Assessment of relevant assets for outage coordination

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Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Abstract

The internationalization of the electrical grid augmented the complexity associated with maintaining the transmission network and coordination between the Transmission System Operators (TSOs) pertaining to the same interconnected electrical grid. From the TSOs' perspective, it is vital to understand and quantify the influence that the interruption of an external network element can have on their control area, to manage the impacts of outside interference that may put at risk the service quality and continuity that they are meant to preserve. In this work, we address three specific problems: (i) how to evaluate the relevance of external assets for outage coordination, (ii) how to identify the relevant assets efficiently and within proper execution times, and (iii) how to minimize the influence of data error in the results. To handle problem (i), we developed a robust and scalable algorithm for Portugal's specific context that computes sensitivity values generated by Spanish outages. The results are then compared against threshold values and submitted under inspection to detect outlier features, such as isolation and cross-border distance. For problem (ii), we propose limiting the disconnected Portuguese assets of the studied outage combinations to Critical Network Elements (CNEs), achieving a decrease in execution time of 82.5%. Finally, to answer problem (iii), we introduce an active power filter that can be turned on or off, depending on the impact of error inserted by scenarios with extreme active power values. Thus, allowing the inclusion of such scenarios, guaranteeing a more reliable representation of the grid's year-long behavior.

Keywords: Outage Planning Coordination, Regional Security Coordinators, Transmission Network, Transmission System Operators

Resumo

A internacionalização da rede elétrica aumentou a complexidade associada à manutenção da rede de transmissão e à coordenação entre Operadores do Sistema de Transmissão (TSO) pertencentes à mesma rede elétrica interligada. Na perspectiva do TSO é vital entender e quantificar a influência que a interrupção de um elemento externo à sua rede é capaz de ter, de forma a controlar o impacto na qualidade e continuidade do seu serviço. Neste trabalho são focados três problemas: (i) como avaliar a relevância dos ativos externos no âmbito de coordenação de indisponibilidades, (ii) como identificar os ativos eficientemente e em tempo útil e (iii) como minimizar a influência que o erro inerente aos dados usados tem nos resultados. Para resolver o problema (i) propôs-se um algoritmo escalável e robusto, desenvolvido para o contexto Português, que calcula valores de sensibilidade gerados por interrupções espanholas e os compara a valores limite, sendo os resultados posteriormente validados ou excluídos dependendo de características como a distância às interligações fronteiriças e se possuem ligações a outros elementos de rede também considerados relevantes. Para lidar com o problema (ii) propôs-se limitar os ativos portugueses interrompidos a ativos classificados como Elementos de Rede Críticos (CNEs), o que reduziu em 82.5% os tempos de execução. Finalmente, para responder ao problema (iii), introduziu-se um filtro de potência ativa, que pode ser ligado consoante o impacto do erro inserido por cenários que apresentem valores extremados permitindo trabalhar com mais tipos de redes garantido uma representação anual fidedigna do comportamento típico da rede.

Palavras-chave: Coordenação de Indisponibilidades, Coordenador de Segurança Regional, Operador do Sistema de Transmissão, Rede de Transmissão

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Acronyms

ACER	Agency for the Cooperation of Energy Regulators
ATR	Autotransformer
CACM	Capacity Allocation and Congestion Management
CCC	Coordinated Capacity Calculation
CCR	Capacity Calculation Region
CEER	Council of European Energy Regulators
CGM	Common Grid Model
CNE	Critical Network Element
CO	Critical Outage
Coreso	Coordination of Electricity System Operators
CSA	Coordinated Security Analysis
CSV	Comma-Separated Values
DSO	Distribution System Operator
EDP	Energias de Portugal
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
HV	High Voltage
IGM	Individual Grid Model
LRT	Last Resort Trader
LV	Low Voltage
MIBEL	Iberian Electricity Market
MV	Medium Voltage

OCR	Outage Coordination Region
OPC	Outage Planning Coordination
ORP	Ordinary Regime Producer
OTDF	Outage Transfer Distribution Factor
PATL	Permanently Admissible Transmission Loading
PSS/E	Power System Simulator for Engineering
REE	Spain Electrical Grid
REN	Rede Elétrica Nacional, S.A.
RNT	National Transmission Grid
RSC	Regional Security Coordinator
SCADA	Supervisory Control and Data Acquisition
SGU	Significant Grid User
SMTA	Short and Medium Term Adequacy
SRP	Special Regime Producer
TSO	Transmission System Operator
UCTE	Union for the Coordination of Transmission of Electricity
VHV	Very High Voltage

1

Introduction

Contents

1.1 Topic overview

The coordination of outages gained traction on November 4, 2006, in Europe, when a severe electrical power disruption plunged more than 15 million households, in more than 10 countries, into darkness for nearly two hours [1].

The incident was a consequence of a poorly performed outage simulation followed by the disconnection of a 380 kV transmission line, which crossed the Ems river in the northeast of Germany, so that the cruise ship, Norwegian Pearl, could cross below the overhead cables. An unfulfilled criterion led to a cascade of line outages that propagated into the Continental European interconnected network splitting the interconnected grid into three islands of different frequency. This event pointed out the dangers of fragile coordination between the Transmission System Operators (TSOs) in Central West Europe [2].

In 2008, as a result of the willingness to better coordinate and exchange information, the first Regional Security Coordinators (RSCs) were created. Coordination of Electricity System Operators (Coreso), was one of the first regional technical coordination centers for electricity and is Portugal's RSC. Coreso's mission is to proactively help TSOs ensure the security of supply on a European regional level by identifying and implementing medium and long-term measures as well as developing and performing coordination services, while TSOs remain responsible for the operation [3].

In Portugal, the TSO entity is Rede Elétrica Nacional, S.A. (REN), which is a shareholder of Coreso and responsible for operating, maintaining, and developing the transmission in very high voltage electricity along with the transport of high-pressure natural gas.

One of the coordination services provided by Coreso is the Outage Planning Coordination (OPC), a service to be applied to all interconnected European grid capable of delivering remedial actions to help the TSOs coordinate each other outages. In Portugal's context, the coordination of outages is primarily within Portugal and Spain's integrated electrical systems since Portugal only has direct cross-border interconnections with Spain, which expand Spanish outages' influence into Portugal's national network assets.

One of the challenges faced during the application of OPC service at a European level was the magnitude of the number of network elements that comprise Europe's interconnected grid. Coreso operates in the Continental Europe region (former Union for the Coordination of Transmission of Electricity (UCTE)) illustrated in grey in Figure 1.1 which is the largest synchronous area of Europe. Coreso and the other RSCs of the Continental Europe region supply electricity to about 450 million people, covering twenty-three European countries with a total of about 220,000 km of transmission lines. It would be unfeasible for the RSCs to conceive a service that tested all possible combinations of outages and delivered remedial actions under the time constraints imposed by the type and frequency of the analysis it performs. For this reason, TSOs are asked to propose and present a list of all the external relevant assets whose individual availability statuses have a significant influence on the internal network elements of their control area. These network elements list should be updated if the control areas concerned are subject to change.

To provide the said list, the TSOs jointly proposed a methodology for the identification of relevant elements for the outage coordination process.

Figure 1.1: Map of the Continental Europe synchronous area

The motivation for this thesis comes from understanding the importance of the OPC and the development of a robust and scalable algorithm that can apply the methodology for assessing the relevance of assets for outage coordination proposed in accordance with Article 84 of Commission Regulation (EU) 2017/1485 of August 2017.

This work was only possible with REN's collaboration, which shared the data needed to run, test, and optimize the algorithm for real scenarios.

1.2 Objectives

The research question under analysis in this master's thesis is as follows: "How to evaluate the relevance of external assets for outage planning coordination?".

To answer this question we propose as this thesis main objective the creation of a fully functioning, scalable, and robust algorithm capable of analyzing power flow data from different scenarios and conclude which network assets are relevant during the coordination of outages.

To complement the main objective, the following operational goals were formulated:

- consider different scenarios, so that the results are eligible and representative of the grid's year-long behavior;
- study the impact on the execution time of the program by limiting the internal asset outages to Critical Network Elements (CNEs);
- compare the results for each scenario and conclude on the differences observed;
- mitigate errors induced by simulation conditions and power flow computations;
- identify the most adequate and coherent power flow influence threshold combination to provide the best relevant assets list;
- optimize the tool in order to process and deliver results in adequate time.

1.3 Thesis outline

This thesis is organized into six chapters. Chapter 1 addresses the motivation, objectives, and structure of the thesis. Chapter 2 introduces the background and state-of-the-art needed to comprehend the methodology for assessing relevant assets in Outage Planning Coordination and explains the main concepts and the context in which the metric started to be discussed at the European level. Chapter 3 describes and explains the details of the methodology and formalizes the algorithm proposal. Chapter 4 focuses on the implementation of the algorithm, how the scenarios were chosen, how the data was produced and presents necessary optimizations. Chapter 5 exhibits the results in two different research stages and elaborates on the parameters used during threshold selection. In conclusion, chapter 6 sums up this thesis' main findings while emphasizing its contributions and suggesting possible future lines of work.

2

Outage Planning Coordination - Background and Related Work

Contents

This chapter starts with an overview of the electric energy system and its fundamental concepts, focusing on the transmission grid, the TSO's role, and related entities such as the RSC and ENTSO-E.
Outage Planning Coordination is then explained in detail as one of the services provided by the RSC to its integrating TSOs, alluding to the gap of published work on this topic.
Posing as the basis of this thesis, it is presented the methodology, defined at a European level and to be followed by each TSO, for the assessment of asset's relevance for outage coordination.

2.1 Electric energy system

The journey of electric energy begins in Medium Voltage (MV) modules of power generation, where it is produced (except for low-power generation stations where it is produced in Low Voltage (LV)). While the production occurs at MV due to economic and optimization reasons, the transmission and distribution grids operate at different voltage levels (see Figure 2.1); thus, it is usual to mount transformers at the exit of the power generation modules. The transformers behave as a bridge between generation and the transmission (or distribution) network by elevating the voltage level to an adequate value for transmission (or for distribution, in the case of low power generation) and providing a protective layer against atmospheric overvoltages that may occur in the grid to which they are connected.

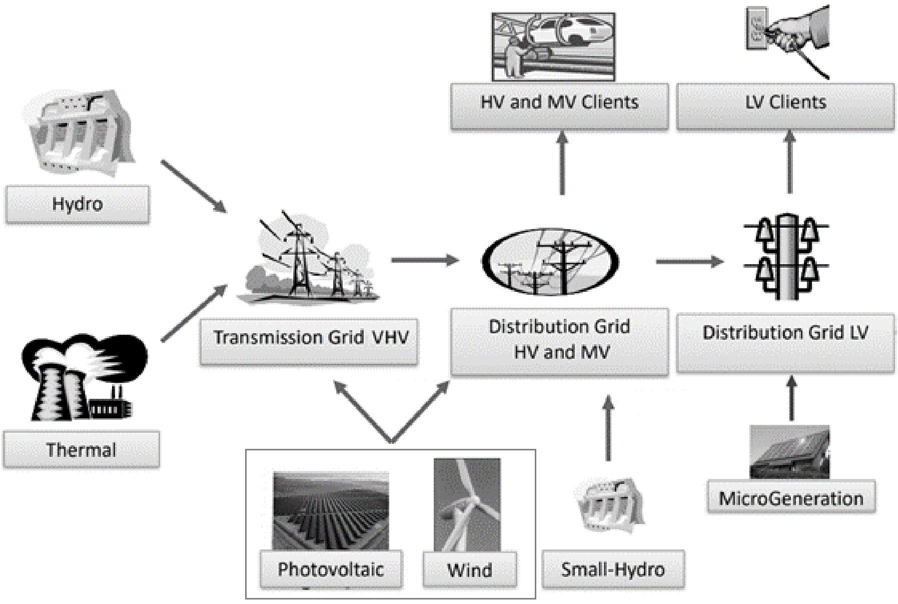

Figure 2.1: Electric energy system (adapted from [4])

Once delivered to the transmission grid, the electricity flows through Very High Voltage (VHV) transmission lines that transmit the electricity to the desired destination as if they were superhighways of energy.

At the other end of the transmission network are other transformers that, unlike the first mentioned, will reduce the voltage level in order for the distribution grid to be able to distribute the electricity through its distribution lines in High Voltage (HV), MV and LV.

Finally, the distribution grid provides the electricity received to domestic or industrial consumers. LV distribution lines connect the domestic consumers' household appliances and devices, MV feeds the transformation substations, while the HV supplies energy to the substations.

In Portugal, the primary energy sources used to reply to consumer demand are natural gas, wind and hydraulic, followed by biomass, coal and solar, with the renewable sources accounting for approximately 69% of Portugal's installed capacity in 2019 (see Table 2.1), while also representing the majority of 2019 production (55%) as one can observe in Figure 2.2.

Table 2.1: Installed capacity at the end of the year of 2019 (adapted from [5])

units in (**MW**)

Total	20 208
Renewable	13 847
Hydraulic	7 216
Wind	5 208
PV	730
Others	693
Non-Renewable	6 361
Natural gas	4 597
Coal	1 756
Others	8
Pumps	2 698

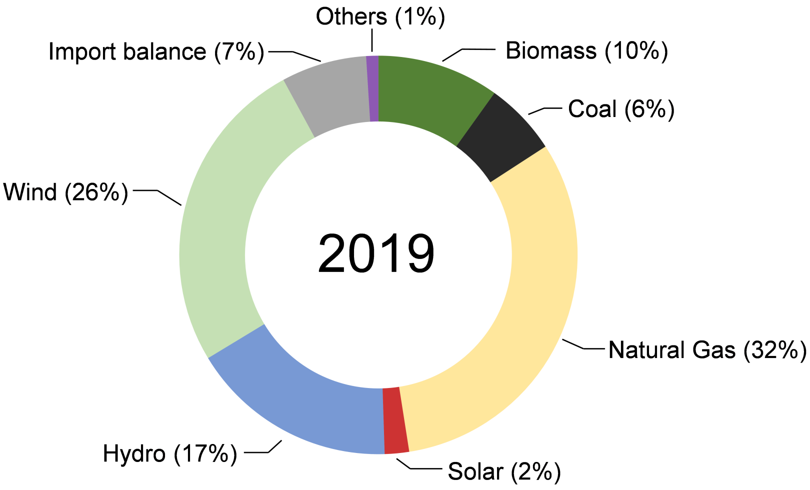

Figure 2.2: Generation sources of 2019 (adapted from [5])

As illustrated in Figure 2.1, both the transmission and distribution grids receive energy directly from the producers. The concept of electricity production can be divided into Ordinary Regime Generation, which encompasses the traditional non-renewable energy sources and the large hydroelectric power stations, and Special Regime Generation, which comprehends cogeneration and renewable energy production.

The Ordinary Regime Producers (ORPs) have the possibility of selling the electricity produced through the bilateral contracts with final clients and with electricity suppliers, or through the participation in organized markets, which in Portugal's case would be the Iberian Electricity Market (MIBEL).

The Special Regime Producers (SRPs) benefit from the right of selling their electricity production to the Last Resort Trader (LRT)[1]. LRT is a universal service with the purpose of protecting the consumers by offering a guarantee of supply continuity and quality.

Both SRPs and ORPs can provide system services by entering into contracts with the system operator or by participating in organized markets under the terms provided by the law [6, 7].

The production market is liberalized, meaning that the access to the activity depends solely on the initiative of the people concerned. All interested may have access to the transmission and distribution grid by paying a regulated tariff.

A well-designed alternating current electric energy system obeys to quality criteria, such as keeping the frequency constant, the voltage waveform sinusoidal and its value between well-defined boundaries, supplying all the requested demand, balancing production and consumption, minimizing the costs of production and the environmental impacts associated.

Portugal's electrical network belongs to the largest synchronous area of Europe, Continental Europe area, as illustrated in Figure 2.3, making frequency a global variable that must be kept under a strict range, typically $\pm$ 0.1% of the nominal value.

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[1] Portugal's main LRT is EDP Serviço Universal.

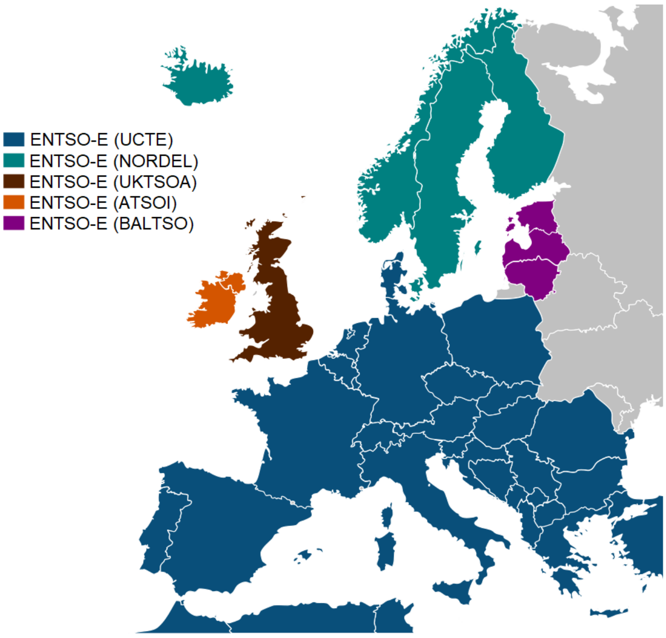

Figure 2.3: Synchronous grids of Europe and North Africa (adapted from [8])

In the Continental Europe synchronous area, the frequency nominal value is 50 Hz, and its regulation is intimately related to the maintenance of the equilibrium between production and consumption of active power. On the other hand, voltage regulation is intimately connected with reactive power flow in the grid and is less demanding, typically accepting a range of variation of ±5% of the nominal value, and in some specific cases such as of transmission grids where the number of direct consumers is relatively low, the range of variation can be of ±10% of the nominal value. This nominal value is defined locally, meaning that, unlike frequency, it is not the same for all of Europe [9].

To guarantee that the infrastructures are operational and reliable, large players need to collaborate to prevent failures, such as outages, and to maintain the system's continuity, which is vital to modern society.

From a national standpoint, the two main players are the TSO and the Distribution System Operator (DSO)[2]. Between the two, there is an intrinsic relationship since the latter manages countless resources, aggregating these to a level of abstraction so that the TSO has sufficient operational visibility to what is behind the scenes concerning Distributed Energy Resources (DER). With this sort of cooperation, the TSO can manage its system with better information while allowing for both to coordinate and operate in concert to enhance reliability and market efficiency.

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[2] Energias de Portugal (EDP) - Distribuição is the mainland Portugal's distribution system operator and detains the operation of the distribution grids of High (60 kV) and Medium (30, 15 and 10 kV) Voltage, by concession of the State, and also Low Voltage (400 and 230 V) by concessions of the municipalities [10, 11].

2.2 Transmission System Operator

In the transmission network, energy can be found either in the form of natural gas or electricity. The natural gas is transported through pipelines from gas producers to gas distribution companies, while electricity is transmitted through VHV transmission lines from generating stations to substations.

This infrastructure can extend to national or regional level and is supervised by the TSO. European Network of Transmission System Operators for Electricity (ENTSO-E) defines the TSO as “a company that is responsible for operating, maintaining and developing the transmission system for a control area and its interconnections” [12].

This entity’s responsibilities include securing the country’s power supply while responding to real-time consumption fluctuations as it oversees electricity flows over VHV networks and ensures that the maximum transmission capacity of the infrastructure is respected. The operator is also accountable for the dispatch of the production resources while preventing the transmission grid’s congestion. All the TSO decisions are based on knowledge of the electrical system features and complex calculations, consumption forecasts, power stations and network elements availability, and reserve capacities and recovery plans in the event of incidents.

The shift in primary energy sources from fossil fuels to renewable energy sources introduced a new level of complexity to the transmission grid management. The unpredictability and variability of renewable energy pose a handicap while the TSO attempts to adapt and maintain the balance between demand and production.

This challenge is particularly significant since the production aspect became much more susceptible to change due to its now stronger intrinsic connection to weather conditions. An increase in production forecast errors leads to more scenarios in which the grid is in a state of imbalance between production and consumption.

Underproduction, meaning that the generation available is insufficient to satisfy the system’s demand, leads to a decrease in frequency. On the other end of the spectrum, if energy production is above the expected value of demand – overproduction – the frequency will experience an increase. Remembering that Continental Europe synchronous area’s quality criteria state that the frequency of the synchronous area should be kept at 50 Hz $\pm$ 0.1%, if the frequency experiences a variation of the magnitude of 1 Hz, it can put the electric energy system at risk of a blackout, if the appropriate measures such as generators trip and load shedding intervention are not implemented.

Another issue that TSOs maneuver while balancing the production and consumption is the risk of congesting the transmission network, which implies that some of the transmission lines are operating above the power that they can carry at any given moment, which in terms of current means that the current value flowing through the lines is also above the recommended value. This state of operation is quite troublesome because it raises the temperature of the transmission line. The power lines’ temperature needs to be limited because the conductor material starts to expand, causing the power lines to sag. Although some sag is expected, it needs to be carefully limited since the conductor may touch nearby objects, triggering short-circuits that may be damaging or even lethal [13].

To prevent the occurrence of congestion, a constraint called Permanently Admissible Transmission Loading (PATL) is introduced, which represents the limit value in megawatts that the transmission line can carry at any given moment. PATL values can change by season, time of day, or with system conditions.

As mentioned in the beginning of this section, the TSO is also responsible for the interconnections of the control area it operates, maintains and develops. These cross-border electricity interconnections ensure energy exchange and address undesirable events such as power outages and blackouts [14].

In Portugal's case, these interconnections also allow for Portuguese electricity producers in ordinary regime and producers from Spain to sell the electricity generated in the organized market MIBEL, which resulted from the collaboration between the Portuguese and Spanish Governments to promote the integration of both countries' electrical systems [7, 15].

Like other public utilities, a TSO is a natural monopoly since the high infrastructural costs do not allow for competition.

Redes Energéticas Nacionais, SGPS, S.A.

REN - Redes Energéticas Nacionais, SGPS, S.A. is a Portuguese energy sector company and current concession holder of Portugal's two main energy infrastructure networks: the National Transmission Grid (RNT) and the National Natural Gas Transportation Grid. This company is primarily engaged in the management of energy transmission and the reception, storage, and regasification of liquefied natural gas. The group is also involved in other sectors such as telecommunications (via RENTELECOM), consultancy, and commercial services.

REN - Rede Elétrica Nacional, S.A. is Portugal's TSO and operates on the RNT in the transmission of HV and VHV electricity and manages the public electricity supply system. The RNT covers the whole country with a circuit length of 9,002 km [16]. The 400 kV grid lines mainly run from the Alto Lindoso power station to the Algarve, with interconnections along the way with the Spanish grid. The 220 kV lines run between Lisbon and Oporto.

The Portuguese Government granted the RNT concession to REN, with exclusivity to be used as a public utility. This concession includes planning, construction, maintenance, and operation of the grid and covers the national energy system's planning and technical maintenance. This way, the continuity of public service, proper functioning of the grid's infrastructures, and security are assured.

The Portuguese Government also granted the concession to operate a pilot area to generating electricity from sea waves to Enondas - Energia das Ondas. S.A., and the concession to Portgás to operate the second-largest natural gas distribution network in Portugal, with about 4,760 km. Both these companies are owned by REN - Redes Energéticas Nacionais, SGPS, S.A. [17].

2.3 Regional Security Coordinator

Regional Security Coordinators (RSCs) are entities created by TSOs to help them maintain the electricity system's operational security.

Changes in interconnected system operating conditions resulted in an increase of occurrences of unforeseen severe disturbances – most notably the well-known system split observed in the continental synchronous area on November 4, 2006 – which led to the creation of the first Regional Security Coordination Initiatives (now RSCs) in 2008. These entities have allowed TSOs to further coordinate system operations, network planning, system adequacy analysis, and market setups.

As of today, there is a total of five operational RSCs and one additional in the making [18, 19]:

- Coreso (2008), based in Brussels (Belgium) by nine TSOs.
- TSCNET (2008), based in Munich (Germany) by fourteen TSOs.
- Security Coordination Centre SCC (2015), based in Belgrade (Serbia) by three TSOs.
- Nordic RSC (2016), based in Copenhagen (Denmark) by four TSOs.
- Baltic RSC (2016), based in Tallinn (Estonia) by three TSOs.
- SEE RSC is being built in Thessaloniki (Greece) by seven TSOs.

Coreso

Coreso, located in Brussels, in the heart of the Western European energy sector, was established in 2008 and comprises nine TSOs (including REN), who are its shareholders (see Figure 2.4).

Coreso's team comprises about fifty engineers, who foresee 24 hours a day, seven days a week, the operation of a continental network, serving more than 400 million Europeans, both in the short term and the long term [20]. In addition to a common model developed from consumption and production forecasts, this coordination process enables its members to identify: (a) critical elements most affected by cross-border exchanges, (b) potential hazards such as the disconnection of a transmission line or generation unit and mitigation measures available to relieve monitored network elements, (c) the preferred options for programming specific high-impact interventions on the network, (d) potential risk adequacy absence based on the information provided by the TSOs and (e) valuable information for the prevention of incidents with a wide range of impacts.

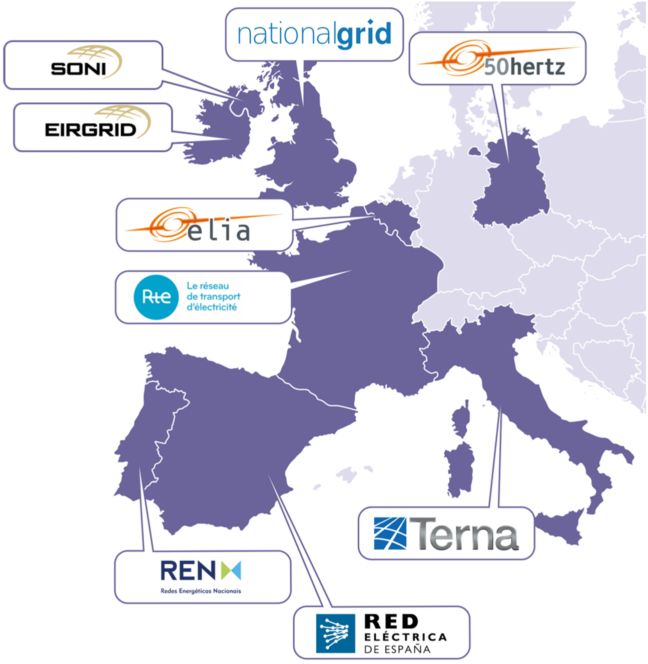

Figure 2.4: Coreso's shareholders. Source: [20]

In total, Coreso provides REN five services [21]:

- Individual Grid Model and Common Grid Model Delivery;
- Coordinated Security Analysis;
- Coordinated Capacity Calculation;
- Short and Medium Term Adequacy Forecasts;
- Outage Planning Coordination.

A brief explanation of the first four services will now be presented. In the case of OPC, since it is one of the main topics of this thesis, it will be explained in more detail in a further section of this chapter.

In the first place, we address the **Individual Grid Model (IGM) and Common Grid Model (CGM) delivery** service. This service works on the basis that each TSO publishes its computer model, which is the dynamic representation of its electricity grid, known as IGM. By an iterative process, RSC engineers receive various IGMs from each TSO, which they then merge to produce a pan-European collective grid model, known as CGM, representing the electricity grid at the European level. This collaboration between TSOs allows for a broader overview of electricity sharing in Europe since all European TSOs then have the same accurate overview of flows on high-voltage lines to study their behavior and guarantee security.

This service also provides quality and plausibility checks of the IGMs shared by the TSOs and CGM model improvement based on the CGM methodology pursuant to Article 17 of the guideline on Capacity Allocation and Congestion Management (CACM) [22] and agreed procedure pursuant to Article 12 and 15 of the network codes on Operational Planning and Scheduling [23].

RSCs can provide this service a year, a week or a day in advance, or even several times a day. For time frames close to real-time, this service can be simplified when creating the corresponding CGMs, e.g., using TSO snapshots [24].

In the second place, we tackle the **Coordinated Security Analysis (CSA) service**. For TSOs, the security of the European electricity system has always been and remains a vital issue. They are now supported by the RSCs that offer coordinated analysis conducted at the regional level to help ensure security of supply.

Using the CGM, engineers study the grid's future behavior, looking to anticipate the various combinations of potential risks.

Suppose the grid runs too great of risk the RSCs, in agreement with the TSOs, coordinate to identify corrective measures so that the TSOs can dispatch flows and avoid congestion. These reports enable TSOs to identify the best options to manage tense situations and avoid major disruption.

In summary, the CSA service aims at (a) identifying risks of operational security limit violations in any part of the regional area, mainly triggered by cross-border interdependencies; (b) finding relevant Remedial Actions (cross-border relevant ones) and (c) coordinating findings and Remedial Actions proposals with other adjacent RSCs [25].

In the third place, we focus on the **Coordinated Capacity Calculation (CCC)**. This service provides a solution to coordinate and harmonize the capacity calculation and allocation in the day-ahead time frame and the intraday time frame.

This solution rose from the fact that energy is a very much sought-after commodity; as long as one has it, one can sell it. However, since energy is not stored on a large scale and power transmission lines have limited capacity due to heating reasons, it was deemed necessary to define exchange rules to limit congestion risks.

The exchange rules include calculation methods suggested by the TSOs and adopted by the regulators that allow to define the highest flow rate possible for the exchanges. This way, the TSOs can operate their lines at maximum capacity while maintaining grid security [26].

In the fourth place, we address the **Short and Medium Term Adequacy (SMTA)**. This service is a solution used by the RSCs to maintain the balance between generation and consumption. To do so, RSCs use a calculation mechanism to check whether energy generated in the short term at a regional level is sufficient to meet demand and thereby avoid a shortage. If the power grid is short on energy, RSC engineers evaluate with TSOs what coordinated action can be taken to correct these imbalances.

Proposals are submitted to the TSOs, which assess their feasibility and adapt them to their grid's real-time situation. The proposals might suggest solutions such as making use of reserve generation or that certain customers reduce their consumption [27].

Besides these five services, Coreso also acts as a developer of criteria and procedures for ENTSO-E.

2.4 ENTSO-E

The European Network of Transmission System Operators for Electricity (ENTSO-E) is the formal representation of the TSOs in Europe. The organization was established and given legal mandates by the European Union (EU)'s Third Legislative Package for the Internal Energy Market in 2009, aiming to further liberalize the EU's gas and electricity markets. ENTSO-E Secretariat is located in Brussels, the focal point for technical, market, and policy questions for all European TSOs.

ENTSO-E's tagline is "Reliable, Sustainable, and Connected." In its members' opinion, these three adjectives need to always be in mind when looking into Europe's future to achieve their mission. It is ENTSO-E responsibility to plan Europe's electricity infrastructures for the next decades, manage the cross-border system operations and development, and the electricity market activities of the 42 electricity TSOs, covering a total of 35 countries.

ENTSO-E's ten-year network development plan is the blueprint to complete this enormous task. This plan's vision is to cut 80% of EU power systems emissions which will build a bridge to Europe's low-carbon energy future. The organization proposes to achieve this goal with a transparent platform, network codes, guidelines, and European-wide methodologies.

The role of the TSOs and their cooperation in ENTSO-E is crucial to ensure the security of supply (reliability), complete a competitive and fair electricity market (connectivity), and successfully integrate large volumes of renewable energy into the system (sustainability).

The importance of the relationship between TSOs and ENTSO-E is emphasized in this thesis because the methodology used as its baseline came from a shortcoming identified by the TSOs with respect to outage planning, which was reported to ENTSO-E. In turn, the latter defined the methodology and the thresholds at the European level that were afterward approved and published by the Agency for the Cooperation of Energy Regulators (ACER).

2.5 Outage Planning Coordination

As mentioned in section 2.3 of this chapter, OPC is one of the five mandatory services provided by the RSC to the TSO under the European Commission Regulation, establishing a guideline on electricity transmission system operation.

OPC development comes from the fact that generation and transmission systems such as overhead lines, transformers, breakers, or measuring devices have a service life. Therefore, regular maintenance work is required to keep the systems healthy. While maintenance work is ongoing, the equipment is unavailable; therefore, the TSOs need to be informed when their counterparts are carrying out work to avoid particularly tense situations on the grid. The RSC suggest studying all possible combinations of upcoming work to see if any will jeopardize the grid's availability [28].

2.5.1 Objectives and requirements

This service aims at:

- Identifying outage incompatibilities between relevant assets (grid elements, generators, and loads) whose availability status has cross-border impact which limits the outages that can be performed at pan-European level.
- Proposing solutions to relieve these incompatibilities.
- Coordinating findings and Remedial Actions proposals with other adjacent RSCs.
- Increasing the operational security of Europe's power system by coordinating outage planning on a weekly basis, based on generation and demand forecast provided by all ENTSO-E Member TSOs.

To implement this service, RSCs require common reference scenarios established by the TSOs and corresponding CGMs, as well as knowledge of all preliminary planned outages on the main transmission network - Alternating Current (AC) and Direct Current (DC) [29].

The OPC tool prototype was elaborated by TSCNET, but the delivery of this pan-European IT tool has required continuous engagement and work across the whole TSO community.

Tahir Kapetanovic, Head of the Control Centre of Austrian Power Grid (APG), the Austrian TSO, and Chairman of the ENTSO-E System Operation Committee, said: "Cross-border coordination and intensive cooperation of all national TSOs are the preconditions for a smooth functioning of the European power system." adding that the OPC tool allows uniform norms and standards for network operation to be put into practice [30].

2.5.2 Related work

To the author's knowledge, there are no studies proposing an algorithm to solve the assessment of asset's relevance for outage planning coordination. However, there is some related work focused on the challenges of interconnected power systems and the importance of coordination between neighboring countries.

For instance, a paper was found studying the impacts of cross-border electricity interconnections on the reliability and vulnerability of interconnected power systems. The paper presents two complementary approaches to risk management – high-probability but low-impact events (reliability approach) and low-probability but high-impact events (vulnerability approach) – and states that there is space to consider both in a unified decision framework to study cross-border interconnections [14].

The importance of managing interconnected power systems, which is related to the role of the RSC mentioned in section 2.3, is addressed by Silvio D'Alberto et al. They describe the main characteristics and services provided by the RSCs while studying the opportunity for a different initiative of regional cooperation for the Greece-Italy region power system integration [31]. While doing so, OPC is briefly mentioned as being one of the responsibilities of the RSC.

Another paper we found recognizes the newer challenges introduced by the increasing integration of renewable energies in the French electricity network, such as the inadequacy of existing maintenance outage planning methods [32].

Although somewhat related to the importance of maintenance through outage planning and to the impacts of interconnected power systems on neighboring countries, no study was found explicitly connecting these two elements and focusing on the relevance of outage planning coordination or the application of the methodology for the assessment of relevant assets, showcasing a gap in the literature that this thesis proposes to fill.

Coreso itself, when mentioning the scope of the OPC service, states that this is still a topic under development and that its definition is subject to evolution depending on the outcomes of the experimentation [29].

This ties into one of the most significant contributions of this paper, which is working on this methodology that is still being actively worked on by REN in coordination with Coreso and ENTSO-E.

In order for Coreso to provide its TSOs the OPC service, it needs from each one a list of relevant assets. The list is obtained by applying the methodology established to assess the relevance of assets in accordance with Article 84 of Commission Regulation (EU) 2017/1485 of 2 August 2017 [33].

In the following section, we will clarify the methodology key requirements.

2.5.3 Methodology for assessing the relevance of assets

In this section, we will: (i) indicate to whom this methodology is applicable, (ii) how to define the area of study, (iii) how the relevance should be assessed, and (iv) what the TSOs are required to present to their RSC in order for them to provide the OPC service.

In the first place, the methodology applies to TSOs, DSOs, Closed Distribution System Operators (CDSOs)[3], and Significant Grid Users (SGUs).

In the second place, the TSO has to identify its Outage Coordination Region (OCR) to know which external assets should be considered. ACER decided the division of regions in accordance with the Commission Regulation (EU) 2015/1222 of 24 July 2015 on CACM Regulation [36], meaning that the OCR was defined to be the same as the Capacity Calculation Region (CCR) unless the involved TSOs decide to merge coordination regions into one unique OCR. TSCNET defines CCR as “geographical areas in which coordinated cross-border capacity calculation, capacity allocation and congestion management are applied” [37]. In the Portuguese context, the CCR also includes Spain and France, as shown in Figure 2.5.

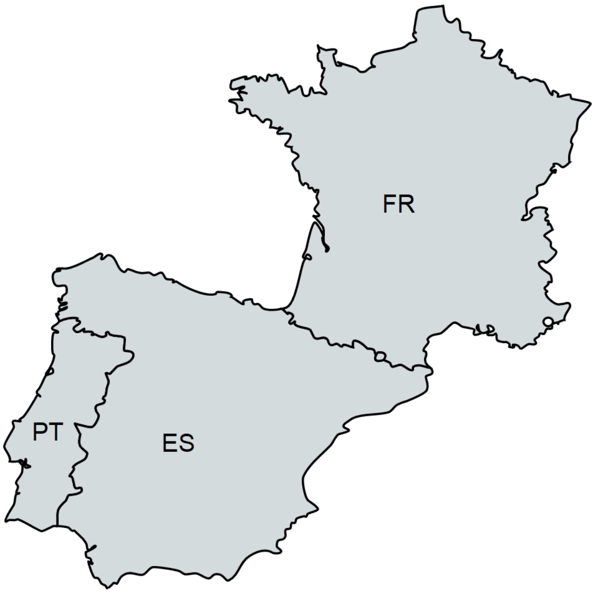

Figure 2.5: Capacity Calculation Region 6: South-west Europe (SWE) (adapted from [38])

In the third place, to quantify the relevance of the assets, ACER published an influence computation method applicable on a year-ahead CGM developed in accordance to Article 67 of Commission Regulation (EU) 2017/1485 of 2 August 2017 [23], that outputs a relative or absolute value of power flow or voltage variation whose result can be compared against defined thresholds.

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[3] The Council of European Energy Regulators (CEER) defines Closed Distribution System (CDS) as “the classification of systems which distribute energy in a confined industrial or commercial setting and not to household customers” [34,35]. This subgenre of the distribution system is employed for security reasons related to the type of services it supplies.

This computation method allows to measure the power flow influence factor of simultaneous interruptions of network elements connected outside the TSO's control area on network elements inside the TSO's control area. In circumstances where the power flow influence factors are insufficient to identify relevant external network assets, the TSO can use voltage influence factors to determine its proposal of relevant assets, as long as all the affected TSOs are informed.

In Table 2.2, we can see the range of thresholds published by ACER, from which each TSO needs to choose a value.

Table 2.2: Range of influence thresholds for power flow and voltage (adapted from [33])

Power flow identification influence threshold	Power flow filtering influence threshold	Voltage influence threshold
15 - 25%	3 - 5%	3 - 5 %

The major difference between both power flow influence thresholds is that while the identification one is used to check if the asset is relevant or not, the filtering threshold is used to check if the asset's sensitivity is greater or less than the data sensitivity to measurement errors.

The power flow influence threshold values are inherently related to the TSO's control area and independent of the element of which the influence is assessed, while the voltage influence threshold is highly dependent on the load and generation pattern of the element in the investigated scenarios. If the TSO chooses to use the power flow analysis, he has to choose one value for the power flow identification influence threshold and one value for the power flow filtering influence threshold. On the other hand, if the TSO opts to perform a voltage analysis, he must choose one value within the range published for the voltage influence threshold.

The influence factors calculated for each network element will then be compared to these selected threshold values, and if the influence factors are greater than the thresholds, then the network element can be considered a relevant asset. Network elements can be power generation modules, demand facilities connected to a TSO, transmission power lines, Autotransformers (ATRs), and SGUs. Unlike other network assets, SGUs, do not need to verify the two power flow influence thresholds to be considered a relevant asset. TSOs can limit the SGU elements to those higher than 100 MW.

In the fourth and final place, it is asked by ACER that TSOs of the same OCR have in their relevant assets list the following information: (a) combination of network elements connected outside of its control area whose simultaneous outage can threaten the system security of its control area; (b) network elements connected outside its control area whose outage can impact on the operation of High Voltage Direct Current (HVDC) systems between synchronous areas and (c) network elements connected outside its control area whose outage can have an impact on the operation of its control area, such as the stability, function of protections and short-circuit assessment [33].

The relevance of external network elements should be reassessed at least every three years after the first assessment. Moreover, after obtaining the list of relevant assets, the TSOs shall complement it with the critical network elements identified in accordance with the CACM Regulation [33, 36].

2.5.4 Critical network element

Critical network elements (CNEs) are grid assets, such as national VHV transmission lines (150 kV, 220 kV and 400 kV) and transformers, that, according to CACM Regulation, restrain the cross-border exchanges through the interconnection lines. In this specific case study, we are talking about the cross-border exchanges between Portugal and Spain. The CNEs limit the interconnection lines' transmission capacity because, during the CACM service development, these network assets were observed as having significant sensitivity to cross-border power flow variations [36]. Due to the sensitivity these network elements present, it becomes crucial to closely monitor them since they affect the security of the RNT and the energy market.

What makes for a significant sensitivity was defined by REN through data analysis and experience, and it was concluded that a grid element is considered a CNE if the power flow variation is greater than or equal to 5% when the power flow of the interconnections increases or decreases 100 MW [39].

As one can observe in Figure 2.6, both lines are transmitting 10 MW when there is 1000 MW flowing from Portugal to Spain (P_{PT-ES}), but when that power flow increases 100 MW, the change in the power flow of line 1 (red line) is 10% and of line 2 (green line) is 2%. From this change, one can conclude that line 1 is a CNE and that line 2 is not, since it was defined that network elements that have a power flow variation greater than or equal to 5% are CNE.

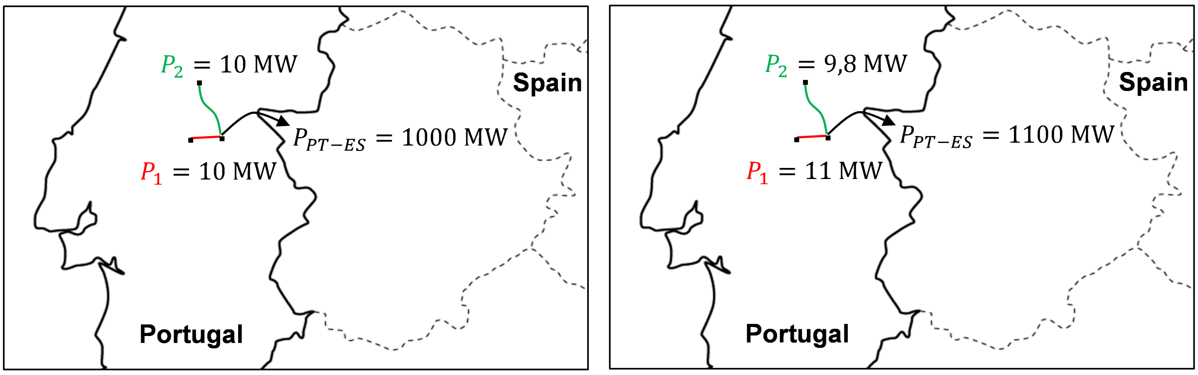

Figure 2.6: Example of the identification process of a CNE

2.6 Types of outages

In this thesis' scope, the output resulting from the application of the methodology for assessing the relevance of assets will present Spanish network elements that when disconnected are relevant to REN since they will directly affect the outage coordination of the RNT. For this reason, it is explained in this section what are outages and the different types of outages that one can encounter.

The Energy Services Regulatory Authority (ERSE) defines outage as the absence of electric energy supply to grid infrastructure, production installation, or a demand installation [40].

Outages are classified according to their origin, type, and cause, as presented in Table 2.3.

Table 2.3: Classifications of outages (adapted from [40])

Origin	Type	Cause
Production, transmission or distribution	Planned	i. Public interest reasons
		ii. Public service reasons
		iii. Fact attributable to the client
		iv. Agreement of the client
		v. Other networks or installations
	Unplanned	i. Security reasons
		ii. Fortuitous events
		iii. Cases of force majeure
		iv. Own causes
		v. Other networks or installations

2.6.1 Planned outages

The planned outages are outages from which the client receives an advanced warning. How advanced the warning is emitted is established in the Commercial Relations Regulation (RRC). There are multiple causes that can trigger a planned outage as it is mentioned in Table 2.3, such as (i) public interest reasons – outages that arise directly from national energy crises plans, approved by administrative authorities in the condition that it has been disclosed with the TSO/DSO with a minimum notice of 36 hours; (ii) public service reasons - outages that arise from the pressing need of maneuvers, linking purposes, repairs or maintenance of the grid in the condition that it has been disclosed with the TSO/DSO with a minimum notice of 36 hours; (iii) fact attributable to the client; (iv) agreement of the client; and (v) other networks or installations – outages that started in the network or installations of another operator, electric energy producer or client.

In cases where the planned outage introduces an imbalance between generation and load, the energy market rules provide for a balance equilibrium as the unavailable generation can be compensated either by local units or by imports.

2.6.2 Unplanned outages

The unplanned outage or contingencies are all the other outages for which no warning is emitted since they were unexpected. Unplanned outages also have different causes, such as (i) security reasons – outages performed when the continuity of supply directly puts at risk the security of people and assets; (ii) fortuitous events; (iii) cases of force majeure; (iv) own causes – outages that do not fit in any of the aforementioned categories and can be classified as an atmospheric phenomenon, natural actions (animals, vegetation, or earth movement), domestic source (design defects or errors during the assembly/maintenance process), or other causes (any other reason that was not mentioned); and (v) other networks or installations.

In cases where the contingency introduces an imbalance between generation and load, the balance is restored and ensured by reserve activation.

2.6.3 Critical outages

In the scope of the methodology for the assessment of relevant assets for outage coordination, there is another outage type named Critical Outage (CO). This outage classification is attributed to the interruption of the assets identified as relevant and is based on the influence factor chosen for the assessment.

On the one hand, if the analysis is based on power flow influence factor, the CO definition is attributed to external network assets that, when disconnected, trigger significant power flow influence factors on the TSO's control area internal assets. The values resulting from the computation of both power flow influence factors (Filtering and Identification) must be greater than their correspondent influence threshold values since the two influence factors are interdependent, meaning both must verify the criteria in order to validate the outage classification.

On the other hand, if the analysis is based on voltage influence factor, the CO definition is attributed to external network assets that, when disconnected, trigger significant voltage deviation on a node of the TSO's control area. The voltage influence factor must be greater than the correspondent influence threshold value to validate the outage classification.

The approach chosen to classify the critical outages in this thesis will be further discussed in chapter 3, when we address the algorithm.

2.7 The role of data analytics

Historically, there has been little need for monitoring capabilities in the transmission network since it would suffice if the network were designed for maximum load conditions and expect it would perform adequately the rest of the time. “Operations normally consisted of routine line switching, outage scheduling, and power flow and alarm monitoring. Real-time, frequent, and low latency monitoring was generally not required” [41]. Nowadays, however, a more empirical measurement is required to ensure ongoing safety and reliability since renewable energies made problems like excessive generation, circuit congestion, and equipment overloading potential much more common.

As measurements increase, raw data volumes can grow dramatically, which raises new implications for monitoring such as the increasingly significant role of data analytics, beyond mere data collection and the need to design data handling strategies from the viewpoint of compatibility and interoperability.

With larger volumes of data comes the responsibility of translating it into actionable operational intelligence. Data analytics plays a vital role because it is no longer feasible to examine through the numbers to find meaning without it.

Good data analytics practices are intrinsically tied to this thesis since our main objective is to present a robust and scalable algorithm capable of supporting REN in identifying relevant assets for OPC.

2.8 Conclusion

In this chapter, we introduced the main concepts and players related to this thesis’ subject matter. In sections 2.1 and 2.2, we gave an overview of the electric energy system and introduced the Transmission System Operators, their role in the management of the transmission grid, and focused on REN as the Portuguese TSO. Next, in section 2.3 and 2.4, we addressed how TSOs found a gap in outage planning coordination between neighboring countries, which led to the creation of RSCs and ENTSO-E, while also addressing how the relationship between REN, Coreso (Portugal’s RSC) and ENTSO-E was established. In section 2.5, we focused on the outage planning coordination service and how it is a relatively recent topic that is still being debated and regulated to this date by all the parties involved. We presented the related work found and showcased the literature gap that this thesis proposes to fill. Afterward, we created a subsection to detail the main motivator of this thesis – the methodology for assessing the relevance of assets for OPC. In turn, in section 2.6, we discussed the different types of outages, and how the identification of critical outages allows to identify the relevant assets. Finally, in section 2.7, we highlighted the critical role that good practices of data analytics play in this thesis’ context.

3

Proposed Algorithm

Contents

In the previous chapters, we presented the background and fundamental notions to understand the methodology for assessing OPC's relevant assets. In this chapter, we describe the algorithm developed to apply the methodology and its requirements.

3.1 Problem statement

The integration of Portugal and Spain's electrical systems is carried out by using interconnections that facilitate cross-border energy exchanges between the two countries.

These interconnections allow the neighboring countries to establish an Iberian energy market and provide a solution to deal with the variability of renewable energy sources, enabling further investment in this type of energy.

Nonetheless, interconnections also insert some vulnerability into the transmission grids. By granting them the ability to make changes in power flow, it also concedes the capability of influencing Portugal's national network assets, particularly through the occurrence of outages, either planned or forced.

Having said this, not all the outages that occur in Spain influence Portugal's TSO's control area; some have no relevant impact, meaning it is necessary to identify the critical outages, which are Spanish assets that, when disconnected, have the capability to affect REN's control area. This information is then shared with Coreso, who will afterward suggest remedial actions.

3.2 Proposed framework

To solve this problem, this paper proposes the application of ACER's approved methodology for assessing the relevance of assets for outage coordination. The expected outcome is the identification of the Spanish outages that arise significant power flow variations in assets that belong to the control area of REN. Thus, an algorithm encompassing a program written in the high-level programming language PYTHON [42] was developed for Portugal's specific case as a robust and scalable tool.

The algorithm is prepared to analyze two different network conditions:

- N-1, when one asset of the grid is disconnected. The asset can be internal ("N-1 PT") or external ("N-1 ES") to the TSO's control area.
- N-2, when two assets of the grid are disconnected. These can be simultaneously from a control area external to the TSO ("N-2 ES") or one internal to the TSO's control area and the other external ("N-1 PT + N-1 ES").

This contingency analysis is critical to understand the power system conditions pre-emptively before taking corrective control. N-k contingency means a contingency resulting in the loss of k grid elements, where k can be any natural number (1, 2, 3, 4, ...). The higher the value of k, the more prepared the TSO is to possible contingencies, such as elements kept out of service due to maintenance or tripping of one element due to short-circuit. However, there is a computational limit associated with the value of k due to the combinatorial nature of the contingency analysis. For example, assuming we have a grid with 316 network elements, there are 316 N-1 contingencies, 49,770 N-2 contingencies, 5,209,260 N-3 contingencies, 407,624,595 N-4 contingencies.

In this thesis, the transmission networks under evaluation have more than the 316 network elements used as examples. Across all the studied scenarios, we are handling over 1,116,000 N-2 contingencies, which represents around 38.5 GB of data. Due to the volume of contingency combinations beyond the N-2, it is unfeasible to analyze all the possible combinations of outages in the time frames TSOs and RSCs typically conduct the power flow analysis. Therefore, the contingency analysis is limited to N-1 and N-2, being the latter reserved for the most relevant network elements.

The analysis of “N-2 ES”, unfortunately, will not be addressed in the context of this thesis results, only in the context of the tool specifications. The reason behind this is that the tool is ready to operate data for the “N-2 ES” study, but due to delays related to COVID-19, we were not able to incorporate the necessary data in this thesis. Having said this, in the context of the results it was studied the “N-1 PT + N-1 ES” case, having as base case the “N-1 PT”.

3.3 Influence threshold

As mentioned previously in section 2.5.3, to apply the methodology proposed by ENTSO-E and approved and published by ACER, each TSO must choose a value for the thresholds applicable to their analysis, from the range presented in Table 2.2.

If the methodology is applied using power flow, then two values must be chosen – one for the power flow filtering influence threshold and another for the power flow identification influence threshold. If the methodology is applied using voltage, then the TSO needs to choose one value for the voltage threshold. As previously stated, the TSO may opt to apply the methodology by recurring to a voltage analysis in circumstances where the power flow influence factors are insufficient to identify relevant external network assets that can cause significant voltage variations in the TSO’s control area.

3.3.1 Voltage influence threshold

When we compare voltage sensitivities to the voltage influence threshold, we are verifying if external assets disconnected outside the TSO’s control area can trigger a significant voltage deviation on a node of the TSO’s control area. Voltage deviations are related to reactive power generation and consumption.

Excessive reactive power in the grid raises the voltage while insufficient reactive power decreases the voltage.

The voltage control is essential, because as we mentioned in section 2.1, voltage should be kept within an accepting range of variation (±10% of the nominal value). This is because both the customer and the power system are designed to operate within the defined range. When operating at lower voltages the power system is not capable of pushing the active power demanded by the loads through the transmission lines and without active power there is no energy to run motors, heat homes or illuminate. When operating at higher voltages than expected, the equipment will either automatically trip, which may lead to a cascade of outages, or overheat and get damaged, which ultimately results in the shortening of their service life. Either way, the result is a decrease in profit and energy quality.

The transmission system as a whole is a nonlinear consumer of reactive power, depending on system loading. At light loading, the system produces reactive power that must be consumed, while at heavy loading, the system consumes a large amount of reactive power that must be replaced.

In the scope of outages, the loss of a generator or a major transmission line can have the compounding effect of reducing reactive power supply and increase the reactive power the system is consuming. This leads to a decrease in the reactive power, which consequently decreases the voltage precluding the transmission of active power to the consumer.

In the Portuguese context, the RNT does not suffer heavily from voltage deviations because of voltage support provided by hydroelectric and thermal generators, synchronous compensators, and due to investment in grid components such as shunt reactors, transformer tap-changers, and capacitor banks.

The hydroelectric and thermal generators depending on the excitation current can produce or consume reactive power to regulate the voltage at its terminals. The synchronous compensators are machines designed exclusively to provide reactive support with the response speed and controllability advantages of generators without the need to construct the rest of the power plant.

The shunt reactors absorb the surplus of reactive power in order to avoid voltage rises, while the capacitor banks generate reactive power in order to avoid voltage collapses. The tapping transformer, on the other hand, allow to automatically regulate the voltage on one of the bus to which it is connected.

Since Portugal's voltage issues are almost nonexistent, meaning that the disconnection of Spanish assets would not affect Portugal's voltage context for the application of the methodology for assessing the relevance of assets, we focused solely on an active power flow analysis [9].

3.3.2 Power flow influence thresholds

In total, there are two applicable power flow influence thresholds. The power flow filtering influence threshold represents the associated precision of measurement expected of the control system Supervisory Control and Data Acquisition (SCADA), state estimation computations, and the models used to calculate the power flows. If the power flow filtering influence factor is less than or equal to the correspondent threshold, then we know that the power flow measurements used to compute the influence factor are affected by the measuring and transmission systems errors; therefore, they should not be considered relevant assets.

In turn, the power flow identification influence threshold represents the minimum active power flow variation value necessary for the TSO, based on its experience, to identify and deem a change relevant. A change greater than the defined threshold should be seen, independently of the cause, as warning information in need of careful evaluation and monitoring from the dispatcher. When the variations of active power flow are less than or equal to the defined threshold, the external assets should not be identified as relevant for the coordination of outages.

Each TSO chooses a value associated with the power flow filtering influence threshold and another one associated with the power flow identification influence threshold. These two chosen values, which are within the range of values defined by ENTSO-E, are independent of the asset type.

Choosing the correct threshold is an iterative process, and for this thesis, it was studied in collaboration with REN.

When analyzing different combinations of thresholds, to decide which one to use, we have to consider the following criteria:

- thresholds should be low enough to minimize the risk of not including all relevant grid elements that can threaten the security of neighboring control areas;
- thresholds should be high enough to avoid overly lengthy relevant asset lists filled with noise, thus leading to an inefficient process, potentially not compatible with time requirements of the outage coordination process.

3.4 Power flow influence factors

According to the guideline on electricity transmission system operation, influence factor is “the numerical value used to quantify the greatest effect of the outage of a transmission system element located outside of the TSO’s control area excluding interconnectors, in terms of a change in power flows or voltage caused by that outage, on any transmission system element. The higher is the value the greater the effect” [23].

For each external asset r there are two influence factors – the power flow filtering influence factor and the power flow identification influence factor.

To explain these two factors, one needs to introduce the Outage Transfer Distribution Factor (OTDF), a sensitivity measure of how a change in a line’s status affects the active power flow on other lines in the system. Each external asset r has as many OTDFs as the total number of combinations of assets t and i ($t \times i$) considered in the analysis.

$$OTDF = \frac{P^{t}_{s,n-i-r} - P^{t}_{s,n-i}}{P^{r}_{s,n-i}} \tag{3.1}$$

The power flow filtering influence factor, $IF^{pf,f}_{r}$, is the maximum OTDF of an external element r on any given internal element t, in any scenario s, and taking into account any element i disconnected.

$$IF^{pf,f}_{r}\,(\%) = MAX_{\forall i \in I, \forall s, \forall t \in T}\left(\frac{P^{t}_{s,n-i-r} - P^{t}_{s,n-i}}{P^{r}_{s,n-i}} \times 100\right) \tag{3.2}$$

The power flow identification influence factor, $IF^{pf,id}_{r}$, is the maximum normalized OTDF of an external element r on any given internal element t, in any scenario s, and taking into account any element i disconnected.

$$OTDF_{normalized} = \frac{P^{t}_{s,n-i-r} - P^{t}_{s,n-i}}{P^{r}_{s,n-i}} \times \frac{PATL^{s,r}}{PATL^{s,t}} \tag{3.3}$$

$$IF^{pf,id}_{r}\,(\%) = MAX_{\forall i \in I, \forall s, \forall t \in T}\left(\frac{P^{t}_{s,n-i-r} - P^{t}_{s,n-i}}{P^{r}_{s,n-i}} \times \frac{PATL^{s,r}}{PATL^{s,t}} \times 100\right) \tag{3.4}$$

In equations (3.1), (3.2), (3.3), and (3.4):

s stands for scenario.

i stands for network element connected either in the TSO's control area or outside TSO's control area considered disconnected from the network when assessing the expression. This network element cannot be the same as element t nor r.

r stands for the network element connected outside TSO's control area whose power flow influence factor is assessed.

t stands for the network element connected inside TSO's control area where the active power difference is observed.

T, I, and R represent the set of their respective lowercase.

$P^{t}_{s,n-i-r}$ represents the active power flow through the network element t, in scenario s, with network elements r and i disconnected from the network.

$P^{t}_{s,n-i}$ represents the active power flow through element t, in scenario s, with network element r connected to the network and network element i disconnected from the network.

$P^{r}_{s,n-i}$ represents the active power flow through the element r, in scenario s, when connected to the network, considering the network element i disconnected from the network.

$PATL^{s,r}$ represents the loading in MVA or MW that can be accepted by network element r, in scenario s, for an unlimited duration.

$PATL^{s,t}$ represents the loading in MVA or MW that can be accepted by network element t, in scenario s, for an unlimited duration.

The difference between the two power flow influence factors is that the power flow filtering influence factor is only an image of the load transfer and is independent of the flow of the assessed element, while the power flow identification influence factor is better at describing the risk of overload since by considering the grid elements PATL values, it is capable of simulating the consequences of occurring an outage in highly loaded network elements. Looking at equations (3.2) and (3.4), we can instantly point out this difference between the two, which is expressed through the division of $PATL^{s,r}$ by $PATL^{s,t}$. This division is the numerical representation of the ratio of PATL between the influencing element r and the influenced element t, which has the purpose of normalizing the OTDF value.

PATL is the capacity an asset of the network has of accepting power during an unlimited quantity of time. This parameter describes how loaded an asset can be before it trips out of service. Not all the assets of the network have the same PATL; some have higher values than others. Thus, it is necessary to take PATL into account since, for example, a variation of 30 MW has a more significant impact on an asset with a $PATL = 300\,\text{MW}$ than an asset with a $PATL = 1000\,\text{MW}$. The normalization is crucial in cases where there are high discrepancies of loading between the elements t and r.

To further clarify these concepts, next, we present two practical examples to explain power flow influence factors.

Example 1.

In the first example, we assume a power flow filtering influence threshold equal to 3% and disregard the power flow identification influence threshold.

Figures 3.1 and 3.2 illustrate a system of very high voltage transmission lines, where: t_1 represents a Portuguese transmission line connected to the network; t_2 represents a Portuguese transmission line connected to the network; r represents a Spanish transmission line which is connected in situation N-1 and disconnected in situation N-2; i represents a Portuguese transmission line disconnected from the network.

In Figure 3.1, in situation N-1, the active power transmitted through the element t_1 is 46 MW; meanwhile, in element r, the transmitted active power is 600 MW. In situation N-2, we disconnect element r and observe new values of transmitted active power through the system elements, in particular, of element t_1, whose transmitted active power increased from 46 MW to 52 MW.

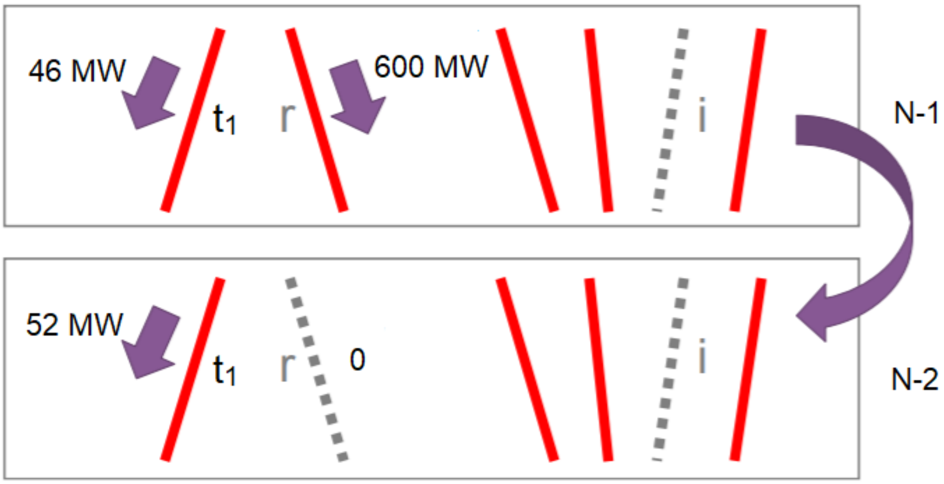

Figure 3.1: Computation of power flow filtering influence factor – part 1 (adapted from [43])

From this, we calculate $OTDF_1 = (52 - 46)/600 = 1\%$. This means that the methodology identifies a sensitivity of 1% in the active power transmitted in element t_1. This sensitivity value is lower than the precision of 3% associated with measurement errors (filtering influence threshold).

Analogously, in Figure 3.2, we keep every line illustrated in Figure 3.1 except line t_1 which is substituted by line t_2. In situation N-1, the active power transmitted through the element t_2 is 33 MW, while in element r, the transmitted active power is 600 MW. In situation N-2, we disconnect element r and observe new values of transmitted active power through the elements of the system, particularly of element t_2 whose transmitted active power increased from 33 MW to 57 MW.

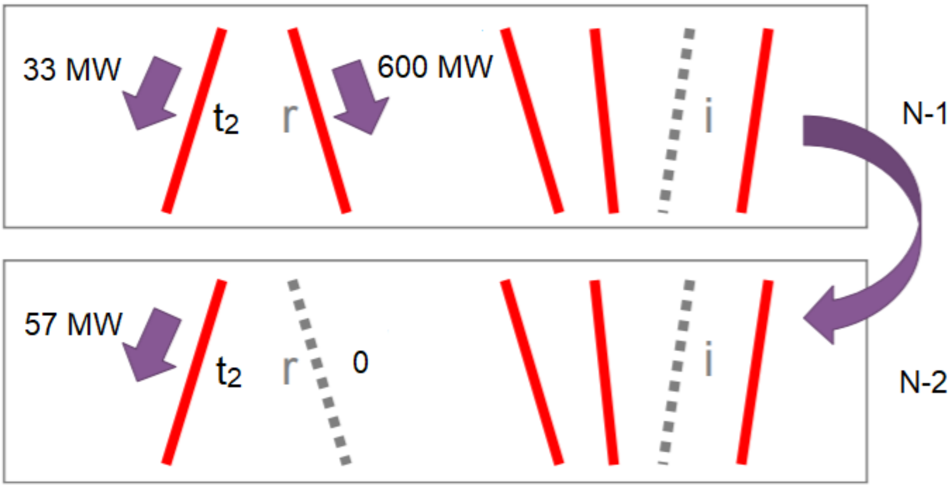

Figure 3.2: Computation of power flow filtering influence factor – part 2 (adapted from [43])

In this case, $OTDF_2 = (57 - 33)/600 = 4\%$ which means that the methodology identified a sensitivity equal to 4% in the active power transmitted in element t_2. This sensitivity value is greater than the precision of 3% associated with measurement errors (filtering influence threshold).

From these two examples, we would conclude that the power flow filtering influence factor of element r is equal to 4%, since from the two OTDFs computed, the maximum OTDF is $OTDF_2$ equal to 4%.

Example 2.

Now, in the second and last example, in which we explain the power flow identification influence factor, we assume, as we did in the first example, that the power flow filtering influence threshold is equal to 3%, but introduce four new constants: a power flow identification influence threshold equal to 15%, a $PATL_r = 2500$ MW for both Figures 3.3 and 3.4, a $PATL_{t_1} = 1000$ MW in Figure 3.3, and a $PATL_{t_2} = 300$ MW in Figure 3.4.

Similarly to the first example, Figures 3.3 and 3.4 illustrate a system of very high voltage transmission lines.

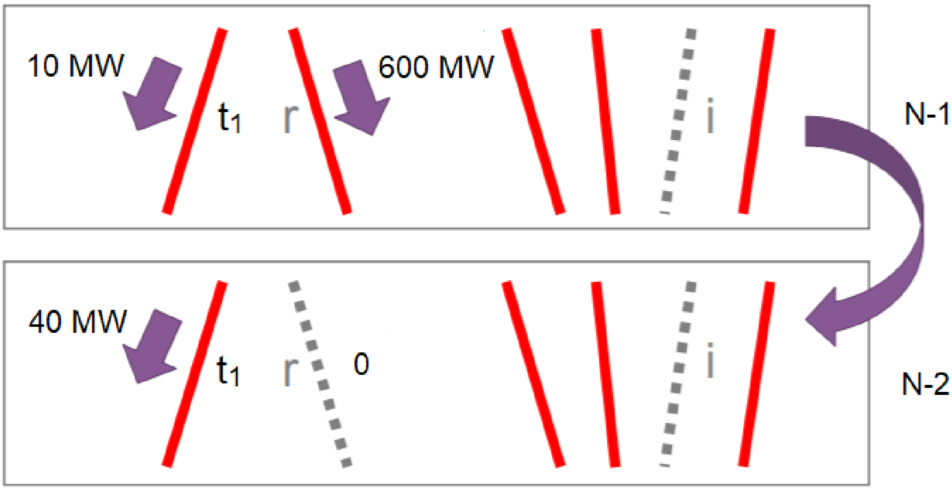

Figure 3.3: Computation of power flow identification influence factor – part 1 (adapted from [43])

In Figure 3.3, we compute a $OTDF_1 = (40 - 10)/600 = 5\%$ which is greater than the power flow filtering influence threshold (3%). This means that the sensitivity computed has greater precision than the estimated measurement errors;

Since $OTDF_{1_{normalized}} = 5\% \times 2500/1000 = 12.5\%$ which is less than the 15% defined as the power flow identification influence threshold, the asset r is not considered a relevant asset to the TSO, as the active power transmitted by element t_1 is not sensitive enough to status[1] variation of the element r.

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[1] If the element is connected or disconnected from the network.

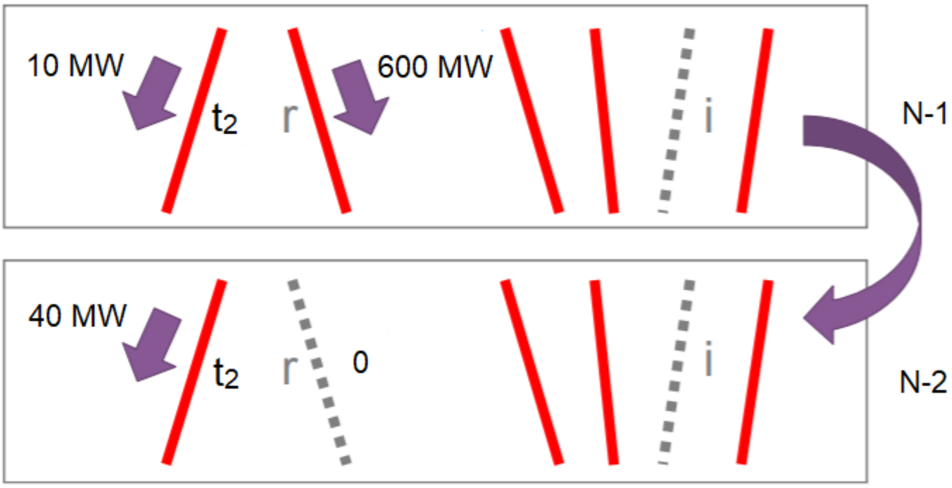


Figure 3.4: Computation of the power flow identification influence factor – part 2 (adapted from [43])

In Figure 3.4, we substitute the transmission line t_1 by t_2, whose $PATL_{t_2} = 300$ MW. This results in an $OTDF_2 = (40 - 10)/600 = 5\%$, which, again, is greater than the defined power flow filtering influence threshold (3%). As previously stated about the asset t_1, t_2 has a sensitivity value with greater precision than the estimated measurement errors.

However, unlike what we experienced with t_1, $OTDF_{2_{normalized}} = 5\% \times 2500/300 = 41.67\%$. This value is greater than the defined power flow identification influence threshold (15%), which means that element r should be considered a relevant asset, as the active power transmitted by element t_2 is sufficiently sensitive to status variations of element r.

From the example illustrated in Figures 3.3 and 3.4, we would conclude that the power flow identification influence factor of element r is equal to 41.67% since this is its maximum normalized OTDF.

In conclusion, these two examples showcase the importance and necessity of only considering the maximum OTDF and maximum normalized OTDF, which correspond respectively to the power flow filtering influence factor and power flow identification influence factor. Without looking at the maximum values, we cannot positively guarantee that the external asset is not relevant.

Having understood the reason for only considering the maximum values, we will dive into two other examples to explore the more symbiotic side of the OTDF and normalized OTDF.

Example 3.

In the third example, we will study the influence the external network element r has on our fictional internal network comprised of transmission line t_1 and t_2, considering a power flow filtering influence threshold equal to 3% and a power flow identification influence threshold equal to 15%.

Observing the information displayed in Table 3.1, one might say that the network element r has a $IF_r^{pf,f} = 10\%$ and a $IF_r^{pf,id} = 40\%$ and for that reason it should be identified as relevant for outage coordination.

Table 3.1: Outage transfer distribution factors of t_1 and t_2 triggered by the disconnection of r

Network element		**OTDF**	**Normalized OTDF**
External	Internal		
r	t_1	2%	40%
	t_2	10%	12%

However, element r is not considered a relevant network element. In fact, r by default has both influence factors equal to zero because for both t_1 and t_2 one of the OTDFs is less than the defined influence threshold values.

Table 3.1 outlines that the t_1's OTDF fails to surpass the defined filtering influence threshold value (3%) while pointing that t_2 normalized OTDF misses to exceed the identification influence threshold value (15%).

Example 4.

As the fourth and final example, we evince the last scenario necessary to comprehend the power flow influence factors' intricacies. In this example, we consider the same values of power flow influence thresholds as we did for example 3.

As we can see, Table 3.2, presents a version of Table 3.1 in which the external element r is considered a relevant asset as in this circumstance both t_1 and t_2 have OTDF and normalized OTDF above the set influence thresholds.

Table 3.2: Outage transfer distribution factors of t_1 and t_2 triggered by the disconnection of r

Network element		**OTDF**	**Normalized OTDF**
External	Internal		
r	t_1	4%	40%
	t_2	10%	16%

In conclusion, for an OTDF to be considered a filtering influence factor it is imperative that the associated normalized OTDF is greater than the corresponding influence threshold and vice-versa.

3.5 Algorithm description

As stated in chapter 3.2, this thesis' main contribution is the proposal of an algorithm that will apply the methodology, approved by ENTSO-E, for assessing the relevance of assets for outage coordination. The algorithm, presented in Figure 3.5 analyzes different combinations of power flow influence thresholds and selects the most coherent and reliable relevant assets list for outage planning coordination to submit to Coreso.

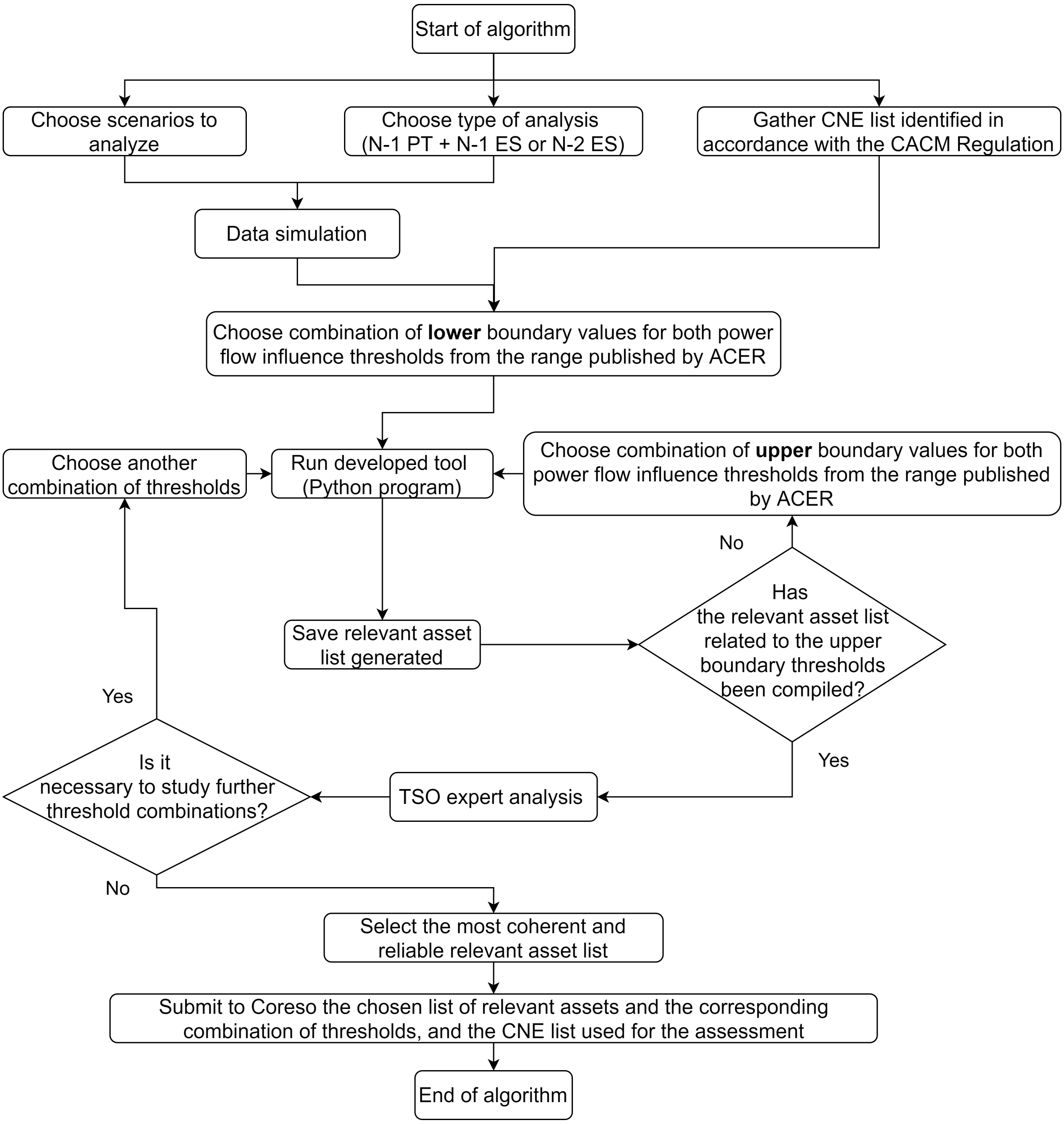


Figure 3.5: Proposed algorithm for TSO's implementation of the methodology

The algorithm encompasses three main steps: (i) data simulation, (ii) power flow influence factors computation, and (iii) threshold selection.

The first step of this algorithm is the data simulation since the computation of power flow influence factors is performed by resorting to data extracted from simulations made with models of the known grids. To generate the data files, the algorithm needs multiple scenarios representative of the grid's different and relevant states throughout the year. Moreover, it is also essential to define the type of N-2 contingency analysis intended, "N-2 ES" or "N-1 PT + N-1 ES".

Parallel to the data simulation, the algorithm needs the CNEs list identified in accordance with the CACM Regulation [38] for both the power flow influence factors computation and as a deliverable document.

The second and most demanding step of this algorithm lies in computing the power flow filtering influence factor and the power flow identification influence factor due to the number of iterations necessary. To overcome this challenge, we developed a PYTHON [42] program envisioned for the specific case of Portugal.

For the program's execution, some assumptions regarding the data organization were necessary, such as the overall data hierarchy, the name structure of folders and files, and the data organization within each file. These assumptions were made based on the manner in which the files were delivered and presented by REN and are further explained in Appendix A.

The flowchart of the program, in its entirety, is illustrated in Figure 3.6.

To fully comprehend the flowchart, we remember and further contextualize the meaning of the t, r, and i variables introduced in section 3.4.

t stands for the network element connected inside TSO's control area where the active power variation is observed. In this thesis' context, t it is a Portuguese network element that displays a sensitivity value to an outage in Spain.

r stands for the network element connected outside TSO's control area whose power flow influence factor is assessed. In the context of this thesis, r it is a Spanish network element that, when disconnected, triggers a sensitivity value in Portugal's network elements.

i stands for network element connected either in the TSO's control area or outside TSO's control area considered disconnected from the network when assessing the expression. This network element cannot be the same as element t nor r. In this dissertation's context, we use as base case the N-1 situation, since we want to guarantee the N-1 criterion even when there is an outage in the Iberian transmission network, and i is the Portuguese asset that is disconnected in the N-1 contingency scenario.

The program per scenario considers 320 possible network elements i, 320 possible network elements t, and about 1180 possible network elements r.

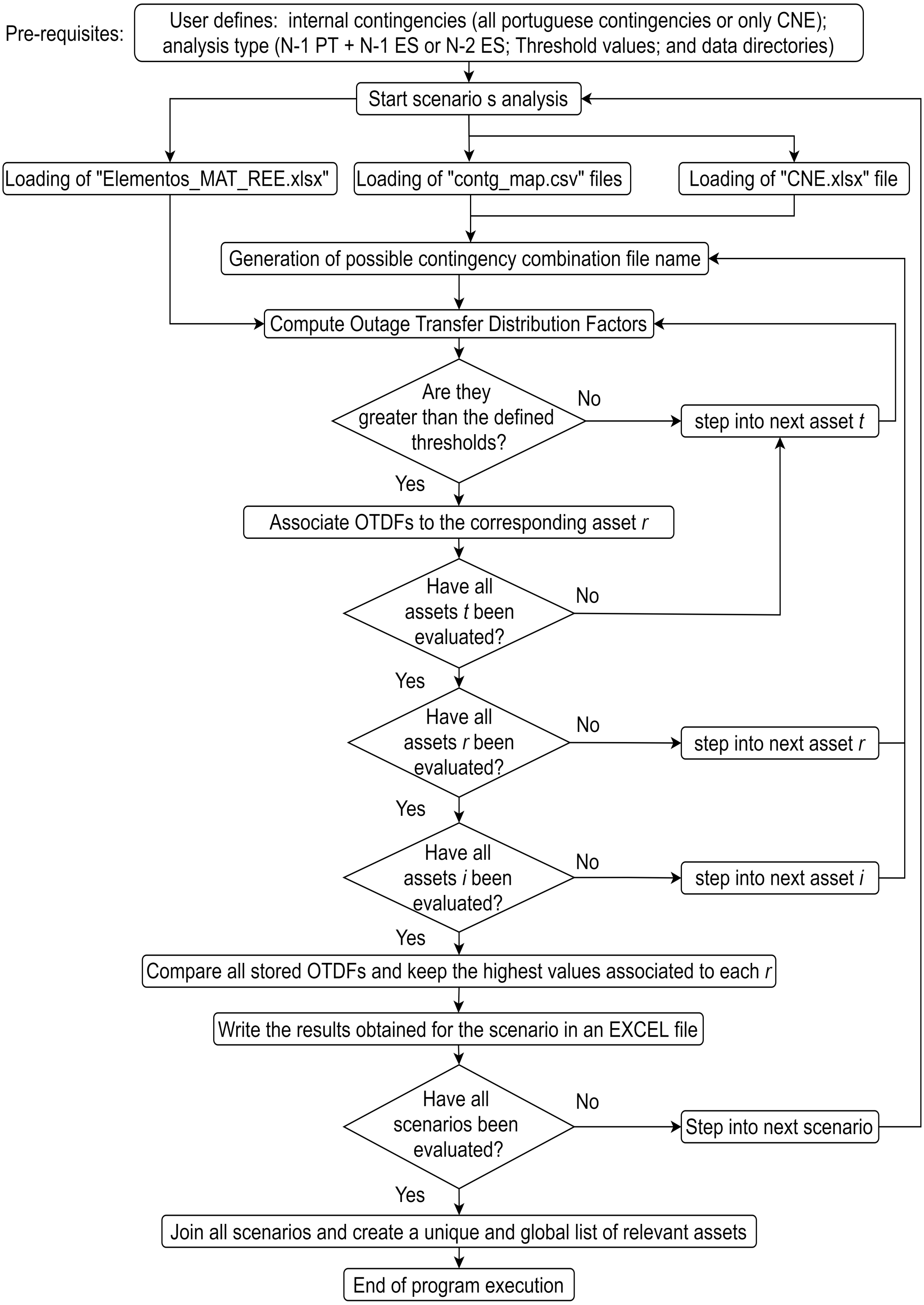


Figure 3.6: Flowchart of the program specifications

As one can see, to compute the power flow influence factor of each asset r, both filtering ($IF_r^{pf,f}$) and identification ($IF_r^{pf,id}$), the program deconstructs the equations (3.2) and (3.4) in the following steps:

1. For scenario s, compute the OTDF (equation (3.1)) and normalized OTDF (equation (3.3)) of asset r on asset t.
2. Compare the computed values to the thresholds defined in the pre-requisites. If the values are less than or equal to the thresholds, they are rejected, and the program moves on to the next asset t. However, if the values computed are greater than the thresholds defined, the values are stored in the respective dictionary associated with the asset r.
3. Replicate the above steps for every asset t.
4. Replicate the above steps for every asset r.
5. Replicate the above steps for every asset i.
6. Compare all the stored values and keep only the maximum values of the OTDFs and normalized OTDFs of each r.
7. Write both power flow influence factors of each asset r ($IF_r^{pf,f}$ and $IF_r^{pf,id}$), of scenario s, in an EXCEL® file.
8. Replicate the above steps for every scenario s.
9. Lastly, compare all the power flow influence factor values for each asset r and keep only the maximum values, thus creating a final EXCEL® file with a unique and global list of the relevant assets r and respective power flow influence factors.

When developing the program, it was ensured that all the data necessary for the computation of the two elementary factors of influence was organized quickly and with low memory consumption; there was a screening of anomalous results by applying filters before computations to avoid the presence of bad data in the final results; the presentation of the results was organized by scenarios and as a global assessment.

The output EXCEL® files have three sheets organized according to different priorities – power flow filtering influence factor, power flow identification influence factor, and alphabetical. This approach was based on the fact that the power flow influence factors have different meanings, and depending on the context, one influence factor might be more relevant than the other. For example, the power flow identification influence factor is more significant for system security analysis since it better describes the risk of overload.

The third and final step of the algorithm is a testing phase, where different combinations of power flow influence thresholds – filtering and identification – will be compared to conclude which one produces the most coherent and reliable list of external relevant assets for the coordination of planned outages.

To optimally compare the different combinations of values for both thresholds, it is proposed that the user computes first the extreme values (lower and upper boundary) from the range published by ACER (see Table 2.2) and then run extra combinations until a satisfactory conclusion is reached. This combinatorial analysis is dependent on the TSO's expert evaluation and its knowledge of the transmission grid since the lists of relevant assets generated may feature assets that are not actually relevant or ignore assets that should be considered.

Finally, after comparing the different lists of relevant assets produced by different threshold combinations, we select the most coherent and reliable list of assets for outage coordination, along with the corresponding values for both power flow influence thresholds.

4

Implementation and Optimization of the Algorithm

Contents

In the previous chapters, we presented the background needed to comprehend the methodology for assessing relevant assets in Outage Planning Coordination and proposed an algorithm that would apply said methodology. This chapter focuses on the implementation of the algorithm, namely how the data was chosen, the characteristics we looked for in each of the considered scenarios, and necessary optimizations.

4.1 Data simulation

The computation of the power flow influence factors, and consequently, the list of relevant assets, mentioned in chapter 3, are performed by resorting to data extracted from simulations made with models of the known grids.

In this thesis, we used the software Power System Simulator for Engineering (PSS/E) to define and configure the data, namely dates, assets to be disconnected, and networks of interest.

The dates were defined to have the desired profiles of consumption and production, the disconnected grid elements were defined to represent the possible outage combinations, and the networks of interest were defined to only include impactful neighboring networks (Spain Electrical Grid (REE)'s transmission grid). Regarding the latter, initially, we considered the OCR defined by ACER, as mentioned in section 2.5.3, but given the accumulated experience of REN who is collaborating in this thesis, we knew that France's electrical grid is secluded enough from Portugal that it would not have a significant influence in the power flow values of Portugal's transmission network, meaning that it is unlikely that an outage in France would harm Portugal's transmission system security, reliability or availability. Thus, only data from the REE's transmission grid was considered. After setting the desired conditions, we used PSS/E to export the data in Comma-Separated Values (CSV) files that are to be used by the developed algorithm to perform the computations. PSS/E used Coreso's CGM and CCC services introduced in chapter 2 as a model to run the power flow simulations.

REN, being Portugal's TSO, operated the processes mentioned above and provided different scenarios representative of the behaviors of the grid throughout the year. Having different scenarios allows to encompass the climatic and consumption differences observed in the different seasons of the year, such as wind, solar and water availability, as well as temperature fluctuations.

4.2 Proposed scenarios

When choosing the best scenarios to focus on, we decided the days by analyzing the load profiles of previous years. One of those years was 2018, presented in Figure 4.1, in which we have four curves representing four characteristic days that illustrate specific and relevant load behaviors.

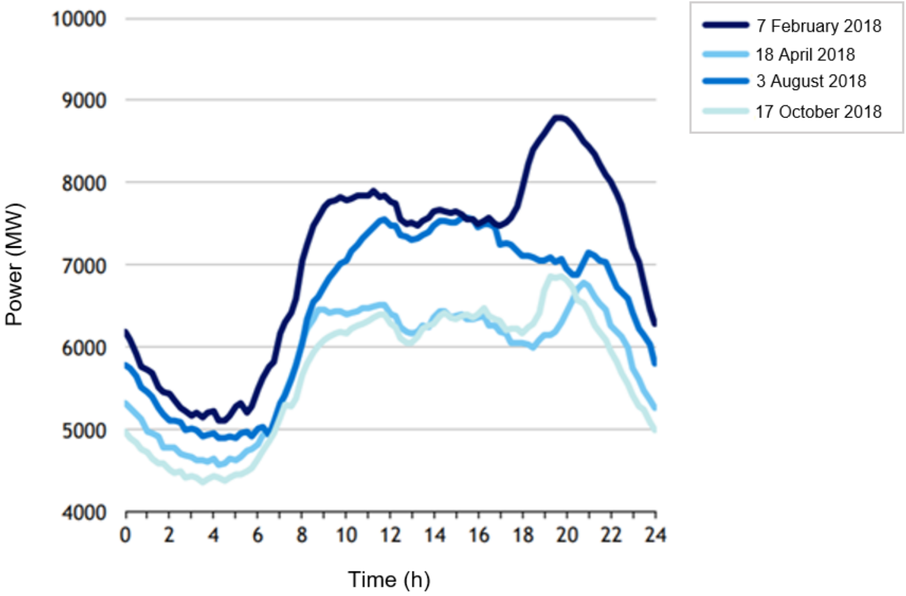


Figure 4.1: Load diagram of National Transmission Grid profiling days of 2018 (adapted from [44])

The two curves with the highest power consumption values were on February 7, 2018, and August 3, 2018, while the curves with the lowest values of power consumption were on April 18, 2018, and October 17, 2018. We can conclude from these dates that the periods when the transmission grid showcases its most extreme conditions coincide with the different meteorological seasons of the year: winter, summer, spring, and autumn.

For the methodology that we pretend to apply, these extreme conditions are the ones we look for since the grid is in a fragile state, increasing the network elements' sensitivity to external power flow changes. Having said this, we chose one scenario for winter and one scenario for summer, both during periods where we note a peak in consumption since these are the seasons in which consumption is at its highest, but at different times of the day. In addition, we chose two scenarios for spring, the first during a period where consumption was around its peak and the second where the consumption was at its lowest, as this season, much like autumn, displays the lowest peak and off-peak power values.

Unfortunately, there is no scenario during autumn, but as we can see in Figure 4.1, the curves of October 17, 2018, and April 18, 2018, follow a very similar distribution, meaning that conclusions taken from the spring scenario can be extrapolated for the missing autumn scenario.

The four scenarios we selected to study were the following:

- Monday, February 17, 2020, during the peak consumption period;
- Wednesday, May 13, 2020, during the off-peak consumption period;
- Wednesday, May 13, 2020, during the peak consumption period;
- Thursday, July 30, 2020, during the peak consumption period.

These dates were specifically chosen because they had high power values on the key attributes that mainly characterize the season to which they belong. We also had to have in mind, since we are using 2020 scenarios, which are the most relevant and up-to-date scenarios, if Coreso's services CCC and CGM had the grid models available. The unavailability of grid models is something inherent to newer projects and restricted the pool of options. In addition, even when the grid models were available, we also had to guarantee that the power flow values converged during simulations, i.e., the mismatch of active power flow was low enough to consider the scenario stable.

For the winter scenario, we wanted high power consumption values, a strong component of hydroelectric and wind energy generation, a weak thermal component, and a positive import balance. The strong component of hydro and wind is due to the fact that these sources of generation are the most prevalent during winter since we observe heavy rain and strong winds. The positive import balance increases the transmission grid's sensitivity to external power flow variations and is usually correlated with a reduction in domestic thermal production. February 17, 2020, during the evening, verified all the above conditions while also having the grid model available and stable power flow computations.

For the spring scenarios, we sought one where we could observe a low value of consumption and another where we could detect a high value of consumption. The desired conditions were a strong wind and hydroelectric component in the national production that featured a positive import balance for the same reasons stated for the winter scenario. May 13, 2020, showcased off-peak and peak consumption values in line with the sought-after tendencies. The first during small hours and the latter during the beginning of the afternoon. The grid model of this day was available and also showed stable power flow computations.

In the case of the summer scenario, the specifications we sought were different from the ones mentioned so far. We wanted a weak hydroelectric and wind generation component and a strong thermal production since these are the most representative features of this season. We also wanted a negative import balance since it typically correlates to higher values of thermal production. July 30, 2020, during the beginning of the afternoon, verified all the above conditions, had the grid model available and stable power flow computations.

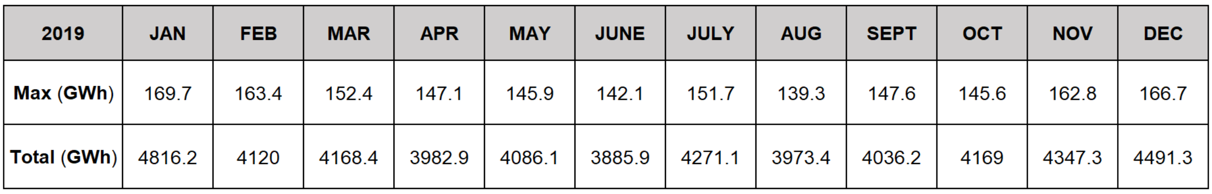
As mentioned before, for the computation performed by the proposed algorithm, we used Coreso's service CCC [26], with a D-2 (for Day-Ahead capacity allocation) time frame. These are grids prepared two days in advance, meaning they are an estimate of the state in which the grid will be. We do not use real-time grids because they do not represent Portugal and Spain's interconnected grid in its totality. The grids we used, although based on predictions, are seamlessly modeled, which is the best approach for the study this thesis proposes to perform. Using this type of predicted grids means that we are not using snapshots of the grid in real-time, but the accuracy with which the profiles of generation and production are anticipated is good enough to the point that the scenario envisioned two days in advance is equal to the observed in real-time.

In this section, it is also worth mentioning, as a follow-up to explaining the relevance of the meteorological seasons in the scenario choice, that the seasons also affect the PATL used for the computations performed by the developed tool.

During the implementation of the proposed framework, it was necessary to decide which season division felt adequate for the analysis. In the end, because of the energy consumption profile during the year illustrated in Table 4.1, we decided that instead of the regular calendar season, what better represented the consumption tendencies associated with the changes related to the weather conditions was the following:

- Spring (PRI): March 1 to May 31,
- Summer (VER): June 1 to August 31,
- Autumn (OTO): September 1 to October 31,
- Winter (INV): November 1 to February 29.

Table 4.1: Monthly energy consumption profile



2019	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
Max (**GWh**)	169.7	163.4	152.4	147.1	145.9	142.1	151.7	139.3	147.6	145.6	162.8	166.7
Total (**GWh**)	4816.2	4120	4168.4	3982.9	4086.1	3885.9	4271.1	3973.4	4036.2	4169	4347.3	4491.3

Overall, the chosen division for the seasons follows the same structure as the traditional one (four seasons: winter, spring, summer, and autumn). However, it diverges in two aspects: (i) the beginning and end of seasons occur at the beginning and end of months, (ii) the month of November is included in winter instead of autumn. Regarding aspect (ii), as it is visible in the maximum daily values registered in October, November and December, the value of energy consumed in November is more similar to the one in December than to the one in October. This leads to conclude that November already encompasses a consumption profile predominant of winter instead of autumn.

With the scenarios defined, REN proceeded to simulate and generate the data necessary. Once this process was finished, we delved into the implementation and optimization process introduced and discussed in the following section.

4.3 Algorithm optimizations

In this section and as mentioned in section 3.2, we will focus on the specific case of the "N-1 PT + N-1 ES" contingency analysis.

The first optimization of the algorithm was to verify the importance of only considering as possible element i assets defined as CNEs[1] in accordance with the CACM Regulation [36]. The results obtained from this approach were then compared with results achieved by considering as possible i all Portuguese contingencies for the scenario under analysis. The criteria used to compare the two is composed of execution time and results.

From Table 4.2, we can infer that by limiting the network element i to CNEs, we obtain results that are equal to the ones contemplated when we consider all the Portuguese contingencies, and we observe a decrease in execution time of 82.5%.

Table 4.2: Comparison between the results considering as element i only CNEs and all Portuguese contingencies

	Number of identified assets		Execution time (min)	
	Critical network elements	All contingencies	Critical network elements	All contingencies
February 17, 2020	24	24	2	10
May 13, 2020 (off-peak)	32	32	1.5	10
May 13, 2020 (peak)	125	125	1.5	10
July 30, 2020	23	23	2	10
All scenarios	136	136	7	40

Due to the recursive and time-constrained nature of the analysis performed, we conclude that using CNEs is the best approach.

The second optimization performed was developed to guarantee the robustness of the algorithm through the introduction of a filtering condition that identified when the program was dealing with a network element t that belonged to a tripod node. This filtering condition limited the validation of the asset r so that the r was dismissed as a relevant asset if only one of the transmission lines associated with this tripod node was defined as relevant, as it is improbable that only one of the transmission lines was critically sensitive to the outage of the said external asset since they share a common node, as illustrated in Figure 4.2.

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[1] The CNEs considered during the implementation of the proposed algorithm are present in Table B.1

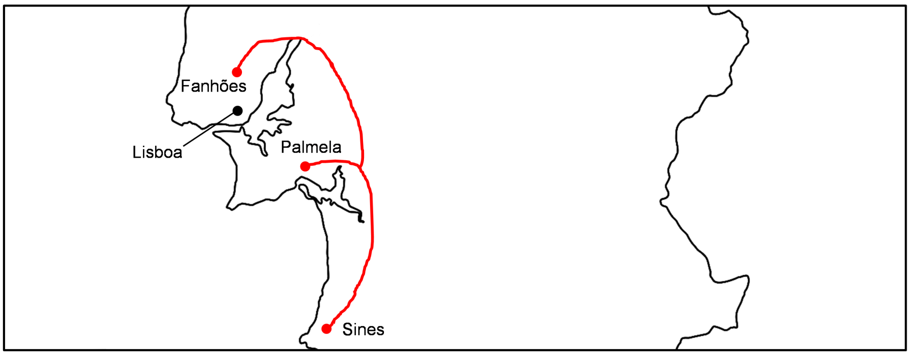

Figure 4.2: Tripod node of the 400 kV transmission lines connecting Sines, Palmela and Fanhões substations

The third and final optimization was introduced as a supplementary solution to the power flow filtering influence threshold. Upon compiling and saving the relevant assets lists, the number of assets included in the output proved to be greater than expected. Some of the identified asset's geographical position would not realistically allow for the values of sensitivity computed.

The approach we took was to tune the threshold values. In Figure B.1, we exhibit the identified network elements distribution throughout Spain when considering the power flow filtering threshold equal to 3% and the power flow identification influence threshold equal to 15%. As we can see, the number and the location of the assets are respectively high and disperse. In Figure B.2, we illustrate the identified network elements distribution again but considering a power flow filtering influence threshold equal to 5% and a power flow identification influence threshold equal to 25%. Although we can observe a decrease of 52.2% in the number of assets identified as relevant, the number is still quite elevated, and the assets' dispersion persisted. For this reason, it was decided to study each scenario separately to locate the source of the problem.

We used the developed tool's capability to assess each date independently to look at each scenario's contribution to the final output. As one can see in Table 4.3, it became clear that the contribution of the scenario of May 13, 2020, during the peak consumption period, is vastly more significant than the contribution of the other three scenarios. Therefore, we determined that this spring scenario needed further inspection and asked for expert analysis to look into the simulation conditions and power flow computations of that specific scenario.

Table 4.3: Relevant assets per scenario for filtering threshold equal to 3% and identification threshold equal to 15%

	Number of identified assets
All scenarios	136
February 17, 2020	24
May 13, 2020 (off-peak)	32
May 13, 2020 (peak)	125
July 30, 2020	23
All scenarios minus May 13 (peak)	38

After consulting with REN, we concluded that the scenario indeed introduces some noise into the results due to the fact that the simulation conditions generate extreme power flow values, which made the influence of errors associated with the criteria of convergence of power flow computation more impactful than desired. Even though the computation did converge with acceptable errors in accordance with the parameter of the power flow tool used by the TSO, the errors introduced noise that could not be filtered solely by the range of thresholds published by ACER. Thus, we developed active power filtering conditions to include this spring scenario without affecting the other scenarios used.

To analyze and classify the contribution of the filtering conditions, we display Table 4.4, in which we contrast the contribution of each scenario, when the PYTHON [42] program does not use the active power filter (first column) and when it does use the filter (second column).

Table 4.4: Active power filter effect in the number of relevant assets for filtering threshold equal to 3% and identification threshold equal to 15%

	Number of identified assets	
	Without active power filter	**With active power filter**
February 17, 2020	24	16
May 13, 2020 (off-peak)	32	15
May 13, 2020 (peak)	125	15
July 30, 2020	23	13
All scenarios minus May 13 (peak)	38	24
All scenarios	136	25

Highlighted in a shade of blue, we point to the total of relevant assets featured in the final output list when we consider all the scenarios and the active power filter. When this value is crosschecked to the number of assets present in the final output, when the scenario of May 13, 2020, during the peak consumption period is excluded, we find that the results are more resemblant than when we consider all the scenarios without the filter.

We also present in Figures B.3 and B.4 the assets' geographical position for a power flow filtering influence threshold equal to 3% and a power flow identification influence threshold equal to 15%. To produce Figure B.3, we did not use the active power filter and the problematic spring scenario. In contrast, in Figure B.4, we used the active power filter and considered the problematic spring scenario.

Jointly, Figures B.1, B.3, and B.4, and Table 4.4 allow us to observe the effect of the active power filter and how it enabled us to consider the scenario that otherwise would have to be excluded from the analysis.

The active power filter is an optimization that can be turned on and off. It is only necessary when the transmission networks under analysis work mostly with scenarios where the interconnection lines operate at extreme values of active power flow.

In the following subsection, we present in more detail the filtering conditions of the active power filter.

Active power filter

At the beginning of the filter development process, we applied the current filtering conditions since, through the value of current, we could infer the amount of loading a line would be supporting. If a transmission asset would suffer high sensitivity values but dealt with low values of load, then its impact on the overall internal network is not significant enough for it to be included in the relevant assets list. The criteria for the active power filter was the following:

- $\Delta I1^t = ||I1^t_{N-2}| - |I1^t_{N-1}|| \geq 50\,\mathrm{A}$,
- $|I1^t_{N-2}| \geq 50\,\mathrm{A}$,
- $|PFLOW1^r_{N-1}| \geq 10\,\mathrm{MW}$,

where:
$N-1$ means that the asset is being analyzed considering that there are one network elements disconnected;
$N-2$ means that the asset is being analyzed considering that there are two network elements disconnected;
$\Delta I1^t$ is the difference observed in the value of current injected in node 1 of the network asset t between situations N-1 and N-2;
$|I1^t_{N-2}|$ is the absolute value of the current injected in node 1 of the network element t in contingency situation N-2;
$|PFLOW1^r_{N-1}|$ is the absolute value of the active power injected in node 1 of the network element r in contingency situation N-1.
However, we soon realized that in some assets, due to high reactive power flow and low active power flow, their current values would pass the criteria previously defined. This meant that these filtering conditions would wrongly approve assets, that when looked into with expertise, their topology within the grid would not justify the values of sensitivity obtained. Therefore, it was necessary to come up with other criteria that would remedy these flaws. To create the new filter, we calculated what 50 A would represent in megawatts. We kept the value since the previous filter's problem was the parameter we were testing and not the value itself. This way, we could identify transmission assets strongly loaded with active power, neglecting the reactive component. With this new approach, it was necessary to create a distinction between the filtering values based on the voltage level of the assets.

For assets that work on a voltage level equal to 400 kV, on the assumption of a power factor equal to 1, since 50 A would amount to $\sqrt{3} \times 400\,\text{kV} \times 50\,\text{A} \approx 35\,\text{MW}$, we wrote the following filters:

- $|PFLOW1^{t}_{N-2}| \geq 35\,\text{MW}$,
- $\Delta PFLOW1^{t} = |PFLOW1^{t}_{N-2} - PFLOW1^{t}_{N-1}| \geq 25\,\text{MW}$,
- $|PFLOW1^{r}_{N-1}| \geq 10\,\text{MW}$,

where:
$|PFLOW1^{t}_{N-2}|$ is the absolute value of active power injected in node 1 of network element t in contingency situation N-2;
$\Delta PFLOW1^{t}$ is the absolute value of the difference observed in the value of active power injected in node 1 of the network asset t between situations N-1 and N-2;
$PFLOW1^{t}_{N-1}$ is active power value injected in node 1 of network element t in contingency situation N-1;
$|PFLOW1^{r}_{N-1}|$ is the absolute value of active power injected in node 1 of network element r in contingency situation N-1;
While for assets that work on a voltage level equal to 220 kV, on the assumption of a power factor equal to 1, since 50 A would amount to $\sqrt{3} \times 220\,\text{kV} \times 50\,\text{A} \approx 20\,\text{MW}$, we wrote the following filters:

- $|PFLOW1^{t}_{N-2}| \geq 20\,\text{MW}$,
- $\Delta PFLOW1^{t} = |PFLOW1^{t}_{N-2} - PFLOW1^{t}_{N-1}| \geq 15\,\text{MW}$,
- $|PFLOW1^{r}_{N-1}| \geq 10\,\text{MW}$.

In the case of ATRs, the program considers the highest voltage level, which means that if the voltage increase is from 150 kV to 220 kV, it should be applied the filtering conditions for assets with a voltage level of 220 kV. If the voltage increase is from 220 kV to 400 kV, the filtering conditions defined for assets with a voltage level equal to 400 kV should be applied.
After some testing, these new filtering conditions proved to successfully neglect reactive power flow, which was the root cause of the outlier results.
The chosen values to limit the variation of active power flow between situation N-1 and N-2, and the limitation on the active power flow value of the asset r in N-1, were determined through an empirical approach, meaning that they were defined through multiple testing and iterations until we found a good value that would only consider assets that were significantly loaded.
This filter proved to be more effective than the previous one, successfully neglecting values that would otherwise create outlier results.

Figure 4.3 illustrates a flowchart explaining the implementation of the active power filter. The figure suggests how the filter would fit in the greater scheme of the developed Python tool and the changes it introduces in the computation process.

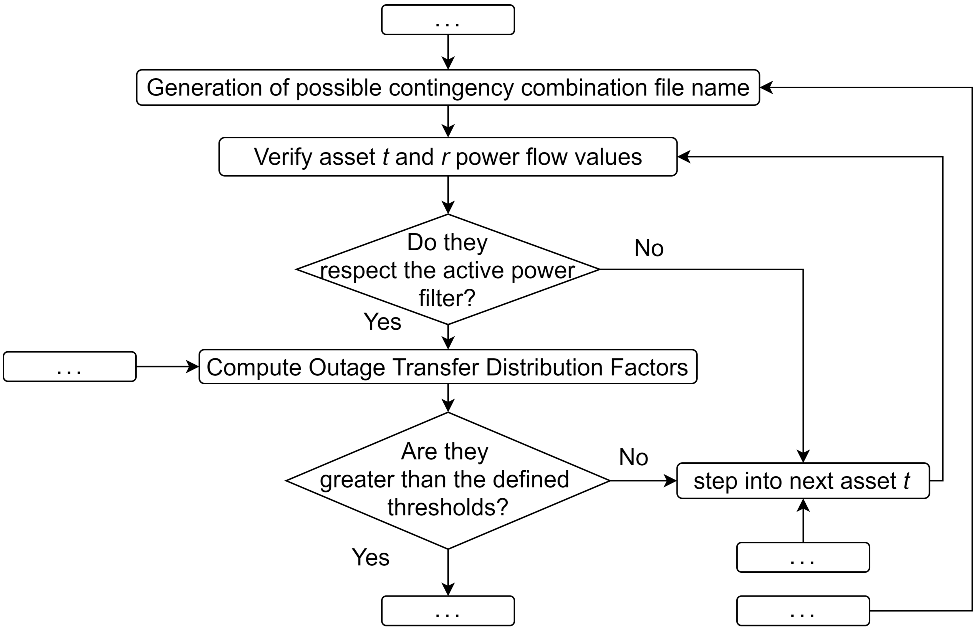

Figure 4.3: Flowchart of the active power filter implementation

The illustration of the program flowchart with the active power filter turned on is present on Appendix A. In conclusion, the three algorithm optimizations addressed proved to be positive additions to the already established methodology. Therefore, we can move to the next chapter, where we present and discuss the algorithm application results and focus on one of the objectives of this thesis, which is to identify the most adequate and coherent power flow influence threshold combination to provide the best relevant assets list possible.

5

Results and Discussion

Contents

So far, we discussed the state-of-the-art for the assessment of relevant assets for outage coordination (Chapter 2), exhibited the proposed algorithm to implement the methodology for the assessment mentioned above (Chapter 3), and presented the scenarios, how they were chosen, and a few algorithm optimizations (Chapter 4). This chapter presents the results obtained through the implementation of the proposed algorithm, compares the different approaches taken, and discusses the findings' reliability.

Due to privacy and security reasons, some of the tables and figures discussed in this chapter will not be displayed as usual. Instead, they are presented in the attached Appendix B of this thesis.

5.1 Research stage 1

As mentioned throughout the paper, one of the objectives of the algorithm is the identification of the most suiting combination of power flow influence thresholds from the range of thresholds published by ACER (see Table 2.2).

Therefore, as suggested in the algorithm description (see Figure 3.5), the first iteration was performed by defining the minimum threshold values for both the filtering and identification influence thresholds (combination I). In contrast, the second was executed by setting the maximum threshold values for both the power flow influence thresholds (combination II). This strategy allowed us to observe what it meant to use the most permissive definition of thresholds and how the results evolved as more restrictive the algorithm became.

The most permissive definition of thresholds would be combination I since the lower the threshold values, the lower are the sensitivities that need to be observed for an external asset to be included in the relevant assets list, meaning that more assets will be included in the output list. On the contrary, the most restrictive combination of thresholds would be combination II as the greater the threshold values, the less external assets will present power flow influence factors that meet the threshold values, therefore restricting the number of network elements included in the algorithm's output.

In Table B.2 and Figure B.4, we present the results[1] obtained from analyzing the four chosen scenarios with a power flow filtering influence threshold equal to 3% and power flow identification influence threshold equal to 15% (combination I). In total, the relevant assets list generated with this combination contains 25 assets (twenty-four 400 kV transmission lines and one 220 kV transmission line).

By contrast, Table B.3 and Figure B.5 present the results obtained from analyzing the four chosen scenarios with a power flow filtering influence threshold equal to 5% and a power flow identification influence threshold equal to 25% (combination II). In total, the relevant assets list generated with this combination contains eight 400 kV transmission lines.

When we compared combination I to combination II, we realized that as the threshold values increased,

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[1] All the results published in this section were obtained with the active power filter feature turned on (see section 4.3).

the cluster of transmission lines gravitated to the border between Portugal and Spain, which is expected as what allows different control areas to influence one another in the first place is the interconnections present at the borders. We also noticed that the total number of assets in combination II is 68% lower than in combination I.

These observations validate the algorithm by demonstrating that it performs as expected since as more restrictive we got, the fewer assets were defined as relevant, and the ones that still got assessed as relevant show a geographical position near the border of Portugal-Spain, which is where those assets theoretically should be located.

5.2 Research stage 2

As a complementary analysis, we studied the influence of each power flow threshold separately through two extra combinations. These combinations and the previously mentioned are presented in Table 5.1.

Table 5.1: Combination of thresholds and respective quantity of identified relevant assets

	Power Flow Influence Thresholds		Number of relevant assets identified
	Filtering	Identification	
Combination I	3%	15%	25
Combination II	5%	25%	8
Combination III	5%	15%	25
Combination IV	3%	25%	8

On the one hand, as we can see in Table 5.1, the difference between considering the power flow filtering influence threshold equal to 3% or 5% is nonexistent (combination I versus III or II versus IV). This lack of influence does not mean that the range of thresholds published by ACER is inadequate; it is related to the introduction of the active power filter in chapter 4.

The active power filter was created to solve problems associated with errors introduced during the simulations and power flow computations, and the power flow filtering influence threshold job is to filter power flow filtering influence factors that are less than or equal to the expected sensitivity associated with computation and model errors. By sharing the same purpose of filtering errors from the results, they end up overshadowing each other's influence.

In the specific case study of this thesis, there was a scenario whose simulation conditions and ultimately power flow values were so extreme that the introduction of optimizations was necessary to allow for that specific scenario to be considered. Otherwise, the scenario would have to be excluded from the analysis, limiting the transmission grid's behavior representation throughout the year.

On the other hand, the difference between considering the power flow identification influence threshold equal to 15% or 25% is quite noticeable as from combination I to IV (or II to III), we observe a decrease of 68% in identified relevant assets.

Acknowledging the previous conclusions about the influence of the power flow filtering threshold, these results converge with the ones observed when studying the lower and upper boundary values (combination I vs. II), again illustrating that the relevant assets concentrate near the border of Portugal and Spain, and also that the assets that trigger the highest values of sensitivity are near the border, validating the theoretical expectations.

The comparison between the extreme values of combination I and II served the purpose of demonstrating the most permissive output and the most restrictive output, while combination III and IV emphasized the effects of each threshold in the output of the relevant assets list.

With the results obtained so far, we can analyze and discuss the threshold combination that can produce the most coherent and reliable relevant assets list.

5.3 Thresholds selection

The results obtained from combination I (and III) are quite promising as they include a reasonable amount of network elements and demonstrate a coherent geographical position and distribution (see Figure B.4). However, we could still identify a maverick transmission assets that most likely should be excluded from the end result.

The particular network element that caught our attention was a 400 kV transmission line located in Spain's east coastal area (LC4). This asset's inclusion in the output list is somewhat dubious because of how distant it is from all the other identified assets (see Table B.2 and Figure B.4). For this reason, we looked at both its power flow identification influence factor (16.0002%) and power flow filtering influence factor (14.78%). From these two values, we could infer that increasing the power flow filtering influence threshold would not affect this asset's inclusion, but the power flow identification influence threshold would.

Because of that, we increased the power flow identification influence threshold to 16.1% and reran the algorithm to exclude the questionable transmission line from the output (see Figure B.6). However, two other assets were also excluded as a result of this increase, even though they do not share the same geographic characteristics as the asset we wanted to disregard.

From this point onward, two approaches can be taken. The first is to define the final power flow identification influence threshold equal to 16.1%, while the second is to keep the power flow identification influence threshold equal to 15% and manually remove the problematic transmission line from the output.

To decide which approach fits our objectives best, we need to study the LC4 transmission line and the two assets affected by this decision weighing the value of only excluding the dubious transmission line versus excluding the three network elements.

In this case, the two transmission lines are close to the border between Portugal and Spain and share common nodes with other transmission lines that are also listed in the relevant assets file. Contrarily, the transmission line LC4, as already stated, stands distant and isolated from the border, meaning that it is far from the interconnection lines that allow the asset to influence the Portuguese network elements and that it has no adjacent connections also identified as relevant. The distance parameter is an important characteristic because both the Portuguese and Spanish national transmission grids are quite meshed, which means that there are alternative routes for power to flow in case of outages, making the propagation of congestion to a Portuguese element t significantly less likely the further away the external asset r is from the interconnections.

To further substantiate the argument that LC4 is an outlier and not an odd exception, we look to try to answer the questions: “How many times does this asset r verify the conditions necessary to be considered a relevant asset?” and “In how many of the considered scenario is LC4 classified as relevant?”.

To answer the first question, we made the algorithm count how many times the LC4 generated an OTDF and normalized OTDF greater than the defined thresholds. In total, we counted four validations – when most of the relevant assets have 30 to 1500 validations.

To answer the second question, we looked at each scenario’s results individually and observed that LC4 was considered relevant in only one scenario – May 13, 2020, during the off-peak consumption period – when most are considered at least in two scenarios.

To summarize, LC4 is distant from the interconnection lines, it does not have any of its adjacent connections considered relevant network elements, its relevancy is only validated four times, and those validations only occur in one of the four considered scenarios. Therefore, we find that the probability of the influence values obtained repeating is low and should not be used as a reference to set the power flow identification influence threshold at the cost of discluding two geographically relevant assets.

Thus, in this thesis scope, we propose to opt for the second approach since it generates the most inclusive result and guarantees that we are not eliminating any asset crucial for the correct application of the OPC service. Having to exclude a network element from the output list manually does not call into question the contribution that the implemented algorithm provides, as it should be noted that we had data from approximately 1,100 Spanish assets, which was reduced significantly (about 97.7%). Only with this reduction of the assets pool could we make a careful and detailed analysis that would allow an asset to be manually removed from the output list. In conclusion, we can observe that there is value in allowing space for the TSO to rule out specific assets in cases where increasing the threshold values would harm the overall relevant assets list.

Having set the value for the power flow identification influence threshold, we need to attribute a value to the power flow filtering influence threshold to close the final combination. Although it is true that in the results obtained it was indifferent if the power flow filtering influence threshold was 3% or 5%, we believe that throughout the paper it was proven how crucial it was to decontaminate the results from the noise introduced by the grid models and power flow computations. Therefore, we consider that the best proposal for situations similar to the one studied is to consider the most restrictive value (5%) as a precaution measure.

On a final note, we refer the reader to Appendix B, where we illustrate in Figure B.7 and exhibit in Table B.4, the final list of relevant assets for the optimal combination of power flow influence thresholds suggested (power flow filtering threshold equal to 5% and power flow identification influence threshold equal to 15%), with the qualitative assessment of the TSO.

6

Conclusion and Future Work

Contents

6.1 Conclusions

As this master's thesis main objective, we proposed to answer the following research question: "How to evaluate the relevance of external assets for outage planning coordination?".

To do so, we developed a fully functioning, scalable, and robust algorithm capable of analyzing power flow data from different scenarios in an N-2 contingency analysis and concluded which network assets are relevant for the Portuguese TSO during the coordination of outages. The algorithm encompasses a PYTHON [42] program developed for the specific case of Portugal that analyzes different combinations of power flow influence thresholds and selects the combination that produces the most coherent and reliable relevant assets list for outage planning.

When implementing the algorithm, different scenarios were considered so that the results are eligible and representative of the transmission grid's year-long behavior. During the implementation tests, different optimization studies were performed. For once, it was studied the impact of only considering "N-1 PT + N-1 ES" contingencies in which the disconnected Portuguese assets belonged to the Critical Network Element (CNE) list, which proved to significantly cut on execution time (82.5% faster) while maintaining the quality of the results. Due to the recursive and test-heavy aspect of the proposed algorithm, another criterion of success for this thesis was guaranteeing that the developed tool was highly efficient while managing memory and resources within feasible execution times, allowing for multiple iterations so that multiple thresholds values could be tested sequentially.

Another key aspect of the tool is the possibility to compare the results for each scenario and conclude on the differences observed and mitigate induced errors by scenarios operating at extreme conditions. During implementation, this feature propelled the creation of an active power filter that can be turned on or off, depending on the simulation conditions and power flow computations. In the specific case study of this thesis, it allowed to integrate a scenario that had extreme values, that was introducing errors associated with the converging criteria of the power flow computations, and that the power flow filtering influence threshold was not filtering – even when it was set as the maximum value of the range of thresholds published by ACER.

With a fully functioning and optimized algorithm, the last goal to meet was the identification of the power flow influence threshold combination that provided the most adequate and coherent relevant assets list. As the first step, we computed the extreme values (lower and upper boundary) from the range published by ACER and ran different combinations until a satisfactory conclusion was reached.

This evaluation produced a relevant assets list of 25 network elements for the most permissive combination – twenty-four 400 kV and one 220 kV transmission line – and 8 for the most restrictive combination – eight 400 kV transmission lines. We then mapped the geographical position of the identified network elements and observed that the most influential assets were near Portugal and Spain's border and had at least one adjacent connection that was also considered a relevant asset.

Although the most promising combination of thresholds included a power flow identification influence threshold equal to 15%, we debated if some adjustments were necessary due to the identification of a possible outlier. Two new evaluation parameters were conceptualized to guarantee that we were indeed in the presence of an outlier and not in the presence of an odd exception. The two parameters consisted of counting the number of times the external asset generated sensitivity values greater than the defined thresholds and in how many scenarios the asset was identified.
In the end, we arrived at the following conclusions:

- For the power flow filtering influence threshold, we concluded that it did not introduce changes in the number of relevant assets due to the converging role with the active power filter applied to include all scenarios. Nonetheless, we suggest considering the maximum value of 5% for this threshold as a precaution strategy since it is crucial for the algorithm to eliminate outliers that would otherwise contaminate the results.
- For the power flow identification influence threshold, we presented two different approaches. The first suggested that the threshold value should be increased to guarantee the elimination of network assets that are geographically dubious. The second suggested to keep the threshold value at the minimum of 15% and allow space to manually rule out specific network elements in cases where increasing the threshold value would come at the cost of eliminating assets that were not previously considered outliers. In the end, we decided that the second approach was the best as we found that the first could result in the elimination of assets that could reveal to be crucial in the outage planning coordination.

6.2 Future work

As stated by Coreso, the topic of outage coordination is still under investigation, so several possible directions of study could be taken as a follow-up of this work.
The following research directions would be interesting to explore:

- Expand the testing of N-2 functionality to two network elements connected outside the TSO's control area since, due to time constraints, it was not possible to generate the necessary scenarios to do so. Although the developed tool is ready to receive the scenarios, without them, it was impossible to perform any testing to detect possible bugs.
- Apply the methodology to more scenarios to introduce some redundancy in the scope of the grid behaviors, to further validate the conclusions obtained in this dissertation. For example for the same season have more than one scenario with the same desired characteristics.

The succeeding improvements to the algorithm's PYTHON tool would be appealing:

- Create a feature that could print a map with the assets deemed relevant since the study and assessment of relevant assets are intrinsically connected with the network elements' geographical position and connections. An example approach would be to have a base Iberian map in which it could be overlayed images of the grid elements classified as meaningful for outage coordination.
- Develop a more friendly and appealing interface that could provide the user with a more streamlined multi-testing experience.

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A

Code of Project

A.1 Algorithm description

A.1.1 Data organization assumptions

For the execution of the algorithm some assumptions regarding the data organization were necessary, such as the overall data hierarchy, the name structure of folders and files, and the data organization within each file. These assumptions were made based on the manner in which the files were delivered and presented by REN.

The data hierarchical organization starts with the parent folders named after the transmission grid situation considered: “N-2 ES”, “N-1 PT + N-1 ES”, “N-1 PT” and “N-1 ES”. As mentioned in section 3.2 the algorithm is prepared to consider both N-2 situations, even though only “N-1 PT + N-1 ES” is used for this thesis case study. Inside the parent folders there are as many folders as the total number of scenarios available (see Figure A.1).

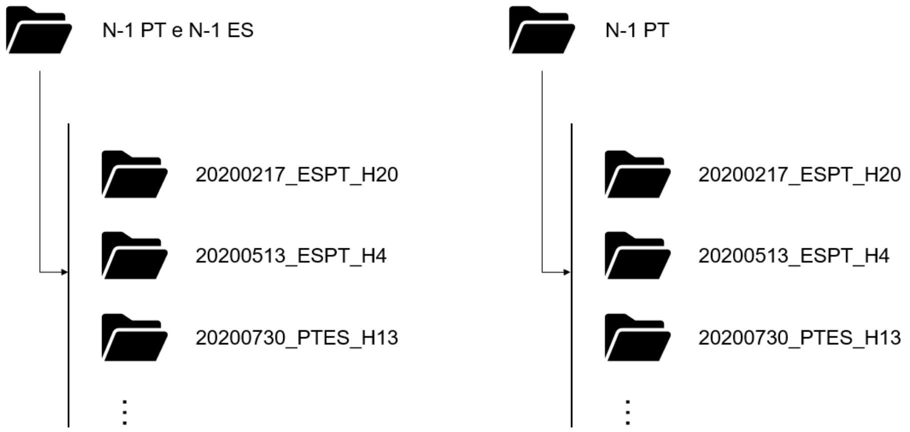


Figure A.1: Folder arrangement and hierarchy

These subfolders are named after the date of the scenarios and hour where the extreme consumption value was verified, and follow the structure presented in Figure A.2.

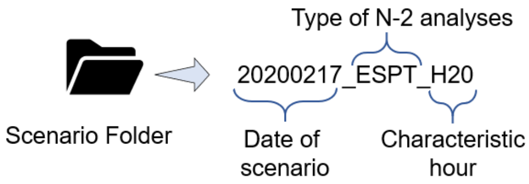


Figure A.2: Scenario folder name structure

Inside these subfolders there are several CSV files. Depending on the parent folder the files have different structures for their name, as illustrated in Figure A.3.

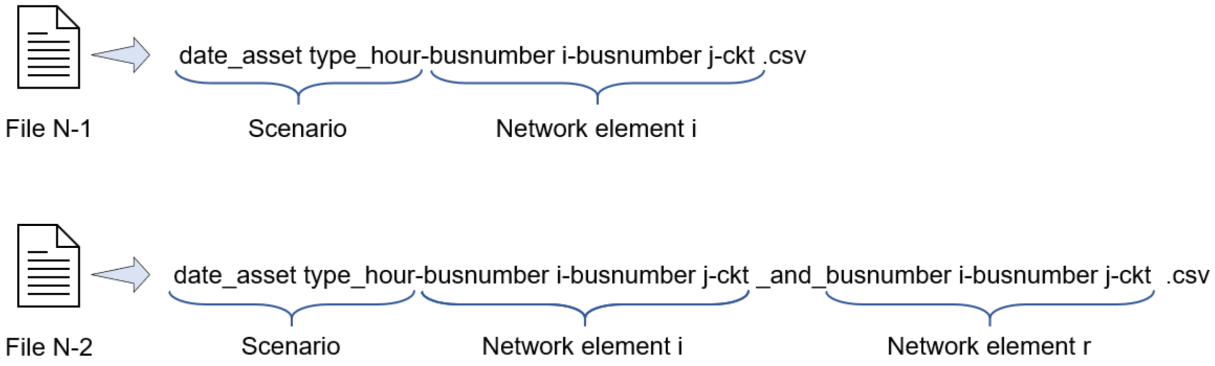
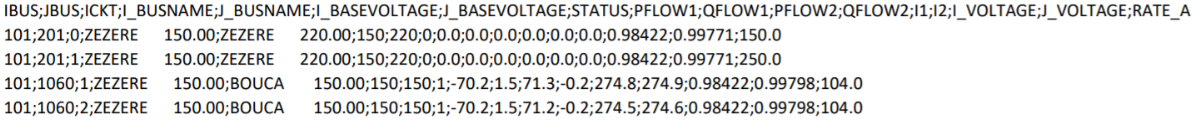


Figure A.3: Filename structure

Files in parent folder “N-1 PT + N-1 ES” follow the structure specified for “File N-2”, while files in parent folder “N-1 PT” follow the structure specified for “File N-1”. The network elements ids that assemble the name of “File N-1” and “File N-2” correspond to disconnected network elements. The contents of these files are assets and information about their ids, names, voltage levels, injected active power, injected reactive power, injected current and their PATL. Figure A.4 illustrates an example of the contents mentioned.



```
IBUS;JBUS;ICKT;I_BUSNAME;J_BUSNAME;I_BASEVOLTAGE;J_BASEVOLTAGE;STATUS;PFLOW1;QFLOW1;PFLOW2;QFLOW2;I1;I2;I_VOLTAGE;J_VOLTAGE;RATE_A
101;201;0;ZEZERE     150.00;ZEZERE     220.00;150;220;0;0.0;0.0;0.0;0.0;0.0;0.0;0.98422;0.99771;150.0
101;201;1;ZEZERE     150.00;ZEZERE     220.00;150;220;0;0.0;0.0;0.0;0.0;0.0;0.0;0.98422;0.99771;250.0
101;1060;1;ZEZERE     150.00;BOUCA     150.00;150;150;1;-70.2;1.5;71.3;-0.2;274.8;274.9;0.98422;0.99798;104.0
101;1060;2;ZEZERE     150.00;BOUCA     150.00;150;150;1;-70.2;1.5;71.2;-0.2;274.5;274.6;0.98422;0.99798;104.0
```

Figure A.4: Example of content inside files N-1 and N-2

Besides the file types illustrated in Figure A.3, there is another type of file – “File mapping” – present in each scenario folder (see Figure A.5). These files contain a list of all the possible contingencies that may occur in a TSO’s control area (as presented in Figure A.6). For each “N-1 PT” scenario there is only one contingency map from REN, per folder, while for each “N-1 PT + N-1 ES” scenario there are two contingency maps per folder, one from REN and the other from Spain’s TSO, REE.

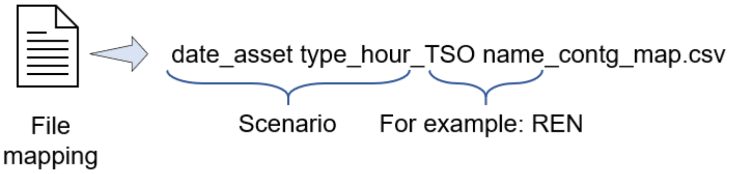
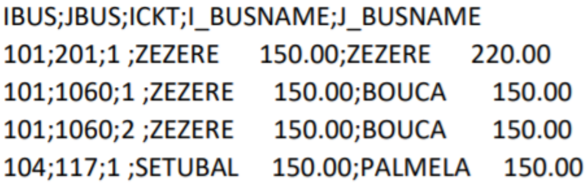


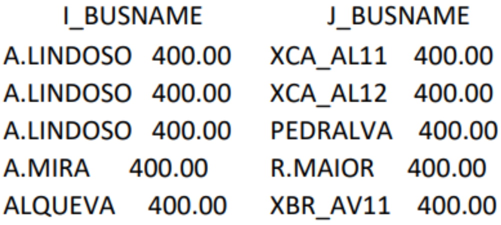
Figure A.5: Filename structure



```
IBUS;JBUS;ICKT;I_BUSNAME;J_BUSNAME
101;201;1 ;ZEZERE     150.00;ZEZERE     220.00
101;1060;1 ;ZEZERE     150.00;BOUCA     150.00
101;1060;2 ;ZEZERE     150.00;BOUCA     150.00
104;117;1 ;SETUBAL     150.00;PALMELA     150.00
```

Figure A.6: Example of content inside mapping files

At the same hierarchic level of the parent folders, there is an EXCEL® file titled “CNE.xlsx” with all the portuguese assets in REN’s control area, classified as CNE in accordance with the CACM Regulation [36], with their corresponding busnames (see Figure A.7)



```
      I_BUSNAME              J_BUSNAME
A.LINDOSO   400.00     XCA_AL11    400.00
A.LINDOSO   400.00     XCA_AL12    400.00
A.LINDOSO   400.00     PEDRALVA    400.00
A.MIRA      400.00     R.MAIOR     400.00
ALQUEVA     400.00     XBR_AV11    400.00
```

Figure A.7: Structure of file of critical network elements (CNE)

A.1.2 Inputs

Once started the program execution, the user is asked to insert a few inputs.

The inputs are (a) what contingencies does the user pretend to analyze, (b) does he wish to run the program with previously defined directories or does he want to insert new ones, (c) does the user pretend to perform the analysis with the active power filtering conditions, (d) what scenarios does the user desire to study, and finally (e) what are the power flow influence thresholds.

The input (a) allows the user to opt between limiting the disconnected Portuguese asset to CNEs or to study all the available "N-1 PT + N-1 ES" outage combinations, or to study outage combinations where the two disconnected assets are external to the TSO's control area ("N-2 ES").

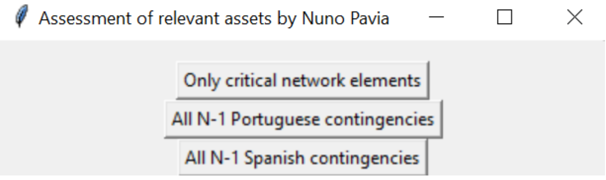
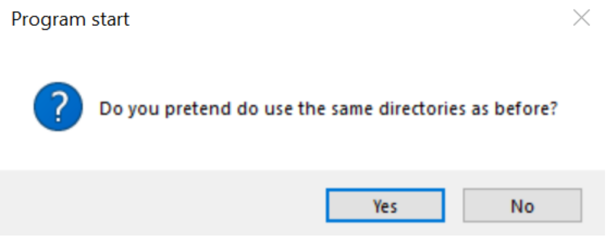


Figure A.8: Screenshot of interface: Selection of contingency analysis

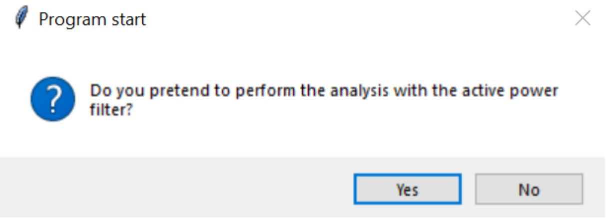
The question asked in (b) is to determine if the user saved the input data in the expected directories or if the data was saved in a alternative location. This step is specially important when new users are executing the program for the first time.



Do you pretend do use the same directories as before?

Figure A.9: Screenshot of interface: Directory definition

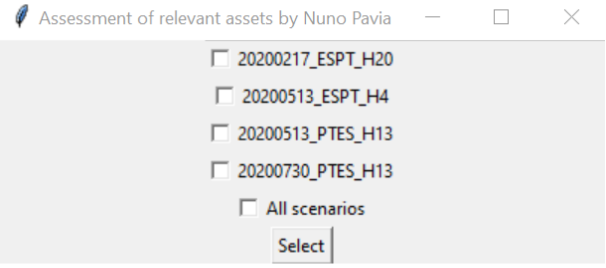
The element (c) allows the controller to define if the analysis performed includes the active power filter. This course of action is recommended when the scenarios being studied display extreme power flow values that have proven to introduce outliers into the results.



Do you pretend to perform the analysis with the active power filter?

Figure A.10: Screenshot of interface: Active power filter

The option provided in point (d), provides the operator the possibility of only studying a specific scenario. This is specifically helpful when some of the relevant assets are considered outliers and there are leads that the problem is begotten in a specific scenario.



Assessment of relevant assets by Nuno Pavia

☐ 20200217_ESPT_H20

☐ 20200513_ESPT_H4

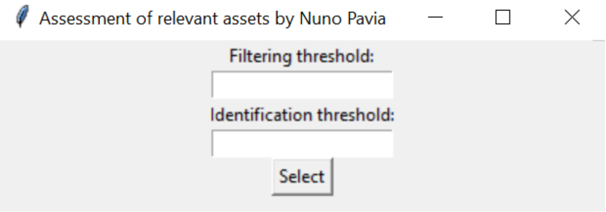
☐ 20200513_PTES_H13

☐ 20200730_PTES_H13

☐ All scenarios

Figure A.11: Screenshot of interface: Scenario selection

Finally, (e) asks what threshold values should be used to provide the most coherent and reliable relevant assets list. The acceptable values are limited to the range of threshold published by ACER.



Assessment of relevant assets by Nuno Pavia

Filtering threshold:

Identification threshold:

Figure A.12: Screenshot of interface: Selection of thresholds values

A.1.3 Outputs

In the beginning of the program execution, the user defines the directory in which the files will be stored. If no directory is given, the output files, by default, are stored in the same directory of folders containing Files N-1 and N-2.

Each output EXCEL® file has three sheets as depicted in Figure A.13. In all sheets the assets presented are the same, what distinguishes them is the prioritization given. In the first sheet, it is given prioritization to the power flow filtering influence factor, in the second sheet to the power flow identification influence factor and in the final and third sheet it is given an alphabetical prioritization of the identified relevant assets. This choice was based on the fact that influence factors have different meanings and depending on the context one influence factor might be more relevant than the other. This is the case for the power flow identification influence factor, as it is more significant for system security, since it better describes the risk of overload.

Figure A.13: Organization of results output

As a final note, the data volume processed was the following:

- Four scenarios;
- About 280 000 N-2 type files in each scenario;
- About 275 N-1 type files in each scenario;
- About 400 lines and 18 columns of content in N-2 files;
- About 2 500 lines and 18 columns of content in N-1 type files;
- About 1 200 lines and five columns of content in the external mapping files;
- About 320 lines and five columns of content in the internal mapping files;
- And 36 lines and 3 columns of content in the monitored resources files.

A.1.4 Flowchart of the developed PYTHON tool

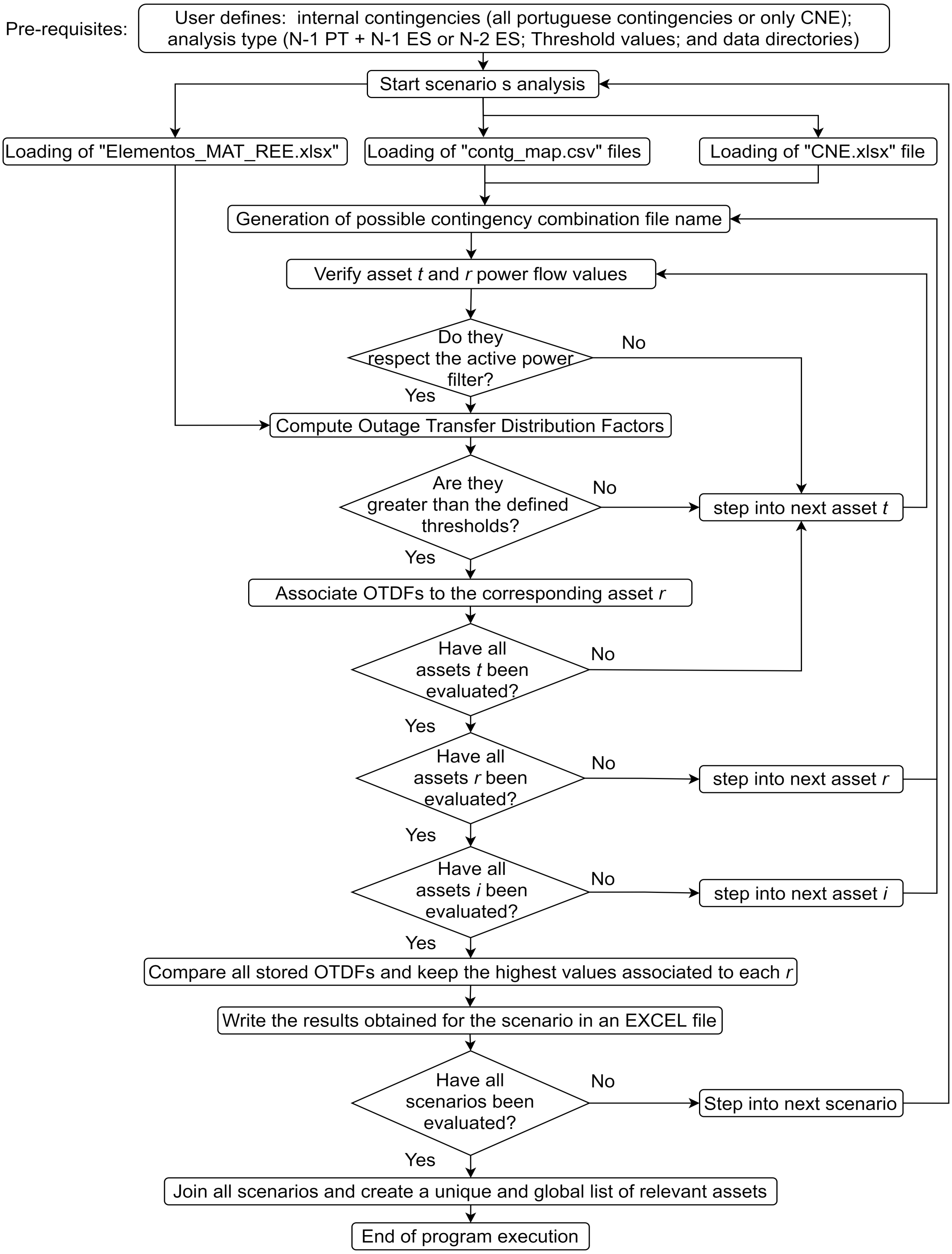


Figure A.14: Flowchart of the program specifications with the active power filter turned on