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Modelling Power Disruption Scenarios and Assessing Resilience of a Power System

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Abstract: The paper addresses resilience assessment of a power system due to disruption of interconnecting power lines. The power system analysed is based on an anonymized EU region well interconnected with other Member States. We analyse several disruption scenarios and rank them by introducing a resilience index. The selected disruptions are modelled using the - open source – PyPSA-Eur software tool. The study aims to quantify and rank importance of interconnecting supply routes to the security of power supply in the analysed region.

Keywords: resilience assessment, power system, modelling of disruptions, energy security, PyPSA, energy not served, HVDC cable, critical energy infrastructure.

Introduction

Modern power systems are highly complex, interdependent and interconnected. Power supply is often dependent on well-functioning flows via interconnectors. This is becoming more essential when power systems are increasingly shifting towards higher share of intermittent renewable generation. The power systems can also be heavily affected by current geopolitical situation that might result in incidents and attacks on- and off-shore [1]. Under such circumstances, power system resilience assessments play important role to analyse, understand and mitigate various disruptions by contributing to robust strategies to protect critical energy infrastructures, from any threat, attack or technical failure [2].

Recent events have starkly illustrated the vulnerability of critical energy infrastructures to disrupting incidents. Deliberate damage of the gas pipelines and power undersea cables in the Baltic Sea underscore the vital importance of key energy interconnection points among countries [3]. These incidents demonstrate the urgent need for enhanced monitoring, safeguarding, and contingency strategies to protect energy assets, in particular with regards to cross-border energy interconnections, which form the backbone of Europe's interconnected power systems [4]. The European Commission has made safeguarding energy infrastructures one of its top priorities. Furthermore, the European Union has implemented key policies aimed at bolstering the resilience of critical infrastructures and the energy sector. Notable examples include electricity [5] and gas [6] Security of Supply Regulations, or Directive on Critical Entities Resilience (CER) [7]. These legislations stress the need to improve critical infrastructure resilience, address interdependencies, govern cascading effects, and increase resilience of power and gas systems [8].

To tackle the complex challenges posed by attacks to energy infrastructures, simulation and analytical modelling are essential tools for assessing the impact (time and quantification of the disruption, region and population affected, lack of substitutability, preventive measures, etc.) and safeguarding the resilience of energy infrastructures [9]. There are many modelling tools such as Plexos or PyPSA-Eur software, which allow simulating the performance of energy systems, including power grids and cross-border interconnections [10]. Damage to these interconnections can lead to cascading failures that affect multiple regions, further amplifying the impact [11]. The disruptions could result in power outages, lost load, increased operational costs, making it critical to model the effects of such incidents to better prepare for and mitigate potential impacts.

This paper aims to examine the effects of cross border power disruptions in an anonymized region of Europe. By defining 10 disruption scenarios, the paper aims to offer a comprehensive analysis of how different disruptions to interconnections could affect the stability of the power grid. Consequently, this paper simulates selected power outage scenarios with the aim to assess the resilience of the system. The findings of this study have the potential to furnish key perspectives for national authorities, policy makers and stakeholders responsible for resilience of energy infrastructure and security of energy supply.

The structure of the paper is as follows: Section 1 provides an overview of the modelling tool (PyPSA-Eur), offering a synopsis of the various open-access databases that the software utilizes for a comprehensive representation of the European power grid. Section 2 concentrates on the input data required for the evaluation and presents the range of scenarios under investigation while also outlining the outcomes to be assessed. Section 3 presents research findings on the time needed to repair submarine cables and overhead power lines as input data for the disruption of cross border connections. Before exploring the crisis scenarios, Section 4 discusses the Base Case Scenario, providing a foundation for understanding the energy system before delving into crisis scenarios. Section 5 presents the ten different cases of cross border disruptions. The paper concludes with Section 6.

1. PyPSA-Eur

The modelling is done using the PyPSA-Eur model, based on PyPSA, an open-source tool on Python environment designed for Power System Analysis. PyPSA is widely used in the industry and academia, by actors such as the International Energy Agency, several European Transmission System Operators (Austrian Power Grid, Transnet BW etc.), Canadian Energy Regulator, or companies such Shell and Saudi Aramco [12].

PyPSA-Eur provides an optimization model of the European electricity transmission system with high spatial and temporal resolution, employing optimal power flow solutions to address network-based problems. Based on a modular and open-source approach, PyPSA-Eur integrates a wide range of datasets, including land cover and protected areas, hydrological and time series weather data, transmission lines, power plants, loads, costs, etc.

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, availability time series for renewable energy (including potential and limits) and installed power capacity, providing a robust framework for analysing 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 diverse constraints (i.e. transmission, CO_2 emissions, etc.). 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.

2. Input data and presentation of disruption scenarios

2.1. *Input data*

The PyPSA-Eur model has been tailored to forecast the 2025 power network, based on weather year 2016 (renewable generation), as this was a very cold year in the region. Most data are sourced from country specific estimations for ERAA 2022 (European Resource Adequacy Assessment). The thermal capacity is based on installed capacity data from ENTSO-E 2023.

The scenarios are specifically designed to assess the consequences of disruptions of electric interconnections in an anonymous region. The region of study is composed of 7 countries, the specific region (countries A, B, C), and 4 neighbouring countries (Countries 1, 2, 3, 4). The affected interconnectors are presented in Table 1, defining the country links and the nature of the connection (submarine, overhead).

Table 1. Available interconnectors.

Link	Countries	Type
Link 1	Countries A - 3	Submarine HVDC cable
Link 2	Countries A - 3	Submarine HVDC cable
Link 3	Countries C – 4	Overhead AC line
Link 4	Countries C – 2	Submarine HVDC cable

The scenarios are simulated from January to March 2025, and include the restoration of disrupted connections, based on the repair times outlined in the subsequent section.

2.2. *Presentation of disruption scenarios*

A total of ten scenarios have been simulated, which are categorized into two groups: four scenarios addressing a single cross-border disruption, and six scenarios involving simultaneous disruptions of two cross-border connections. Table 2 shows the scenarios to be assessed, based on disruptions on different connections.

Table 2. Scenarios to be assessed.

Fault	Link 1	Link 2	Link 3	Link 4
Link 1	Link1	Link1+2	Link1+3	Link1+4
Link 2		Link 2	Link2+3	Link2+4
Link 3			Link3	Link3+4
Link 4				Link4

2.3. *Simulation and outcomes assessment*

The outcomes are presented in three main parameters: energy not-served (ENS), energy prices, and an estimation of resilience assessment index, which allow to quantify severity and resilience of each scenario:

- **Energy Not Served** (GWh): This metric will offer insights into the extent of power shortages, aiding in devising targeted strategies.
- **Energy Price** (€/MWh): ENS costs (set at 10,000 €/MWh) directly affects the cost of electricity, allowing understanding the criticality of the scenario.
- **Resilience Score Index:** A resilience index is assessed for each disruption scenario, aiming to rank disruptions from ENS perspective.

3. Repair time of HVDC cables and overhead lines

High Voltage Direct Current (HVDC) cable faults, depending on the complexity of the cable system and the extent of damage, can be particularly troublesome occurrences due to the potential difficulty in pinpointing their locations and the considerable amount of resources needed for their restoration. As of submarine cables, additional factors that can significantly affect the repair time include weather conditions and the availability of repair vessels. Thus, faults in submarine cables necessitate unique ships for repairs and often result in a much more extended repair period compared to those in land cables and overhead lines in particular. Faults in cables can result in extended forced outages for the HVDC connection and the repairs can incur significant expenses.

To understand repair times, it is essential to recognize the components that constitute an HVDC system and their vulnerability to failures. HVDC systems are comprised of converters, transmission lines, substations, and ancillary services. Each component has its own set of potential failure modes, which can be categorized as electronic, mechanical, or environmental. Not all failures have the same frequency. Based on the Lindblad's [13] analysis of surveys '*CIGRE worldwide HVDC performance 10-year statistics 2005-2014*' and '*ENTSO-E DISTAC group's 6-year statistics of HVDC outages and limitations 2012-2017 concerning Nordic HVDC-links*', the primary issues related to the reliability and availability of HVDC technology are that forced outages of overall HVDC systems are quite frequent.

According to CIGRE, average number of forced outages per link and year is seven, while this number is four according to Nordic statistics. These levels of outages are significant. Another thing to be considered is the high unavailability of overall HVDC systems due to these forced outages, which can vary from hours, to days all the way to several months. The most frequent type of failure is that caused by external mechanical damages, which account for 70% of total incidents, while 40% of failures are related to insufficient information exchange between cable operators and construction companies.

A survey among European TSOs reports an average repair time of 60 days for submarine cables [13]. Furthermore [14] mentions that for a fault of a single pole of submarine HVDC cable, the typical repair time is two to three months. In another case, mentioned in [15], the repair time of submarine cables was 1440 h, approximately two months. According to GHD's report for Ofgem [16], the figures in Table 3 below are representative for a submarine cable repair in water depths of 30 m where the cable and suitable vessels are available, while naturally the submarine cable repair time is sensitive to equipment/vessel availability and weather.

Table 3. Submarine Cable Repair Times [16].

Activity	Duration, days
Mobilisation of repair vessel to site	15
Surveying, de-trenching and recovery of cable	10
Repair and testing of cable	15
Lay-down, reburial and surveying	10
Weather contingency	15
Total	**65**

Regarding overhead AC lines, the repair times are generally lower compared to those of underground and submarine cables. Although failure frequency of a cable link does not differ significantly from the failure frequency of an overhead line, the repair time of underground cable connections can be up to a hundred times longer [15]. As stated in [17], the usual time to repair overhead lines range from 8 to 48 hours, although this can be longer depending on the fault's location, cause, and extent of the damage. When a high voltage transmission line fails with one or more damaged structures, the responsible utility incurs huge monetary losses and hundreds of non-transmission (outage) hours. Given that the total losses and/or damages are directly proportional to the outage duration, time is a crucial factor in reinstating or remediating the damaged/fallen structure(s). In some cases, the process of formally rebuilding a new line can take as long as 5 to 6 weeks. Naturally, TSOs and utilities will have an Emergency Restoration Plan (ERP) in effect to revive the transmission network as soon as possible after a fault. ERP is a combination of technical or engineering processes and financial planning. Therefore, by using an effective ERP, the damaged/fallen transmission structures (towers or poles) can be replaced in a few hours depending on the nature and depth of the damage. Proper planning not only maximizes restoration efficiency but can also minimize inventory levels [18]. In certain situations, provisional or temporary poles and lines can be set up while the damage made to the main structures and elements is repaired.

In this paper we have studied faults on three HVDC submarine cables and one overhead AC line (Table 4). For the purpose of our calculations, we have considered two months of repair time needed after a fault on a submarine HVDC link and one month of repair time after a fault on an overhead AC line.

Table 4. Studied cross-border links.

Link (countries connected)	Type	Repair time, months
Link 1 (A-3)	Submarine HVDC cable	2
Link 2 (A-3)	Submarine HVDC cable	2
Link 3 (C-4)	Overhead AC line	1
Link 4 (C-2)	Submarine HVDC cable	2

Following repair times based on single and double (combined) faults of submarine HVDC and overhead links in the region are in Table 5.

Table 5. Repair times in months (m) of cross-border links based on ten studied faults in the region.

Fault	Link 1	Link 2	Link 3	Link 4
Link 1	2 m	3 m	2 m / 1 m	2.5 m
Link 2		2 m	2 m / 1 m	2.5 m
Link 3			1 m	1 m / 2 m
Link 4				2 m

For cases where single faults (e.g. Link 2) occur, the repair times correspond to the ones in Table 4. If the double HVDC fault happens on links connecting same countries (e.g. Link 1+2), it was assumed that the same stakeholders and maintenance crews would be impacted in dealing with both cables, therefore three months are considered. If the double fault of HVDC cables happens in different countries (e.g Link 1+4), 2.5 months were envisaged, considering possible involvement of the same or connected stakeholders (cable manufacturer, specific crew skillset etc.). For the combination of overhead AC line and submarine HVDC cable, different actors are involved, thus repair times correspond to the repair times of the individual element.

4. Base Case Scenario

Before exploring the crisis scenarios, the Base Case Scenario (without disruptions) will be analysed. This scenario provides a foundation for understanding the generation patterns of the different countries as well as their interdependencies. Demand is plotted for the 3-country region (Fig. 1), showing larger demand in January compared to February or March 2025.

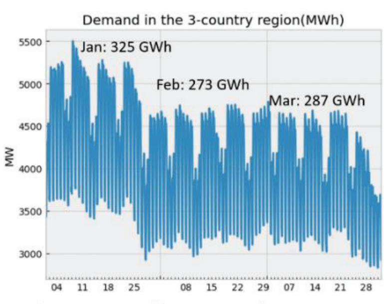

Fig. 1. Internal energy generation in GWh (January – March 2025)

The parameters that will be tackled are: the energy internal generation (Figure 2), the energy flows (Table 6) and the electricity prices (Figure 2). The calculations cover the period January – March 2025.

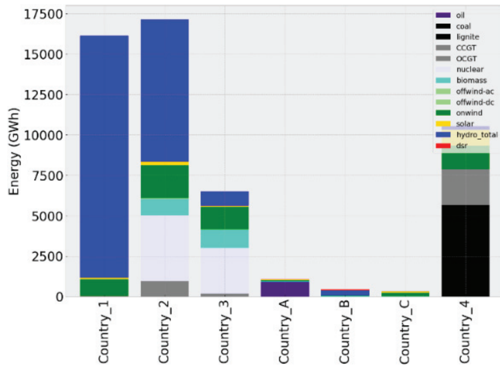

Fig. 2. Internal energy generation in GWh (January – March 2025)

Concerning the regional energy flow, an important remark is that the load demand in the specific region of study (Countries A, B, C is just 5% of the regional demand, and is net importer in the period. Thus, any impact on interconnections or grid disruption in neighbour countries could greatly affect their stability.

The main parameters of energy flow (demand, generation and exchange position) are shown in Table 6. The net exporters in the region are Countries 1, 2, B. Net importers are Countries 3, 4, A and C.

Table 6. Regional energy flow (demand, internal generation, interconnection, lost load), in GWh (January- March 2025)

	demand	int_gen	intercon	lost-load
Country_1	-14990	16397	-1406	0
Country_2	-13862	17044	-3180	0
Country_3	-8530	7074	1456	0
Country_A	-868	682	185	0
Country_B	-738	782	-44	0
Country_C	-1290	534	755	0
Country_4	-14785	10092	4692	0

Interconnections: (+) importing / (-) exporting

Finally, electricity costs are lower in Country 1 and higher in Country 4 (see Fig. 33).

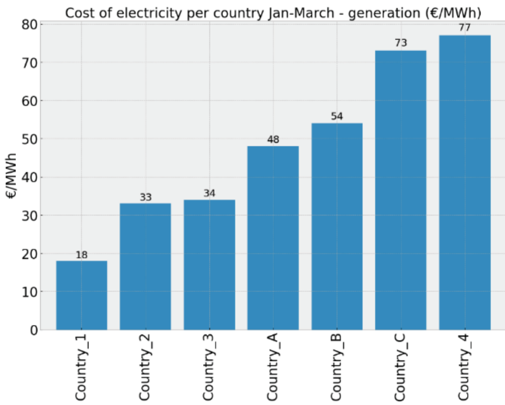

Fig. 3. Average cost of electricity, €/MWh (January March 2025)

5. Assessment of interconnection disruptions

Once having visualised the base case scenario, 10 disruption scenarios will be evaluated, based on the assessment of energy non-served and the energy price.

5.1. *Energy non-served (GWh/month)*

The estimation of ENS is presented in GWh/month (see Fig. 4). Among the single disruption scenarios, Link 3 is the most critical disruption, followed by Link 4.

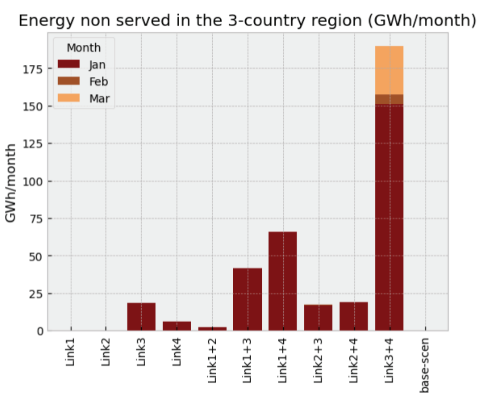

Fig. 4. Energy non-served in the region in GWh/month, for Jan to Mar 2025.

However, the most critical scenarios arise when there is a simultaneous disruption of two interconnections:

- The most critical scenario is the disruption of Link 3+4, which accounts for 151 GWh of ENS in January
- Other critical scenarios are the disruption of Links 1+4 and 1+3, with 66 GWh and 42 GWh of ENS respectively (in January).

Lost load just occurs in January, with no lost load in the subsequent months, due to overhead lines being repaired within one month and to a general decrease in load demand. Despite the fact that submarine cables faults require two - three months to repair, the system remains robust enough to ensure a stable supply in most cases.

5.2. *Electricity prices*

Regarding the costs, the assessment focuses on the average monthly electricity costs in the specific region (countries A, B, C) (see Fig. 5). To achieve this, the cost was first calculated for each country and then a weighted average was applied.

The electricity prices peak in January due to the disruptions, but standard values are recovered in the subsequent months as the lost load is resolved. The recovery in subsequent months is attributed to a return to normal functioning and the alleviation of stress on the power system caused by the disruptions.

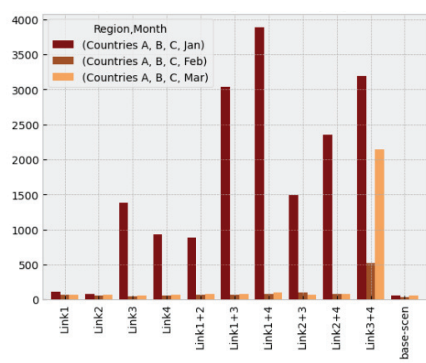

Fig. 5. Average electricity price in the region (Countries A, B, C) for January to March 2025

The disruption of Links 1+4 provokes the highest average price (3886 €/MWh in January), followed by the disruption of Links 3+4 (3192 €/MWh) and Links 1+3 (2988 €/MWh). The highest average price resulting from the disruption of Links 1 and 4 could be attributed to the widespread impact of ENS, affecting all countries within the region.

It is important to highlight that these prices are hypothetical and do not represent the typical behaviour of the market, as they do not account for the significant reduction in electricity demand that typically occurs due to high prices. The price construction is based on the assumption that the cost of unsupplied energy is €10,000/MWh, in line with the ACER's recommendation for the value of lost load (VoLL) when no specific data is available.

5.3. *Resilience index*

The resilience score is designed to rank disruptions in terms of the most significant damage to the network, considering ENS as the criterion. This resilience score prioritizes ENS during the first month and extrapolates further based on repair time, without considering variations in demand or generation. The result is an index that evaluates the system's resilience across different disruption scenarios, independent of demand and generation fluctuations.

Single disruptions (Link1, Link2, Link3, Link4) and double disruptions involving Link1+2 and Link2+3 cause less disturbances to the grid, resulting in high resilience scores. In contrast, double disruptions affecting Link1+3, Link1+4 and Link3+4 more severely disrupt energy supply, resulting in lower resilience score.

The resilience scoring aligns with the previous estimation of ENS, where Link3+4 disruption was identified as causing the most severe impact, followed by Link1+4 and Link 1+3. The lower the resilience score, the greater is the need for improvement actions. This implies that mitigation actions should first target disruption Link3+4 that is ranked the first by the resilience score.

Table 6. Resilience Index Score

	ENS-Jan (GWh/m)	Repair time (m)	ENS total (GWh/m)	Resilience score index
Link 3+4	151	2m/1m	226.5	1
Link 1+4	66	2.5	165	2
Link 1+3	42	2m/1m	63	3
Link 2+4	19	2.5	47.5	4
Link 2+3	17	2m/1m	25.5	5
Link 3	19	1	19	6
Link 4	6	2	12	7
Link 1+2	2	3	6	8
Link 2	0	2	0	9
Link 1	0	2	0	10

6. Conclusions

This paper highlights the critical importance of safeguarding cross-border energy interconnections in Europe against the growing risk of possible attacks. The results emphasize the urgency of leveraging simulation tools like PyPSA-Eur to model potential disruptions, thus serving to strengthen the resilience of the power sector.

By examining 10 scenarios of disruptions to cross-border energy infrastructures, the research offers valuable insights into how disruptions can trigger cascading effects across multiple regions, leading to power outages, increased costs, and operational challenges. The findings underline the necessity for comprehensive resilience-building efforts among the EU to protect their critical energy infrastructure. The modelling of the power disruptions allows for a better understanding of the impacts and provides then key insights for policy makers, national authorities and stakeholders to put in place effective mechanisms for enhancing resilience of the system due to disruptions. A sensitivity analysis could be next step for increase the robustness of the resilience score index.

Overall, this research contributes to the growing need of knowledge on energy infrastructure resilience, enabling analytical tools to address the complex challenges posed by various threats in an increasingly interconnected and vulnerable energy landscape. Grasping specific impacts of disruptions of cross border interconnections, the study enables regional actors to employ resilience index and rank disruptions by severity of their consequences.

Disclaimer. The opinions expressed in this article are those of the author(s) only and should not be considered as representative of the European Commission's official position.

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