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The Impact of CBAM and Variable Renewable Energy Integration on Energy Systems and Cross-Border Electricity Trade

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Abstract: This paper explores the energy system planning for Croatia and Bosnia and Herzegovina (HR-BA zone) in response to the Carbon Border Adjustment Mechanism (CBAM) and the growing need for renewable energy integration between 2025 and 2035. Using the Dispa-SET unit commitment and dispatch model, three scenarios, NECP, LRES, and HRES, were developed to evaluate how different levels of Variable Renewable Energy Sources (VRES) integration and CO2 pricing impact the region's energy system. In the NECP scenario, Bosnia and Herzegovina's electricity exports decrease from 3.39 TWh in 2025 to 1.29 TWh in 2035, driven by CBAM implementation and the rise in renewable energy use. The HRES scenario shows aggressive renewable energy deployment, resulting in 2.35 TWh of electricity export in 2035, but also reveals substantial curtailment issues, with a maximum hourly curtailment value reaching 3,926 MW and occurring over 4,114 hours during 2035. These findings underscore the difficulties of integrating large amounts of renewable energy without significant upgrades to grid infrastructure and storage solutions.

Keywords: CBAM, Dispa-SET, ETS, NECP, VRES.

1. Introduction

The global transition towards a low-carbon future is accelerating, primarily driven by the urgent need to mitigate climate change and reduce greenhouse gas emissions. The European Union (EU) has been at the forefront of this movement, introducing the Carbon Border Adjustment Mechanism (CBAM) [1] to prevent carbon leakage and ensure that imported products adhere to the same environmental standards as those produced within the EU [2] and [3]. CBAM specifically targets carbon-intensive sectors such as cement, aluminium, and electricity, which are essential for the energy transition [4].

The energy systems of Bosnia and Herzegovina (BA) and Croatia (HR), both part of the interconnected Western Balkans energy network, rely heavily on coal and natural gas. Both countries are under growing pressure to reduce their reliance on these fossil fuels and to increase the integration of Variable Renewable Energy Sources (VRES), such as wind and solar [5]. However, the intermittent nature of VRES introduces significant challenges in maintaining grid stability and avoiding curtailment, especially in interconnected power markets like those of the EU and the Energy Community [6] and [7]. Pumped Hydro Storage (PHS), heat and electric storage, and demand-side management have been identified as key solutions for enhancing the flexibility of power systems and supporting the integration of renewables. Flexible hydropower enables better management of VRES, helping to mitigate curtailment and balance supply and demand on the grid [8] and [9].

To evaluate the long-term impacts of CBAM and carbon pricing mechanisms, energy system models such as Dispa-SET are increasingly utilised. Dispa-SET is an open-source model designed for multi-zonal and multi-sector power dispatch optimisation, with applications across Europe and beyond [9] and [10]. The model provides insights into the operational and economic dynamics of power systems under various renewable energy integration and CO2 pricing scenarios [11] and [12]. In Bosnia and Herzegovina, where lignite remains a dominant source of electricity, introducing CO2 pricing under CBAM presents significant challenges. The country risks transitioning from being an electricity exporter to an importer, as carbon costs render lignite economically unviable [13].

In addition to technical challenges, the economic impacts of CBAM will be profound, particularly for non-EU countries exporting electricity to the EU. Studies have highlighted that cross-border electricity trade between

Bosnia and Herzegovina and Croatia is highly sensitive to fluctuations in CO2 prices and fossil fuel costs [14]. Under higher CBAM factors, countries without robust renewable energy portfolios or carbon pricing strategies may face significant economic pressures, making investments in renewable energy and grid infrastructure critical for maintaining competitiveness [15]. Moreover, understanding the role of sector coupling is essential for future energy transitions. Sector coupling involves integrating power, heating, and transportation systems to achieve greater flexibility and decarbonisation [16]. The concept has been explored in the context of European energy systems, demonstrating the potential to optimise energy use across sectors while reducing overall CO2 emissions [9] and [17].

The scientific contribution of this paper lies in its comprehensive analysis of the impact of the Carbon Border Adjustment Mechanism (CBAM) and varying levels of Variable Renewable Energy Sources (VRES) integration on the energy systems of Croatia and Bosnia and Herzegovina from 2025 to 2035. By utilising the Dispa-SET model, this study uniquely integrates CO2 pricing and renewable energy scenarios to simulate cross-border electricity flows, curtailment, and system flexibility. The novelty of the research stems from its application of the CBAM phase-in to a non-EU country (Bosnia and Herzegovina), providing valuable insights into how gradually rising carbon costs influence electricity trade and renewable energy utilisation. Additionally, the study highlights the importance of infrastructure upgrades, grid flexibility, and energy storage in mitigating the growing challenges of curtailment under high renewable energy penetration, offering critical policy and operational recommendations for energy transitions in interconnected regions.

2. Method

The Dispa-SET model, an open-source unit commitment and dispatch optimisation tool, is designed to simulate power systems across multiple zones and sectors. It is particularly effective for analysing power systems with a high share of variable renewable energy sources (VRES), such as wind and solar, alongside conventional power plants, energy storage solutions (e.g., pumped hydro and batteries), and cogeneration systems. The model utilises a Mixed-Integer Linear Programming (MILP) approach, implemented in Python and GAMS, to minimise total system costs. These costs include fuel consumption, plant start-up and shutdown operations, ramping, and load-shedding costs, all optimised within technical and regulatory constraints, such as generation capacities, transmission limits, and environmental policies. Dispa-SET can simulate operations on different time scales, from hourly dispatch to annual system planning, making it adaptable for both isolated power systems and large interconnected grids.

The main objective of the Dispa-SET model is to minimise total system costs by accounting for both operational and market-related expenses. The model operates under several constraints, such as limits on generation capacity, minimum up/down times for power plants, ramping limitations, and transmission capacities. Input data, such as detailed power plant characteristics, renewable energy generation profiles, and electricity demand, feed into the model, which then optimises generation across zones. Power plants are represented by parameters such as capacity, operational efficiency, ramp rates, and emissions, while transmission constraints ensure that electricity transfers between zones respect network limits and capacities. Moreover, the model incorporates existing power plant operations and the integration of new generation technologies, whether fossil-based or renewable, allowing for comprehensive analysis of the transition to a renewable-dominated system.

Dispa-SET is effective in simulating cross-border electricity flows, making it a valuable tool for assessing the economic and operational impacts of energy policies, such as carbon pricing. The model can simulate energy trading across zones with different carbon pricing schemes, offering valuable insights for policymakers focused on decarbonisation strategies. The model has been widely applied in various contexts, including evaluating renewable energy integration in the Western Balkans, assessing the operational flexibility required for systems with high shares of wind and solar energy [18] and [5], and exploring the water-energy nexus in African power pools [10]. Additionally, Dispa-SET has been used to assess strategic decisions in market-coupled zones, exploring how different energy policies and infrastructure investments impact cross-border electricity flows and system costs [13]. These applications demonstrate the model's flexibility in simulating regional and continental power systems under a wide range of policy and technical constraints.

3. Planning of the energy system in Croatia (HR) and Bosnia and Herzegovina (BA): The HR-BA zone

The reference energy system for Croatia and Bosnia and Herzegovina (HR-BA zone) serves as the foundation for this energy transition analysis. The system includes the existing generation mix in both countries, comprising fossil fuel power plants (coal, gas, and oil), hydropower, and Variable Renewable Energy Sources (VRES), such as wind and solar. Transmission interconnections between Croatia, Bosnia and Herzegovina, and their neighbouring countries are also considered. To accurately simulate operational conditions, power plant characteristics, such as capacity, efficiency, and ramp rates, are collected and integrated into the model. Renewable energy production profiles are derived from historical data, while electricity demand profiles remain constant throughout the analysis period, ensuring the reference system mirrors the actual operational structure of the HR-BA zone.

The data needed to design the reference energy system was obtained from multiple sources to ensure both accuracy and relevance. Key power plant characteristics, including capacities, efficiencies, and ramp rates, were obtained from various studies [5], [19], [20]. Electricity demand profiles were derived from historical consumption data and remained constant throughout the analysis period. Renewable energy production profiles were derived from historical weather data and generation records, ensuring that hourly variations in wind and solar output were adequately captured [21] and [22]. Transmission capacities and interconnections between Croatia, Bosnia and Herzegovina, and neighbouring countries were collected from reports published by the European Network of Transmission System Operators for Electricity (ENTSO-E), ensuring that cross-border flows and transmission limits accurately reflect real-world conditions [21].

Three energy transition scenarios were developed to assess the impact of different levels of VRES deployment and CO2 pricing. These scenarios, designed explicitly for Bosnia and Herzegovina's potential alignment with the European Union's Emissions Trading System (EU ETS) by 2035, examine the combined effects of the Carbon Border Adjustment Mechanism (CBAM) and renewable energy integration on fossil fuel power plants and the broader energy market.

- **NECP Scenario**: This scenario aligns with the National Energy and Climate Plans (NECPs) of Bosnia and Herzegovina [23] and Croatia [24], projecting renewable energy capacities based on official targets for 2035. By 2035, Bosnia and Herzegovina aims to install 1,220 MW of wind power and 2,890 MW of solar photovoltaic (PV) capacity, while Croatia plans to install 1,980 MW of wind power and 1,825 MW of PV capacity. Other generation technologies remain unchanged compared to the reference scenario. This scenario serves as the baseline for comparing the effect of CBAM and VRES integration on the energy market in both countries.
- **LRES Scenario (Low Renewable Energy Source Integration)**: In this scenario, Bosnia and Herzegovina adopts a more conservative approach to VRES deployment, with significantly lower installation rates for wind and PV plants compared to the NECP scenario. By 2035, wind capacity is expected to reach only 402 MW and PV capacity is projected to be 980 MW. Croatia maintains the same renewable energy targets as in the NECP scenario. This scenario evaluates the potential impacts of slower renewable energy integration on fossil fuel dependency and CO2 pricing.
- **HRES Scenario (High Renewable Energy Source Integration)**: This scenario envisions an accelerated deployment of renewable energy in Bosnia and Herzegovina, with wind capacity increasing to 2,440 MW and PV capacity reaching 3,825 MW by 2035. Croatia's renewable energy targets remain aligned with the NECP scenario. The HRES scenario assesses the impacts of a rapid shift towards renewable energy on system flexibility, cross-border electricity flows, and the responsiveness of the energy market to rising CO2 prices.

These scenarios were analysed using the Dispa-SET model, which simulates electricity generation, demand, and cross-border electricity flows. This approach provides insights into the economic and operational effects of different energy transition pathways in the HR-BA zone. The results from each scenario support the evaluation of policy decisions aimed at optimising renewable energy integration, reducing CO2 emissions, and enhancing energy security.

In the scenarios for Bosnia and Herzegovina, the Carbon Border Adjustment Mechanism (CBAM) was introduced gradually, aligning the country with EU carbon pricing. Bosnia and Herzegovina starts with no CO2 pricing in 2025 (0%), with the CO2 price gradually increasing from 2.5% in 2026 to 100% by 2035, based on the CBAM phase-in factors. The hourly CO2 price used in Croatia's EU ETS in 2022 is applied as a baseline, and Bosnia and Herzegovina's CO2 price increases incrementally each year according to the CBAM schedule. This phased approach models the economic impact of Bosnia and Herzegovina's gradual integration into a carbon-regulated market, reflecting the transition towards full alignment with EU carbon policies by 2035.

4. Results

This section presents the results of the energy system analysis for Croatia (HR) and Bosnia and Herzegovina (BA) for the period 2025-2035. The analysis incorporates the Carbon Border Adjustment Mechanism (CBAM) and varying levels of CO2 pricing across different scenarios. The results also take into account the levels of installed Variable Renewable Energy Sources (VRES), which have a significant impact on cross-border electricity flows, curtailment, and overall system flexibility. The key findings are illustrated in Figure 1 – Figure 4, highlighting electricity trade and curtailment dynamics between the two countries.

Figure 1 shows the electricity exchange between Bosnia and Herzegovina (BA) and Croatia (HR) from 2025 to 2035, with a focus on how CO2 pricing under the CBAM phase-in and varying levels of renewable energy integration affect cross-border flows.

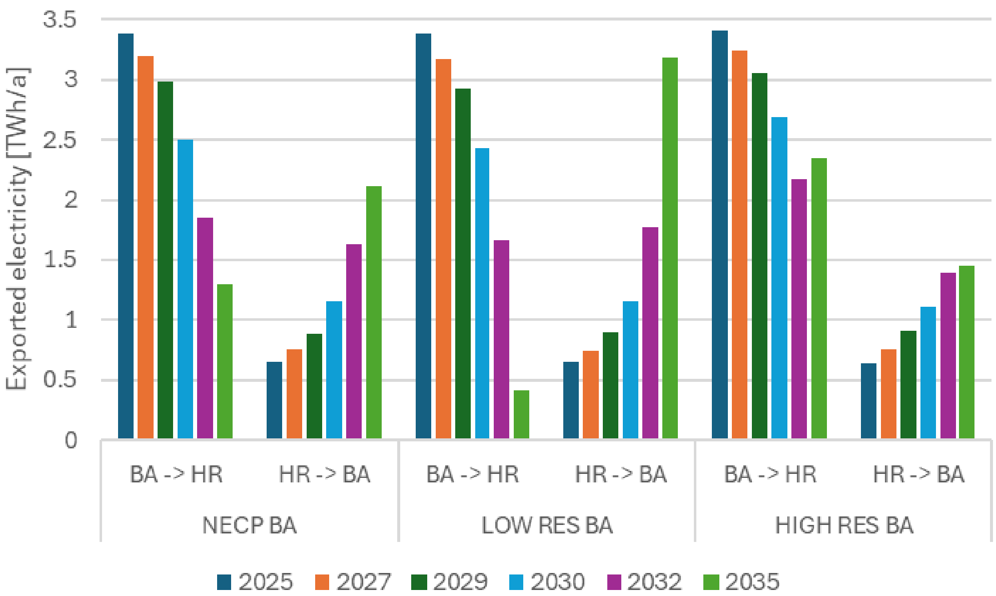

Figure 1. Electricity export per zone and scenario

In the NECP scenario, Bosnia and Herzegovina remains a net exporter of electricity to Croatia, starting with 3.39 TWh exported in 2025 and declining to 1.29 TWh by 2035. This decline is driven by higher CO2 prices and increased renewable energy capacity in Bosnia (1,220 MW of wind and 2,890 MW of solar by 2035). Croatia, on the other hand, gradually increases its electricity exports to Bosnia, rising from 0.65 TWh in 2025 to 2.11 TWh in 2035, as higher CO2 costs under the EU ETS make it more competitive.

In the LRES scenario, Bosnia and Herzegovina's slower renewable energy deployment (with only 402 MW of wind and 980 MW of solar by 2035) results in a more significant reduction in electricity exports, from 3.39 TWh in 2025 to just 0.41 TWh by 2035. The higher CO2 price in Bosnia, due to the CBAM phase-in, reduces fossil fuel reliance, but also limits its ability to maintain high export levels. Conversely, Croatia becomes a more attractive source of low-carbon electricity, with its exports increasing to 3.19 TWh by 2035.

In the HRES scenario, Bosnia and Herzegovina undertakes aggressive renewable energy deployment (2,440 MW of wind and 3,825 MW of solar by 2035), enabling it to maintain higher exports to Croatia compared to the NECP scenario, ending at 2.35 TWh in 2035. However, Croatia's exports to Bosnia decrease after 2030 due to the increase in renewable capacity in Bosnia, reaching 1.46 TWh in 2035. This scenario demonstrates that high levels of renewable energy can mitigate the effects of rising CO2 prices, especially under the CBAM regime.

Curtailment in these scenarios primarily affects the integration of wind and solar energy in Bosnia and Herzegovina. With increasing VRES capacity and rising CO2 prices under the CBAM phase-in, Bosnia faces challenges in fully utilising its renewable energy potential, as surplus generation often exceeds grid capacity or local demand. Curtailment levels vary based on the scenario's renewable deployment and system flexibility, with higher curtailment seen in scenarios with more aggressive renewable growth.

Figure 2 compares the curtailment duration in Bosnia and Herzegovina under the NECP scenario between 2025 and 2035. In 2025, curtailment is minimal, with the highest curtailment reaching 598 MW for just 1 hour, and no curtailment for 8,672 hours. However, as the renewable energy capacity increases and CO2 prices rise, curtailment becomes more frequent and severe. By 2035, the maximum curtailment reaches 2,733 MW, with curtailment affecting 1,911 hours. This represents a significant increase in both frequency and magnitude compared to 2025, highlighting the growing challenge of integrating renewable energy as the system evolves.

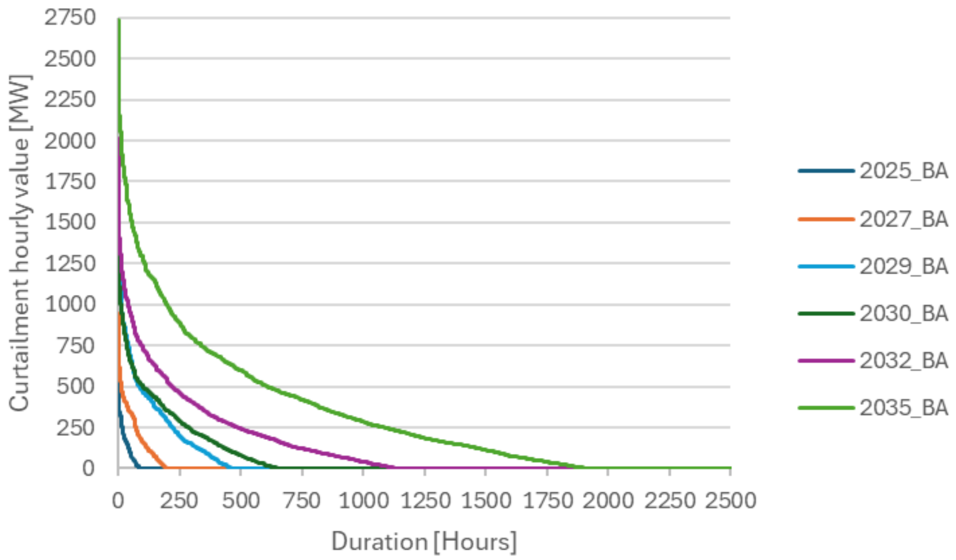

Figure 2. Curtailment duration curve for NECP scenario in zone BA

Figure 3 compares curtailment in Bosnia and Herzegovina under the LRES scenario between 2025 and 2035. In this scenario, slower renewable energy integration leads to lower curtailment throughout the period.

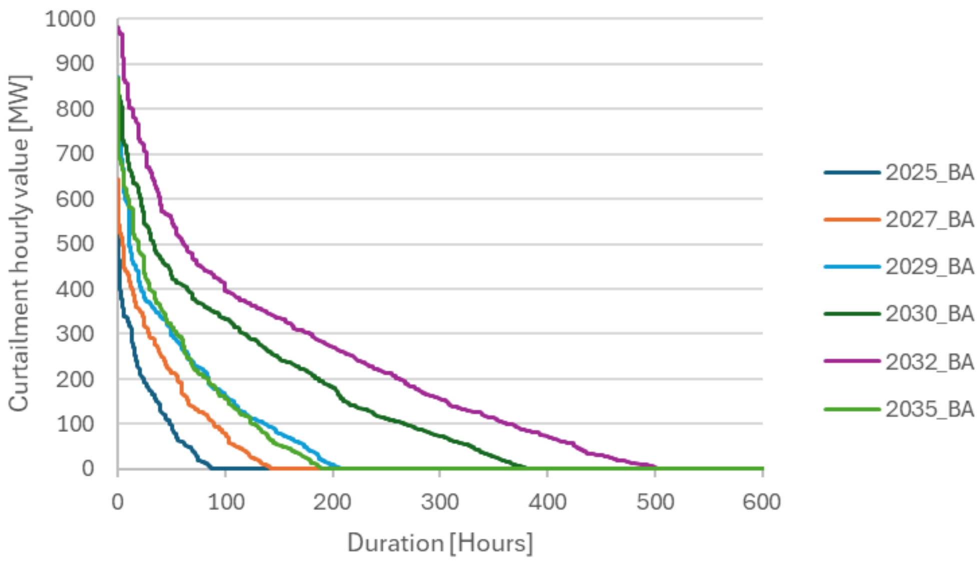

Figure 3. Curtailment duration curve for LRES scenario in zone BA

In 2025, curtailment is almost negligible, with the maximum curtailment of 598 MW occurring for only 1 hour, and no curtailment for 8,672 hours. By 2035, curtailment increases as renewable energy capacity grows, but remains controlled compared to scenarios with faster renewable integration. The maximum curtailment in 2035 is 867 MW, occurring for 192 hours, with 8,568 hours experiencing no curtailment. The moderate increase in curtailment reflects the limited expansion of renewable energy in this scenario, allowing the system to manage renewable generation without overwhelming the grid.

Figure 4 compares curtailment in Bosnia and Herzegovina under the HRES scenario from 2025 to 2035. In this scenario, rapid and aggressive renewable energy deployment results in significantly higher curtailment levels by 2035.

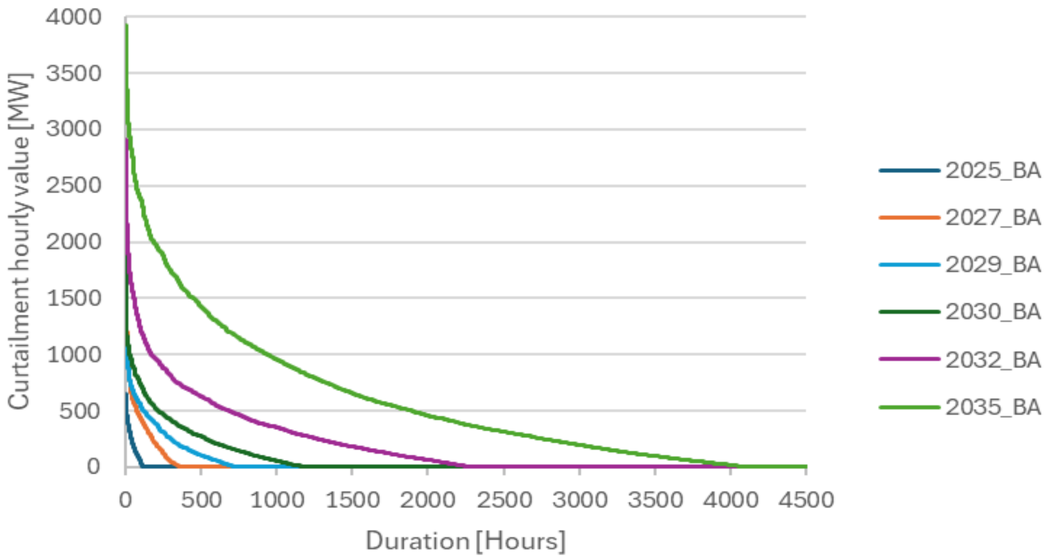

Figure 4. Curtailment duration curve for HRES scenario in zone BA

In 2025, curtailment is minimal, with a maximum curtailment of 646 MW occurring for 1 hour and no curtailment for 8,644 hours. However, as renewable capacity rapidly increases, curtailment becomes much more frequent and severe. By 2035, curtailment peaks at 3,926 MW, affecting 4,114 hours. This means that nearly half the year experiences curtailment, reflecting the difficulties of integrating large volumes of renewable energy without adequate investments in grid flexibility, storage, or demand-side management. The significant rise in curtailment highlights the challenge of fully utilising the renewable energy generated, leading to substantial energy wastage.

The results of these scenarios clearly show that the system's ability to manage surplus renewable energy diminishes as renewable capacity expands and CO2 prices rise under the CBAM phase-in. By 2035, curtailment affects a substantial portion of the year, particularly in the HRES scenario, where more than 50% of the year faces curtailment. These findings underscore the urgent need for infrastructure upgrades, storage solutions, and demand-side management to fully utilise renewable energy and ensure grid reliability.

5. Conclusion

The analysis of the energy systems in Croatia and Bosnia and Herzegovina from 2025 to 2035 reveals significant differences in the impacts of renewable energy integration and CO2 pricing across the three scenarios (NECP, LRES, and HRES). The results show that in the NECP scenario, Bosnia and Herzegovina remains a net exporter of electricity, with exports declining from 3.39 TWh in 2025 to 1.29 TWh in 2035, reflecting the increasing effect of rising CO2 prices and renewable energy deployment (1,220 MW of wind and 2,890 MW of solar by 2035). In the LRES scenario, slower renewable integration results in minimal curtailment and lower export levels, with Bosnia's exports dropping from 3.39 TWh in 2025 to only 0.41 TWh by 2035. In the HRES scenario, aggressive renewable energy deployment (2,440 MW of wind and 3,825 MW of solar by 2035) leads to higher exports, reaching 2.35 TWh in 2035, but also results in substantial curtailment.

The curtailment analysis highlights the growing challenge of integrating large shares of renewable energy into the grid. In the NECP scenario, curtailment increases moderately, with a maximum curtailment of 2,733 MW occurring for 1,911 hours by 2035. In contrast, the HRES scenario sees curtailment peaking at 3,926 MW, affecting 4,114 hours in 2035, indicating that nearly half of the year is impacted by curtailment. This underscores the need for enhanced grid flexibility, storage solutions, and demand-side management to effectively manage surplus renewable energy and fully utilise the benefits of renewable deployment. The findings emphasise that without these infrastructure upgrades, higher levels of renewable energy can lead to significant energy wastage, particularly under rising CO2 prices.

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