

# Impact of the EU Carbon Border Adjustment Mechanism on Electricity Trade with Energy Community Contracting Parties

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## Abstract

The European Union Emission Trading System (EU ETS) is a market mechanism that prices CO<sub>2</sub> emissions, driving decarbonisation in the EU energy sector and carbon-intensive industry. To further enhance the EU ETS and prevent carbon leakage, the EU has introduced the Carbon Border Adjustment Mechanism (CBAM). CBAM imposes a duty levy on importing certain CBAM goods, such as electricity, into the EU from third countries and territories without implementing the ETS mechanism or carbon pricing. This paper examines the impact of introducing CO<sub>2</sub> pricing in Bosnia and Herzegovina (BA), a third country connected to the EU electricity market without an ETS, and its electricity trade with Croatia (HR), an EU member state with an established EU ETS. The analyses are conducted using the multi-zonal and multi-sector unit commitment optimisation model Dispa-SET, with the primary goal of providing insights into the implications of CO<sub>2</sub> pricing on the energy market interactions between Bosnia and Herzegovina and Croatia under the CBAM framework. The study examines 100 scenarios, each considering various CO<sub>2</sub>, lignite, and fossil gas prices, and analyses factors such as electricity import/export dynamics, average electricity prices in the zones, total system costs, and load duration curves for fossil power plants in each zone. Results indicate that low fossil gas prices reduce lignite plant operations in Bosnia and Herzegovina, and introducing CO<sub>2</sub> pricing causes a transition from an electricity exporter to an importer. Cross-border line congestion analysis reveals that higher CBAM factors increase congestion, necessitating infrastructure upgrades. Electricity costs in the HR-BA zone rise substantially under high CO<sub>2</sub>

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28 prices, emphasising the need for balanced CO<sub>2</sub> pricing strategies and more deployment of  
29 renewables.

30

31 **Keywords:** Dispa-SET; Carbon Border Adjustment Mechanism (CBAM); ETS; Electricity  
32 Market; Energy Transition; Energy Community Contracting Party; Load Duration Curve

## 33 1. Introduction

34 The introduction of the European Union Emissions Trading System (EU ETS) has significantly  
35 contributed to achieving the EU's climate goals. At the same time, carbon emissions were  
36 displaced to countries not bound by the EU ETS system, especially in carbon-intensive  
37 industries and the power sector [1]. In order to reduce the risk of "carbon leakage" and to  
38 increase the decarbonisation of specific sectors in countries that do not have the Emission  
39 Trading System (ETS) implemented, the EU started designing various environmental policy  
40 measures such as the Carbon Border Adjustment Mechanism (CBAM) [2]. The CBAM will cover  
41 six sectors, which are all energy and carbon-intensive: aluminium, cement, electricity,  
42 fertilisers, iron and steel, and hydrogen. However, measures could be expanded to other  
43 sectors and industries [3]. While the impact of CBAM on third countries has been analysed in  
44 several studies, these analyses primarily focus on the import/export dynamics of high-volume  
45 goods such as aluminium, cement, fertilisers, iron, and steel [4] and [5]. In contrast, the  
46 impact of CBAM on electricity imports has not been extensively studied, with only a few  
47 analyses, such as implementing the CBAM mechanism in California for electricity import from  
48 other USA States, Canada and Mexico [6].

49

50 The introduction of CBAM, or national carbon policy, has significant implications for  
51 underdeveloped and developed countries. Analysis conducted in [7] indicates that  
52 implementing a carbon tariff will negatively impact the economic development, trade levels  
53 and social welfare in India, China, Brazil and South Africa unless they adopt different carbon  
54 tax policies across sectors and actively reduce emissions in the power sector and carbon-  
55 intensive industry. Authors in [8] analysed the emissions of electric power systems in Europe  
56 and their development throughout history. Analyses have shown that the electrical systems  
57 of the Energy Community Contracting Parties have the highest emissions and the most  
58 significant potential for reducing emissions in these countries, but also the most significant  
59 threat of introducing CBAM, or national carbon policy. However, potential support for  
60 implementing CBAM is very high due to historical trade relations, the Common But  
61 Differentiated Responsibilities (CBDR) principles within the Paris Agreement and EU aid  
62 policies for lower-income countries [9].

63

64 Previous research has examined how CO<sub>2</sub> emissions and policies influence carbon market  
65 prices. The findings suggest the need to develop national ETS or carbon taxation levies [10],  
66 enhance national and cross-border transmission networks, and transition to an electricity  
67 supply portfolio with lower carbon intensity [11]. The introduction of CO<sub>2</sub> taxation  
68 significantly impacts transmission capacity expansion, cross-border electricity exchange,  
69 economic trade benefits, renewable energy development, and CO<sub>2</sub> reduction [12]. CO<sub>2</sub>  
70 taxation is identified as a key element in reducing electricity costs and CO<sub>2</sub> emissions in the  
71 power sector based on a high share of fossil fuel power plants [13]. Additionally, national ETS  
72 and carbon pricing are key policies for supporting the low-carbon transformation of carbon-  
73 intensive industries, and the introduction of emissions taxation should be considered as a  
74 fundamental strategic response to mitigate climate change [14]. Analyses conducted in  
75 previous studies indicate that the introduction of national ETS or carbon taxations would  
76 increase the cost of electricity supply and could adversely impact consumers in some  
77 countries unless the revenue from the carbon tax is utilised as a protective measure, i.e. the  
78 fees collected are used for the installation of new technologies and investment in research  
79 and development. The countries or territories where carbon emission trading mechanisms  
80 are introduced should use their regional advantages and establish an integrated carbon  
81 emission trading market [15]. Moreover, international cooperation regarding the  
82 export/import of electricity is needed, primarily because domestic electricity does not  
83 necessarily provide net economic benefits [16].

84

85 A planning modelling tool is needed to analyse the impact of the introduction of CBAM or  
86 national carbon policy on cross-border energy flows, energy transition pathways, and long-  
87 term energy planning of future power systems with a high share of renewable energy [17].  
88 The energy system analysis tool EnergyPLAN [18] is used to design future sustainable energy  
89 solutions, such as a strategy for a fully decarbonised Danish society based on a smart energy  
90 system approach [19]. The modelling of electricity trade among interconnected energy  
91 markets, day-ahead energy markets, and the development of long-term energy planning  
92 strategies for countries or territories in the interconnected energy market has been analysed  
93 with the multi-zonal unit-commitment power-dispatch model DispaSET [20]. In order to  
94 identify a cost-optimal decarbonisation pathway for the Italian energy system until 2050 and  
95 assess how renewable technology cost scenarios affect the optimal solution, the long-term

96    bilevel optimisation model of the energy system H2RES is used [21]. The H2RES model is also  
97    used to assess the importance of hourly variability of renewable energy in evaluating carbon  
98    neutrality scenarios until 2050 [22]. Analyses conducted in previous studies using the models  
99    mentioned above indicate that evaluating the influence of the introduction of CBAM or  
100   national carbon policy is complex, and the integration of different technologies, sectors and  
101   policies can significantly impact the evaluation of scenarios and development of strategies  
102   and recommendations for policymakers.

103

104   This study focuses on Bosnia and Herzegovina (BA) and Croatia (HR) due to their strong cross-  
105   border electricity exchange, long-standing infrastructure integration, and contrasting carbon  
106   pricing regimes. As an EU member state, Croatia participates in the EU Emissions Trading  
107   System (ETS), while Bosnia and Herzegovina, although a Contracting Party to the Energy  
108   Community, has not yet implemented a formal CO<sub>2</sub> pricing mechanism. Despite this  
109   regulatory gap, Bosnia and Herzegovina exported approximately 2.23 TWh of electricity to  
110   the EU via Croatia in 2023, placing it under the EU's CBAM obligations for electricity [23]. This  
111   physical and economic interdependence creates a strategically relevant case for evaluating  
112   the implications of introducing carbon pricing in a non-EU country under the CBAM  
113   framework. Moreover, the countries differ significantly in generation structure: Croatia relies  
114   on imported fossil gas and has advanced its renewable energy deployment, while Bosnia and  
115   Herzegovina's energy mix remains dominated by domestically sourced lignite [24]. This  
116   contrast provides a robust basis for modelling diverse decarbonisation dynamics and  
117   assessing the operational and economic consequences of CBAM across interconnected but  
118   asymmetrical electricity systems.

119

120   The main objective of this paper is to assess how the phased implementation of the EU Carbon  
121   Border Adjustment Mechanism (CBAM) affects electricity trade patterns, system operation,  
122   and CO<sub>2</sub> emissions in interconnected EU and non-EU regions. The analysis focuses on Bosnia  
123   and Herzegovina and Croatia as a representative cross-border case study, marked by strong  
124   physical interconnection and electricity market coupling but contrasting carbon pricing  
125   regimes. This unique configuration, where the countries are "linked" in market terms but  
126   "non-aligned" in climate policy, creates a compelling context for evaluating CBAM  
127   enforcement in the electricity sector. The novelty of this research lies in shifting the analytical

128 focus from industrial goods such as steel, cement, and aluminium, which dominate existing  
129 CBAM literature, to the electricity sector, where carbon pricing asymmetries have immediate  
130 and measurable effects on cross-border trade, system operation, and emissions. Despite its  
131 regulatory inclusion in the CBAM scope under Regulation (EU) 2023/956, electricity remains  
132 underexplored in scenario-based modelling studies, particularly in interconnected but policy-  
133 divergent systems. By modelling 100 scenarios that combine varying CO<sub>2</sub>, lignite, and fossil  
134 gas prices, the study provides a granular assessment of how CBAM influences dispatch  
135 behaviour, cross-border flows, electricity price formation, and emissions intensity. By  
136 simulating the phased introduction of CO<sub>2</sub> pricing in a non-ETS country, the study offers a  
137 transferable modelling framework that supports the alignment of third countries with EU  
138 climate policy. This alignment is critical for mitigating carbon leakage, safeguarding cross-  
139 border electricity trade, and ensuring competitive neutrality within the integrated European  
140 energy market. The methodological approach is adaptable to other "linked but non-aligned"  
141 electricity systems, making this work broadly relevant for international energy policy  
142 development and decarbonisation planning.

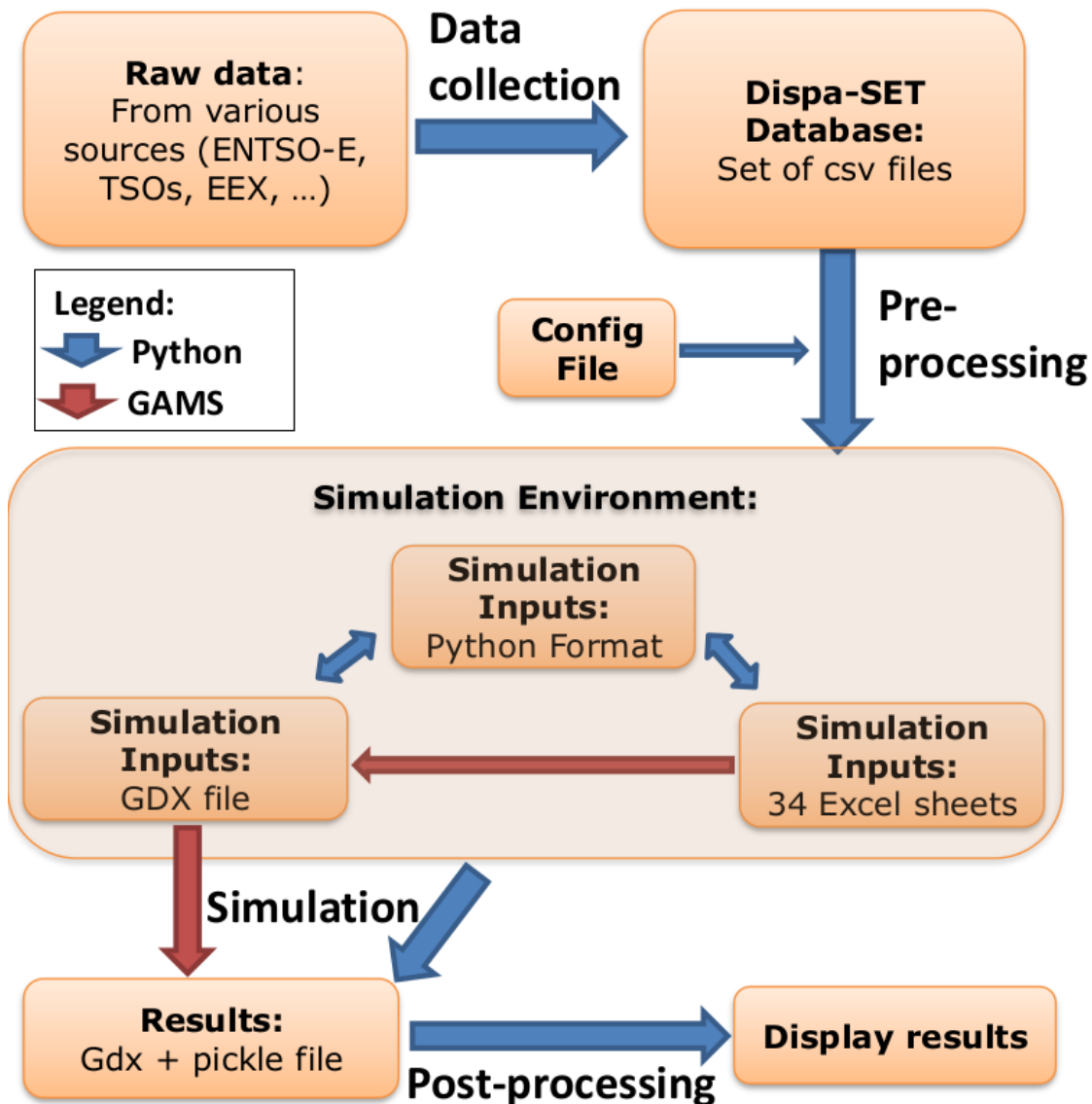
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144 The remainder of the paper is structured as follows. Section 2 provides a policy overview of  
145 the Carbon Border Adjustment Mechanism (CBAM) and details the methodological approach,  
146 including the modelling tool and CO<sub>2</sub> pricing assumptions. Section 3 outlines the design of the  
147 CBAM scenarios, the energy system configuration of Croatia and Bosnia and Herzegovina, and  
148 the key input data used for simulation. Section 4 presents the scenario analysis results,  
149 covering electricity generation, cross-border flows, load duration curves, system costs, and  
150 CO<sub>2</sub> emissions under varying policy and fuel price assumptions. This section also includes a  
151 discussion of infrastructure constraints and system limitations. Finally, Section 5 concludes  
152 the paper with a synthesis of findings and provides policy recommendations relevant to the  
153 EU and its neighbouring electricity trading partners under the CBAM framework.

## 154 **2. Method**

### 155 **2.1. Modelling tool**

156 The multi-zonal and multi-sector unit commitment and power dispatch optimisation model,  
157 Dispa-SET [25], is used to analyse power system operations under different CBAM exemption  
158 scenarios. This open-source model is formulated as a mixed-integer linear programming  
159 (MILP) problem implemented in Python and GAMS (General Algebraic Modelling System).  
160 Dispa-SET can simulate detailed decarbonisation strategies by evaluating energy systems'  
161 operational feasibility and cost-efficiency under various policy and technical conditions. The  
162 model was previously applied to analyse integrating a wide range of technologies to reduce  
163 CO<sub>2</sub> emissions, lower system costs, and minimise renewable energy curtailment. These  
164 include pumped hydro energy storage [26], cogeneration units with thermal storage [27], and  
165 interactions across regional market zones [28], as well as continental-scale electricity market  
166 coupling scenarios [29] and [30]. The model's data flow and simulation architecture are  
167 illustrated in Figure 1.



168

169 Figure 1. Dispa-SET flow chart of the consecutive data entities and processing steps [31]

170

171 The objective function of the Dispa-SET model is to minimise the total power system costs,  
 172 which are defined as the sum of different cost items such as fixed costs of units, variable  
 173 production costs determined by fuel and emission prices, start-up and shut-down costs, costs  
 174 of ramping up and ramping down of a unit, load shedding costs (voluntary and involuntary),  
 175 transmission-related, and loss of load costs. The inputs consist of the power plant database,  
 176 fuel consumption per technology and unit, storage and hydro capacity, power plant outages,  
 177 hourly data for interconnections occurring between the simulated zones and between  
 178 simulated zones and the Rest of the World (RoW), and net transfer capacities between the  
 179 simulated zones and the rest of the world. The power plant database consists of installed

180 power or heat capacity, number of blocks, efficiency, CO<sub>2</sub> intensity, minimum load, ramp-up  
181 and ramp-down rate, minimum up and down time, and start-up and ramping costs. In the  
182 case of CHP units, additional parameters such as power-to-heat ratio, maximum heat  
183 production, and heat storage capacity need to be defined. The detailed model formulation  
184 can be found in the analysis conducted for the Western Balkan power system [32] and [33],  
185 in the report from the Joint Research Centre [34], and on the Dispa-SET model webpage [25].

186

187 The Dispa-SET model is a modular, open-source platform for flexible adaptation to various  
188 national and regional contexts. Its structure allows system operators and analysts to input  
189 country-specific data on generation fleets, transmission networks, demand profiles, and  
190 operational constraints. The model can be customised for application in non-European  
191 regions by adjusting plant characteristics to reflect local technologies, introducing country-  
192 specific fuel price assumptions and policy mechanisms (e.g. CO<sub>2</sub> taxes or subsidies), and  
193 modifying dispatch rules to align with different market structures. These adaptations allow  
194 the model to reflect country-specific energy structures (e.g. fuel mixes or renewable  
195 penetration), market mechanisms (e.g. centralised vs liberalised dispatch), and policy  
196 environments (e.g. emissions regulations or subsidy schemes). This approach has been  
197 successfully implemented in diverse settings, including several African power pools [30],  
198 Bolivia [35] and Western Balkan countries [33], demonstrating its scalability from national  
199 systems with centralised dispatch to regional multi-zone configurations with variable  
200 renewable integration and hydropower coordination. These examples confirm that Dispa-SET  
201 can serve as a robust planning and operational tool across heterogeneous energy policy  
202 environments and levels of market maturity.

203

204 The simulation process is organised into four main stages: data collection, pre-processing,  
205 simulation, and post-processing (see Figure 1). Raw data are collected from standardised  
206 sources, including ENTSO-E, national TSOs, and electricity markets (e.g., EEX) and are first  
207 structured into a central database composed of CSV files. These are converted into formatted  
208 simulation inputs through pre-processing scripts written in Python based on configuration  
209 files defining model parameters, temporal resolution, and scenario-specific assumptions.  
210 Dispa-SET accepts input in GDX (GAMS Data Exchange) and Python formats, allowing for  
211 flexibility in linking with external modelling frameworks or data repositories. In this study, the

212 simulation environment was configured to reflect the operational characteristics of the HR-  
213 BA power system, including technical constraints of thermal units, hydropower availability,  
214 and hourly demand profiles. Simulation results, stored in GDX and pickle formats, are then  
215 post-processed to generate dispatch schedules, emissions, curtailment rates, and cross-  
216 border electricity flows.

217

218 This study applied the Dispa-SET model to simulate hourly electricity system operations under  
219 various policy and fuel price scenarios. Key assumptions include fixed fossil and hydropower  
220 capacities, scenario-dependent scaling of variable renewables, and CO<sub>2</sub> prices aligned with  
221 the CBAM phase-in schedule. Electricity demand, fuel prices, and renewable generation  
222 profiles were treated as exogenous inputs derived from national energy plans and publicly  
223 available sources. Cross-border exchanges were modelled using hourly historical flows and  
224 projected interconnection capacities. To simulate the impact of CBAM, a phased CO<sub>2</sub> pricing  
225 structure was applied to Bosnia and Herzegovina, reflecting its progressive alignment with  
226 the EU ETS through 2035. Full details on model formulation, constraints, and emissions post-  
227 processing are available in the official Dispa-SET documentation [25], ensuring transparency  
228 and replicability.

229

## 230 **2.2. Carbon Border Adjustment Mechanism (CBAM)**

231 The European Union's Carbon Border Adjustment Mechanism (CBAM) is a financial  
232 instrument designed to be compatible with World Trade Organization (WTO) rules [3]. The  
233 CBAM ensures that the carbon price paid for specific imported goods is equivalent to those  
234 produced within the EU covered by the EU Emissions Trading System (ETS). The sectors  
235 covered by CBAM include cement, aluminium, fertilisers, iron and steel, hydrogen, and  
236 electricity. Only import of specific goods from these sectors, as listed in Annex I of Regulation  
237 (EU) 2023/956, are subject to CBAM [3].

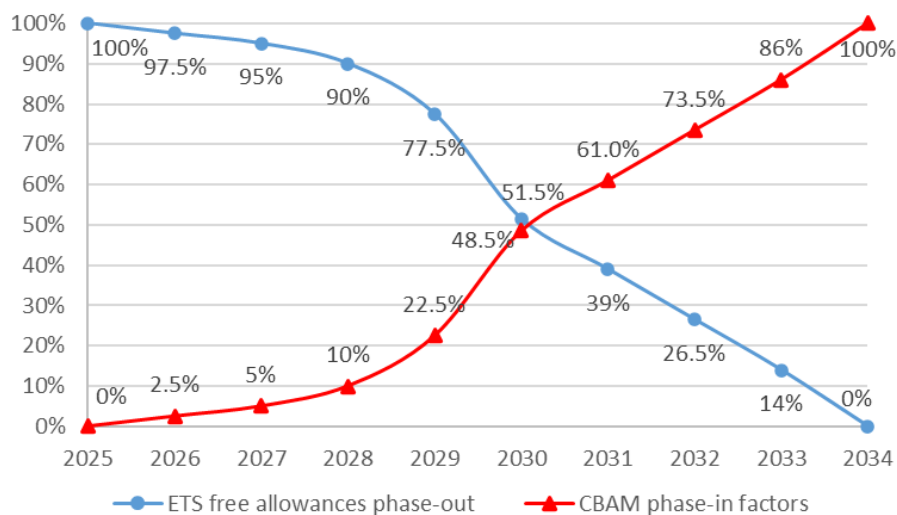
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239 The Carbon Border Adjustment Mechanism (CBAM) was established to prevent "carbon  
240 leakage", which occurs when carbon-intensive industries relocate from the EU to third  
241 countries with less stringent CO<sub>2</sub> emissions and energy efficiency policies. This relocation can

242 increase the import of more carbon-intensive products, undermining the EU's efforts to  
243 reduce greenhouse gas emissions. The introduction of the CBAM is divided into three phases:

- 244 - **CBAM transitional period:** from 1 October 2023 to 31 December 2025 with a reporting  
245 obligation only. During this phase, purchasing or surrendering CBAM certificates is not  
246 required.
- 247 - **CBAM phase-in period:** from 1 January 2026 to 31 December 2034, with the obligation  
248 to purchase and surrender CBAM certificates. The cost of these certificates will be  
249 based on the weekly average of the EU ETS allowance price. During this phase, free  
250 allowance for CBAM sectors covered by the EU ETS will be gradually phased out.  
251 Simultaneously, the CBAM will apply only to the share of emissions that does not  
252 benefit from free allowance under the EU ETS. Free allowance phase-out and CBAM  
253 factors are presented in **Figure 2** [36].
- 254 - **CBAM fully phased in:** from 1 January 2035, the CBAM certificate will equate to the  
255 full price of EU ETS allowance, and free allocation to CBAM sectors under EU ETS will  
256 be completely phased out.

257  
258



259

260 Figure 2. EU ETS free allowance phase-out and CBAM phase-in factors for the period 2025-  
261 2034 [36]

262

263 Certain CBAM goods, like electricity, may be exempted from CBAM if third countries or  
264 territories integrate their electricity market with the Union electricity market and commit to  
265 decarbonise their electricity generation with a high share of renewable energies. They must

266 also implement carbon pricing mechanisms similar or equivalent to EU ETS until 2030. To  
267 import electricity exempted from CBAM, a third country or territory must implement market  
268 coupling with the Union's internal market for electricity and fulfil conditions set in Article 2(7)  
269 of the EU Regulation (EU) 2023/956 on the CBAM [3]. These conditions include the  
270 implementation of the Union laws and regulations in the field of electricity, energy,  
271 environment and competition, a commitment to climate neutrality by 2050, alignment of  
272 carbon pricing and ETS with the Union, and implementation of an effective system to prevent  
273 indirect import of electricity from third countries or territories that do not meet the condition  
274 stipulated in Regulation (EU) 2023/956.

275

276 Recent literature has expanded the analytical scope of the EU CBAM by examining its broader  
277 economic, legal, and geopolitical implications. In [37], the authors critically assess whether  
278 the CBAM will achieve its dual objectives of mitigating carbon leakage and ensuring fair  
279 competition, highlighting institutional design limitations and potential WTO-related  
280 constraints. A global trade analysis conducted in [7] investigates the economic impact of  
281 CBAM on the BASIC countries, showing that carbon tariffs can undermine economic growth  
282 and trade competitiveness unless accompanied by differentiated policy responses. The study  
283 in [38] shifts focus to intra-EU dynamics, identifying distributional inequalities, with Eastern  
284 European countries facing higher vulnerability due to the phase-out of free allowances. In  
285 [39], an input-output modelling framework is used to evaluate the disproportionate burden  
286 placed on least developed countries and the potential benefits of a refund mechanism based  
287 on historical emissions and green innovation. Finally, [40] presents a case study on Serbia,  
288 showing how introducing carbon pricing in a lignite-dependent electricity sector may impact  
289 GDP in the short to medium term, emphasising the importance of revenue recycling and  
290 phased policy alignment. These studies highlight the multidimensional impacts of CBAM and  
291 underscore the importance of flexible, context-sensitive approaches in its implementation,  
292 especially for electricity trade between "linked but non-aligned" systems.

### 293 **3. Scenario analysis**

#### 294 **3.1. CBAM scenarios**

295 A comprehensive set of scenarios was developed to analyse the impact of CBAM and fuel  
296 prices on the power systems of Bosnia and Herzegovina (BA) and Croatia (HR) and cross-

border energy flows between the two countries. These scenarios consider three key parameters: fossil gas, lignite, and CO<sub>2</sub> price. The influence of the price of fossil gas and lignite is analysed because the primary fuel used for producing electricity in Croatia is imported fossil gas, while the main fuel used in Bosnia and Herzegovina is domestic lignite. Both energy systems are heavily dependent on electricity produced from hydropower plants.

The average yearly fossil gas price was used to represent various years from recent history, indicating future price changes. Table 1 presents the average annual fossil gas prices in specific years used in designing CBAM scenarios and energy system analyses.

Table 1. Fossil gas prices used in designing CBAM scenarios [41] and [42]

€/MWh	ELGAS -2020	LGAS -2021	MGAS -2023	HGAS - 2022
<b>Fossil gas price</b>	13.74	22.00	44.00	97.00

In Table 1, the extra low fossil gas price (ELGAS) corresponds to the year 2020, reflecting the period when the coronavirus crisis started and industry demand rose; the low fossil gas price (LGAS) represents the year 2021 when the industry began to recover; the high fossil gas price (HGAS) represents the year 2022 when the fossil gas crisis began; and the medium fossil gas price (MGAS) represents the year 2023 when fossil gas prices fell and the market stabilised.

The average yearly lignite price was used to represent the most dominant fuel used in the energy system of Bosnia and Herzegovina and to reflect the recent fossil gas crisis in the period 2020-2023, which directly impacted lignite price and export of electricity from lignite-based energy systems such as Bosnia and Herzegovina. Table 2 presents the average annual lignite prices in specific years used in designing CBAM scenarios and energy system analyses.

Table 2. Lignite price used in designing CBAM scenarios [43] and [44]

€/MWh	ELL -2020	LL -2019	ML -2021	HL - 2023	EHL - 2022
<b>Lignite price</b>	8.0	9.3	12.0	12.8	14.0

In Table 2, the extra low lignite price (ELL) corresponds to the year 2020, reflecting the period when the coronavirus crisis started and industry demand rose; the low lignite price (LL) represents the year 2019; the medium lignite price (ML) represents the year 2021 when the worldwide industry began to recover; the extra high lignite price (EHL) represents the year

325 2022 when the fossil gas crisis began; and the high lignite price (HL) represents the year 2023  
326 when fossil gas prices fell and the market stabilised.

327

328 Combining the different fossil gas prices (ELGAS, LGAS, MGAS, HGAS) with the various lignite  
329 prices (ELL, LL, ML, HL, EHL), a comprehensive set of scenarios is presented in Table 3. Each  
330 scenario name represents a combination of fossil gas and lignite prices, allowing for a detailed  
331 analysis of their combined effects on the power systems of Bosnia and Herzegovina and  
332 Croatia. This structured approach enables the assessment of how varying fuel prices and the  
333 implementation of CBAM influence cross-border energy flows and the broader energy  
334 transition pathways.

335

Table 3. Reference fuel price scenarios

<b>Fuel price scenarios</b>	<b>ELL</b>	<b>LL</b>	<b>ML</b>	<b>HL</b>	<b>EHL</b>
<b>ELGAS</b>	ELGAS-ELL	ELGAS-LL	ELGAS-ML	ELGAS-HL	ELGAS-EHL
<b>LGAS</b>	LGAS-ELL	LGAS-LL	LGAS-ML	LGAS-HL	LGAS-EHL
<b>MGAS</b>	MGAS-ELL	MGAS-LL	MGAS-ML	MGAS-HL	MGAS-EHL
<b>HGAS</b>	HGAS-ELL	HGAS-LL	HGAS-ML	HGAS-HL	HGAS-EHL

336

337 CO<sub>2</sub> pricing was introduced into the power system of Bosnia and Herzegovina to create CBAM  
338 scenarios and conduct analysis. Bosnia and Herzegovina currently has no established CO<sub>2</sub>  
339 pricing mechanism, whereas Croatia has implemented CO<sub>2</sub> pricing through the EU Emissions  
340 Trading System (ETS). This approach demonstrates how CO<sub>2</sub> pricing can be modelled in  
341 countries without existing CO<sub>2</sub> pricing mechanisms and can be applied to analyse the impact  
342 of introducing such mechanisms. The CBAM phase-in and the reduction of free allowances  
343 were introduced using a factor representing the percentage of CO<sub>2</sub> charged to electricity  
344 generated in countries without an implemented emission trading system, indicating the  
345 gradual implementation of CBAM. The analysis used hourly distribution data for EU ETS CO<sub>2</sub>  
346 prices from 2022, collected from EEX [45].

347

348 CO<sub>2</sub> prices were modelled as a percentage of the EU ETS price in 2022 for each scenario to  
349 explore the impact of introducing CO<sub>2</sub> pricing in Bosnia and Herzegovina and the influence of  
350 different fossil gas and lignite prices. Each reference fuel scenario was analysed with varying  
351 CO<sub>2</sub> prices for Bosnia and Herzegovina, while CO<sub>2</sub> prices in Croatia's power system remained

352 constant at 2022 levels. These percentages are introduced based on the phased  
353 implementation plan outlined in the CBAM regulation, which aims to gradually incorporate  
354 CO<sub>2</sub> pricing into the cost of imported goods to match the EU's internal carbon pricing  
355 mechanisms. The CO<sub>2</sub> price in Bosnia and Herzegovina's power system was introduced in  
356 steps:

- 357 • 0CO<sub>2</sub> - 0% of the 2022 EU ETS CO<sub>2</sub> price represents the current situation with no CO<sub>2</sub>  
358 pricing,
- 359 • 25CO<sub>2</sub> - 25% of the 2022 EU ETS CO<sub>2</sub> price representing the implementation of CBAM  
360 factors in the year 2029,
- 361 • 50CO<sub>2</sub> - 50% of the 2022 EU ETS CO<sub>2</sub> price representing the implementation of CBAM  
362 factors in the year 2030,
- 363 • 75CO<sub>2</sub> - 75% of the 2022 EU ETS CO<sub>2</sub> price representing the implementation of CBAM  
364 factors in the year 2032,
- 365 • 100CO<sub>2</sub> - 100% of the 2022 EU ETS CO<sub>2</sub> price represents a full implementation of CBAM  
366 by 2034.

367 As detailed in the CBAM directive, this phased approach is designed to align non-EU countries  
368 progressively with the EU's carbon pricing, reducing the risk of carbon leakage and ensuring  
369 fair competition. The phases correspond to the timeline for gradually phasing out free  
370 allowances under the EU ETS, as depicted in Figure 2 and outlined in Section 2.2.

371

372 This approach created five additional scenarios for each reference fuel scenario, resulting in  
373 one hundred CBAM scenarios. These scenarios capture the influence of different fuel and CO<sub>2</sub>  
374 pricing levels, enabling a comprehensive understanding of how these factors influence the  
375 power systems and cross-border energy flows. The same methodology can be applied to any  
376 other country, whether or not it has an established CO<sub>2</sub> pricing mechanism, to evaluate the  
377 impact of introducing CO<sub>2</sub> pricing and CBAM.

### 378 **3.2. Reference energy systems and data inputs**

379 For comparing CBAM scenarios, 2022 was selected as the base year and modelled in the  
380 Dispa-SET. Primary input data, such as heating, day-ahead total load forecast, actual total

381 load, cross-border physical flow, forecasted day-ahead transfer capacities, minimum hydro  
382 levels, and RES availability, are in the form of hourly time series.

383

384 The hourly profiles of the day-ahead total load forecast, actual total load, cross-border  
385 physical flows, and forecasted day-ahead transfer capacities were obtained from the ENTSO-  
386 E transparency platform for the year 2022 [23]. Hydro data, including reservoir levels and  
387 scaled water inflows, were sourced from previous analyses conducted for the Western Balkan  
388 region [33] and [46]. Hourly production data for wind and solar power plants are obtained  
389 from the ENTSO-E transparency platform for the year 2022 [23]. Load curves for hourly district  
390 heating demand were obtained from previous studies [24] and [47] and adapted to the yearly  
391 total heat generation values obtained from the International Energy Agency (IEA) for the year  
392 2022 [48].

393

394 The installed capacity of power plants in the energy system of Bosnia and Herzegovina and  
395 Croatia were obtained from [33] and [24] and updated with the newest data from the ENTSO-  
396 E transparency platform [23], Bosnia and Herzegovina Integrated Energy and Climate Action  
397 Plan [49], Croatian Energy Market Operator (HROTE) [50] and Energy in Croatia: Annual  
398 Energy Report [51]. The total installed capacity of power plants in Bosnia and Herzegovina  
399 consists of 1888 MW of lignite power plants, 138 MW of wind onshore power plants, 107 MW  
400 of PV power plants, 9 MW of biomass power plants, 1 MW of biogas power plants and 2088  
401 MW of hydropower plants of which 420 MW of pumped storage hydropower plants (PHPS),  
402 1050 MW of conventional hydro dam power plants (HDAM) and 618 MW of hydro run-of-  
403 river power plants (HROR). In Croatia, the total installed capacity of power plants consists of  
404 199 MW of fossil hard coal power plants, 745 MW of fossil gas power plants, 1043 MW of  
405 wind onshore power plants, 182 MW of PV power plants, 98 MW of biomass power plants,  
406 61 MW of biogas power plants and 2096.55 MW of hydropower plants of which 518.4 MW of  
407 pumped storage hydropower plants, 1053.7 MW of conventional hydro dam power plants  
408 and 524.45 MW of hydro run-of-river power plants. Table 4 presents a detailed overview of  
409 the installed thermal power plants in Croatia, Bosnia and Herzegovina, along with key  
410 technical parameters such as efficiency, ramping characteristics, and CO<sub>2</sub> intensity. These  
411 data are crucial for modelling operational behaviour and assessing system performance under  
412 various CBAM and CO<sub>2</sub> pricing scenarios using the Dispa-SET model.

413  
414

Table 4. Installed capacity of thermal power plants in Croatia (HR) and Bosnia and Herzegovina (BA), and the primary technical data used in the Dispa-SET model for analysis of the energy system in the HR-BA zone [32], [33], [46], [24]

Unit	Power plant Capacity [MW]	Zone	Fuel	Efficiency [%]	Minimum up time [h]	Minimum down time [h]	Ramp Up Rate [%/min]	Ramp Down Rate [%/min]	Start-Up Cost [EUR]	Ramping Cost [EUR/MW]	Minimum load [%]	Efficiency at minimum load [%]	Start-up time [h]	CO2 Intensity [tCO2/MWh]
TPP "Tuzla"	650	BA	Lignite	0.32	6	1.5	0.025	0.025	99,000	2.37	0.65	0.25	6	1.062
TPP "Kakanj"	408	BA	Lignite	0.33	6	1.5	0.025	0.025	62,300	2.37	0.63	0.25	6	1.062
TPP "Ugljevik"	279	BA	Lignite	0.32	6	1.5	0.025	0.025	41,540	2.37	0.56	0.25	6	1.062
TPP "Gacko"	276	BA	Lignite	0.32	6	1.5	0.025	0.025	41,540	2.37	0.65	0.25	6	1.062
TPP "Stanari"	275	BA	Lignite	0.34	6	1.5	0.025	0.025	41,540	2.37	0.55	0.25	6	1.01
TPP "KTE Jertovec"	78	HR	Fossil gas	0.36	2	2	0.06	0.06	6,200	0.66	0.06	0.49	3	0.398
TPP "EL-TO Zagreb"	50	HR	Fossil gas	0.31	2	2	0.06	0.06	4,000	0.66	0.12	0.15	3	0.398
TPP "TE-TO Zagreb"	300	HR	Fossil gas	0.31	2	2	0.06	0.06	19,150	0.66	0.15	0.3	3	0.398
TPP "TE-TO Osijek"	89	HR	Fossil gas	0.39	2	2	0.06	0.06	19,150	0.66	0.28	0.32	6	0.398
TPP "TE-TO Sisak"	228	HR	Fossil gas	0.31	2	2	0.06	0.06	19,150	0.66	0.15	0.3	3	0.398
TPP "Rijeka"	303	HR	OIL	0.52	6	1.5	0.025	0.025	42,000	2.37	0.40	0.29	6	0.517
TPP "Plomin 2"	199	HR	Hard coal	0.42	6	1.5	0.025	0.025	11,500	2.37	0.30	0.29	6	1.062

415

416

417 In addition, Table 5 lists the installed hydropower plant capacities in both countries, reflecting  
 418 the significant contribution of hydropower to their electricity generation mix. These values  
 419 play a key role in determining the flexibility and decarbonisation potential of the regional  
 420 energy systems.

421 Table 5. Installed capacity of conventional hydro dam power plants (HDAM), hydro run-of-  
 422 river power plants (HROR) and pumped storage hydropower plants (HPS) in Croatia (HR)  
 423 and Bosnia and Herzegovina (BA) [32], [33], [46], [24]

Croatia (HR)			Bosnia and Herzegovina (BA)		
Unit name	Power plant capacity [MW]	Technology	Unit name	Power plant capacity [MW]	Technology
HPP Zakucac	538	HDAM	HPP Trebinje 1	168	HDAM
HPP Senj	216	HDAM	HPP Grabovica	114	HROR
HPP Dubrovnik_HR	126	HDAM	PSHPP Capljina	420	HPS
HPP Vinodol	90	HDAM	HPP Visegrad	315	HDAM
HPP Peruca	61.2	HDAM	HPP Salakovac	210	HROR
HPP Sklope	22.5	HDAM	HPP Jablanica	181	HDAM
PSHPP Velebit	276	HPS	HPP Rama	160	HDAM
PSHPP Orlovac	237	HPS	HPP Bocac	110	HDAM
PSHPP Vinodol	5.4	HPS	HPP Dubrovnik_BA	108	HDAM
HPP Kraljevac	46.4	HROR	HPP Mostar	72	HROR
HPP Dale	40.8	HROR	HPP Mostarsko Blato	60	HROR
HPP Varazdin	94.64	HROR	HPP Jajce 1	60	HROR
HPP Dubrava	79.78	HROR	HPP Jajce 2	30	HROR
HPP Cakovec	77.44	HROR	HPP Pec Mlini	30	HROR
HPP Gojak	56	HROR	HE Trebinje 2	8	HDAM
HPP Lesce	41.2	HROR	HE Bogatici	7	HROR
HPP Rijeka	36.8	HROR	HE Novakovici	5.77	HROR
HPP Miljacka	24	HROR	HE Mesica Nova	4.9	HROR

424  
 425 To accurately model energy systems in Dispa-SET, it is necessary to define detailed technical  
 426 parameters for each power plant unit. Start-up and ramping costs for lignite and fossil hard  
 427 coal power plants were sourced from [33] and adjusted to inflation in 2022. Additional  
 428 parameters, including minimum load, efficiency at minimum load, overall efficiency, ramp  
 429 rates, start-up time, and minimum up/down times, were obtained from [33] and [52]. These  
 430 inputs ensure a robust and precise simulation of power system behaviour under different  
 431 scenario conditions.

432

#### 433 **4. Results and discussion**

434 This section thoroughly evaluates how CO<sub>2</sub> and fuel pricing affect technical performance,  
435 economic viability, and cross-border energy interactions between Bosnia and Herzegovina  
436 and Croatia. This analysis provides critical insights for policymakers and stakeholders to  
437 balance economic and environmental objectives in energy planning and policy formulation.  
438 The technical analysis includes the aggregated load duration curves of lignite power plants in  
439 Bosnia and Herzegovina and fossil gas power plants in Croatia, conducted with varying fuel  
440 and CO<sub>2</sub> prices. Furthermore, the connection between both systems is examined for all CBAM  
441 scenarios through cross-border line congestion analysis, identifying potential bottlenecks and  
442 their impact on system stability. The economic analysis assesses the average electricity cost  
443 in the HR-BA zone and the total cost of operating the HR-BA system under different CBAM  
444 scenarios, providing insights into the economic implications of CBAM implementation. This  
445 section also explores the cost-effectiveness of various fuel mixes and CO<sub>2</sub> pricing strategies,  
446 offering a detailed comparison of operational costs. Additionally, the results discuss the  
447 broader implications of CBAM on energy policy and market dynamics in the region,  
448 emphasising the potential benefits and challenges associated with implementing CO<sub>2</sub> pricing  
449 mechanisms. The paper highlights the trade-offs between economic efficiency and  
450 environmental benefits by comparing different scenarios.

##### 451 **4.1. Load duration curve, import-export of electricity and cross-border line congestion** 452 **analysis**

453 This section offers a comprehensive evaluation of the load duration curves (LDCs) for lignite  
454 power plants in Bosnia and Herzegovina (BA) and fossil gas power plants in Croatia (HR) under  
455 varying fossil gas price scenarios. The LDCs illustrate the operational frequency at different  
456 load levels, providing insights into these power plants' utilisation patterns and operational  
457 dynamics.

458

459 Figure 3 and Figure 4 presents a detailed visual representation of the LDCs for lignite power  
460 plants in Bosnia and Herzegovina Figure 3 (a, b, c, d) and fossil gas power plants in Croatia  
461 Figure 4 (a, b, c, d) under varying fossil gas price scenarios. These LDCs offer insights into how

462 frequently these power plants operate at different load levels, illustrating their utilisation  
463 patterns and dynamics. Furthermore, load duration curves reflect different fuels' economic  
464 viability and competitiveness under changing market conditions.

465

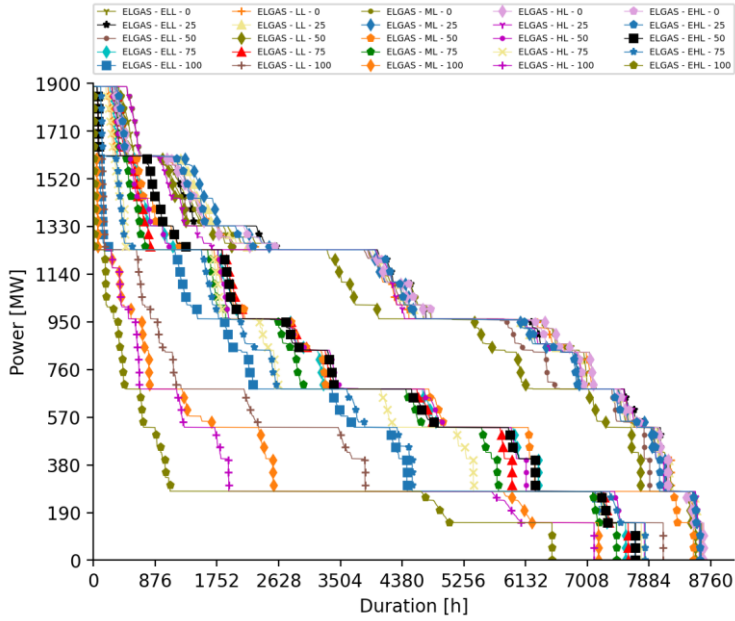
466 Results of LDCs analysis for lignite power plants in Bosnia and Herzegovina in Figure 3 (a, b, c,  
467 d) show the following trends:

- 468 • Impact of low fossil gas prices (ELGAS, LGAS): When gas prices are low (ELGAS-ELL,  
469 ELGAS-LL), lignite power plants show reduced operation at higher loads, reflecting a  
470 shift from lignite to cheaper gas, leading to a decline in the load duration curve. The  
471 reduced operational duration indicates that lignite plants become less economically  
472 viable than gas plants in such scenarios.
- 473 • Response to medium to high fossil gas prices (MGAS, HGAS): With increasing fossil  
474 gas prices (MGAS-HL, HGAS-EHL), lignite plants operate more frequently and at  
475 higher loads. This upward shift in the load duration curves signals a higher reliance  
476 on lignite as gas becomes more expensive, making lignite plants more competitive  
477 and heavily utilised.
- 478 • Effect of Varying Lignite Prices: Different lignite price scenarios (ELL, LL, ML, HL, EHL)  
479 influence the LDCs. Higher lignite prices reduce the operational duration of lignite  
480 plants, but this effect is less pronounced than the impact of gas prices. High gas prices  
481 and lower lignite prices maximise lignite plant operation.

482 The result of the LDCs analysis for fossil gas power plants in Croatia in Figure 4 (a, b, c, d)  
483 reveals the following observations:

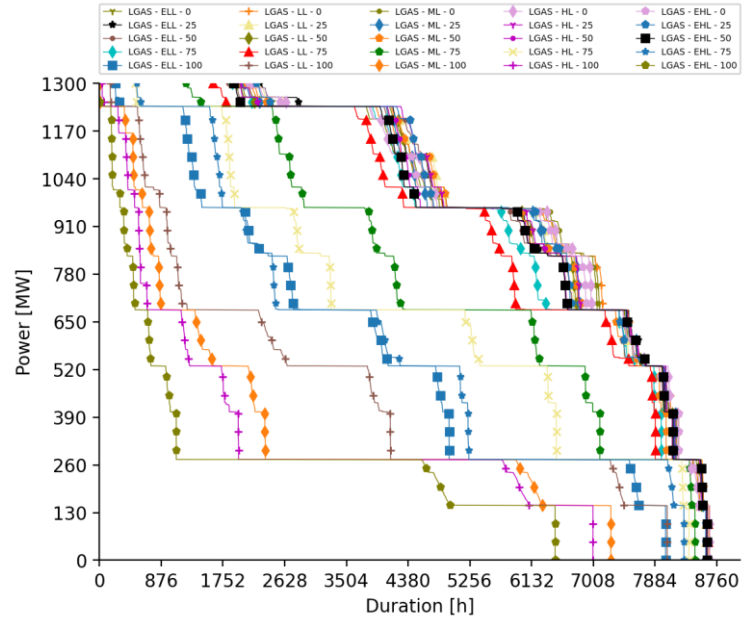
- 484 • Behaviour under low fossil gas prices (ELGAS, LGAS): Fossil gas power plants operate  
485 more frequently and at higher loads in scenarios with low fossil gas prices. This  
486 results in higher load duration curves, indicating increased utilisation of gas plants  
487 due to their cost-effectiveness relative to lignite and other alternatives.

LDC (LIG)-BA-ELGAS



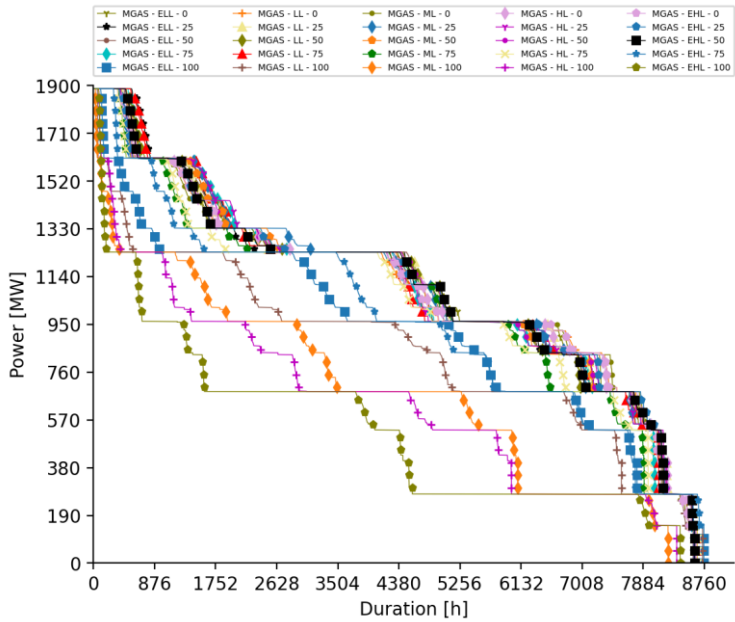
a)

LDC (LIG)-BA-LGAS



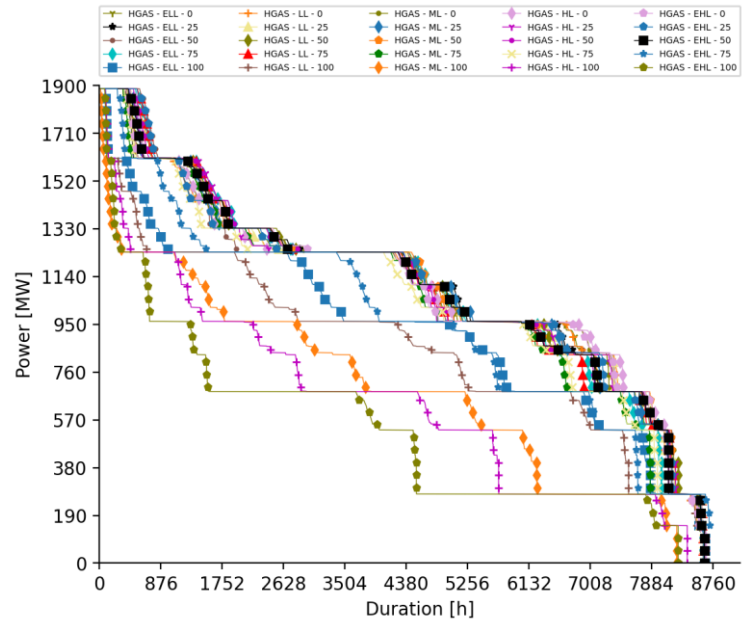
b)

LDC (LIG)-BA-MGAS



c)

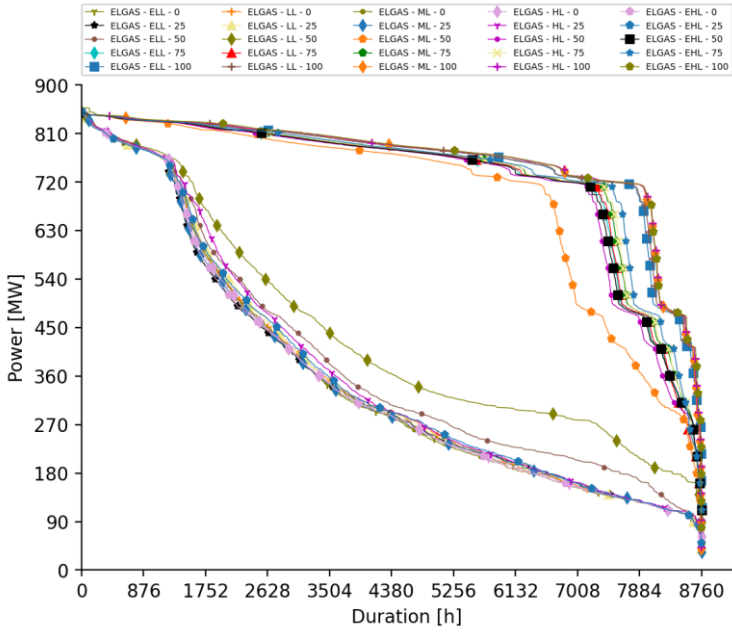
LDC (LIG)-BA-HGAS



d)

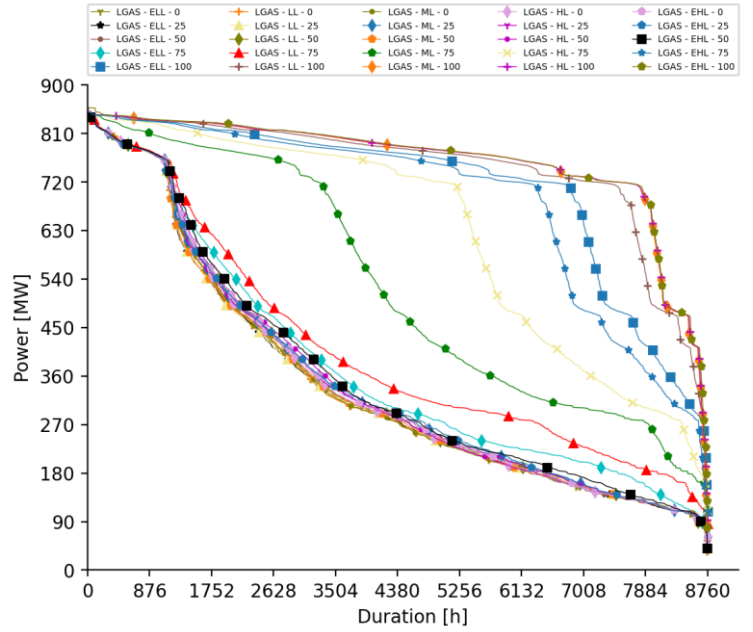
Figure 3. Load duration curve of lignite power plants in Bosnia and Herzegovina (BA) (a, b, c, d) under different prices of fossil gas

LDC (GAS)-HR-ELGAS



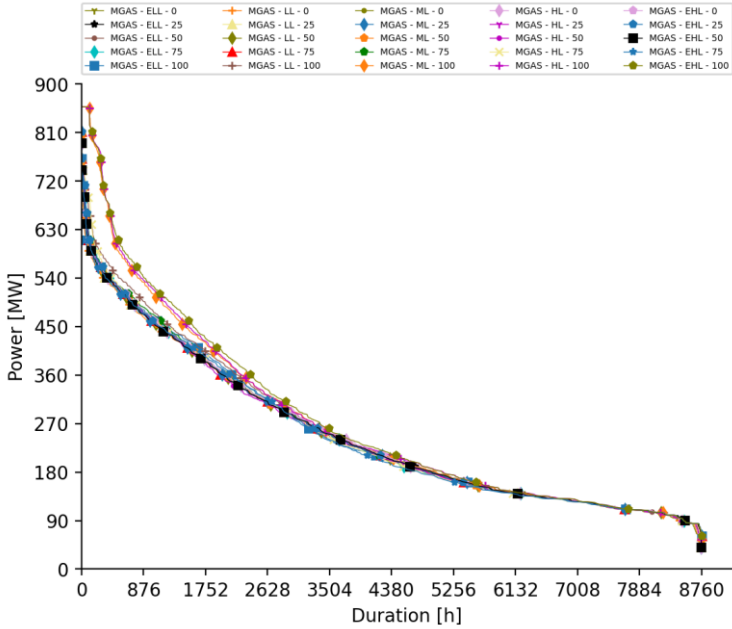
a)

LDC (GAS)-HR-LGAS



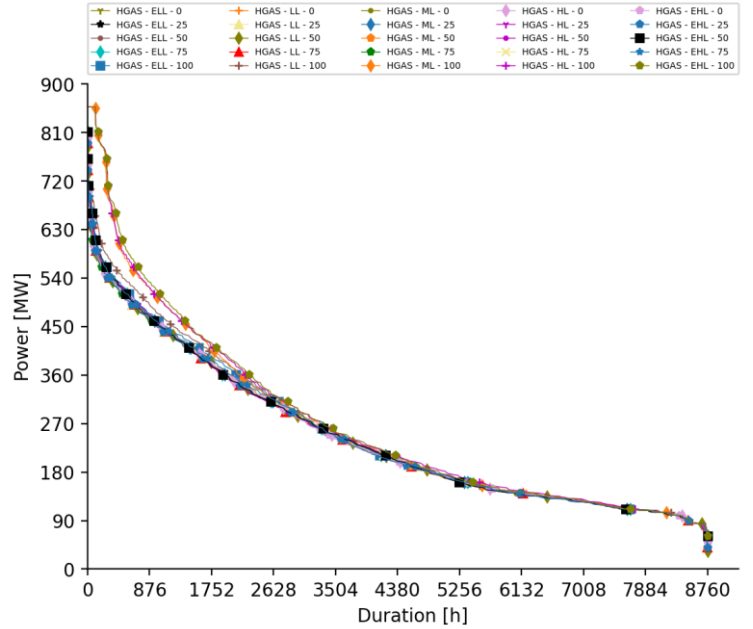
b)

LDC (GAS)-HR-MGAS



c)

LDC (GAS)-HR-HGAS



d)

Figure 4. Load duration curve of fossil gas power plants in Croatia (HR) (a, b, c, d) under different prices of fossil gas

- 514 • Impact of medium to high fossil gas prices (MGAS, HGAS): As fossil gas prices rise,  
515 there is a significant decrease in the operational duration of gas plants. The load  
516 duration curves shift downward, showing reduced utilisation as fossil gas becomes  
517 more expensive, suggesting a possible shift to other energy sources or an increase in  
518 electricity imports to meet demand.
- 519 • Fuel switching dynamics: The substantially reduced gas plant operation at higher gas  
520 prices indicates a fuel-switching behaviour. Expensive fossil gas leads to a transition  
521 away from gas plants, possibly to more affordable lignite or renewable energy  
522 sources, highlighting the system's adaptability to changes in fuel prices.

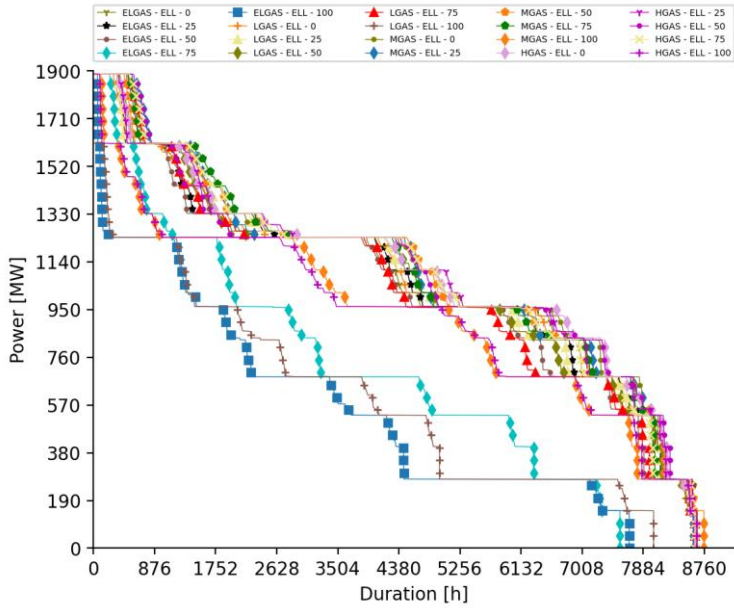
523

524 The load duration curves for lignite power plants in Bosnia and Herzegovina and fossil gas  
525 power plants in Croatia under varying lignite price scenarios are presented in Figure 5 and  
526 Figure 6. The LDCs demonstrate how often power plants operate at different load levels,  
527 reflecting their utilisation patterns. The key observations from this figure are as follows:

528

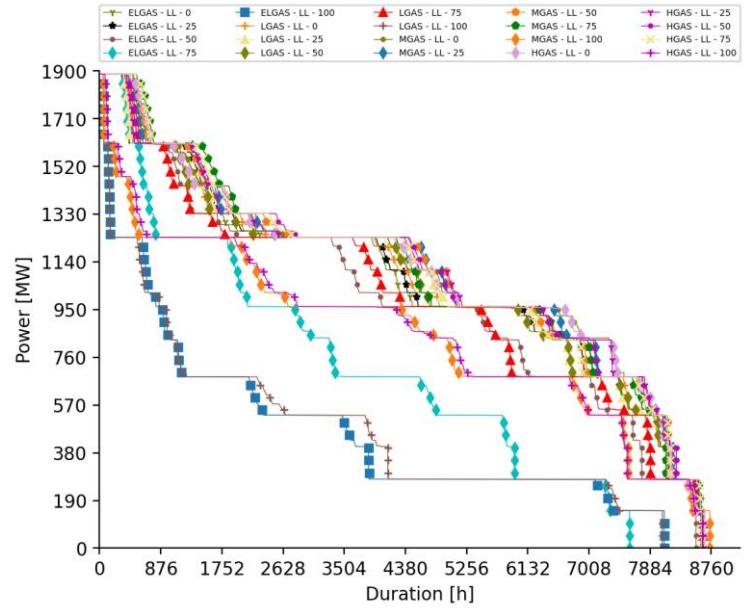
- 529 • Impact of low lignite prices: When lignite prices are low (ELL, LL), the load duration  
530 curve indicates a higher operational frequency of lignite power plants. This finding  
531 means that lignite power plants are more economically viable and frequently used  
532 to meet the demand.
- 533 • Effect of medium to high lignite prices: As lignite prices increase (ML, HL, EHL), there  
534 is a noticeable reduction in the operational frequency of lignite power plants. The  
535 LDCs shift downward, indicating that higher lignite prices make these plants less  
536 competitive, reducing their utilisation.
- 537 • Comparative analysis: The comparison between different lignite price scenarios  
538 shows that lower lignite prices lead to more prolonged and frequent use of lignite  
539 power plants, while higher prices discourage their use, favouring other energy  
540 sources or increasing electricity imports

LDC (LIG)-BA-ELL



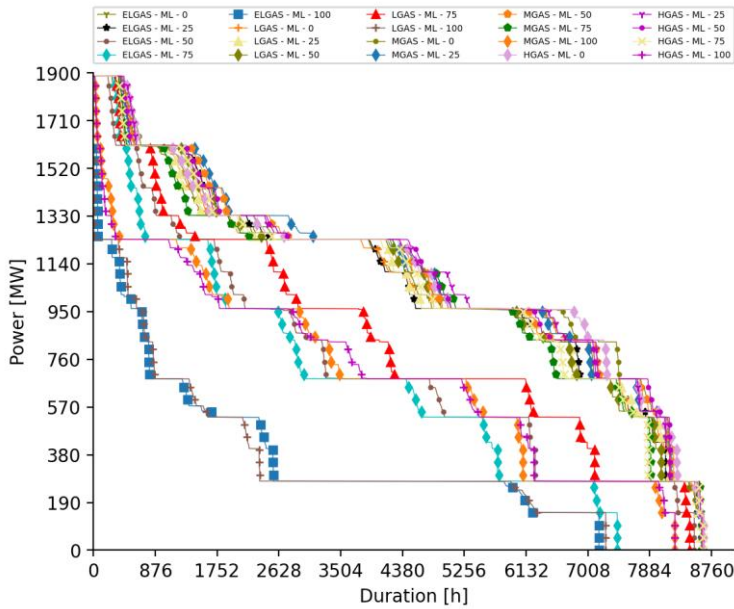
a)

LDC (LIG)-BA-LL



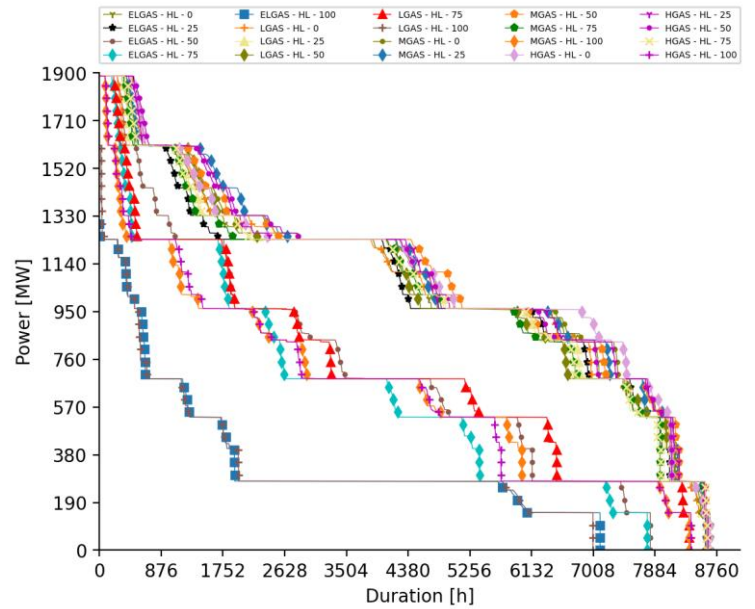
b)

LDC (LIG)-BA-ML

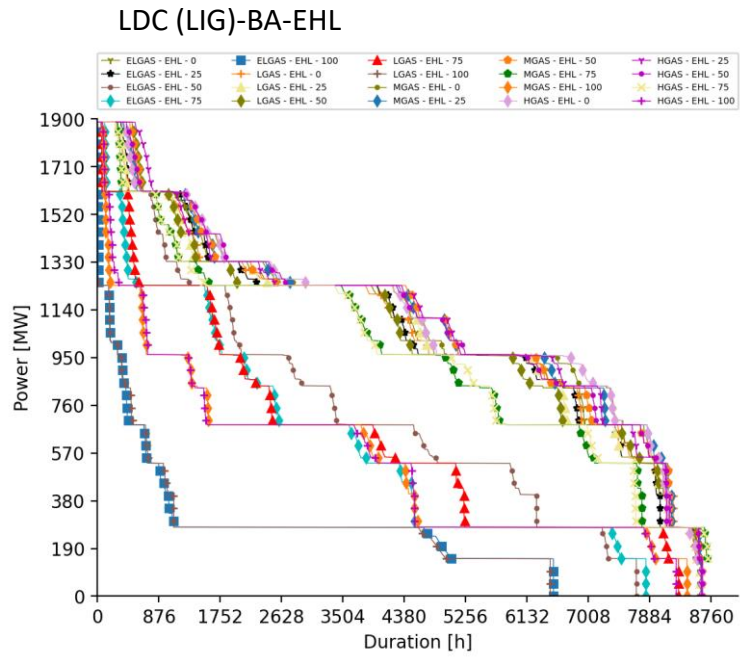


c)

LDC (LIG)-BA-HL



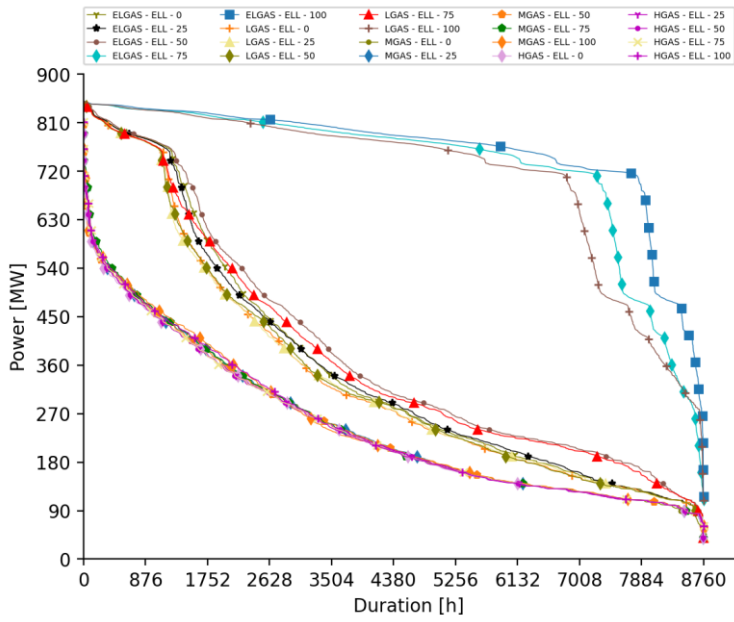
d)



e)

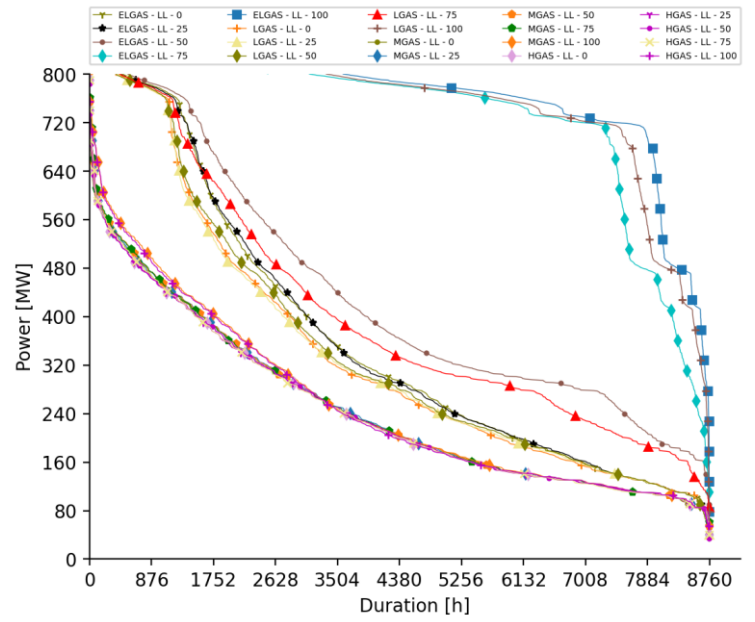
Figure 5. Load duration curve of lignite power plants in Bosnia and Herzegovina (BA) (a, b, c, d, e) under different lignite price

LDC (GAS)-HR-ELL



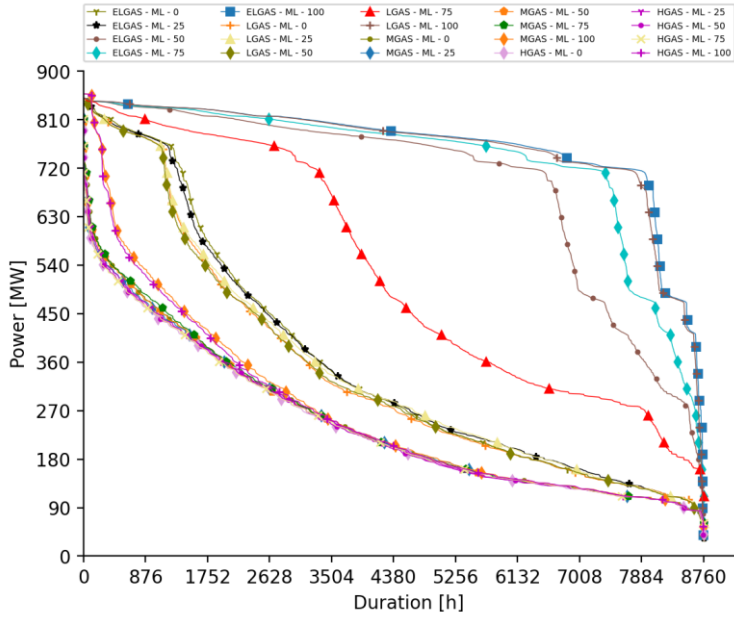
a)

LDC (GAS)-HR-LL



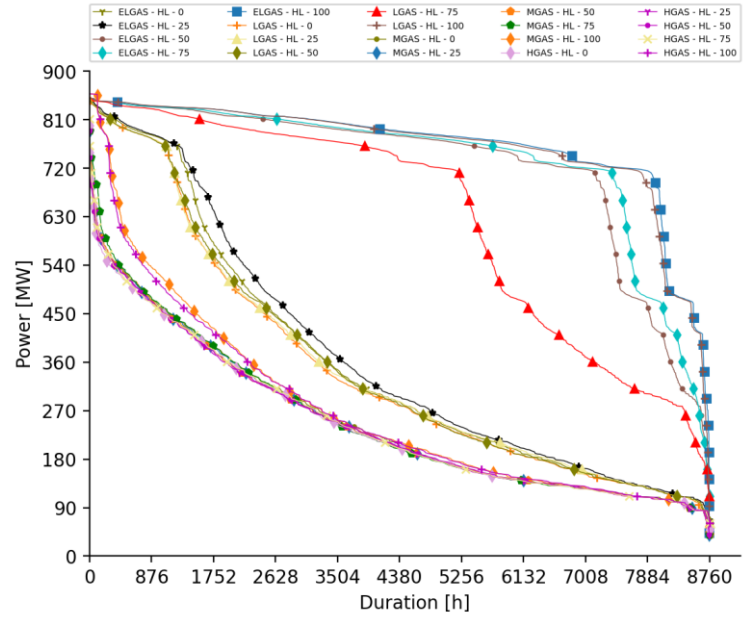
b)

LDC (GAS)-HR-ML



c)

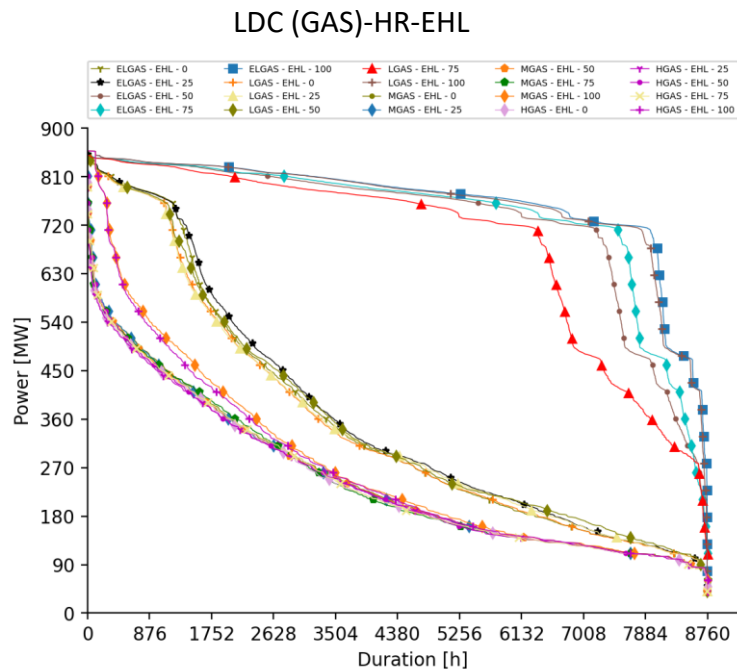
LDC (GAS)-HR-HL



d)

571

572



e)

573

574

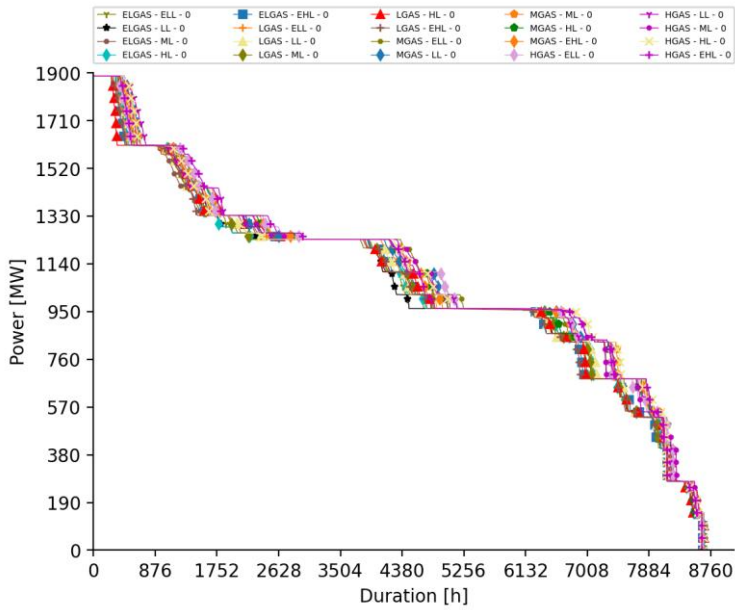
575 Figure 6. Load duration curve of fossil gas power plants in Croatia (HR) (a, b, c, d, e) under  
576 different lignite price

577

578 The load duration curves for lignite power plants in Bosnia and Herzegovina and fossil gas  
579 power plants in Croatia under varying CO<sub>2</sub> price scenarios are presented in Figure 7 and  
580 Figure 8. The presented results help to understand the impact of CO<sub>2</sub> pricing on the operation  
581 of lignite power plants in Bosnia and Herzegovina and fossil gas power plants in Croatia. The  
582 main findings are the following:

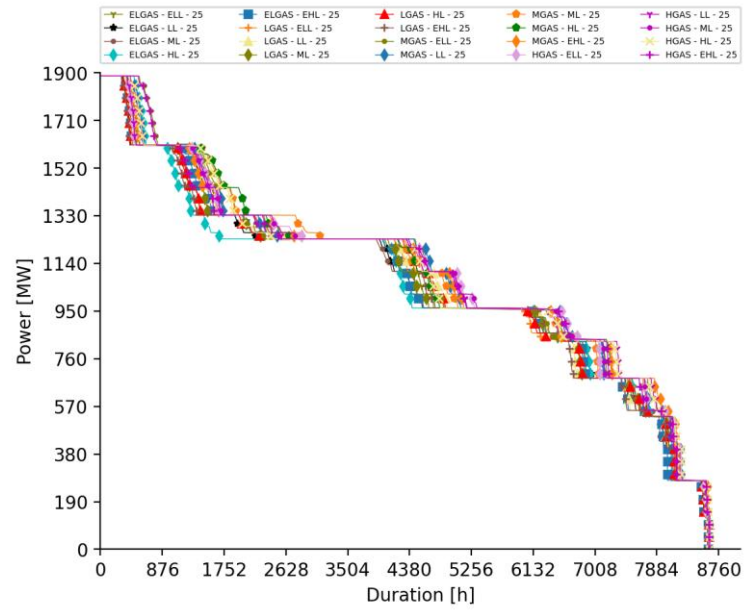
- 583 • Low CO<sub>2</sub> price impact: At lower CO<sub>2</sub> prices, lignite and gas power plants operate more  
584 frequently at higher loads. The LDCs show a higher operational duration, suggesting  
585 that low CO<sub>2</sub> prices do not significantly deter the use of these fossil fuel plants.
- 586 • Medium to high CO<sub>2</sub> price impact: As CO<sub>2</sub> prices increase, there is a marked reduction  
587 in the operation of both lignite and gas power plants. The LDCs shift downward,  
588 reflecting a decrease in utilisation as the cost of CO<sub>2</sub> emissions rises, making these  
589 plants less economically attractive.
- 590 • Fuel switching dynamics: The substantially reduced plant operation at higher CO<sub>2</sub>  
591 prices indicates a shift towards cleaner energy sources or increased reliance on  
592 electricity imports. This finding demonstrates the effectiveness of CO<sub>2</sub> pricing in  
593 promoting decarbonisation by reducing the attractiveness of fossil fuel plants.

LDC (LIG)-BA-0CO<sub>2</sub>



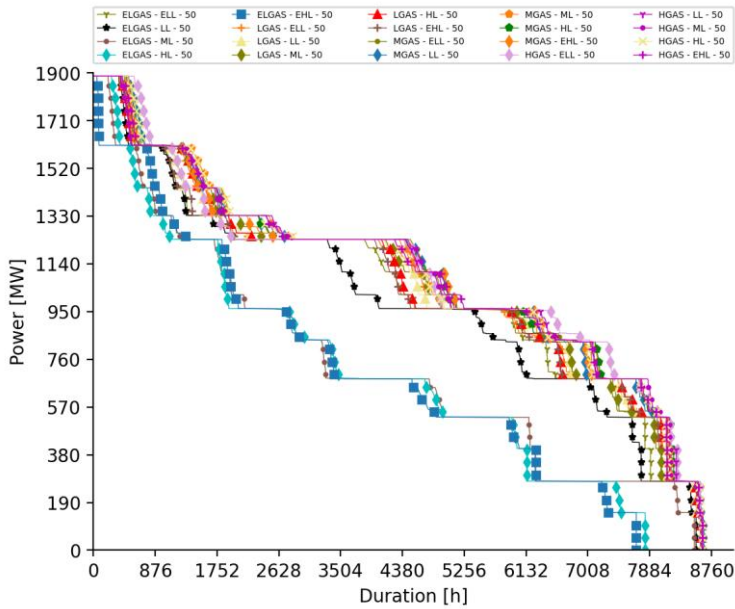
a)

LDC (LIG)-BA-25CO<sub>2</sub>



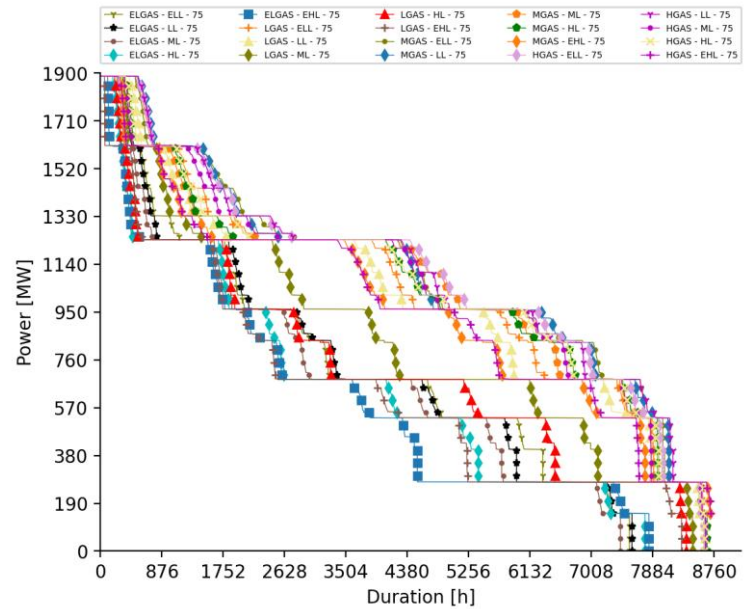
b)

LDC (LIG)-BA-50CO<sub>2</sub>

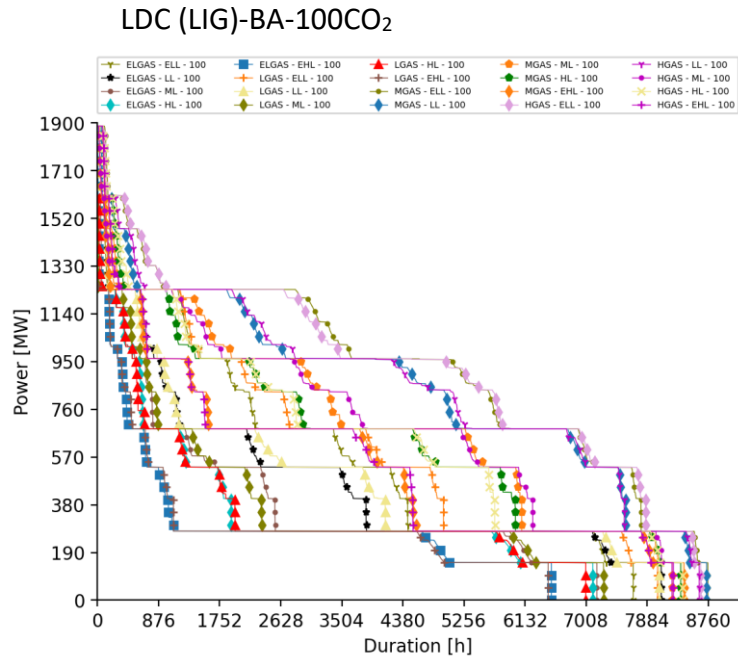


c)

LDC (LIG)-BA-75CO<sub>2</sub>



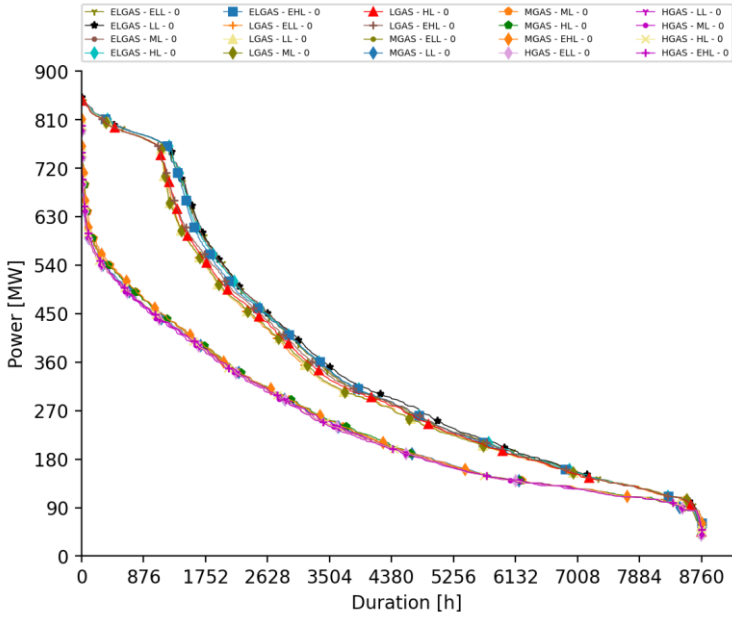
d)



e)

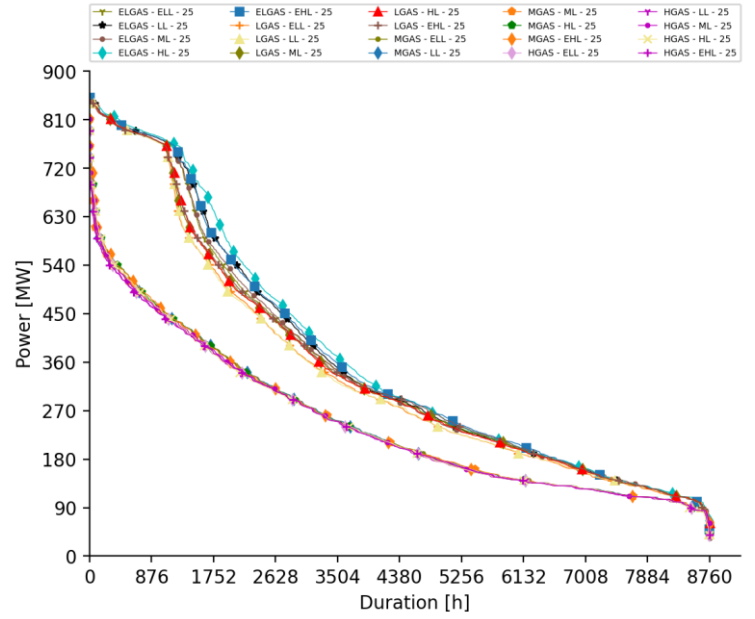
Figure 7. Load duration curve of lignite power plants in Bosnia and Herzegovina (BA) (a, b, c, d, e) under different CO<sub>2</sub> prices

LDC (GAS)-HR-0CO<sub>2</sub>



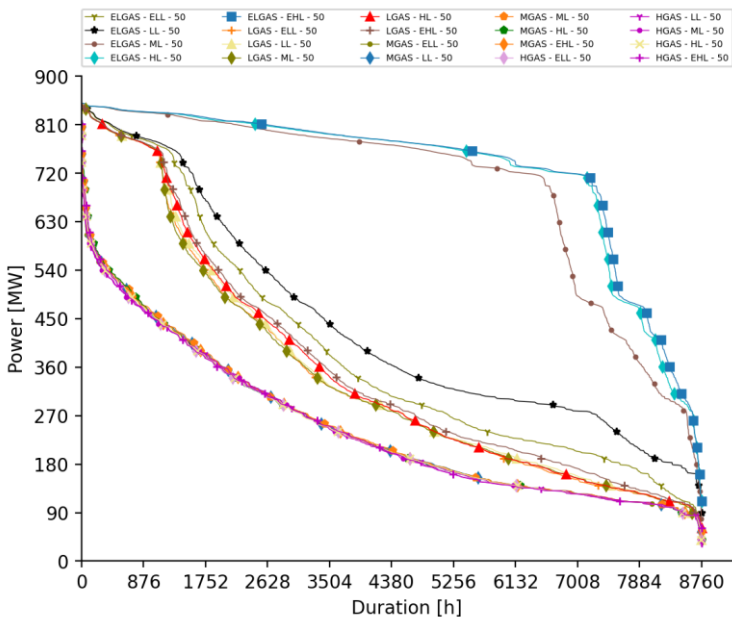
f)

LDC (GAS)-HR-25CO<sub>2</sub>



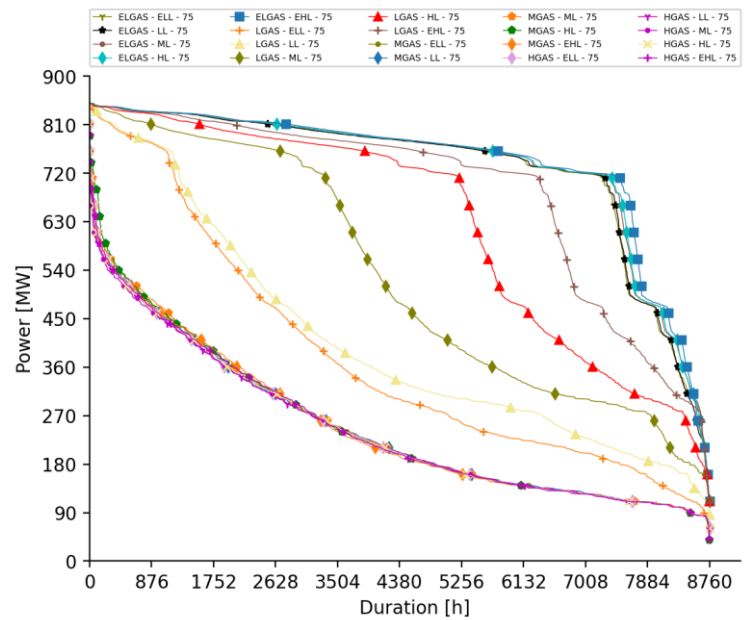
g)

LDC (GAS)-HR-50CO<sub>2</sub>



h)

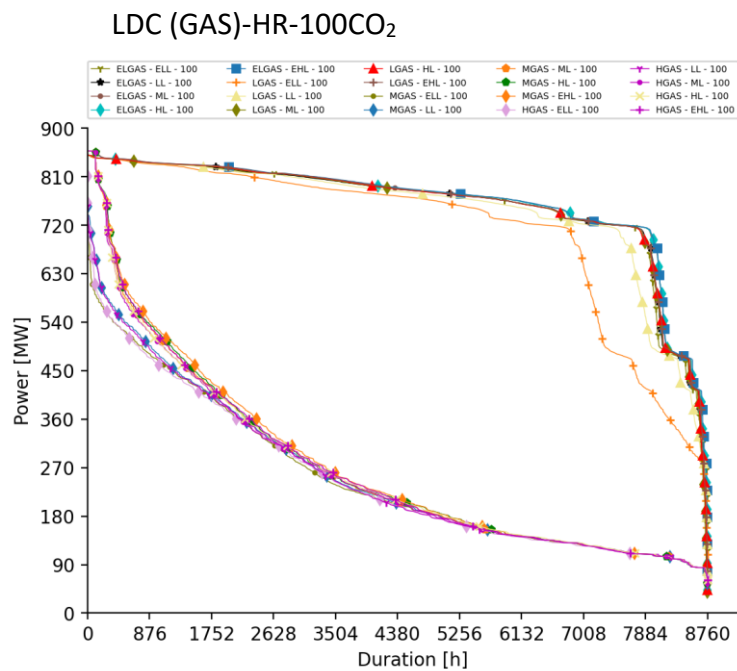
LDC (GAS)-HR-75CO<sub>2</sub>



i)

623

624



625

626

j)

627

Figure 8. Load duration curve of fossil gas power plants in Croatia (HR) (f, g, h, i, j) under different CO<sub>2</sub> prices

628

629

630

The total yearly electricity export in the HR-BA zone under different CBAM scenarios is presented in Figure 9. The analysis indicates that electricity exports significantly decrease as the CBAM factors and CO<sub>2</sub> prices rise. This situation is particularly evident in scenarios with high CO<sub>2</sub> pricing, where Bosnia and Herzegovina transitions from an electricity exporter to an importer. Figure 9 highlights the impact of CO<sub>2</sub> pricing on the economic viability of lignite-based electricity generation, showing a clear correlation between increased CO<sub>2</sub> prices and reduced export capacity.

637

CO2	Electricity export HR -> BA [TWh]					Electricity export BA -> HR [TWh]				
	ELGAS-ELL	ELGAS-LL	ELGAS-ML	ELGAS-HL	ELGAS-EHL	ELGAS-ELL	ELGAS-LL	ELGAS-ML	ELGAS-HL	ELGAS-EHL
0	0.443	0.452	0.446	0.451	0.453	3.687	3.658	3.686	3.691	3.713
25	0.450	0.463	0.473	0.470	0.481	3.701	3.666	3.713	3.583	3.650
50	0.544	0.687	1.509	1.694	1.720	3.515	3.226	1.837	1.753	1.740
75	1.749	1.739	1.937	2.036	2.212	1.744	1.693	1.625	1.492	1.379
100	2.368	2.595	2.877	2.992	3.309	1.199	0.984	0.731	0.596	0.407
CO2	LGAS-ELL	LGAS-LL	LGAS-ML	LGAS-HL	LGAS-EHL	LGAS-ELL	LGAS-LL	LGAS-ML	LGAS-HL	LGAS-EHL
0	0.443	0.444	0.434	0.444	0.448	3.726	3.737	3.708	3.698	3.653
25	0.453	0.463	0.459	0.451	0.480	3.772	3.766	3.676	3.674	3.667
50	0.464	0.463	0.463	0.455	0.488	3.748	3.700	3.739	3.655	3.602
75	0.552	0.623	1.105	1.502	1.952	3.556	3.317	2.477	1.847	1.531
100	2.136	2.507	2.881	3.011	3.309	1.383	1.003	0.732	0.601	0.400
CO2	MGAS-ELL	MGAS-LL	MGAS-ML	MGAS-HL	MGAS-EHL	MGAS-ELL	MGAS-LL	MGAS-ML	MGAS-HL	MGAS-EHL
0	0.404	0.411	0.397	0.402	0.409	3.991	4.004	3.987	3.973	3.987
25	0.400	0.416	0.417	0.415	0.397	3.990	4.008	4.009	3.999	3.986
50	0.391	0.406	0.394	0.397	0.395	3.982	3.986	3.956	3.983	3.936
75	0.423	0.410	0.528	0.520	0.740	3.958	3.951	3.744	3.713	3.340
100	0.761	0.845	1.382	1.435	1.778	3.267	3.029	2.391	2.098	1.674
CO2	HGAS-ELL	HGAS-LL	HGAS-ML	HGAS-HL	HGAS-EHL	HGAS-ELL	HGAS-LL	HGAS-ML	HGAS-HL	HGAS-EHL
0	0.410	0.395	0.404	0.400	0.390	4.021	3.992	4.017	4.006	4.003
25	0.408	0.395	0.415	0.394	0.405	3.998	3.980	4.020	3.983	3.995
50	0.398	0.399	0.388	0.398	0.411	3.981	3.999	3.969	3.966	3.977
75	0.417	0.412	0.541	0.514	0.750	3.990	3.968	3.828	3.757	3.341
100	0.746	0.853	1.373	1.466	1.783	3.235	3.083	2.385	2.144	1.688

638

639

Figure 9. Total yearly electricity export in the zone under different CBAM scenarios

640

641

Figure 9 also reveals that under high CBAM scenarios, the economic pressure on Bosnia and Herzegovina's lignite-based power plants becomes unsustainable, leading to a complete halt in electricity exports and necessitating substantial electricity imports to meet domestic demand. This result underscores the urgent need for Bosnia and Herzegovina to diversify its energy mix and enhance its renewable energy capacity to mitigate the economic impacts of high CO<sub>2</sub> pricing and ensure energy security.

647

648

Analyses of cross-border line congestion between Bosnia and Herzegovina and Croatia under various CBAM scenarios are presented in Figure 10. The figure provides insights into how different levels of CO<sub>2</sub> pricing and CBAM implementation affect cross-border electricity flows.

651

Key points include:

652

- Low CBAM impact: At lower CBAM factors, cross-border line congestion is minimal, indicating smooth electricity trade between the two countries. This finding suggests that low CO<sub>2</sub> pricing does not significantly impact cross-border flows.

653

654

- 655 • High CBAM impact: With higher CBAM factors, there is increased congestion,  
656 reflecting the strain on cross-border lines as countries adjust to higher CO<sub>2</sub> prices.  
657 This finding indicates potential bottlenecks and highlights the need for infrastructure  
658 upgrades to accommodate changes in trade dynamics.
- 659 • Policy implications: The congestion analysis underscores the importance of  
660 coordinated energy policies and infrastructure investments to manage cross-border  
661 electricity flows effectively, especially under high CBAM scenarios.

Congestion HR -> BA [%]						Congestion BA -> HR [%]				
CO2	ELGAS-ELL	ELGAS-LL	ELGAS-ML	ELGAS-HL	ELGAS-EHL	ELGAS-ELL	ELGAS-LL	ELGAS-ML	ELGAS-HL	ELGAS-EHL
0	2.35	2.63	2.64	2.39	2.52	39.79	38.53	37.27	38.32	40.71
25	2.48	2.55	2.60	2.45	2.89	39.00	38.98	39.37	36.97	38.21
50	3.86	4.74	12.72	17.33	17.41	37.09	32.47	15.42	13.87	14.02
75	18.14	17.61	20.75	22.76	24.99	13.97	12.87	12.11	11.68	10.32
100	24.58	31.46	36.36	36.64	41.76	8.30	6.27	3.54	3.58	2.80
CO2	LGAS-ELL	LGAS-LL	LGAS-ML	LGAS-HL	LGAS-EHL	LGAS-ELL	LGAS-LL	LGAS-ML	LGAS-HL	LGAS-EHL
0	2.84	2.45	2.26	2.64	2.27	40.37	41.46	40.32	38.29	38.92
25	2.71	2.52	2.73	2.52	2.58	42.63	41.24	39.68	39.51	37.93
50	2.59	2.84	2.64	2.50	2.98	41.40	39.55	41.21	38.28	36.96
75	3.46	4.29	10.15	15.15	21.40	38.16	32.97	20.94	13.30	10.86
100	23.13	30.86	36.67	36.62	41.42	9.63	6.32	3.71	3.78	2.58
CO2	MGAS-ELL	MGAS-LL	MGAS-ML	MGAS-HL	MGAS-EHL	MGAS-ELL	MGAS-LL	MGAS-ML	MGAS-HL	MGAS-EHL
0	2.45	2.37	2.18	2.23	2.25	45.59	46.21	45.40	45.42	44.79
25	2.12	2.37	2.20	1.99	2.17	44.12	46.00	46.97	46.63	44.69
50	2.15	2.15	2.26	2.36	2.20	46.20	46.55	45.37	46.62	43.70
75	2.43	2.36	4.60	5.17	9.16	45.00	44.28	38.81	36.61	31.42
100	7.47	8.40	15.43	13.94	18.80	33.52	28.92	21.77	16.91	12.92
CO2	HGAS-ELL	HGAS-LL	HGAS-ML	HGAS-HL	HGAS-EHL	HGAS-ELL	HGAS-LL	HGAS-ML	HGAS-HL	HGAS-EHL
0	2.36	2.36	2.41	2.27	2.43	46.87	45.75	46.72	44.81	45.87
25	2.47	2.20	2.57	2.04	1.91	46.38	46.55	47.48	45.41	46.24
50	2.05	2.19	2.04	2.33	2.64	44.89	46.83	45.11	45.40	43.74
75	2.44	2.26	5.07	4.75	9.22	46.19	45.71	40.92	38.06	30.29
100	7.41	8.81	15.79	15.37	19.24	32.32	29.36	22.43	18.71	13.28

662 Figure 10. Cross-border line congestion analysis under different CBAM scenarios  
663

664

665 The results in this section underscore the complex interplay between CO<sub>2</sub> pricing, fuel prices,  
666 and cross-border energy interactions. The load duration curves (Figure 3 to Figure 8) reveal  
667 that both lignite and fossil gas power plants in Bosnia and Herzegovina and Croatia are highly  
668 sensitive to fluctuations in fuel prices and CO<sub>2</sub> pricing. Low CO<sub>2</sub> prices allow for frequent and  
669 high-load operation of these plants, while high CO<sub>2</sub> prices significantly reduce their  
670 operational duration, encouraging a shift towards cleaner energy sources or increased  
671 reliance on electricity imports.

672

673 The total yearly electricity export (Figure 9) and cross-border line congestion analysis (Figure  
674 10) further illustrate the broader implications of CBAM and CO<sub>2</sub> pricing. High CBAM factors  
675 and CO<sub>2</sub> prices lead to reduced electricity exports from Bosnia and Herzegovina and increased  
676 cross-border congestion, highlighting the need for infrastructure upgrades and coordinated  
677 energy policies to manage these changes effectively.

678

679 The combined insights from Figure 3 to Figure 10 provide a robust framework for  
680 understanding the technical and economic impacts of CBAM and CO<sub>2</sub> pricing on the  
681 interconnected power systems of Bosnia and Herzegovina and Croatia. These insights support  
682 evidence-based policy development by highlighting trade-offs between system efficiency,  
683 environmental goals, and energy market stability. The transition from an electricity exporter  
684 to an importer in Bosnia and Herzegovina under high CO<sub>2</sub> price scenarios (Figure 9)  
685 emphasises the importance of strategic investments in renewable energy and infrastructure  
686 upgrades to ensure energy security and economic stability.

#### 687 **4.2. Economic evaluation of CBAM scenarios**

688 This section evaluates the economic implications of different CBAM scenarios by analysing  
689 the total system cost and average electricity prices in the HR-BA zone. The focus is on  
690 understanding how varying CO<sub>2</sub> and fuel prices impact the overall economic performance of  
691 the interconnected energy systems of Bosnia and Herzegovina (BA) and Croatia (HR).

692

693 The total cost of operating the HR-BA system under different CBAM scenarios is presented in  
694 Figure 11. Key observations include:

- 695 • Stable costs at low CO<sub>2</sub> prices: The total system cost remains relatively stable under  
696 low CO<sub>2</sub> prices (0% and 25% of the 2022 EU ETS price). This stability indicates that  
697 the energy systems in Bosnia and Croatia can absorb minor CO<sub>2</sub> costs without  
698 significant economic disruption.
- 699 • Rising costs at medium to high CO<sub>2</sub> prices: As CO<sub>2</sub> prices increase to medium (50%)  
700 and high levels (75% and 100%), there is a marked rise in total system costs. This rise  
701 reflects the increased financial burden on fossil fuel-based power plants due to  
702 higher CO<sub>2</sub> emissions costs.

- Economic trade-offs: The distribution of costs across different scenarios highlights the economic trade-offs involved in implementing CBAM. Policymakers should carefully plan and support economic measures to mitigate the financial impacts while transitioning to a low-carbon economy.

Total cost of running the system [Million EUR]					
CO2	ELGAS-ELL	ELGAS-LL	ELGAS-ML	ELGAS-HL	ELGAS-EHL
0	1797	1837	1913	1933	1967
25	1998	2040	2116	2138	2174
50	2207	2240	2305	2323	2348
75	2364	2394	2429	2437	2439
100	2418	2355	2328	2388	2848
CO2	LGAS-ELL	LGAS-LL	LGAS-ML	LGAS-HL	LGAS-EHL
0	1886	1926	2002	2024	2063
25	2093	2126	2204	2226	2261
50	2299	2333	2403	2431	2461
75	2494	2533	2591	2602	2608
100	2595	2544	2516	2583	3175
CO2	MGAS-ELL	MGAS-LL	MGAS-ML	MGAS-HL	MGAS-EHL
0	2033	2062	2147	2169	2205
25	2235	2271	2350	2376	2412
50	2442	2480	2561	2585	2616
75	2649	2687	2756	2775	2745
CO2	HGAS-ELL	HGAS-LL	HGAS-ML	HGAS-HL	HGAS-EHL
0	2444	2485	2557	2589	2621
25	2659	2696	2776	2805	2831
50	2862	2902	2980	3006	3041
75	3073	3109	3179	3202	3170
100	3160	3159	3931	4033	4068

Figure 11. The total cost of running the HR-BA system under different CBAM scenarios

The average electricity cost in the HR-BA zone under different CBAM scenarios is presented in Figure 12. The main findings are:

- Low impact on electricity prices at low CO<sub>2</sub> prices: At lower CO<sub>2</sub> prices, average electricity costs in the HR-BA zone remain relatively low. This finding indicates that the initial phases of CO<sub>2</sub> pricing do not significantly impact electricity prices, allowing consumers to adjust gradually.
- Significant price increase at medium to high CO<sub>2</sub> prices: As CO<sub>2</sub> prices increase, the average electricity cost rises significantly. High CO<sub>2</sub> prices (75% and 100% of the 2022 EU ETS price) lead to substantial increases in electricity prices, reflecting the pass-through of higher operational costs to consumers.

- Policy Implications: The sensitivity of electricity prices to varying CO<sub>2</sub> costs underscores the importance of effective CO<sub>2</sub> pricing strategies. Policymakers must balance environmental objectives with economic impacts to ensure that electricity remains affordable while promoting decarbonisation.

Average electricity cost of HR-BA zone [EUR/MWh]					
CO2	ELGAS-ELL	ELGAS-LL	ELGAS-ML	ELGAS-HL	ELGAS-EHL
0	66.81	68.32	71.12	71.89	73.16
25	74.31	75.85	78.68	79.49	80.86
50	82.07	83.29	85.73	86.37	87.31
75	87.92	89.04	90.31	90.62	90.70
100	89.91	87.58	86.55	88.80	105.89
CO2	LGAS-ELL	LGAS-LL	LGAS-ML	LGAS-HL	LGAS-EHL
0	70.12	71.63	74.43	75.27	76.70
25	77.82	79.05	81.95	82.78	84.09
50	85.50	86.74	89.34	90.40	91.52
75	92.75	94.19	96.34	96.77	96.97
100	96.48	94.60	93.57	96.03	118.06
CO2	MGAS-ELL	MGAS-LL	MGAS-ML	MGAS-HL	MGAS-EHL
0	75.60	76.69	79.82	80.66	81.98
25	83.12	84.47	87.39	88.37	89.71
50	90.81	92.20	95.24	96.13	97.26
75	98.52	99.93	102.50	103.19	102.09
100	101.66	101.35	128.88	135.89	135.97
CO2	HGAS-ELL	HGAS-LL	HGAS-ML	HGAS-HL	HGAS-EHL
0	90.87	92.41	95.08	96.26	97.47
25	98.89	100.24	103.23	104.30	105.28
50	106.43	107.91	110.82	111.78	113.09
75	114.26	115.62	118.20	119.06	117.86
100	117.49	117.47	146.19	149.95	151.26

Figure 12. Average electricity cost in HR-BA zone under different CBAM scenarios

Both figures are instrumental in evaluating the economic and operational impacts of CBAM and CO<sub>2</sub> pricing on the energy systems of Bosnia and Herzegovina and Croatia. They provide critical insights for policymakers to develop balanced strategies supporting environmental and economic objectives, ensuring a sustainable and resilient energy future. The analysis reveals that Bosnia and Herzegovina's transition from an electricity exporter to an importer is driven by high CO<sub>2</sub> prices and certain combinations of high fossil gas and lignite prices, emphasising the need for strategic planning and investment in renewable energy and infrastructure upgrades.

### 735 **4.3. Constraints and limitations of the approach**

736 The methodological framework used in this study is centred on the operational modelling of  
737 the interconnected power systems of Bosnia and Herzegovina and Croatia under varying CO<sub>2</sub>  
738 pricing and fossil fuel cost scenarios. The analysis provides detailed insights into how changes  
739 in lignite and fossil gas prices and the phased introduction of carbon pricing through the CBAM  
740 mechanism affect electricity generation, system dispatch, operational costs, and cross-border  
741 trade dynamics. However, several limitations of the modelling approach should be  
742 acknowledged.

743

744 The Dispa-SET model, employed in this study, is a short-term, unit commitment and dispatch  
745 optimisation tool that operates on an hourly resolution over a one-year simulation period. It  
746 is well suited for evaluating operational outcomes such as load duration curves, cross-border  
747 flows, and system costs under defined technical and economic parameters. However, the  
748 model does not account for long-term investment dynamics, technological learning curves,  
749 or endogenous infrastructure expansion. As such, it does not reflect optimal capacity planning  
750 over multiple years but instead assesses the feasibility and implications of operating the  
751 system within fixed configurations.

752

753 In this analysis, electricity demand is treated as an exogenous input and is not disaggregated  
754 by sector or adjusted dynamically in response to CO<sub>2</sub> pricing. This simplification does not  
755 capture potential behavioural changes or demand-side adaptations, particularly in energy-  
756 intensive industrial sectors that may be significantly affected by CBAM. Furthermore, while  
757 system flexibility is provided through existing fossil and hydro capacity, the model excludes  
758 energy storage technologies, sector coupling, or demand response options, which could  
759 become increasingly important under higher carbon pricing scenarios.

760

761 Although Bosnia and Herzegovina does not currently apply a formal CO<sub>2</sub> pricing mechanism,  
762 the assumption of a phased introduction of carbon costs is grounded in the country's  
763 obligations under the Energy Community Treaty and its anticipated alignment with EU policy  
764 through the Carbon Border Adjustment Mechanism (CBAM). The Energy Community  
765 Contracting Parties, including Bosnia and Herzegovina, have committed to adopting climate

766 neutrality targets and have developed National Energy and Climate Plans (NECPs) which  
767 reflect a pathway toward decarbonisation and carbon pricing. Recent studies commissioned  
768 by the European Commission highlight carbon pricing as a key instrument to meet these  
769 objectives and explore several feasible policy pathways, such as fixed-price ETS systems and  
770 integration into the EU ETS by 2030 [53]. These policy developments provide a credible  
771 foundation for including phased CO<sub>2</sub> pricing in the scenario design of this study.

772

773 In parallel, institutional integration steps are underway to reinforce this policy trajectory.  
774 Bosnia and Herzegovina is included in the planned market coupling integration of the Energy  
775 Community with the EU's Single Day-Ahead and Intraday Markets, as outlined in the  
776 Integration Plan for the Market Coupling Operation (MCO). While this process anticipates full  
777 market coupling by 2026, it also highlights important institutional limitations for Energy  
778 Community Nominated Electricity Market Operators (NEMOs), such as those representing  
779 Bosnia and Herzegovina, whose roles are restricted to "Serviced NEMOs" without voting  
780 rights on methodological or algorithmic changes, and who operate under the coordination of  
781 EU counterparts [54]. These governance and implementation asymmetries may delay or  
782 complicate the harmonisation of carbon pricing frameworks and operational procedures with  
783 EU standards.

784

785 The modelling in this study reflects a best-estimate policy trajectory and incorporates CO<sub>2</sub>  
786 cost signals in accordance with CBAM enforcement expectations. However, it does not  
787 explicitly account for political uncertainty, institutional readiness, or transitional  
788 arrangements that could affect the timing, scope, or implementation of carbon pricing in  
789 Bosnia and Herzegovina. As such, the results should be interpreted with an awareness of  
790 these underlying policy and institutional uncertainties.

791

792 The model's scope is limited to the Croatia-Bosnia and Herzegovina (HR-BA) zone, with  
793 electricity exchanges to other neighbouring systems treated as fixed historical flows. As a  
794 result, broader regional feedback effects, such as those stemming from concurrent carbon  
795 pricing implementation or infrastructure changes in adjacent countries, are not captured. The  
796 model also does not address system balancing at a multi-regional level, where additional  
797 flexibility, congestion, or redispatch needs may significantly affect outcomes. Consequently,

798 developments such as price differentials, loop flows, or the dynamic impact of new  
799 interconnectors fall outside the analytical boundaries. Thus, the assumption of fixed cross-  
800 border flows may lead to underestimating transmission constraints and potential integration  
801 benefits under shifting CO<sub>2</sub> cost conditions.

802

803 Despite these limitations, the approach offers a consistent and transparent framework for  
804 analysing the operational impacts of carbon pricing and fossil fuel cost variations in a real-  
805 world cross-border electricity context. The results should indicate short- to medium-term  
806 effects under current infrastructure and policy conditions, providing valuable input for  
807 ongoing decarbonisation strategies and regional energy policy development.

808

## 809 **5. Conclusion**

810 The detailed analysis of various scenarios offers valuable insights into the operational and  
811 economic dynamics of interconnected energy systems of Bosnia and Herzegovina and Croatia  
812 under different pricing mechanisms. The main conclusions from this research include  
813 significant impacts on the operation of lignite and fossil gas power plants due to the  
814 introduction of CO<sub>2</sub> pricing. Higher prices lead to reduced utilisation and a shift towards  
815 cleaner energy sources, promoting decarbonisation. Additionally, higher CO<sub>2</sub> and fuel prices  
816 increase operational and electricity costs, underscoring the need for balanced CO<sub>2</sub> pricing  
817 strategies that support both environmental and economic objectives.

818

819 The analysis highlights the importance of robust cross-border infrastructure and coordinated  
820 energy policies to manage the impacts of CBAM on electricity trade and system stability.  
821 Bosnia and Herzegovina's transition from an electricity exporter to an importer is influenced  
822 by various scenarios involving changes in CO<sub>2</sub> pricing, fossil gas prices, and lignite prices. This  
823 transition is particularly evident in scenarios with high CO<sub>2</sub> prices and certain combinations of  
824 high fossil gas and lignite prices. When CO<sub>2</sub> prices reach 75% and 100% of the 2022 EU ETS  
825 price, Bosnia and Herzegovina, which primarily relies on lignite power plants, faces increased  
826 operational costs. This effect reduces the economic viability of lignite-based electricity  
827 generation, forcing Bosnia and Herzegovina to import electricity to meet its domestic  
828 demand. In scenarios such as HGAS-HL and HGAS-EHL, where both fossil gas and lignite prices

829 are high, the cost of domestic electricity generation in Bosnia and Herzegovina becomes very  
830 high. This scenario increases the economic pressure on Bosnia and Herzegovina's energy  
831 sector, leading to increased electricity imports. The worst-case scenario involves a  
832 combination of high CO<sub>2</sub> prices (75% and 100% of the 2022 EU ETS price) with high fossil gas  
833 and lignite prices. In these scenarios, Bosnia and Herzegovina cannot sustain its electricity  
834 exports due to high operational costs, thus transitioning to an importer to fulfil its electricity  
835 needs. As CO<sub>2</sub> prices rise, Bosnia and Herzegovina's ability to export electricity reduces  
836 significantly. Consequently, this necessitates a shift towards greater import dependence to  
837 satisfy domestic demand, highlighting the critical need for Bosnia and Herzegovina to explore  
838 alternative energy sources and rapidly increase renewable energy investments.

839

840 Croatia's reliance on fossil gas for electricity generation makes it highly sensitive to  
841 fluctuations in fossil gas prices and CO<sub>2</sub> pricing. Higher fossil gas prices combined with high  
842 CO<sub>2</sub> prices increase the operational costs of fossil gas power plants, leading to higher  
843 electricity prices. This result underscores Croatia's need to diversify its energy mix and invest  
844 in renewable energy sources. The analyses also highlight the critical role of cross-border  
845 electricity trade with Bosnia and Herzegovina. Coordinated energy policies and robust cross-  
846 border infrastructure are essential to managing the impacts of CBAM on the stability and  
847 economic viability of the Croatian energy sector. By strategically planning and investing in  
848 renewable energy, Croatia can mitigate the economic pressures of high CO<sub>2</sub> prices and  
849 enhance its energy security.

850

851 The insights from this analysis can be applied to other non-EU countries with energy systems  
852 connected to the EU. These countries can benefit from understanding the operational and  
853 economic impacts of CBAM and CO<sub>2</sub> pricing and develop strategies to mitigate adverse  
854 effects. Key measures include diversifying the energy mix, investing in renewable generation,  
855 and upgrading grid infrastructure. Coordinated energy policies and cross-border cooperation  
856 will also be critical to sustaining electricity trade and meeting alignment conditions under  
857 CBAM. By leveraging the findings of this study, non-EU countries can better align their energy  
858 policies with EU regulations and contribute to a more sustainable and integrated regional  
859 electricity market.

860

861 This study supports more informed policymaking by providing a detailed assessment of the  
862 effects of CBAM and CO<sub>2</sub> pricing on cross-border electricity flows. The analysis provides  
863 guidance for developing climate and energy policies that balance operational feasibility with  
864 long-term sustainability. Policymakers should prioritise renewable energy investment and  
865 infrastructure upgrades to prepare for increasing carbon pricing and regional market  
866 integration.

867

868 Although this study focuses on short-term operational impacts, future research should  
869 explore the long-term consequences of CBAM implementation. As the mechanism evolves, it  
870 will likely influence investment decisions, energy mix transitions, and system flexibility. Long-  
871 term planning frameworks will be necessary to evaluate decarbonisation pathways,  
872 infrastructure needs, and cumulative system effects over extended time horizons.

873

874 This study also presents a valuable and transferable modelling framework for analysing  
875 phased carbon pricing in non-EU countries. The HR-BA case offers a practical example of how  
876 regulatory asymmetries in interconnected electricity systems affect dispatch behaviour, trade  
877 patterns, and system costs. These findings are relevant not only to Bosnia and Herzegovina  
878 and Croatia but also to Energy Community Contracting Parties and other globally connected  
879 countries facing similar policy alignment challenges.

880

881 Beyond this case, the scenario structure and modelling approach developed here can support  
882 broader regional and international applications. By integrating CO<sub>2</sub> pricing trajectories, fuel  
883 price variability, and cross-border interactions, this work offers a robust framework for  
884 assessing CBAM implementation in diverse contexts. These insights can guide energy policy  
885 design, infrastructure investment, and regional cooperation toward a just and cost-effective  
886 transition to climate neutrality.

887

#### 888 **Author contributions**

889 **Boris ČOSIĆ:** Conceptualisation, Methodology, Software, Data curation, Writing- Original  
890 draft preparation, Visualisation, Writing- Reviewing and Editing. **Marko BAN:** Visualisation,  
891 Writing- Reviewing and Editing. **Neven DUIĆ:** Supervision, Investigation, Writing- Reviewing  
892 and Editing.

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