0)), this state was set as the combined signal. (2) If these signals were not harmonised (one is upwards and other is downwards), the previous signal was checked and (2a) the same state as the previous combined signal was chosen; conversely, (2b) if the previous signal was 0 (no interaction), no interaction was continued. (3) If a shift from upwards to downwards or vice versa based on the signals was estimated, it was ignored, and the combined signal was considered as no interaction (Figure 2). Additionally, for (1), the previous signal was checked with the same purpose. This ensured a smooth transition between the statuses and avoided the sharp changes in the indoor thermal comfort and HVAC operation. Finally, the fifth case (Case Reference) presented the penalty signal-unaware status of the case building.

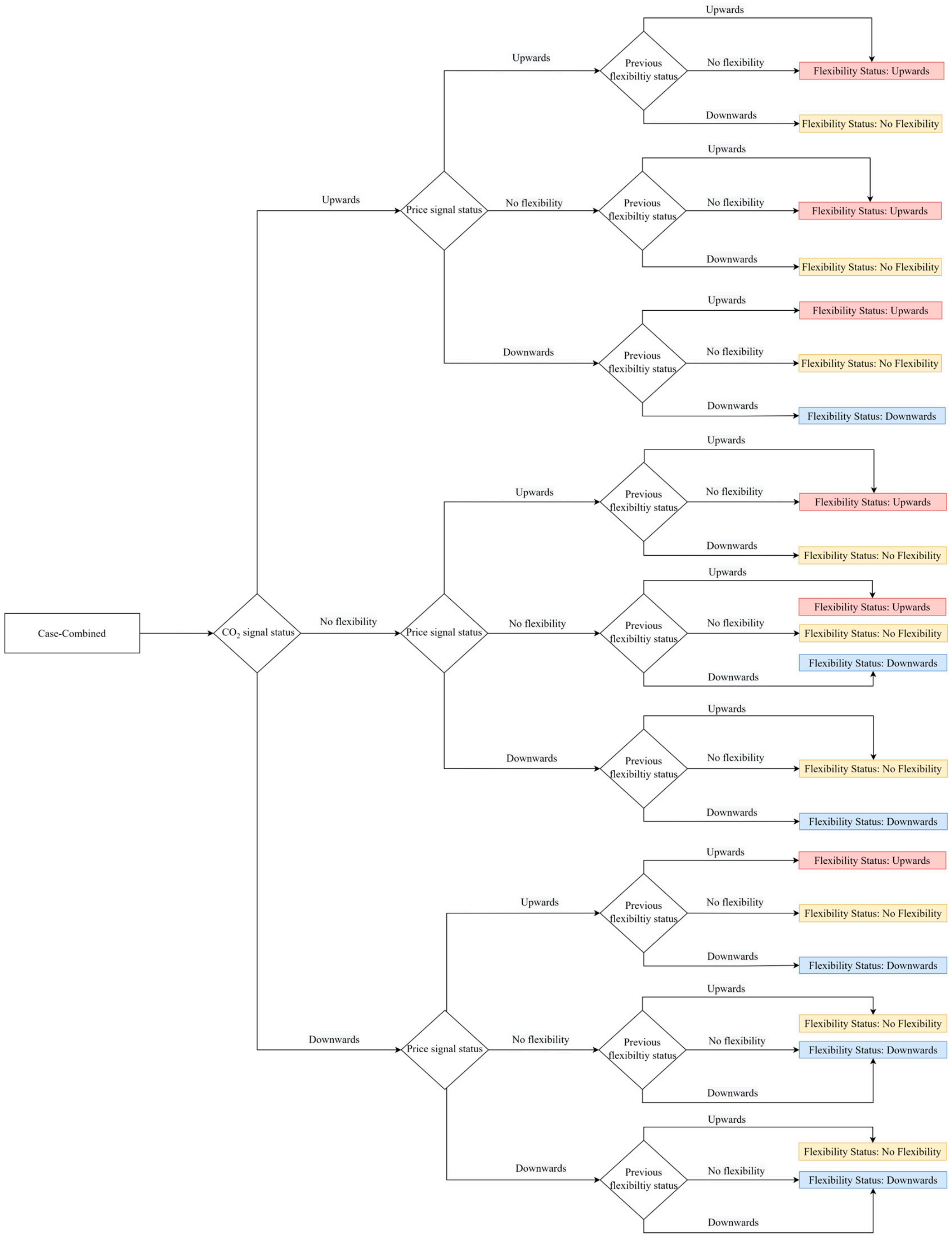


Figure 2. Development of combined signal based on the CO_{2eq}. intensity and price signal.

3. Results

3.1. Dynamic $CO_{2eq.}$ Intensity

Figure 3 presents the share of electricity production technologies between 2017 and 2021. In 2017, the largest contribution was from RES. Although the share of RES decreased in the following years, a growing trend can be observed from 2018 to 2020. Wind energy is the leading technology among RES in Germany, and its overall percentage has been increasing every year. The decreasing trend in production ratio from fossil technologies has reversed, resulting in an increase in 2021. Consequently, electricity generation from RES decreased to nearly 50% in 2021, which was attributed to unfavourable weather conditions [41]. In other words, the current generation in 2021 is approximately 50% dependent on fossil fuel-based power plants.

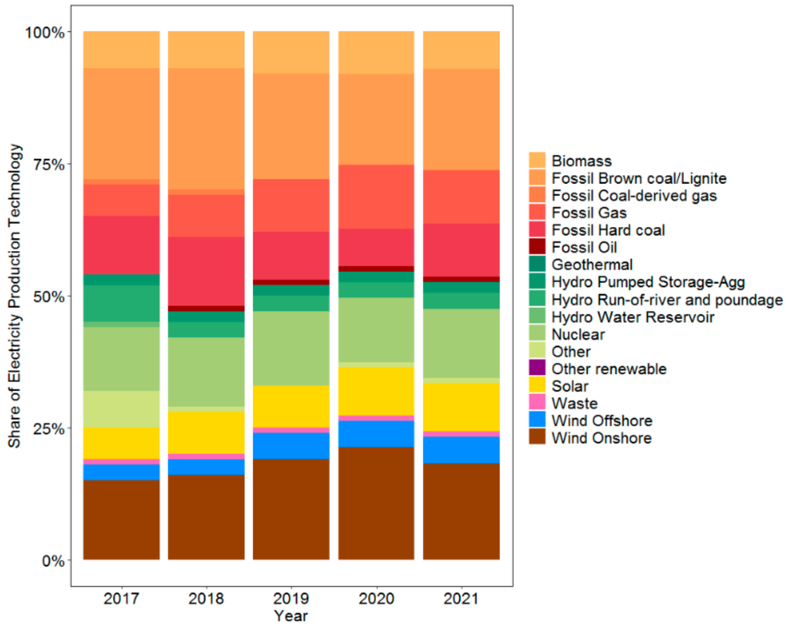


Figure 3. The share of electricity generation technologies in Germany between 2017 and 2021 (Data source: [29]).

Figure 4 presents the grid $CO_{2eq.}$ intensity and electricity spot price for the given years. The yearly average $CO_{2eq.}$ intensity between 2017 and 2021 is calculated as 413, 404, 344, 311, and 439 $gCO_{2eq.}$/kWh, respectively.

The share of electricity production from RES is higher in 2020 compared to other years, leading to lower $CO_{2eq.}$ intensity. Conversely, the highest intensity is observed in 2021 due to a higher share of fossil-based production. The intensity value varies significantly over the year, with the average intensity being approximately 500 $gCO_{2eq.}$/kWh during wintertime and around 300 $gCO_{2eq.}$/kWh in the summer of 2021. The annual average values from Table 2 are reflected in Figure 4 dynamically based on hourly resolution for Germany.

The correlation between the $CO_{2eq.}$ intensity and the electricity spot price is explored for the period between 2017 and 2021, and is illustrated in Figure 5. The results show an upward trend in the correlation factor over this period. As the share of RES in electricity generation increases, a stronger relationship is observed between cheaper generation and CO_2 emission-free generation, particularly between 2017 and 2020. Therefore, the behaviour of $CO_{2eq.}$ intensity as a penalty signal on the energy flexibility reflects the behaviour of the price signal, especially in 2020, when the highest correlation is observed. However, a drastic change occurs in 2021, attributed to the rise of fossil-based production and the increase in electricity spot price by approximately three times compared to 2020 [41]. Further analysis of the relation between $CO_{2eq.}$ intensity and the load in the power grid reveals no significant correlation, thus it is not presented in this study.

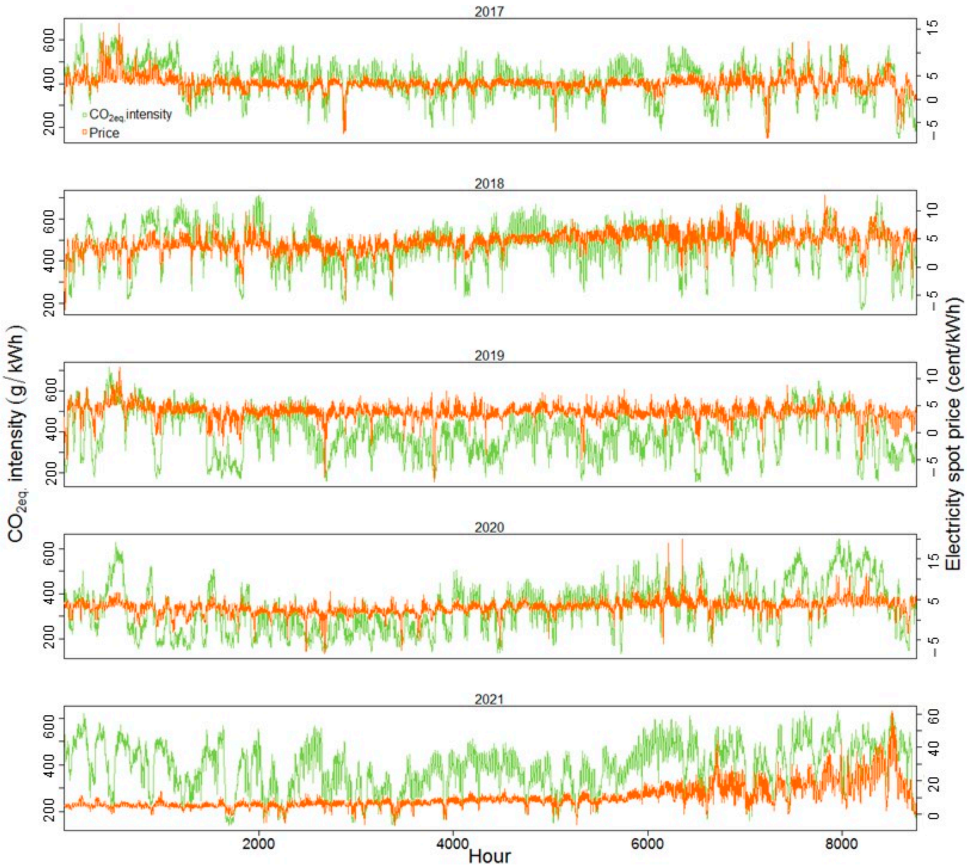


Figure 4. Hourly $CO_{2eq.}$ intensity and electricity spot price between 2017 and 2021 (Data source for electricity spot price: [29]).

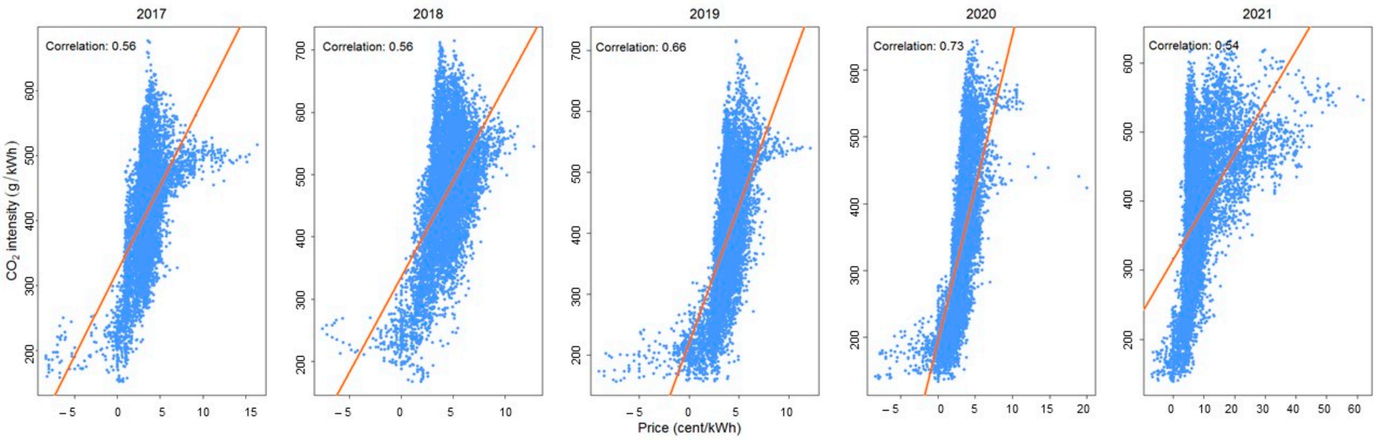


Figure 5. Correlation of hourly $CO_{2eq.}$ intensity and electricity spot price (Data source for electricity spot price: [29]).

As described in Section 2.1, the $CO_{2eq.}$ intensity calculation considers the CO_2 emission from the imported energy, hence, in Figure 6, the $CO_{2eq.}$ intensity profile during import period is examined. One of the highest energy flows to Germany is from the Czech Republic. Along with the import, the $CO_{2eq.}$ intensity in the German power grid rises.

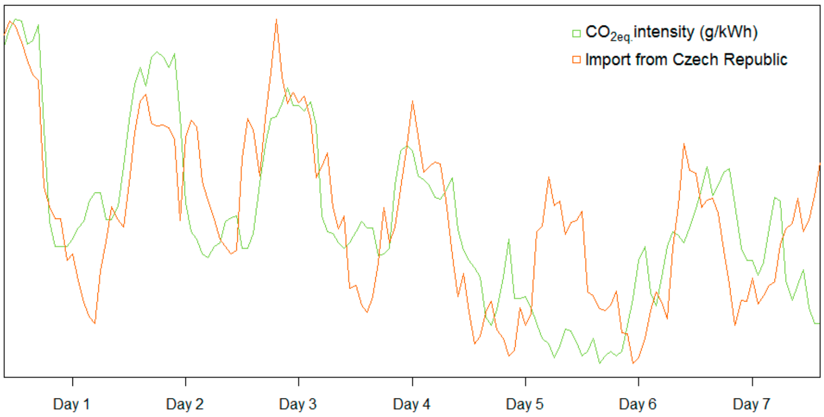


Figure 6. Correlation of hourly $CO_{2eq.}$ intensity and imports with interconnected countries.

3.2. Penalty Signals Threshold

Figure 7 presents the penalty signal thresholds for $CO_{2eq.}$ intensity and electricity spot price for daily aggregation in 2021. The price thresholds vary for each daily aggregation and fluctuate over the course of the year. This raises concerns about the choice of a threshold for a particular day, e.g., selecting the threshold for day_n may result in no positive grid interaction on day_{n+1} or a loss of potential flexibility application hours. Similarly, $CO_{2eq.}$ intensity thresholds vary significantly between days, requiring a threshold to be set for each day. Additionally, the daily $CO_{2eq.}$ intensity thresholds exhibit larger differences throughout the year than the electricity spot price thresholds.

Figure 7. Upper and lower threshold of price and $CO_{2eq.}$ signals with daily observation (red lines represent the upper 25th percentile (downward action) and green lines show the lower 25th percentile (upward action)).

Figure 8 shows the results for biweekly aggregation, with a total of 26 intervals over the course of a year. The electricity spot price threshold values are close to each other among observations than those at daily aggregation, although differences are observed among the seasons. Conversely, $CO_{2eq.}$ intensity threshold exhibits distinct variations during the year.

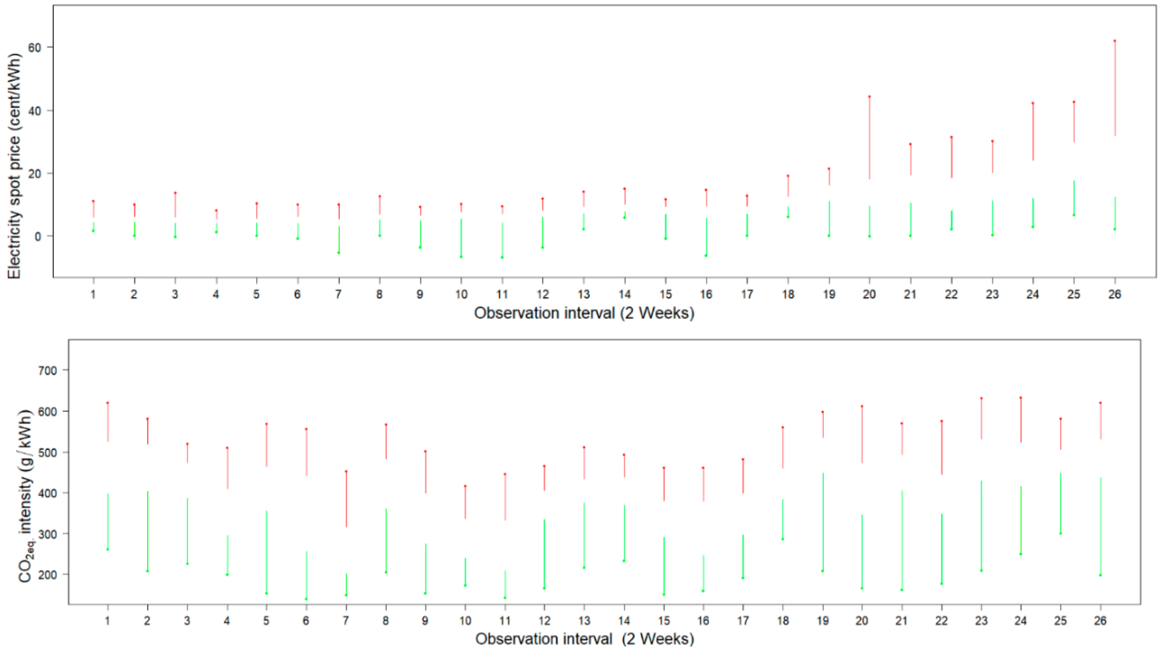


Figure 8. Upper and lower threshold of price and CO_{2eq}. signals with 2 weeks' observation (red lines represent the upper 25th percentile (downward action) and green lines show the lower 25th percentile (upward action)).

The benchmark for threshold limits for $CO_{2eq.}$ intensity signal and price signal between daily and biweekly aggregation was assessed using the upper quartile and lower quartile for the heating season, and the results with the maximum possible flexibility operation hours are presented in Tables 4 and 5. The penalty-aware times are grouped into upward and downward periods. Upward time represents the hours during a day when the penalty signal is less than the lower limit and downward time stands for the periods when the dynamic signal is higher than the upper limit. In Table 4, the differences between aggregations are found as following: In daily aggregation, flexibility application is possible while dynamic $CO_{2eq.}$ intensity signal is higher than 481 $gCO_{2eq.}$/kwh or lower than 447 $gCO_{2eq.}$/kwh for Day 1. The maximum possible flexibility operation hours from the grid side are 6 and 5 h for upward and downward action, respectively. In the case of biweekly aggregation, there can be flexibility when the $CO_{2eq.}$ intensity signal is higher than 531 $gCO_{2eq.}$/kwh and lower than 435 $gCO_{2eq.}$/kwh on the same day, and these are the limits for the next 13 days. On Day 1, the entire day is offered for the upward energy flexibility. By the last day, Day 14, almost no interaction presents based on the calculation results of biweekly aggregation. For this day, 6 h of upward and downward actions are found by the daily aggregation. Comparing the daily and biweekly aggregation cases, a 50% difference is observed for threshold limits, which is the main factor for the variability seen for possible flexibility hours. Besides, rather than having a switch between upward and downward actions, as in the daily aggregation case, the building is intended to have one type of operation in biweekly aggregation.

Table 5 presents the thresholds for the price signal and the maximum possible interaction hours for the heating season. Similar to the $CO_{2eq.}$ intensity signal case, the daily aggregation case shows 5 and 6 h of upward and downward action on Day 1, respectively. However, some days exhibit significant differences by biweekly aggregation by enabling 19 h of upwards flexibility. On Day 14, the flexibility by biweekly aggregation is found as 16 h of downward flexibility. Yet, nearly equal number of flexibility hours (5 and 6 h) for both upwards and downwards are possible with daily aggregation.

Table 4. The thresholds of $CO_{2eq.}$ intensity based on daily and biweekly aggregation—heating season.

	Daily—$CO_{2eq.}$ Intensity Signal				Biweekly—$CO_{2eq.}$ Intensity Signal			
	Upper	**Lower**	**Upward**	**Downward**	**Upper**	**Lower**	**Upward**	**Downward**
	($gCO_{2eq.}$/kwh)		**(Hour)**		**($gCO_{2eq.}$/kwh)**		**(Hour)**	
Day 1	481	447	6	5	531	435	24	0
Day 2	499	465	6	6			7	2
Day 3	527	467	6	5			3	2
Day 4	494	440	6	7			0	9
Day 5	473	333	5	6			7	2
Day 6	553	513	7	5			14	2
Day 7	515	492	6	7			0	23
Day 8	539	497	6	5			0	10
Day 9	481	408	5	7			0	15
Day 10	508	456	7	5			13	2
Day 11	499	473	6	6			4	6
Day 12	464	426	6	6			0	4
Day 13	488	453	5	5			13	0
Day 14	513	481	6	6			0	2

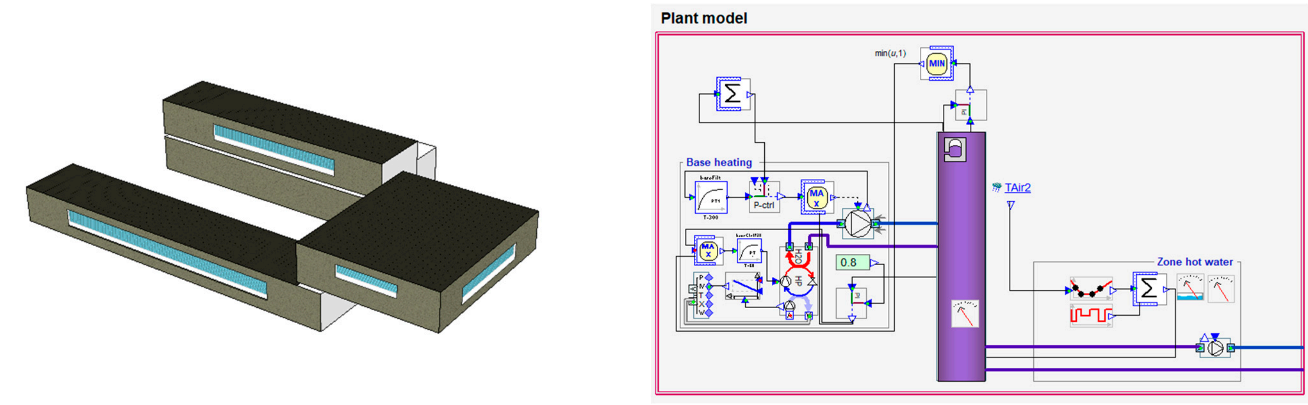
Table 5. The thresholds of price signal based on daily and biweekly observation intervals in the heating season. (Data source for electricity spot price: [29]).

	Daily—Price Signal				Biweekly—Price Signal			
	Upper	**Lower**	**Upward**	**Downward**	**Upper**	**Lower**	**Upward**	**Downward**
	(cent/kwh)		**(Hour)**		**(cent/kwh)**		**(Hour)**	
Day 1	23	17	5	6	32	12	19	0
Day 2	21	9	6	6			6	0
Day 3	33	19	7	6			12	0
Day 4	29	13	5	6			3	11
Day 5	24	10	6	6			8	1
Day 6	34	20	7	6			9	0
Day 7	28	20	5	6			2	13
Day 8	28	21	7	6			3	2
Day 9	24	11	5	6			1	0
Day 10	32	19	7	6			12	0
Day 11	37	20	6	6			5	13
Day 12	34	24	6	6			4	14
Day 13	41	26	6	6			0	14
Day 14	39	27	5	6			0	16

4. A Case Study

The threshold limits are applied to the office zones of a university building assumed to be equipped with an air source heat pump with a constant COP of 4. The university building is located in Wuppertal, Germany and has a total net floor area of 860 m^2 (only for the case zone as presented in Figure 9).

The simulation employs measured climate data from the university weather station and power grid $CO_{2eq.}$ intensity and electricity spot price data from 2021 as penalty signals. The U-values of the external walls (0.22 $W/m^2.K$), window (1.3 $W/m^2.K$), roof (0.20 $W/m^2.K$) and floor (0.28 $W/m^2.K$) were defined as well as the occupancy and ventilation profile (Mon.–Fri. 8:00 a.m. to 6:00 p.m.) in the simulation model. The indoor air temperature set points are designated as the flexibility option.



(**A**) (**B**)

Figure 9. (**A**) The building zone and (**B**) plant model for the simulated case.

The simulation was conducted in hourly time step resolution using the IDA-ICE simulation tool [42], and all five cases are simulated, as outlined in Section 2.3. Daily and biweekly aggregation intervals are used for the simulation for a year, and a rule-based control (RBC) algorithm is employed. The calculated thresholds from Section 3.2 are inserted as input into the control macro, and the indoor temperature levels are adjusted according to the input flexibility status. The indoor temperature set points are 20 °C, 21 °C, and 22 °C for downward flexibility status, no flexibility status and upward flexibility status, respectively, during the heating season. Figure 10 presents the emissions, cost based on the electricity spot market prices (not end user costs), load demand profile, indoor temperature, and the possible flexibility status for Day 1 (from Table 4) as a representative day during the heating season based on daily aggregation, while Figure 11 presents the same metrics for biweekly aggregation intervals (Day 1 from Table 5). The analysis and comparison of the results of the entire 14 days are given in Table 6 with the reference case results. In this research, a simple thermostatic case is simulated for the reference case, and the given costs represent electricity usage coming from the heat pump operation, excluding other zone usage-related costs. It is assumed that end user costs follow the spot market cost profile.

Table 6. The results of the simulated cases for two weeks—heating season.

	Case Emission		Case Price		Case Concurrence		Case Combined		Case Reference
	1 Day	**2 W**	**1 Day**	**2 W**	**1 Day**	**2 W**	**1 Day**	**2 W**	**-**
Load demand (kWh)	690	710	715	740	740	730	710	740	875
CO_2 emission ($kgCO_{2eq.}$)	620	615	690	650	685	690	665	640	840
Cost (Euro)	310	280	245	240	300	305	290	250	380

The minimisation objective is achieved for both daily and biweekly aggregation as illustrated in Figures 10 and 11. The results comparison of observation intervals indicates that savings are higher on biweekly aggregation intervals except for Case Concurrence. In Case Emission, CO_2 emissions are reduced by 26% and 27% with daily and biweekly aggregation, respectively. In Case Price, around a 35% decrement of costs is observed. In Case Concurrence, emission is reduced by 18%, while the cost change is reduced by around 27%. In Case Combined, a 21% and 24% downward change on emissions, besides, a 24% and 34% less cost is calculated for daily and biweekly aggregation, respectively.

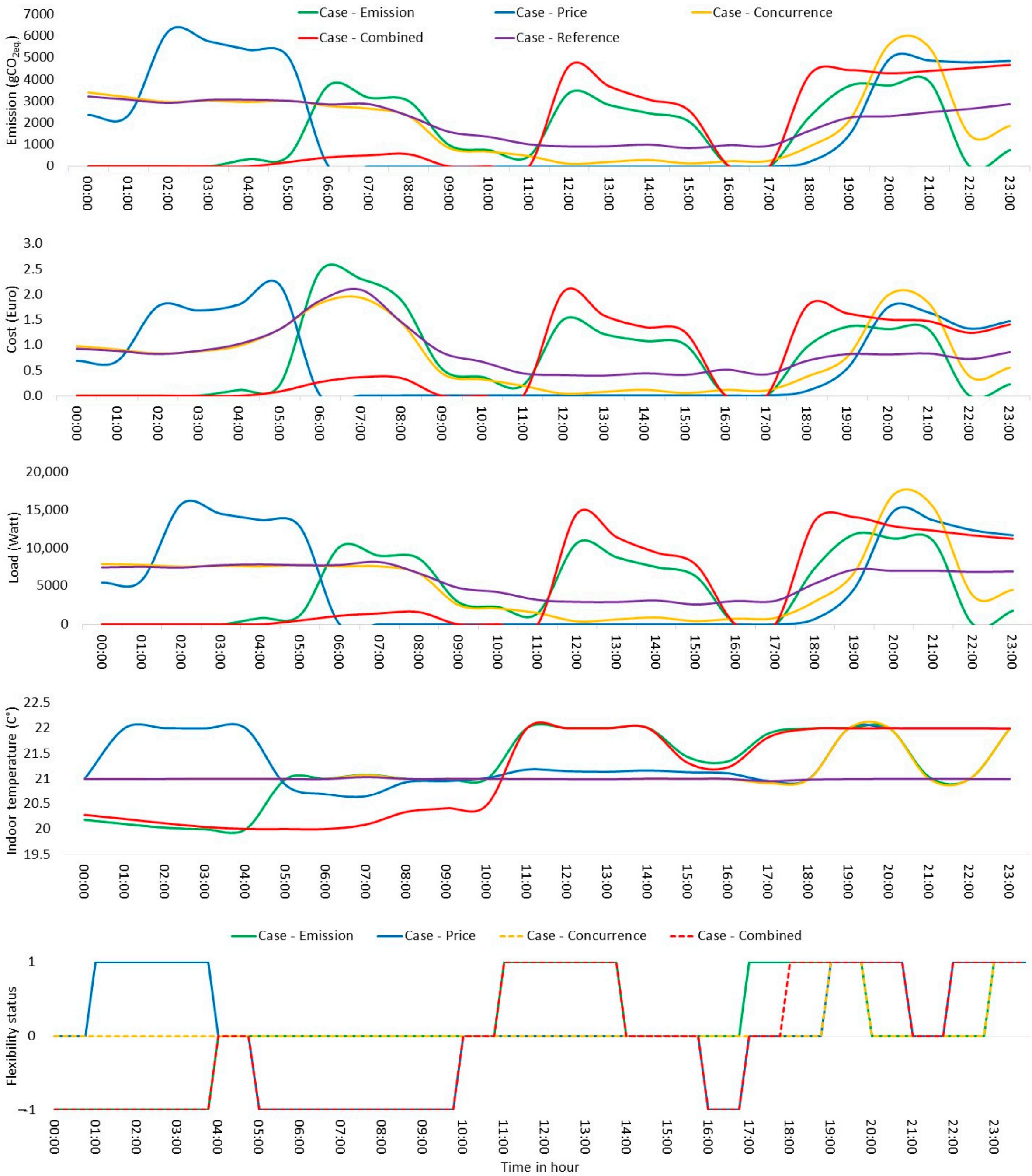


Figure 10. Simulation results of penalty signal with daily aggregation threshold—heating season.

Table 7 provides a comprehensive overview of the yearly savings achieved by the different cases during the heating season. Based on the optimisation parameter (such as emissions for Case Emission and cost for Case Price, etc.), higher savings are calculated in the daily aggregation interval case by a small margin. Case Price results in the highest cost savings, followed by Case Combined. Likewise, the difference in emission savings between Case Emission and Case Combined is negligible. Although the results of Case Concurrence exhibit improvement compared to the reference case, they do not yield any substantial advantage in terms of final metrics. Single penalty signals, such as $CO_{2eq.}$ intensity and price signals, maximise savings for their respective optimisation parameters. However, a holistic optimisation approach can be achieved as demonstrated by Case Combined.

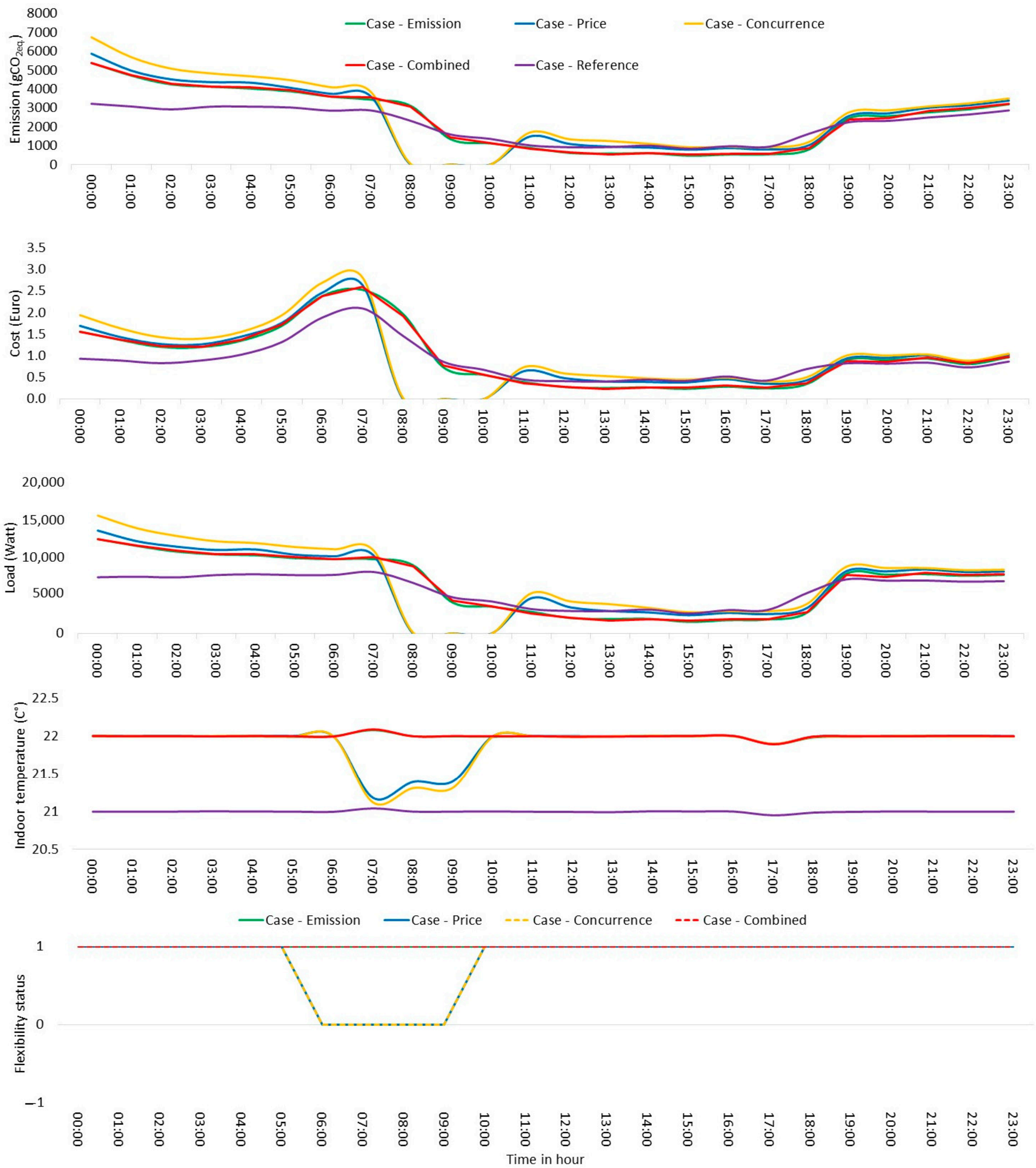


Figure 11. Simulation results of penalty signal with a biweekly observation threshold—heating season.

Table 7. The results of the simulated cases for entire heating season in a year.

	Case Emission		**Case Price**		**Case Concurrence**		**Case Combined**		**Case Reference**
	1 Day	**2 W**	**1 Day**	**2 W**	**1 Day**	**2 W**	**1 Day**	**2 W**	**-**
Load demand (kWh)	20,800	22,200	20,400	21,350	21,000	22,000	20,800	21,700	23,300
CO_2 emission ($kgCO_{2eq.}$)	5660	5900	6170	6120	6240	6260	5900	5960	8290
Cost (Euro)	1500	1450	1270	1300	1530	1515	1360	1330	2070

5. Discussion

The relation between $CO_{2eq.}$ intensity and share of electricity production type are assessed between 2017 and 2021. Following this, the correlation of $CO_{2eq.}$ intensity and electricity spot price is analysed. The decrement of the positive correlation in the last year is highlighted. Moreover, it is seen that the $CO_{2eq.}$ intensity does not depend on local generation technologies but also on the $CO_{2eq.}$ intensity of the interconnected countries. The expansion of the power grid through neighbouring countries limits the value of environmental returns of the existing local RES. Despite the ongoing action plan and the increasing penetration of RES, the share of fossil-fuel based electricity generation does not demonstrate a steady decrease. For a nonemission power grid, the operated generation technology types of the interconnected countries are critical as the local technologies.

Two joint penalty signals and their modelling approach with the motivation of acquiring both environmental and economic savings are introduced. In addition to a single type of penalty signal implementation, their joint impact was able to address improved performance in terms of environment, cost, and load demand. The results from Case Combined presents an option for building operations which ensure remarkable savings on metrics compared to the other cases. Even though each of these parameters can be enhanced more by individual signals (either $CO_{2eq.}$ or price), the overall average outcome is found to be favourable.

The building energy flexibility analysis by applying different penalty signals considering the upper and lower quartiles was performed with the calculated power grid $CO_{2eq.}$ intensity data and historical electricity spot price (before tax) data from the ENTSO-E platform. Two aggregation intervals, namely daily and biweekly, were used for threshold analysis. These thresholds were incorporated into two joint penalty signals as concurrence and combined signals. The approach to develop these signals was described. An office zone group's energy performance, presenting CO_2 emission, cost, load demand, and indoor temperature, was simulated by a building energy simulation tool using the mentioned penalty signals for five given cases. The main findings are listed below:

- The approach for aggregation intervals of penalty signals plays a critical role for the determination of thresholds and the maximum possible interaction hours from the grid side. In the heating season, marked differences were observed for upper and lower thresholds between aggregation intervals.
- Biweekly aggregation intervals might provide an improved building performance based on the time of the year during heating season. However, no significant difference is found between aggregation intervals in the yearly metrics.
- With Case Combined, the environmental and economic performance closely approximates that of Case Emission and Case Price, respectively, thereby achieving the research's objective of minimizing both metrics to nearly the same level.
- Biweekly aggregation reduces peak demand compared to daily aggregation and results in less indoor temperature fluctuation.

The modelling approach of the combined signal ensures more flexibility hours than a single penalty signal, thereby improving both environmental and economic metrics with the use of a joint signal.

6. Conclusions

A simple-structured methodology is presented to calculate the dynamic climate gas emission intensity in the power grid. The calculation method can be used to generate the CO_2 penalty signal in the energy flexibility studies. The main drivers of the emission signals were investigated, following the impact of production technology types, and their share and electricity import in the local power grid are discussed. The relation of $CO_{2eq.}$ intensity was compared to electricity spot price and energy use as a penalty signal in energy flexibility. The biggest challenge was to collect reliable climate gas emission factors of the production technologies and the average emission intensity of the countries, because available data from various sources are not consistent. However, data of electricity production from technologies was easily accessible through transparency platform. For precise emission intensity calculation, the dynamic $CO_{2eq.}$ intensity of the interconnected countries should be considered rather than the average value for energy trade. However, this would complicate the calculation process, especially if there is more than one bidding zone in the connected country. As the penetration of RES is increasing in Germany, a bidding zone configuration might be needed to ensure congestion management. In such a situation, the grid emission intensity in Germany should be calculated on a bidding zone basis and the relation with the price signal should be assessed separately. Additionally, the self-consumption of the production plants should be considered for a more accurate outcome.

A joint signal is necessary for the current mixed power grid but may not be required for future grids based solely on renewable energy sources. In such a scenario, the order of merit for electricity generation could change, potentially simplifying the calculation challenges of marginal emission factors. Then, the dynamic power grid intensity and electricity spot prices would be positively correlated and employed in building energy flexibility applications.

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Nomenclature

Abbreviations	
$CO_{2eq.}$	Carbon dioxide equivalent emissions
COP	Coefficient of performance
GHG	Greenhouse gas
HVAC	Heating, ventilation, and air conditioning
RES	Renewable energy system
Indices	
$h \in \mathrm{H}$	Index and set of hours (hour)
$i \in \mathrm{I}$	Index and set of electricity production technologies (-)
$j \in \mathrm{J}$	Index and set of import countries (-)
$k \in \mathrm{K}$	Index and set of export countries (-)
Parameter	
$CO_{2,i}$	CO_2 equivalent emission coefficient of electricity production technology i
$CO_{2eq,j}$	$CO_{2eq.}$ intensity of country j
Variables	
$EE_{k,h}$	Exported electrical energy to interconnected country k at hour h (kWh)
EE_{Ratio}	Ratio of exported electrical energy (-)
$Export_{CO_2\ emission}$	Total CO_2 emission of exported electricity to interconnected country from Germany ($gCO_{2eq.}$)
$Grid_{CO_2\ emission}$	Total CO_2 emission in the power grid ($gCO_{2eq.}$)
$Grid_{CO_2\ intesity}$	Dynamic CO_{2eq}. intensity in the power grid ($gCO_{2eq.}$/kWh)
$Load_{Grid}$	Total load in the power grid (kwh)
$Import_{CO_2\ emission}$	Total CO_2 emission of imported electricity from interconnected country to Germany ($gCO_{2eq.}$)
$IE_{j,h}$	Imported electrical energy from country j at hour (kWh)
$PT_{i,h}$	Generated electricity from production technology i at hour h (kWh)
$PT_{CO_2\ emission}$	Total CO_2 emission from electricity production technology at hour h ($gCO_{2eq.}$)

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