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Modelling Power Disruption Scenarios In The Baltic Region Using PyPSA

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Abstract

This paper analyzes the impact of hybrid threats on the Baltic region's critical maritime energy infrastructure, aiming to support a tabletop exercise organized by the Joint Research Centre (JRC) and NATO Energy Security Centre of Excellence (ENSECCOE). The analysis uses the PyPSA-Eur model to simulate disruptions to the electricity grid, considering 'Low', 'Medium', and 'High' intensity crisis scenarios. The results focus on energy flow, lost load, and price, providing insights into the grid's vulnerability and aiding in the development of targeted mitigation strategies. The PyPSA-Eur model, customized for the European network in 2025, helps understand how disruptions affect energy flow, load, and prices, identifying vulnerable points in the grid. The analysis highlights the impact on cross-border interactions, areas facing potential power shortages, and the economic implications of disruptions. This work offers valuable insights for national authorities, policymakers, and stakeholders involved in enhancing the resilience of maritime energy infrastructure in the Baltic Sea region against hybrid threats.

Keywords: resilience assessment, risk, crisis scenario simulation, power grid modeling

1. Introduction

In a time of rising geopolitical tensions and security challenges, the Baltic Region's maritime energy infrastructure, situated at the intersection of geopolitical interests, is vital for maintaining regional energy supply and stability. Recent incidents, such as the sabotage of Nord Stream or the Baltic-connector disruption, highlight the vulnerability of this infrastructure, demanding enhanced surveillance, protection, and response measures. The region confronts a unique challenge from hybrid threats, which poses a significant risk to critical energy infrastructure security. The assessment of these risks is key to increase the resilience of critical energy maritime infrastructure, for which modelling plays a pivotal role.

This paper aims to provide the analysis of the modelling results of electricity grid disruptions, stemming from hybrid threats that impact critical energy maritime infrastructure in the Baltic region. The work was performed as a support to the tabletop exercise that JRC jointly organised with NATO ENSECCOE. By understanding the intricacies of hybrid threats and their specific manifestations in the Baltic Region, stakeholders can enhance the region's ability to withstand, adapt, and recover from potential power disruptions, thereby ensuring the continued reliability of vital energy systems.

This paper, thus, serves as a timely and critical exploration into the modelling of power disruption scenarios, offering a nuanced understanding of the challenges faced by the Baltic Region in safeguarding its energy infrastructure amidst evolving hybrid threats. This work could contribute to valuable insights for national authorities, policy makers and stakeholders involved in the resiliency of maritime energy infrastructure in the Baltic Sea against hybrid threats.

The paper is organised as follows. Section II proposes an in depth analysis of the modelling tool (PyPSA-Eur), with an overview of the different free data basis the program interacts to provide a comprehensive map of the

European Network. Section III focuses on the input data used for the assessment, and the assumptions for each scenario covered. Section IV provides the assessment of the base case scenario, while Section V delves on the results of the simulations, for which the grid disruption scenarios are assessed based on three relevant parameters: energy flow, lost load and cost of electricity. Finally, section VI concludes the paper.

2. PyPSA-Eur

The modeling for this study is done using the PyPSA-Eur tool, an open-source Python environment designed for Power System Analysis. PyPSA-Eur provides an optimization model of the European electricity transmission system, employing optimal power flow solutions to address network-based problems. Based on a modular and open-source approach, PyPSA-Eur integrates seamlessly with a wide range of datasets (Hoersch, 2018). The following steps show how data sets are integrated to finally have a precise model of the ENTSO-E area network:

- *Data Retrieval*: Through this step, data bundles are gathered, defining country shapes, land cover and protected areas (Natura 2000 spaces, GEBCO), hydrological data, as well as population and GDP, etc.
- *ENTSO-E Map Integration*: ENTSO-E map is integrated from the transparency platform, ensuring that the model reflects the latest available information on the European energy infrastructure.
- *Voronoi Cell Modelling*: Voronoi cells are used in PyPSA-EUR to divide the geographical area of the network into smaller regions, attaching to them demand, transmission infrastructure, power plants and renewable resources. This division allows for a more detailed and accurate representation of the network, which can be used to improve planning and operation of the energy system. For the ENTSO-E region, the model provides1024 nodes.
- *Time Series, Capacity Factors for renewables and hydro resources and integration through Atlite*: Weather data with a 30 by 30 km resolution (from ERA5 and SARAH 2) are aggregated together with land availability information. Atlite converts the weather data into energy system data, incorporating wind turbine and solar panel models technical design parameters.
- *Power Plant Matching*: Finally, the program merges the dataset of conventional power plants, allowing for the incorporation of custom entries. This step ensures a comprehensive representation of the existing power generation infrastructure in the European Network model.

Thus, the program covers the entire European Network with a high level of resolution (1024 nodes), including more than 6000 alternating current lines ($\geq$ 220 kV), 60 high voltage direct current lines, substations and power plants (9600 aggregated generators). Each load node is furnished with load time series, installed power capacity and availability time series for solar and wind energy deployment (including data outlining the potential and limits), providing a robust framework for analyzing and simulating the energy system.

The model optimizes the energy system through linearized power flow, encompassing essential features such as meeting energy demand at each node and time, while considering transmission and CO2 emissions constraints. The model also integrates the flexibility from several sources (from demand side response, gas, storages, electric vehicles and heating pumps), providing a comprehensive framework with focus on reliability, sustainability, and resilience.

Leveraging the capabilities of PyPSA-Eur, this paper undertakes the task of modelling different power disruption scenarios within the critical maritime energy infrastructure of the Baltic Region. This becomes particularly valuable in the context of hybrid threats, where the multifaceted nature of the challenges demands a comprehensive and adaptable modelling approach.

3. Input data and simulations

The PyPSA Eur model has been customised to anticipate the network in 2025. On the demand side, energy assumptions and demand side response mechanisms were taken from estimations shared by countries for ERAA 2022. On the supply side, the thermal capacity has been kept as of the data of installed capacity from ENTSO-E 2023, while the renewable capacity is aligned with the ERAA 2022 information (ERAA, 2022).

In this analysis, three scenarios were considered for 'Low', 'Medium', and 'High' intensity crises within the timeframe of January to April 2025, together with the Base Case scenario, which shows the grid without any disruptions. The scenarios are consecutive and represent the increasing intensity of disruptions in the critical energy maritime infrastructure elements, which reflect on the demand, generation and energy flow between countries in the region. Figure 1 presents an overview of the energy infrastructure in the Baltic States.

Fig. 1. Critical Maritime Energy Infrastructure in the Baltic States (2025 projection).

Each crisis scenario ('Low', 'Medium', and 'High' Intensity Crisis') targeted different energy maritime infrastructure. While the disruption of electrical infrastructure directly causes a power grid disruption, in case of non-electrical infrastructure, the impact translates into power grid disturbances by affecting the performance of associated power infrastructure. For instance, a disruption of the LNG terminal could lead to a shortage in natural gas supply, subsequently reducing the maximum capacity at gas-fired power plants. All these assumptions underwent validation by the relevant Transmission System Operators (TSOs) in the region.
The results of the analysis are presented through three parameters: energy flow (including cross border power flow exchange), lost load (energy non-served) and cost of electricity, which are then compared across the scenarios.

- By examining energy flow, the analysis provides a holistic understanding of how disruptions impact the entire grid, and enhances the relevance of the cross-border interactions
- The quantification of energy non-served provides insights into the areas/sectors that might face power shortages, aiding in devising targeted strategies. Lost load significantly influences the cost of electricity, as the lost load cost is set at 10,000 €/MWh.
- Impact of incidents in the price of electricity is crucial not only for assessing the economic impact, but also for understanding the criticality of the scenario.

4. Base Case scenario

Before analysing the results of the crisis scenarios simulation, the assessment of the Base Case Scenario (no disruption), provides a good base for understanding the generation patterns of the different countries as well as their dependencies. All assessments are done in the period January – April 2025.
In relation to the energy internal generation, northern neighbors rely on hydro & nuclear (SE, FI). Baltics rely on off-shore wind, shale oil (EE) & gas (LV), while PL relies on coal / lignite & gas (see Figure 2).

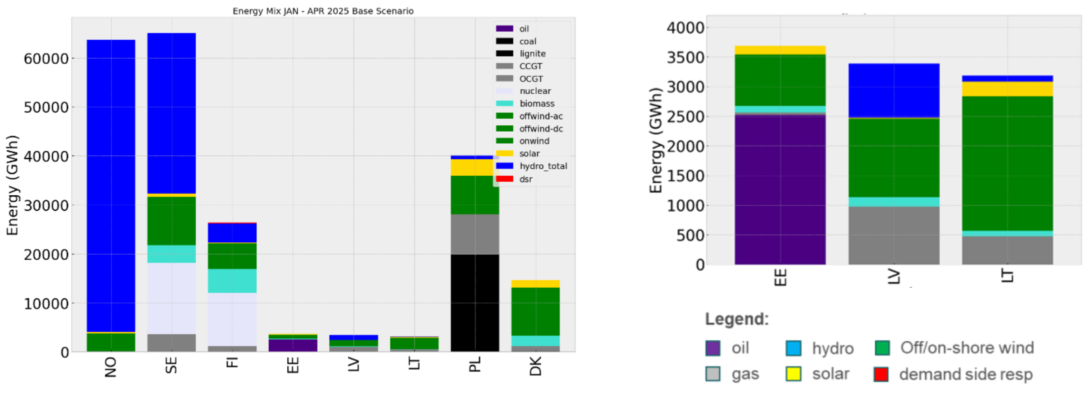

Fig. 2. Internal energy generation in the whole region and in the Baltic States, in GWh (January – April 2025).

Concerning the regional energy flow, Baltic region is net importer during the period (January – April 2025). One important remark is that the load demand in the Baltic States is just 5% of the regional demand (including Nordic countries, Poland and Denmark), and this region is net importer. Thus, any impact on interconnections or grid disruption in neighbor countries could greatly affect their stability.
The net exporters in the region are Norway, Sweden, Estonia (relying mainly on shale oil), and Latvia. Net importers are Finland (importing from Sweden), Lithuania (importing from Swede, Finland, Estonia and Latvia), and Denmark, as shown in Figure 3.

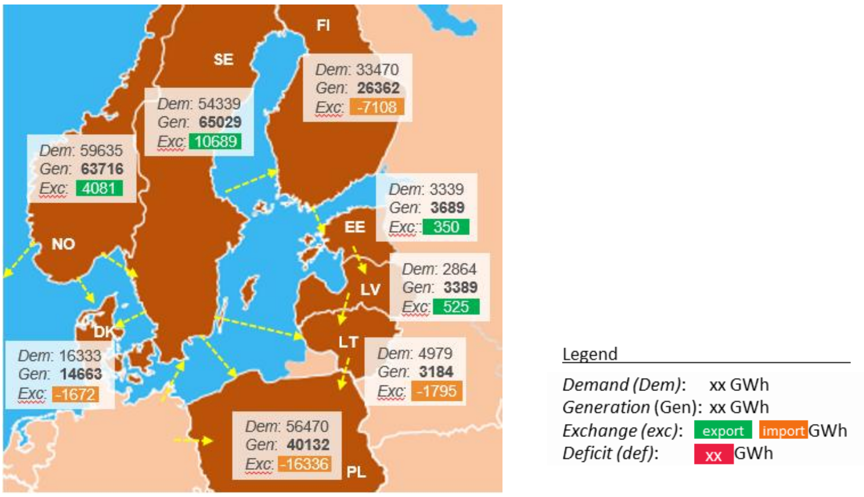

Fig. 3. Regional energy flow, in GWh (January- April 2025).

Concerning electricity costs, these are lower in Norway (primarily hydro-based) and higher in Poland, where reliance on coal is significant (see Figure 4). In Estonia, electricity generation is predominantly from shale oil (70%), with these units categorized as must-run. The unitary cost of electricity in Estonia does not accurately represent the actual cost, as it is offset through heat/ancillary payments.

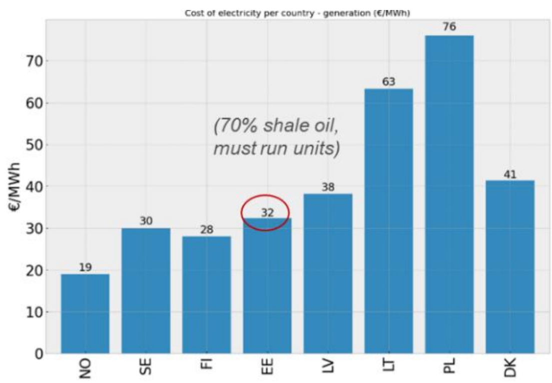

Fig. 4. Average cost of electricity, €/MWh (January – April 2025).

5. Simulation of Low, Medium and High Intensity Crisis Scenarios

The crisis scenarios are consecutive (from low to high intensity). Here below, the figures show the timeline when the different incidents occur, leading to the Low, Medium, and High Intensity Crisis Scenarios. The shared condition across all scenarios involves several generation disruptions in Estonia, Latvia, and Lithuania, as well as generation reduction in Sweden and Finland.

- The Low Intensity Crisis Scenario represents a small disruption scenario.
- The Medium Intensity Crisis Scenario is characterised by a major gas disruption, leading to a limited electricity generation from gas –fired power plants in the Baltic region.
- Under the High Intensity Crisis Scenario, the Baltic States suffer significant damage of energy infrastructures.

We will now assess the impact at each parameter (energy flow, energy lost and price) for the three scenarios.

5.1. Energy Generation, regional flows, and lost load

Figure 5 (Baltics regional electricity flow from January to April 2025), and Figure 6 (Internal energy generation in Baltic countries from January to April 2025), allows understanding the impact of the grid disruption in the different crisis scenarios:

- Under the *Low Intensity Crisis Scenario*, there is a huge reduction of generation in the Baltic States. Estonia becomes an importer country and extremely dependent on shale oil (80% of its internal generation), while Latvia tries to balance its internal generation by increasing generation from gas fired power plants, becoming highly dependent on it (63% of its internal generation comes from them). Lithuania enters in a minor lost load.
- In the *Medium Intensity Crisis Scenario*, the internal generation is highly reduced in Latvia and Lithuania (~ 500 GWh), while Estonia increases its generation from shale oil to support its neighbours. The Baltic States become very dependent on imports. The scenario leads to slight lost loads in Estonia and Latvia a minor lost load in Lithuania (1.7% of its demand during the period January – April 2025). In Latvia, flexibility mechanisms as the demand side response are essential to reduce lost load (2% - 4% of its load in Medium – High Crisis Scenario)

Under the *High Intensity Crisis Scenario*, the lost load in Estonia, Lithuania and Latvia ranges between ~190 GWh (Estonia, Latvia) and 400 GWh (Lithuania) during the period January – April 2025, representing between 5% and 6% of their demand during that period (17% of their demand during the month of March).

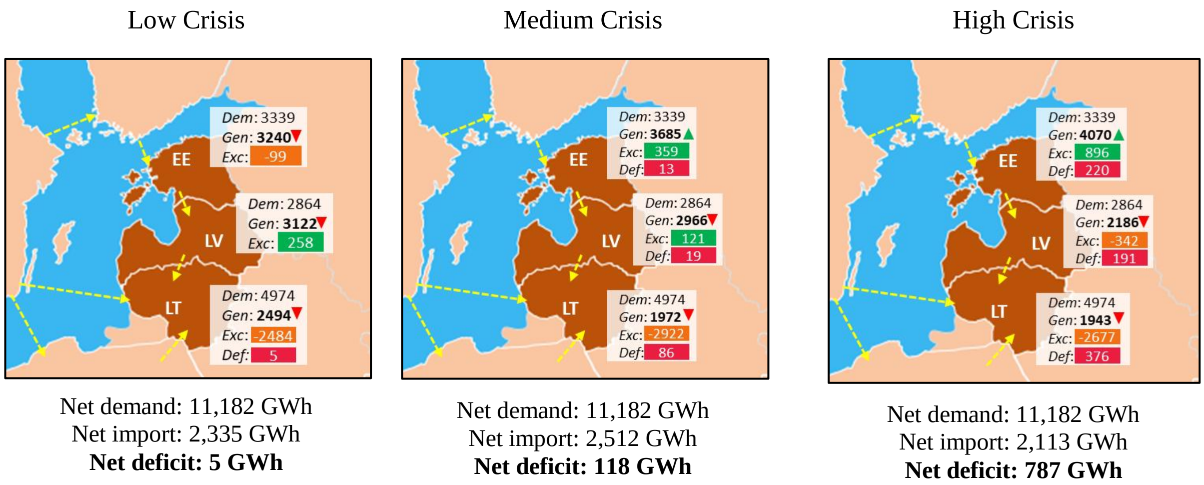

Fig. 5. Baltics regional electricity flow in GWh (January – April 2025).

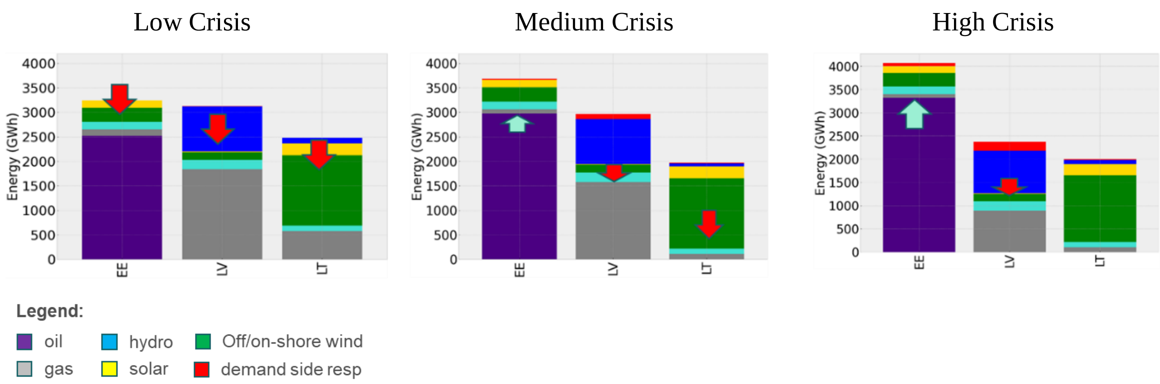

Fig. 6. Internal energy generation in Baltic countries by carrier in GWh (January – April 2025).

5.2. Lost load

As just seen, energy non-served is generalised in the Medium and High Intensity Crisis Scenarios. On top, the cost of electricity is highly dependent on lost load, as the cost of lost load has been set up at 10,000 €/MWh.

For illustrating the impact of the lost load in the cost of electricity, the figures below depict the time series from January to April 2025 of demand/lost load in the Medium Intensity (Figure 7) and High Intensity (Figure 8) Crisis Scenarios, consequence of some disruptions affecting power supply.

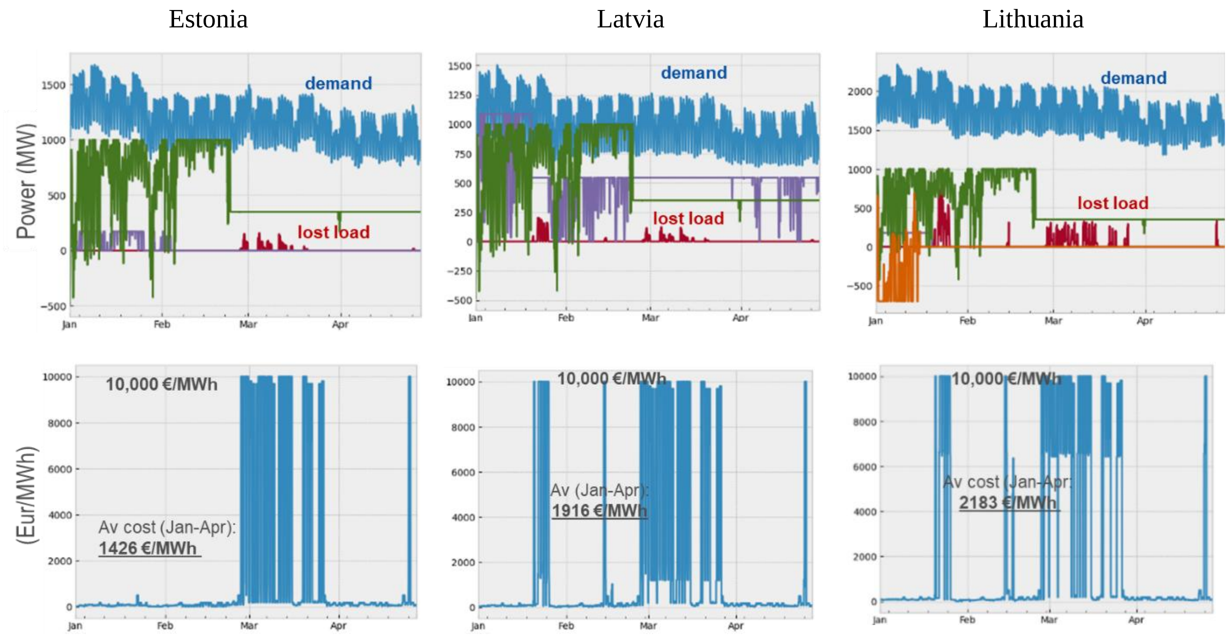

Fig. 7. Demand and Lost Load, electricity price per country for Medium Intensity Crisis Scenario.

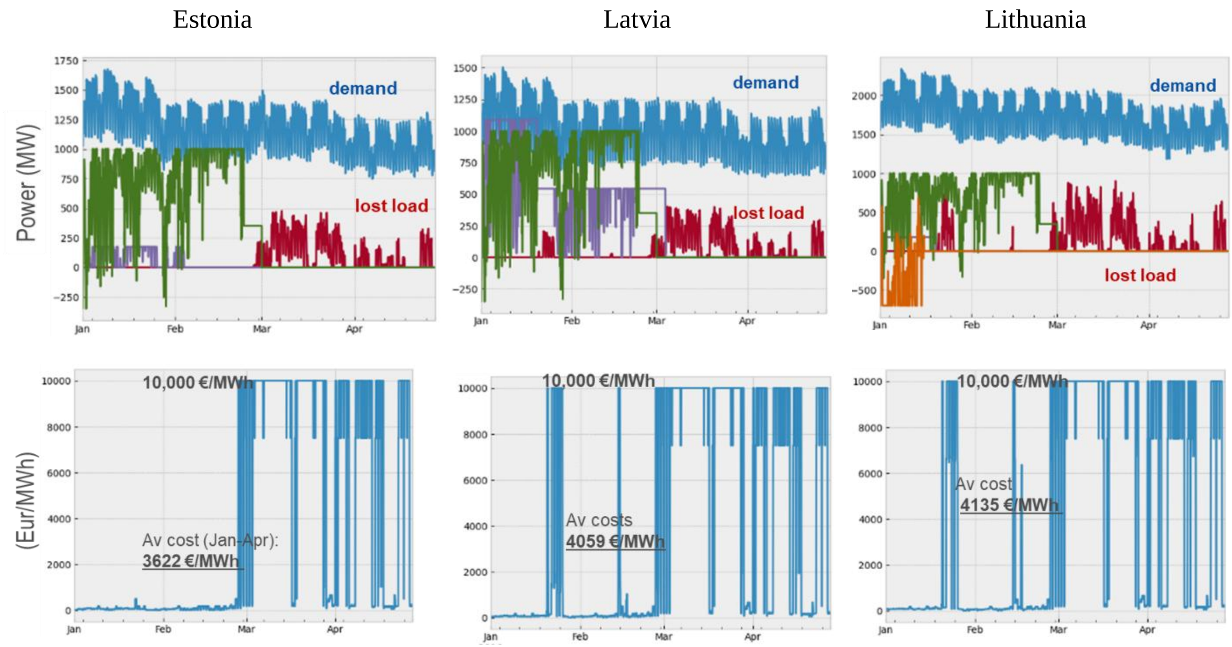

Fig. 8. Demand and Lost Load, electricity price per country for High Intensity Crisis Scenario.

5.3. Electricity price per country

Under the low crisis scenario, electricity costs rises in Estonia (+70%), Latvia (+70%) and Lithuania (+170%), and the lost load is observed in Lithuania.

In the Medium crisis scenario, the cost of electricity hugely increases in the Baltics, due to the lost load in all the countries (which is set up at 10.000 €/MWh), provoked by gas disruptions and the fact that more imports from FI & PL cannot be provided. Most impacted countries are LV & LT (> 1,900€/MWh)

Under the high crisis scenario, Estonia, Latvia and Lithuania face higher lost load. Average price in the period > 3,600€/MWh (Figure 9).

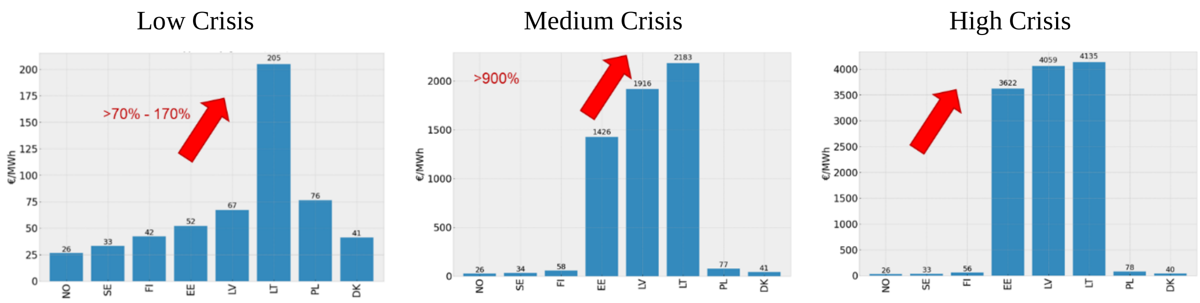

Fig. 9. Average cost of electricity (€/MWh) from January to April 2025 in Low, Medium and High Intensity Crisis Scenarios.

6. Conclusions

The modelling results have been of important support to the tabletop exercise, as they have allowed a more robust evaluation of the supply situation. Understanding how disruptions affect energy flow, load, and prices enables the identification of vulnerable generators and flow routes in the grid (Vasylius et al., 2021). This, in turn, facilitates the development of targeted mitigation strategies to enhance the overall resilience of the energy infrastructure. This work aims to contribute to valuable insights for national authorities, policy makers and stakeholders involved in the resiliency of maritime energy infrastructure in the Baltic Sea against hybrid threats.

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