HVDC-WISE

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Scope and specifications of the tools and model needs

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Executive Summary

The goal of HVDC-WISE is to support further development of HVDC-based transmission grids by developing new reliability and resilience (R&R) oriented planning and analysis tools and identifying HVDC-based grid architectures and technologies that can be readily deployed to improve system performance and facilitate the integration of new renewable sources. WP 5 aims at developing tools for R&R-oriented planning and operation of hybrid AC/DC power systems.

This report presents the conceptual framework of the tools to be developed, their scope and further modelling and development needs. The definition of a conceptual framework for R&R-oriented planning and operation of hybrid AC/DC power systems will allow for the integration of the different tools into a single tool set.

Firstly, a literature review on resilience, its definition and evaluation, and on techno-economic planning (TEP) including HVDC and resilience has been carried out to identify R&R-oriented planning and operation needs. Resilience can be quantified by evaluating the area of the resilience triangle or trapezoid, describing the evolution of a resilience metric. Performance-based metrics such as available generation, served load, etc. could be particularly useful for cost-benefit and planning analyses. The consideration of cascading outages in resilient TEP is the subject of current research, and should include aspects such as congestion management and operator responses, etc. TEP involving HVDC must consider grid-connection requirements as well as the inherent risks, particularities and limitations of HVDC within the modelling approaches. Characteristics of HVDC systems significantly differ from the characteristics of AC systems. The control capabilities of HVDC systems should be considered as well as their DC protection systems. The complexity of large-scale TEP has led ENTSO-e to analyse candidate projects through a cost-benefit analysis (CBA) with four types of indicators: project costs, CBA market indicators, residual impact indicators, and CBA network indicators. The candidate projects respond to identified system needs for the regional and pan-European networks.

Secondly, this document outlines a general framework for R&R-oriented planning and operation of hybrid AC/DC systems. The main challenges relate to the consideration of both reliability and resiliency, and its extension to hybrid AC/DC systems. This general framework enables assessing and comparing different HVDC architectures, by considering not only typical TEP indices quantified by long term static simulations, but also security and resilience indices. By elaborating the R&R indices and in line with the ENTSO-e TEP approach, comprehensive CBA of the HVDC architectures can be carried out. The Figure 1 shows the general framework.

The general framework makes use of a top-down approach where techno-economic (adequacy-like) analyses are performed first, and security and resilience analyses for a subset of operating states follow. The input consists of detailed models and data of the power system, R&R related information, and the predefined HVDC architectures to be analysed. Each architecture is individually assessed, assuming it is connected to the base power system model through the nodes specified by the architecture itself. The framework will provide a list of detailed indicators computed for each architecture analysed.

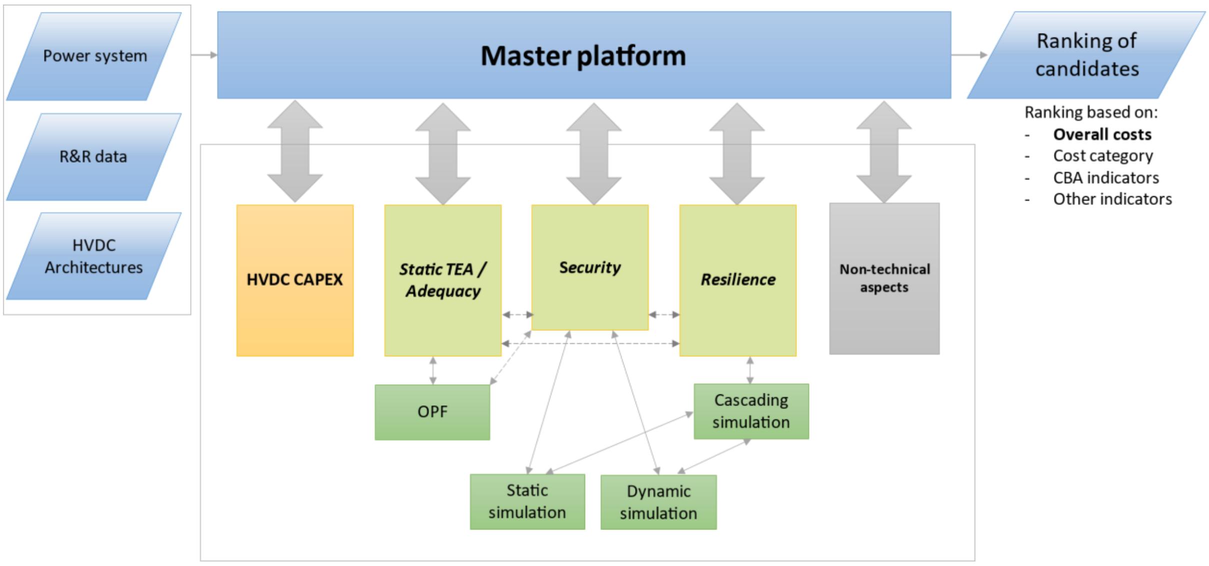


FIGURE 1: A GENERAL FRAMEWORK FOR R&R ANALYSIS IN HVDC-WISE

Thirdly, this deliverable identifies the main software tools the consortium is acquainted with and will be used within the framework. In fact, the consortium members have already been applying these tools to traditional power systems for partial analysis of the kind to be addressed in the current project. A review of the tools included in this document has shown many gaps to be filled before accurate reliability and resilience analysis of hybrid HVDC/HVDC can be carried out. For each tool, its objective, functionalities, input and outputs, limitations with respect to hybrid AC/DC systems and further modelling needs have been described. In addition, the review of the tools together with the general framework has identified cross-integration opportunities of the tools. Such opportunities arise between:

- the two planning tools, FlexPlan and OpTEA soft,
- the above planning tools and power system simulators (Market-Grid Toolchain, HY-ACDC-SIM2, Eurostag/Smartflow, and DPsim),
- cascading failure models (AC-CFM and D-CFM) and the above power system simulators.

This document also emphasises why the achievement of the R&R-oriented planning and operation of hybrid AC/DC power system will require, first of all, the development of new models and functionalities for well-known software tools (some of them developed by members of the consortium before), secondly, the interaction and interfacing of these already existing tools according to the general framework, setting-up a co-simulation environment and, finally, the adoption of protocols and data models to make this interaction and interfacing seamless and efficient. With respect to the interaction of the tools, a challenge for the R&R assessment in a system with HVDC is the selection of an appropriate simulation framework that can give inputs to the R&R assessment tools. A co-simulation environment, that will consist of different solvers for the different layers of the grid (HVAC, HVDC), can be envisaged to combine the accuracy of dynamic phasor or electromagnet transient (EMT) simulators with the large-scale simulation capabilities of phasor domain simulators. With respect to data models and exchange, planning tools, cascading failure models, and power system simulation tools have their own underlying data models. The required data will be initially modelled by making use of the software-imposed models. As far as possible, intra-software data exchange will be sought for those tools based on a common coding or scripting language such as Python and thus can make use of software-related objects.

Finally, the models and tools to be improved or newly developed in this project will be first tested on a few artificially-designed test systems but will later on be taken to more realistic scenarios to validate their contributions.

1. Introduction

1.1 Motivation

The goal of HVDC-WISE is to support further development of HVDC-based transmission grids by developing new reliability and resilience (R&R) oriented planning and analysis tools and identifying HVDC-based grid architectures and technologies that can be readily deployed to improve system performance and facilitate the integration of new renewable sources.

WP 5 aims at developing tools for R&R-oriented planning and operation of hybrid AC/DC power systems. For this purpose, WP 5 is structured in three tasks. Task 5.1 defines the conceptual architecture of the tools, their scope, and further modelling and development needs. Task 5.2 should expand on and enhance existing planning tools to embed reliability and resilience performance alongside other cost trade-offs when comparing available AC/DC architecture options and computing the optimal investment portfolio. Task 5.3 will develop quasi-static and dynamic simulation functions, including the ability to simulate cascading failures and to compute static and dynamic security and resilience indices to be fed back to the planning tools.

1.2 Approach

This report (D5.1) presents the conceptual framework of the tools to be developed, their scope and further modelling and development needs. For this purpose, a brief literature review on reliability and resilience (R&R) assessment, transmission expansion planning (TEP), and on industry practice and perspective with respect to R&R-oriented planning and operation, is carried out. In addition, existing tools within the consortium (planning tools, cascading simulators, and static and dynamic security analysis tools for power systems) are reviewed to identify the functionality gaps that need to be addressed to comply with the needs for R&R-oriented planning and operation.

The definition of a conceptual architecture for R&R-oriented planning and operation of hybrid AC/DC power systems will allow for the integration of the different tools into a single tool set. The conceptual architecture specifies the required interaction and interfaces between different tools. The understanding of these two aspects would help to identify the data and model needs for this project.

1.3 Structure

Section 2 presents a brief literature review. Section 3 proposes a methodology for reliability and resilience (R&R)-oriented planning of hybrid AC/DC power systems and defines the conceptual architecture proposed for the tool set. Section 4 describes the existing tools in the consortium, highlights their limitations and identifies further modelling needs for hybrid AC/DC systems and cross-integration opportunities. Section 0 summarizes the overall work requirements for the tool set for the operation and planning of hybrid AC/DC power systems.

2. Literature Review

This section presents a brief literature review on reliability and resilience (R&R) assessment, on transmission expansion planning (TEP), and on industry practice and perspective with respect to R&R-oriented planning and operation. This allows for the identification of the R&R-oriented planning and operation needs.

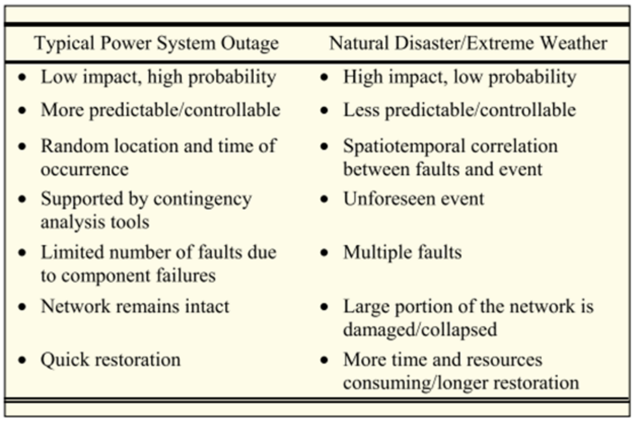
2.1 R&R assessment

2.1.1 Concepts

Electrical power systems are the backbone of any modern society, supporting several other critical infrastructures, such as transportation, communication, water, etc. A disruption in the continuous electricity supply will thus have catastrophic consequences, as experienced during numerous blackouts in the last decades. However, ensuring an uninterrupted electricity supply is challenging, as power systems are exposed to several threats. These threats can be mainly categorized as typical power system outages and extreme events, driven for instance by natural disasters, extreme weather, malicious attacks and common mode failures. There are distinct differences between these two categories, as shown in Table 1 [1].

Hence, electrical power systems have been designed with high levels of reliability to typical threats in mind. Recent events are creating a compelling case for power systems to engender higher levels of resilience to natural disasters and extreme weather, to reduce the frequency and severity of power disruptions. Power systems reliability is a well-known and established concept, and several reliability-oriented studies have been developed by power system engineers and scholars. In contrast, there is much less clarity as to the concept of resilience.

TABLE 1: COMPARISON OF TYPICAL POWER SYSTEM OUTAGES AND THOSE CAUSED BY NATURAL DISASTERS OR EXTREME WEATHER [1]**.**



Typical Power System Outage	Natural Disaster/Extreme Weather
• Low impact, high probability	• High impact, low probability
• More predictable/controllable	• Less predictable/controllable
• Random location and time of occurrence	• Spatiotemporal correlation between faults and event
• Supported by contingency analysis tools	• Unforeseen event
• Limited number of faults due to component failures	• Multiple faults
• Network remains intact	• Large portion of the network is damaged/collapsed
• Quick restoration	• More time and resources consuming/longer restoration

“Resilience” originates from the Latin word “resilio” and, having been first introduced by Holling in 1973 for ecological systems [2], it is a relatively new and emerging concept in power systems. Within this context, power systems resilience can be referred to as the ability of a power system to recover quickly following a disaster or, more generally, the ability to anticipate extraordinary and High-Impact, Low-Probability (HILP) events, rapidly recovering from these disruptive events, and learning lessons to adapt its operation and structure, in order to be better prepared for similar events in the future. A framework for power system resilience, outlining the key differences between power systems reliability and resilience, , are presented in [3]. If the impacts of climate change and the need to reduce

Green-House Gas (GHG) emissions are also considered, then this leads to so-called “low-carbon-resilient” future networks, including both carbon reduction and resilience goals.

2.1.1.1 Reliability in Power Systems

The concept of *Reliability* was introduced to assess the performance of the power system in providing energy to users even in the case of disturbances. Reliability has been defined by several well-recognised institutions, such as CIGRE, IEEE, IEC, NERC, and ENTSO-E, in terms of *adequacy* and *security*. Table 2 summarizes the definitions from these different entities.

TABLE 2: DEFINITIONS OF RELIABILITY, ADEQUACY AND SECURITY.

	Reliability	**Adequacy**	**Security**
CIGRE [4], [5]	A measure of the ability of a power system to deliver electricity to all points of consumption and receive electricity from all points of supply within accepted standards and in the amount desired.	A measure of the ability of a power system to meet the electric power and energy requirements of its customers within acceptable technical limits, taking into account scheduled and unscheduled outages of system components, where: Power system includes all elements of the generation, transmission and distribution systems, and customer facilities that supply or use power and energy, or provide ancillary services; Customers include all parties that supply power and energy or ancillary services, as well as those who consume them; Requirements of customers include their basic power and energy needs, and agreed use of customers’ ability to vary power supply, adjust demand and provide ancillary services; Acceptable technical limits and scheduled and unscheduled outages are those specified in the applicable planning criteria and standards; and System components include all elements of the supply, delivery and utilization systems regardless of ownership or control.	The ability of the power system to withstand disturbances, where: Power system includes all elements of the generation, transmission and distribution systems, and customer facilities that supply or use power and energy, or provide ancillary services; Ability to withstand will vary depending on specific disturbances and applicable criteria or standards, and includes agreed use of customers’ ability to vary power supply, adjust demand and provide ancillary services; Disturbances include electric short circuits, unanticipated loss of system facilities, or other rapid changes such as in wind or solar generation.
NERC [6]	The degree to which the performance of the elements of that system results in power being delivered to consumers within accepted standards and in the amount desired.	The ability of the electric system to supply the aggregate electrical demand and energy requirements of the end-use customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements	The ability of the bulk power system to withstand sudden, unexpected disturbances, such as short circuits or unanticipated loss of system elements.
IEEE [7]	Reliability of a power system refers to the probability of its satisfactory operation over the long run. It denotes the ability to supply adequate electric service on a nearly continuous basis, with few interruptions over an extended time period.	The ability of the electric systems to supply the aggregate electrical demand and energy requirements of their customers at all times, taking into account scheduled and reasonably expected unscheduled outage of system elements.	Security of a power system refers to the degree of risk in its ability to survive imminent disturbances (contingencies) without interruption of customer service. It relates to robustness of the system to imminent disturbances and, hence, depends on the system operating condition as well as the contingent probability of disturbances.
IEC [8]	The ability of a power system to meet its supply function under stated conditions for a specified period of time.	The ability of an electric power system to supply the aggregate electric power and energy required by the customers, under steady-state conditions, with system component ratings not exceeded, bus voltages and system frequency maintained within tolerances, taking into account planned and unplanned system component outages.	The ability to tolerate a credible event without loss of load, over-stress of system components, or deviation from specified voltage and frequency tolerances.

ENTSO-E [9], [10], [11]	The degree of performance of the elements of the bulk electric system that results in electricity being delivered to customers within accepted standards and in the amount desired.	The ability of the electric system to supply the aggregate electrical demand and energy requirements of the customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements.	The ability of the electric system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system elements.

All the reported definitions agree that *reliability* refers to the probability of satisfactory operation of the system in the long term. In this regard, the IEC definition [8] also includes a reference to the time interval of analysis.

The degree of reliability can be measured through the frequency, duration and intensity of instances of service degradation for customers.

As far as ***adequacy*** is concerned, the key concept is the availability of resources and components, or system elements, with suitable capacity to meet load demand without violating operating limits. To be adequate, a power system must be endowed with sufficient resources for generation, storage, demand flexibility, as well as having the transmission capacity to cover the expected demand plus reserves for contingencies, at all times. With regard to planning horizons, this requires a suitable development of the above resources, within the mechanisms defined by the regulatory framework.

All adequacy definitions include the explicit reference to "*unscheduled outages of system components*", i.e. contingencies. In particular, NERC, IEEE and ENTSO-E refer to reasonably expected unscheduled outages, thus also including an application criterion (i.e. the credibility criterion) in the definition.

As for ***security***, CIGRE ([4], [5]), NERC [6], and ENTSO-E ([9], [10], [11]) definitions are perfectly coherent in recognizing security as "the ability to withstand sudden disturbances". The IEC definition [8] includes the requirement of the "*integrity of demand supply*" (i.e., "without loss of load") in case of an event which satisfies a credibility criterion. The IEEE similarly specifies that systems should operate "without interruption of customer service" [7]. In view of this, all security definitions concur that a system can be considered secure if it is in an acceptable operating condition after the occurrence of credible contingencies.

2.1.1.2 Definitions of Resilience

In the context of power systems as critical infrastructures, the concept of resilience has only emerged in the last decade or so. There have been several attempts by organizations worldwide in the power and energy engineering communities, such as the U.K. Energy Research Centre and the U.S. Power Systems Engineering Research Center, to define resilience and distinguish it from the concept of reliability.

According to the U.K. Cabinet Office [15], resilience encompasses reliability, and it further includes resistance, redundancy, response, and recovery as key features. Another pioneering definition comes from the Multidisciplinary and National Center for Earthquake Engineering Research [12], where a generic resilience framework has been developed that is applicable to any critical infrastructure, including power systems. This framework consists of the "4Rs": robustness, redundancy, resourcefulness, and rapidity.

The list of power system resilience definitions is endless, but the majority focuses on the ability to anticipate, absorb, and rapidly recover from an external, high-impact, low-probability shock. Table 3 provides an overview of existing definitions of power system resilience in the literature.

TABLE 3: EXISTING DEFINITIONS OF RESILIENCE IN THE POWER SECTOR.

Source	Definition
UKERC, UK Energy Research Center (UKERC), "Building a Resilient UK Energy System", 2009 [13]	The ability of a power system to withstand extraordinary and high impact-low probability (HILP) events such as due to extreme weather, rapidly recover from such disruptive events and absorb lessons for adapting its operation and structure to prevent or mitigate the impact of similar events in the future.
Haimes [14]	The ability of the system to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable time and composite costs and risks.
NIAC [15]	(Infrastructure resilience) - The ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event.
UK Cabinet Office [16]	The ability of assets, networks and systems to anticipate, absorb, adapt to and / or rapidly recover from a disruptive event.
PSERC [17]	Ability of a system to gradually degrade under increasing system stress, and then to return to its pre-disturbance condition when the disturbance is removed.
NAURC [18]	Robustness and recovery characteristics of utility infrastructure and operations, which avoid or minimize interruptions of service during an extraordinary and hazardous event.
Presidential Policy Directive 21: Critical Infrastructure Security and Resilience, 2013 [19]	The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents.
Sandia Lab 2011 [20]	Given a **disruptive event** (or set of events), the resilience of a system to that event (or events) is the ability to reduce **'efficiently'** both the magnitude and duration of the deviation from targeted **system performance** levels. The **bold words** of this definition are key components of resilience; further discussion follows below: • **Disruptive event**: Different disruptions may affect a system in different ways and thus necessitate different recovery processes. Hence, a system may have different levels of resilience to different disruptions. This definition considers resilience of a system to a specific disruption. • **Efficiently**: Efficiently means using the lowest possible amount of resources during recovery processes; depending on the domain, these resources could be dollars, repair man-hours, infrastructure replacement assets, or time. 1. **System performance**: Given the flexibility of many systems to adjust and reconfigure to a disruptive event, maintaining system structure is not as important as maintaining system performance. Hence, measurement of resilience should evaluate how a disruption affects system performance and causes productivity to decrease relative to targeted system performance levels: that is, how the system should behave during and after disruptive events.
Italian Ministries of Economic Development and of Environment and Land and Sea Protection, Strategia Energetica Nazionale (SEN 2017), 10 November 2017 [21]	The ability of a system not only to resist to stresses which have overcome the withstanding limits of the system itself, but also to come back fast to a normal state of operation. The effectiveness of the resilient system depends on its capability to anticipate, to absorb, to adapt to and/or recover itself from an extreme event.
IEEE Task Force on Definition and Quantification of Resilience, April 2018 [22]	The ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event.
National Security Policy for Critical Infrastructures, Brazilian government, November 2018 [23]	The capacity of the critical infrastructures to be recovered after the occurrence of an adverse situation.
NATF (North American Transmission Forum) [24]	The ability of the system and its components (i.e. both the equipment and human components) to minimize damage and improve recovery from non-routine disruptions, including high impact, low frequency (HILF) events, in a reasonable amount of time. Resiliency includes a diverse range of topics, such as flexibility, hardening, security and recovery.
US National Academies of Science [25]	The ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events.

2.1.1.3 CIGRE C4.47 Definition of Resilience

CIGRE established the working group (WG) C4.47 "Power System Resiliency" in 2019 with the aim to formulate a reference standard definition and approach to resilience. This working group carried out an international survey with over 100 respondents from around the globe including industrial, consultancy, governmental and academic organizations. This survey exposed participants to the wider interpretation of power system resilience and invited them to comment and provide their views on these definitions. It is therefore believed that the definition provided by the WG includes the key features of existing definitions and provides a well-suited definition to be adopted by the electricity sector. CIGRE WG C4.47 defined resilience as the:

"***ability to limit the extent, severity, and duration of system degradation following an extreme event***" [26].

As an integral part of the definition, it includes the following key actionable measures to be taken before, during and after extreme events, such as:

- anticipation
- preparation
- absorption
- sustainment of critical system operations
- rapid recovery; and
- adaptation, including the application of lessons learnt.

2.1.1.4 Resilience Properties of CIGRE Definition

1. Almost all the definitions describe resilience as an "**ability**" of the power system or system or infrastructure. However, most of them are "operationally oriented definitions," that is, they define resilience by using those measures (such as fast recovery, shock absorption) that make the system resilient. Some of the definitions also describe resilience as a contingency-withstanding capability, which does not help clarify the salient characteristics of resilience in response to extreme events resulting in multiple contingencies on the system.
2. The terms "**extent and severity**" in the WG definition respectively refer to the geographical extent and the intensity of the effects of the event on an interconnected power system. This assures a more focused characterization of the dimensions of system degradation while keeping the definition concise and informative. Note that the term "severity" of system degradation must be kept separate from the "severity of the event," which in general does not imply any system degradation. "**Severity**" also depends on the (inter)dependence between essential or mission- critical loads and the disrupted and/or impaired system.
3. The term "**duration**" refers to the time period of the negative effects on system performance with respect to normal operation.
4. The term "**degradation**" refers to a deviation from specified target performances. This term refers to the criteria used to apply the resilience concept in system planning and operation, and it also refers to both infrastructural and operational resilience. Very often, the costs to assure power system reliability in case of multiple contingencies can be unacceptably high and unsustainable; thus, the rationale is to provide a resilience-centric criterion based on maintaining the maximum deviations of system performance within some pre-defined bounds (degradation) in the case of extreme events.
5. The term "**extreme event**" refers to an event with a large impact in terms of degraded system performance, damaged components, the reduction of component operational capabilities,

and the degree of customer service disruption. With this specification, WG C4.47 intends to link the definition of resilience properties with application criteria (i.e. extreme events). Due to the physical nature of large synchronously interconnected transmission systems, extreme events can be accompanied by the loss of multiple components, cascading outages, or a loss of stability followed by widespread interruption to electricity users and, in the worst-case, a total system blackout.

2.1.1.5 Key measures of the CIGRE C4.47 definition

The CIGRE definition clearly separates the definition of the properties from the key actionable measures that can be deployed [Before (B), During (D) and After (A) events] to achieve or enhance resilience, considering the utility's objectives and the lack of an international standardized framework to support decision-making for resilience enhancement investments:

- The process of "anticipation" (B) refers to evaluating and/or monitoring the onset of foreseeable scenarios that could have disastrous outcomes. It assists power system engineers in enumerating plausible disaster scenarios and proposing mitigation plans. It also allows decision-makers to envisage the "multiple" future states and strategies required to contain, avoid, and/ or respond to an emergent threat to the power system.
- "Preparation" (B) is the process required by decision-makers to advance the knowledge gained during the anticipation phase from the resilience strategies to clear objectives. This will guide the deployment of measures considering tolerance to the possible adverse consequences, with emphasis on maintaining mission-critical loads and the minimum system load level. This will ensure the sustainment of a reduced but acceptable functioning of everyday life and orderly functioning of a modern society.
- The process of "absorption" (D) aims to meet defined objectives, whereby a system can absorb the impacts of, and can minimize or avoid the consequences of various extreme events. The outcomes are represented by the slope and degree of the power system performance degradation (as per the power system metric) after the shock has occurred or has been avoided.
- The "sustainment of critical system operations" (D, A) refers to the process of maintaining the operational capability of the impaired power system. This refers to supplying mission-critical loads and a minimum system load level to maintain a reduced but acceptable functioning of everyday life. This will in turn enable the functioning of a modern society that is dependent on so many critical and interdependent infrastructures driven by electricity. This may require the deployment of additional components (for example, mobile generators), systems (for example, uninterruptible power supplies), and distributed energy resources to sustain operations until the power system is restored to a normal or near-normal state.
- The "rapid recovery" (D, A) process requires that the operational response to an initial shock contains or limits the consequence of the disruptive event, by focusing on mission-critical or essential loads that are required to support restoration efforts. This requires an integrated planning approach that develops efficient and effective response plans in a coordinated manner, in order to recover system operation to a normal or near- normal state.
- In the "adaptation" (A) process, changes are carried out in power system management, defence, and operational regimes on the basis of past disruptions, in order to contain and/or limit undesirable situations. This process includes the upgrading of prevention barriers, operational regimes, and maintenance procedures on the basis of lessons learnt from past disruptive events.

2.1.2 Reliability evaluation

Traditional reliability metrics are used to quantify the impact of an event to provide a quantification that is widely used by the industrial community in reliability assessment and benchmarking. The following are the metrics applied in the project [27]:

1. **Loss of Load Expectation (LOLE) (days/yr or hr/yr):** LOLE is the average number of days or hours with loss of load, in a given period T.

$$LOLE = \sum_{i \in S} (p_i \cdot T)$$

where p_i is the probability of system state *i* and *S* is the set of all system states associated with loss of load.

2. **Loss of Load Frequency (LOLF) (occ./yr):** LOLF is the frequency of occurrence of loss of load in a given period T.

$$LOLF = \sum_{i \in S} (F_i - f_i)$$

where F_i is the frequency of departing system state *i* and f_i is the portion of F_i which corresponds to a lower bound between the loss-of-load state set and the non-loss-of-load state set.

3. **Loss of Load Duration (LOLD) (hr/disturbance):** LOLD is the loss of load duration in a given period T, computed by the dividing LOLE by LOLF.

$$LOLD = \frac{LOLE}{LOLF}$$

4. **Expected Energy Not Supplied (EENS) (MWh/yr):** EENS is the expected energy not supplied

$$EENS = \sum_{i \in S} (C_i \cdot F_i \cdot D_i)$$

where C_i is the loss of load for system state *i* and D_i is the duration of the system state *i*.

2.1.3 Resilience evaluation

The topic of resilience quantification has attracted the interest of many scholars around the world, attempting to develop holistic resilience metric systems. This section covers some of the most widely used resilience metrics, starting with risk-driven metrics that focus on tail risks to a power system infrastructure (i.e., high-impact, low-probability events). It then focuses on time-dependent metrics which are key for understanding the behaviour of a system before, during and after the event. Finally, it addresses the attribute-based and performance-based resilience metrics to provide a more generic classification of reported metrics in the literature.

2.1.3.1 Risk-based metrics

In the firstly reported studies on resilience, average or expected metrics (e.g., expected energy not supplied) were used for quantifying resilience. However, there is a consensus in the power system community now that these metrics do not accurately quantify the effects of tail risks (i.e., risks that lie in the tail of a probability distribution of a performance indicator, e.g., energy not supplied). In this context, there is an increasing interest in the use of risk-based metrics, namely value at risk (VaR) and

Conditional Value at Risk (CVaR). VaR measure quantifies the extent of possible losses within a portfolio, whereas CVaR considers only those scenarios representing the worst cases. CVaR indicates the average or expected value across worst-case scenarios, those at the tail of the distribution which lie beyond ENS=v, as illustrated in Figure 2, which takes the example of the amount of Energy Not Supplied (ENS) as the resilience metric, where the value provides an explicit risk indication and (1- α) indicates the size of the considered set of worst-case scenarios.

The expected value of ENS is evaluated by considering all the credible sets of scenarios (i.e., the most likely single events that are included in a contingency analysis, hence lying around the mean value of Figure 1), that could disregard in averaging, the non-credible worst-case outages (i.e., events that are less likely to occur based on the traditional contingency analysis). Therefore, the mean value is used for reliability assessment, whereas its CVaR is used for resilience assessment. The mean and conditional values of the selected metrics are given in equations (1) and (2) (and further illustrated in Figure 2) [28], where *D* corresponds here to the worst-case deviation, *v* the deviation corresponding to the VaR, α corresponds to probability of the ENS=v, and x corresponds to the value of ENS:

$$Mean \ = \int_0^D x \cdot f(x) \cdot dx \tag{1}$$

$$CVaR \ = \frac{1}{1-\alpha}\int_v^D x \cdot f(x) \cdot dx \tag{2}$$

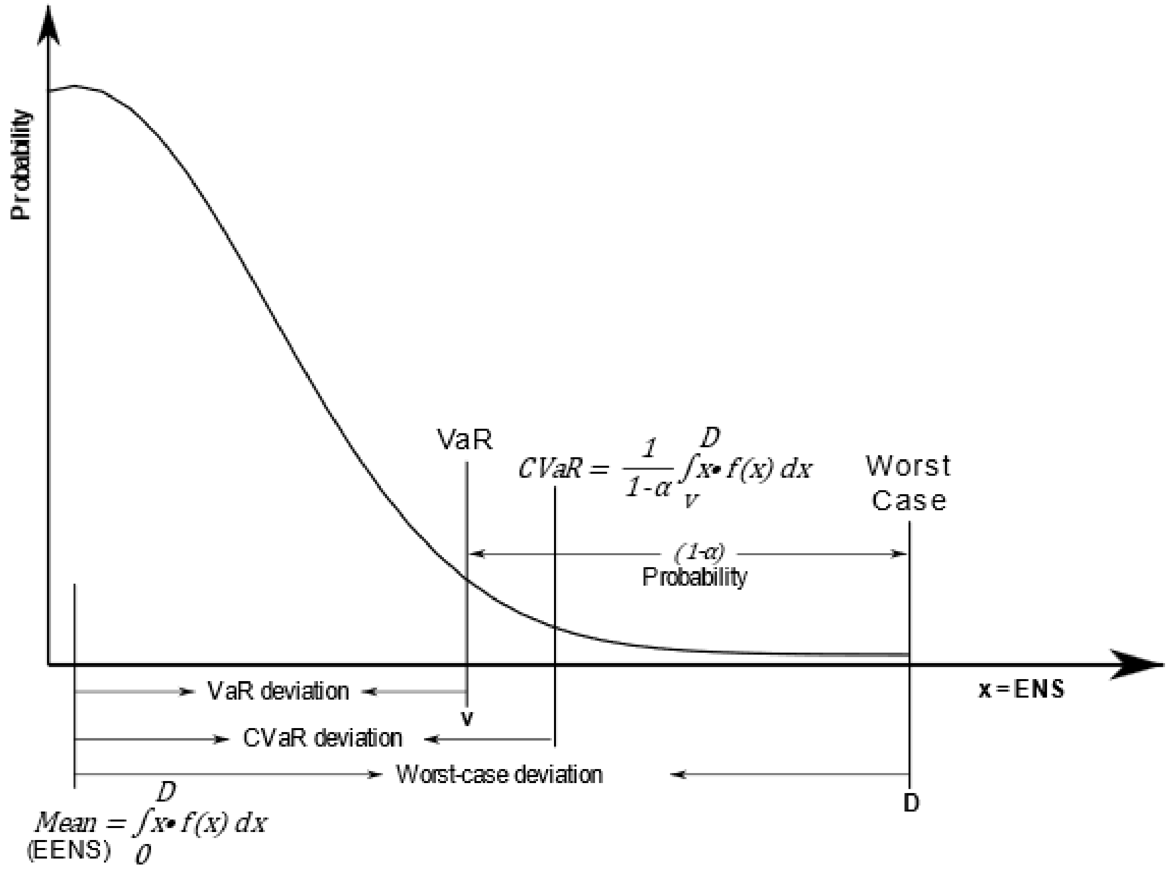


FIGURE 2: RISK-AVERSE RESILIENCE ASSESSMENT [28].

2.1.3.2 Time-Dependent Metrics: The FLEP Metric System

The multi-phase resilience trapezoid [29], shown in Figure 3, indicates the power system resilience during the event as a function of time, quantified by the resilience indicator. Moreover, this figure depicts a system’s operational and infrastructural resilience using the resilience indicator. Here, as the name suggests, operational resilience refers to the ability of the system to ensure an uninterrupted power supply to customers in the face of an event. Infrastructural resilience refers to the physical capability of a power system to withstand the shock and impacts of the external severe event, and maintain the functionality of big portion of the network.

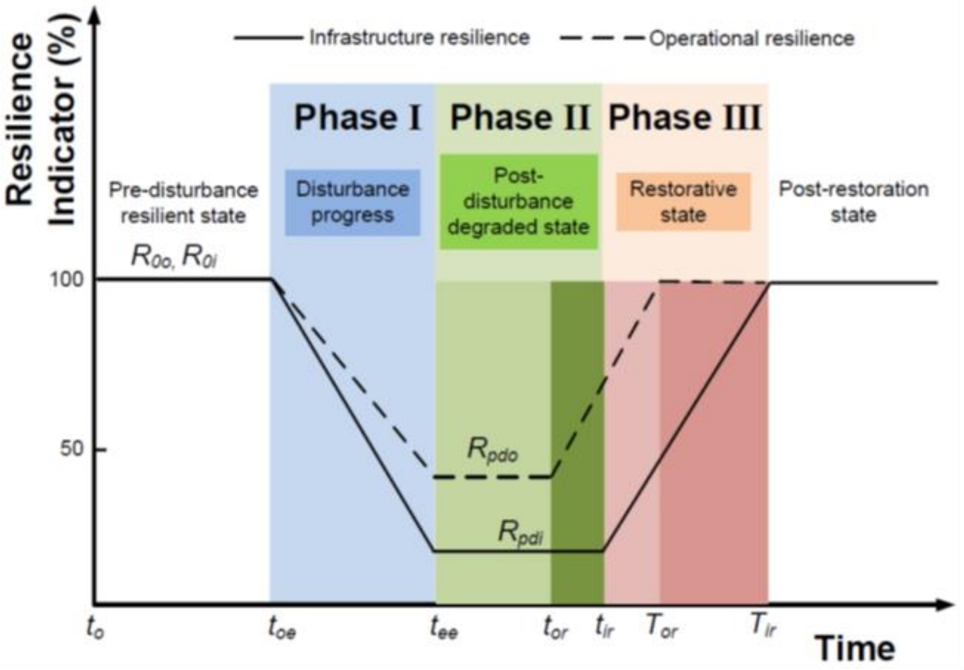


FIGURE 3: MULTI-PHASE TRAPEZOID FOR OPERATIONAL AND INFRASTRUCTURE RESILIENCE [29].

To quantify the resilience of a power system, it is critical to define a set of metrics capable of capturing its performance during the different phases of the resilience trapezoid. The FLEP resilience metrics (as first published in [27]) quantify the system state during each phase shown in Figure 3:

(1) for phase (I): the rate at which the resilience drops is measured,

(2) for phase (I)I: the extent to which the system is degraded is measured and

(3) for phase – III: the promptness of recovery is measured.

It is worth noting that the resilience level or performance of the network might be lower or higher compared to the pre-event state, which highly depends on the actions applied by the system operator and the resources available to withstand and recover from the event.

The mathematical formulation of these metrics is tabulated in Table . For confirmation here, the F-metric shows how fast resilience drops in Phase 1, the L-metric shows how low resilience drops in Phase 1, the E-metric shows how extensive Phase 2 is before the restoration is initiated, and the P-metric shows how promptly the restoration is completed. The “& of network” in the infrastructure resilience indicates the amount of transmission or distribution network that is damaged in Phase 1 (the F and L metrics) and how much of this network is recovered in Phase 3 (the P-metric).

TABLE 4: MATHEMATICAL FORMULATION OF FLEP RESILIENCE METRICS [29].

Metric	Mathematical Expression		Measuring Unit	
	Operational	Infrastructure	Operational	Infrastructure
F	$\frac{R_{pdo} - R_{0o}}{t_{ee} - t_{oe}}$	$\frac{R_{pdi} - R_{0i}}{t_{ee} - t_{oe}}$	MW/hrs	% of network/hr
L	$R_{0o} - R_{pdo}$	$R_{0i} - R_{pdi}$	MW	% of network
E	$t_{or} - t_{ee}$	$t_{ir} - t_{ee}$	Hrs	Hrs
P	$\frac{R_{0o} - R_{pdo}}{T_{0r} - t_{or}}$	$\frac{R_{0i} - R_{pdi}}{T_{ir} - t_{ir}}$	MW/hrs	% of network/hr

The *F-metric* in *Phase I* is evaluated by estimating the slope of the resilience degradation during the event (where t_{oe}-t_{ee} is the duration of the windstorm, *i.e.*, $t_{windstorm}$), while the *L-metric* is defined by the resilience degradation level, i.e., R_{0i}-R_{pdi}, and R_{0o}-R_{pdo} for the infrastructure and operational resilience respectively. The *E-metric,* showing the time that the network remains in the post-disturbance degraded state (*Phase II*), is given by t_{or}-t_{ee} and t_{ir}-t_{ee}, for operational and infrastructure resilience, respectively. The *P-metric* in *Phase III* is defined by the slopes of the operational and infrastructure recovery curves, which consider both the original pre-event resilience level and the time required for reaching this resilience level.

2.1.3.3 Attribute-based and Performance-based Resilience Metrics

Risk-driven metrics provide insights by processing large amounts of data, and generating and analysing probability distributions of different metrics, but they provide limited information on the actual performance on the system during and/or after the event. Complementing risk metrics, resilience metrics can provide such information, and they are usually either attribute-based (qualitative) or performance-based (quantitative) [30], [31].

Attribute-based resilience metrics aim to identify the properties of a system that make the system more or less resilient, such as robustness, resourcefulness, adaptivity, and recoverability. Resilience is then assessed as the degree to which these properties are present within a system. Methods for determining attribute-based resilience metrics include, for example, site visits and questionnaires [32]. This may also include scoring based on qualitative assessment where direct quantitative assessment is not possible. The Argonne National Laboratory's Resilience Measurement Index, which assesses a system's resilience based on scoring of four major components (preparedness, mitigation measures, response capabilities, and recovery mechanisms) is an example of an attribute-based resilience metric [32].

Performance-based resilience metrics (i.e., metrics that measure the behavior, response and performance of a business, organization or infrastructure) are based on quantitative data probabilistically describing the system's behaviour in the event of a disruption. The data may come from historical observations, estimates, or modelling, including data on both the system performance and the asset performance (e.g., through fragility curves) under stressed conditions.

Performance-based metrics are particularly useful for cost-benefit and planning analyses, as they provide a direct evaluation of potential benefits and costs of enhancement measures or investments [30]. Performance metrics are directly related to the performance of the power system, including the availability of generation and the servicing of the load, the duration, frequency and probability of disruptions, and the time-evolution of these characteristics. The latter is often done in the form of a resilience triangle or resilience trapezoid (Figure 3) [1].

The resilience of an infrastructure can be measured by quantifying the area of the resilience triangle and trapezoid respectively, enabling targeted resilience enhancements aimed at minimizing this area. For example, robustness measures for hardening the transmission system can be applied to reduce performance degradation in Phase 1 of the trapezoid (hence reducing the overall area of the entire resilience trapezoid), or more efficient restoration strategies can be adopted to accelerate the restorative phase of the trapezoid (reducing the area under Phase 3). The U.S. Department of Energy has recently funded the "North American Energy Resilience Model" project which aims to improve model-based insights in relation to resilience, quantifying and evaluating the resilience performance of the US critical power infrastructure [33].

2.1.4 Events of interest for R&R assessment

Deliverable D2.1 [34] discusses some of the root causes, responses, and system consequences that are considered of greatest relevance and importance to future hybrid AC/DC system.

Root causes of events and disturbances are difficult to characterise completely: there are many different causes, and they often overlap. Root causes have been classified into routine faults, extreme natural events, common mode failures and physical and cyber-attacks. The extent of the impact of an HILP event also depends on several factors, such as the location and intensity of the event. Some possible extreme natural events and cyber-attacks are listed below ([35], [34]):

- High winds during storms and hurricanes can lead to faults and damage to overhead transmission and distribution lines, either by debris being blown against the lines or even a tower collapse in extremely high winds.
- Rain and floods do not pose a danger to overhead transmission lines, but to substation equipment, such as switchgear and control cubicles. The combination of rain with strong winds or lightning can however be a significant threat to overhead lines
- Lightning strikes on or near overhead conductors can also cause short-circuit faults, which will trigger the protection systems and the disconnection of lines. Such faults are usually transient and are thus rapidly restored to service. However, the voltage surge caused by the strike may be transferred along the line and cause damage to equipment, such as transformer windings.
- Wildfire events can significantly affect all assets of a power system, including transmission and distribution networks [36], as well as the generation system. With regard to overhead transmission and distribution systems, excess heat may greatly decrease the transfer capability of lines, while intense smoke may result in multiple transient outages of the lines, significantly reducing their reliability.
- High temperatures and heat waves limit the transfer capability of transmission lines, and increase energy losses and line sagging.
- Cold snaps, heavy snow and the accumulation of ice can also cause the failure of overhead lines and towers. Under freezing conditions, ice and snow may gather on insulators, which bridge the insulators and provide a conducting path, resulting in flashover faults.
- So-called "Dunkelflaute" conditions refer to prolonged periods of calm winds and overcast conditions, with the knock-on effect of resultant low wind and solar output in grids. Although a type of extreme weather condition, this will not damage the infrastructure, but it will put stresses on the system in terms of how energy needs to be moved around.

- Cyber-attacks on the information and communication infrastructure can create different security issues to the power system infrastructure, such as a lack of observability and controllability of actuators across the system (cyber-attacks will be covered by WP3 in the HVDC-WISE project).

The impact of any event very much depends on the responses from the multitude of devices connected to the power system. In future hybrid AC/DC systems, the overall system response will be strongly affected by the behaviour of HVDC schemes, particularly the converters at the interface between the AC and DC networks. Undesired responses including underdamped oscillations, sub-synchronous torsional interactions, control interactions, converter blocking, common-mode protection and control responses, etc., may appear and must be accounted for.

Depending on the nature and severity of an event or disturbance, and the responses of connected equipment, there could be a range of system-wide consequences that will affect transmission system performance. Examples include overvoltage in off-shore evacuation networks, system splits, etc.

2.2 Academic background on transmission planning

In designing future power systems capable of meeting decarbonisation goals, consideration must be given both to the investment costs of the infrastructure as well as the operability and reliability of the system. This requires an optimised planning process for electricity generation and transmission system development.

One of the main objectives of long-term electrical transmission systems planning is the determination of location for new investment in lines and substations in the transmission grid. Investment and operational costs should be minimised as far as possible while, at the same time, requirements for stability, security of supply, and environmental aspects need to be met[37].

In this context, numerous academic Transmission Expansion Planning (TEP) approaches have been developed to support optimised transmission and generation expansion planning and correspondence to future requirements of the electricity supply system. These academic approaches consider different aspects and objectives in the optimisation of expansion planning [37].

Among others [37], [38], [39], [40], [41] are examples of a state of the art literature with regard to research conducted on expansion planning techniques for electrical transmission systems.

TEP is concerned with solution methods and modelling approaches, aspects of system reliability, aspects of system resilience, consideration of electricity markets, uncertainties, environmental influences, possible congestion and congestion management techniques, as well as reactive power planning or the consideration of equipment such as modern HVDC converters or FACTS, to name several of the aspects that have been considered in this vein of research [37].

Beyond a general overview of the different possible aspects within the TEP, various relevant aspects can be reflected based on the academic background in the development of the tools to be used in HVDC-Wise integrating hybrid HVAC/HVDC structures into the expansion planning process. This involves, for example, aspects related to reliability and resilience. In the literature, various indicators for evaluation and corresponding model formulations are presented, which allow supply and failure security aspects to be integrated into the development of the tools. Consideration of congestion management and the allocation of reactive power and its planning can also be further developed, based on the state-of-the-art literature, to comprehensively assess the resulting benefits and risks of hybrid grid structures.

2.2.1.1 Formulation and Overview

TEP problems can usually be approximated as large, mixed-integer non-linear optimization problems. This problem formulation can typically be structured into the objective function and the equality and inequality constraints limiting the model [37]:

$$\min_{\boldsymbol{x}} z(\boldsymbol{x})$$

$$\boldsymbol{f}(\boldsymbol{x}) = 0$$

$$\boldsymbol{g}(\boldsymbol{x}) \leq 0$$

In the objective function, cost-specific values are defined, in particular, to minimise the sum of investment and operating costs for the construction of new lines and equipment and the cost of operating the system in compliance with prevailing reliability standards. Technical and physical limits of the system components, the fulfilment of the supply task as well as other boundaries can be considered in the problem constraints. Modern collocation methods even hold the promise of incorporating nonlinear system dynamic responses into optimization frameworks. The particular aspects to be considered can be specified within the framework of the TEP by varying the objective function as well as the constraints [37].

TEP problems can be formulated statically, assuming that all modifications and extensions are realized simultaneously, or dynamically, considering individual time steps for the modifications and extensions. Besides the solution method, TEP problems differ, for example, in the type of input data and the underlying uncertainties. These uncertainties can be addressed with deterministic as well as non-deterministic approaches [41].

2.2.1.2 Solving Methods

Solution methods for TEP formulations can generally be divided into mathematical or meta-heuristic methods [37].

Mathematical optimisation methods include linear and non-linear programming as well as mixed-integer solution approaches and decomposition approaches such as Bender's decomposition or dynamic programming. Meta-heuristic optimisation methods include nature-analogue methods such as particle swarm optimisation, ant colony, bee algorithm or artificial immune system as well as genetic algorithms or artificial neural networks [37].

Within the framework of academic research, certain advantages and disadvantages are described for each of the approaches. While mathematical methods generally achieve a solution with appropriate convergence, the optimisation models are particularly oriented towards static investigations. Dynamic and advanced investigations can be implemented and executed much more easily using heuristic methods, but the search for solutions involves approximations and the algorithms might remain in local minima. Meta-heuristic optimisation methods might provide poor convergence behaviour and long runtimes [37].

2.2.1.3 Uncertainty

TEP problems are often associated with existing uncertainties regarding input data and modelling. Existing uncertainties that are investigated in the TEP studies include [37]:

- Load and price forecasts
- Availability of resources
- Approximations and simplifications in modelling
- Markets, fuel availability and costs
- Forecasting the generation of renewable energy plants
- External influences such as political decisions
- Environmental influences

Considering existing uncertainties, mathematical methods based on probabilistic models, fuzzy methods and Monte Carlo simulations can be used to address the uncertainties in TEP problems. This, however, requires sufficient knowledge about the nature of the uncertainty to characterize it with a distribution for a stochastic variable or a fuzzy set [37].

2.2.1.4 **Reliability**

To ensure the reliability of future grid structures, aspects of adequacy, security and reliability are considered in optimised grid expansion planning. Generally, reliability and adequacy are analysed in the first step, and stability and failure analyses are applied afterwards. Reliability requirements can be integrated within TEP modelling frameworks by integrating different quantities as part of the objective function and constraints. Common quantities, as described in Section 2.1.2, used in system analysis are [37]:

- Loss of Load Expectation (LOLE)
- Expected Energy Not Supplied (EENS)
- Loss of load probability (LOLP)
- Loss of load cost (LOLC)

Taking reliability into account, [42] describes a probabilistic model for generation and transmission expansion planning that considers reliability criteria, and accounts for random generator or line outages based on historical outage rates. In addition to installation and operational costs, the model includes the cost of EENS. One objective is to minimize the cost of operation and installation. System reliability is the second objective, minimizing the level of EENS. The model is tested on a modified 6-bus test system, the IEEE 24-bus RTS, and the IEEE 118-bus test system [42]. System reliability was also considered within the European project E-HIGHWAY, by including stochastic scenarios that describe either generation or transmission contingencies within the TEP objective. The model was tested on a reduced Continental Europe grid with 1025 nodes [43].

2.2.1.5 **Resilience**

In order to find the optimal configuration of a transmission grid while considering security constraints, resilience, and robustness, the corresponding constraints are integrated into TEP problems. This may include consideration of indices and constraints to ensure N-k security, and further reflect the system restoration after extreme contingencies, as well as preventing cascading failures in N-1 situations. The N-k criterion is practically often limited to single or a defined set of contingencies. In this context, [44] [44] deals with the influence of security constraints (N-1 contingencies) on TEP modelling. However, formulations that consider only individual failures, are not necessarily sufficient when it comes to exceptional contingencies or cascading failures [45].

The consideration of cascading outages, such as HILP events in resilient grid expansion planning is therefore also the subject of current research, aiming to minimise supply interruptions comprehensively [45].

In [45] the presented Resilient TEP (RTEP) minimizes the impact of cascading outages. In this context a multi-stage solution process based on Bender Decomposition is used to investigate investment decisions and security. Constraints, which consider the N-1 criterion, are therefore integrated into the model formulation and the impact of cascading line outages is considered using a blackout simulation model to address the system resilience. The applied problems are formulated as Mixed Integer Programming optimization models and the presented RTEP is tested on the IEEE 24-bus system [45].

Another approach to minimize the impact of cascading failures and increase the resilience of the transmission system under consideration of the effect of renewable energy systems and energy storage systems in critical transmission grid situations. is presented in [46]. Using a non-linear, non-convex, large-scale problem formulation, a combination of different meta-heuristic techniques is applied to increase the performance of the solution process and to address the computational effort solving large-scale non-linear TEP problems. Maintaining the operating limits as well as the physical constraints is modelled while simulating initial events as triggers for cascading failures [46].

2.2.1.6 Congestion Management

To ensure secure operation congestion management is essential and industry practice. TEP presents a long-term instrument to resolve congestions. Within TEP formulations transmission congestion can be implemented with different objectives. Thus, both operating costs in the course of congestion management, as well as line utilisation and available transmission capacities, can be analysed and optimised within TEP processes [37].

To address the challenging time efforts associated with analysing the different conditions under which the system operates for each expansion variant, a corresponding approach is presented in [47] in which a clustering algorithm is presented to identify a representative set of operational conditions to both improve the accuracy of the planned investments and ensure applicability of the expansion planning to real-scale transmission system structures [47] .

2.2.1.7 Power Flow Modelling Options

There is the option to model TEP problems using either DC or AC power flow models. DC power flow models contain significant simplifications compared with AC models, which can have runtime advantages due to the reduced complexity. However, it is significantly more difficult to represent power losses in DC models. In addition, reactive power considerations cannot be integrated into DC formulations [37].

Modelling the TEP as an AC model usually leads to complex non-linear problems, which require advanced and efficient solution techniques or a reduction of the model complexity by limiting, for example, the operating conditions, considered contingencies or expansion options. However, in AC modelling, for example, FACTS can be integrated and power losses can be captured. In addition, reactive power can be considered as an additional parameter in the AC based TEP. In this way, reliability can also be evaluated regarding reactive power and, based on this, further investigations can be carried out, for example, on voltage stability [37].

2.2.1.8 Reactive Power Planning

The consideration of reactive power in the TEP process can have a major impact on an optimisation result. On the one hand, reactive power flows on transmission lines can reduce the active power transmission capacity of the lines and require the expansion of further lines and additional congestion management. At the same time, an appropriate allocation and provision of reactive power can increase the transmission capacity of the lines and reduce line losses, and in the course of the TEP, fewer lines may need to be built. If reactive power-related variables are considered in the TEP, this can also be used as the basis for inclusion of stability studies, e.g. voltage stability [37].

In [48] the presented TEP model provides a linear representation of reactive power, off-nominal bus voltage magnitudes and grid losses. The linearized AC model is a MILP formulation with an iterative approach to include the (N-1)-criterion within the planning process. Garver's 6-bus system is used to test the presented TEP model and the iterative approach considering the contingency criterion is applied on the IEEE 118-bus system [48].

Linearizations and approximations regarding the representation of the reactive power flows can result in problems in the accuracy of the solutions but the exact representation of AC-TEP problems requires high computation times due to the inherent non-linearities and non-convexities. To obtain a sufficiently accurate AC power flow representation while maintaining acceptable computation times, a mixed integer quadratically constrained quadratic program is presented in [49] together with applied pre-solve techniques. While both voltage magnitude and angle are represented quadratically constrained, the approach achieves comparatively high solution quality by reducing constraint relaxation errors in the course of pre-solving. The presented approach was tested on IEEE 24-bus and IEEE 73-bus systems [49] .

2.2.1.9 HVDC/HVAC

The increasing use of HVDC technologies for the transmission of large amounts of energy in offshore and onshore transmission, requires an expanded approach within TEP. For expansion and planning strategies, it is essential to consider the technical and operational characteristics of HVDC systems, which differ significantly from the characteristics of AC systems, so that the integration of HVDC systems can be comprehensively assessed [41].

The possibility of power flow control by HVDC systems also requires an advanced consideration in optimisation problems compared to AC lines, as the controllable power flows of HVDC systems can be considered as an additional variable in the models [41].

In [50] a TEP is modelled as a mixed-integer linear programme, while HVDC and HVAC technologies are considered in the model. Security constraints are taken into account, as well as the operating costs of the system, and the HVDC lines could be monopolar or bipolar. The presented MILP model was tested using the Southern Brazilian power grid [50].

Table 5 gives an overview of various academic publications and the aspects they consider in relation to TEP approaches involving HVDC technologies [41].

TABLE 5: OVERVIEW OF THE LITERATURE ON TEP INCLUDING HVDC.

	Grid type		**Topology**			**Time horizon**		**Solving Method**			**Objective**
Ref.	**AC**	**DC**	**Radial**	**Linear**	**Meshed**	**Strategic Planning**	**Operative Planning**	**Mathematical**	**Heuristic**	**Simulation**	
[51]	X	X			X		X	X	X	X	Min. cost
[52]	X	X	X		X	X		X			Min. dispatch and investment cost
[53]	X	X	X		X	X		X			Min. planning cost and power losses
[54] [50]	X	X			X	X		X	X		Min. investment and operation costs and losses
[55]	X	X	X		X	N.A.	N.A.	X	X		Min. losses
[56]	X	X			X	X		X	X		Min. investment, load shedding and operation cost
[57]		X	X		X	X		X			Max. social welfare and min. investment cost
[58]	X	X	X		X	X		X	X		Min. investment & operation cost
[59]	X	X			X	X		X			Min. cost and losses
[60]	X	X			X	X		X	X		Min. cost and losses
[61]	X	X			X	X		X	X		Min. cost and losses
[62]		X			X	X		X	X		Max. social welfare and min. investment cost
[63]	X	X	X		X	X		X			Max. social welfare and min. investment and operation cost
[64]	X	X			X		X	X	X		Max. social welfare and min. investment and operation cost
[65]	X	X			X	X		X	X		Max. social welfare and min. cost

[66]	X	X	X	X	X	N.A.	N.A.			X	Min. losses
[67]	X	X	X		X		X			X	Max. social welfare
[68]		X	X		X	X				X	Min. losses
[69]	X	X	X	X	X	X		X	X		Min. cost
[70]		X			X		X	X	X		Max. social welfare and min. transmission cost
[71]	X	X			X	N.A.	N.A.			X	Power flow study
[72]		X			X	N.A.	N.A.			X	N-1 security study
[73]	X	X	X		X	N.A.	N.A.			X	Transient and small-signal stability assessment
[74]	X	X			X		X	X			Min. installation cost and small signal stability

In addition to approaches that only model DC systems, the overview table refers to several scientific studies that consider hybrid grid structures, i.e. both DC and AC grids. The overview distinguishes between radial, linear and meshed grid topologies in the studies.

While most of the studies listed in the overview focus on strategic planning, there are also studies, such as [52], which refer to operative planning. Considering the size of the operative optimization model, a simultaneous evaluation of expansion decision is generally challenging, so an iterative approach is presented in the paper in which the algorithm identifies expansion measures based on the operative optimization model, and the impact of these measures is iteratively evaluated in the operative optimization. The approach is applied and tested on a real scale transmission system in Northern Europe [52] .

Besides mathematical optimization and heuristic solution methods, studies with dynamic simulation techniques (e.g., RMS-type or EMT-type) are presented, which for example are used to evaluate topologies under stability aspects. For the definition of the objective function, various criteria are considered in the studies. In addition to cost minimization, for example aspects of N-1 security are also integrated, as well as the reduction of grid losses [41].

According to [41], the planning criteria for HVDC systems or hybrid HVAC/HVDC systems should include reliability-related criteria such as N-1 security or available capacity as well as loss reduction or reduction of investment and operational costs. Planning approaches must also consider uncertainties in, for example, renewable energy generation or consumption, as well as the need to reduce renewable energy curtailment. Furthermore, the control capabilities of HVDC systems should be considered in planning to capture the value of this available flexibility in addition to traditional cost analyses. The consideration and implementation of DC protection systems and their costs and characteristics is also an important aspect of transmission expansion planning for HVDC systems [41].

2.3 TSO perspectives on R&R transmission planning for AC/DC grids

The structural transition towards climate-neutral power generation is changing the generation profiles within power systems. Conventional power plants located close to loads are being shut down and power electronic-interfaced power plants are being built to replace them. In addition, FACTS and HVDC connections are integrated into the system. Therefore, system behaviour is increasingly dominated by power electronics.

For the planning and operation of HVDC systems, a large number of stability aspects have to be taken into account. For example, the EU regulation from 2016, outlined in [75], already defines a network code with requirements for grid connection of HVDC transmission systems. These serve to harmonise rules for HVDC systems, to provide a clear legal framework for grid connections, facilitate EU-wide trade in electricity, ensure system security, facilitate the integration of renewable electricity sources, increase competition, and allow more efficient use of the network and resources, for the benefit of consumers [75].

To perform R&R oriented transmission expansion planning with respect to hybrid AC/DC systems in the future, the requirements for grid connection of HVDC systems already defined must be considered. In addition, the ability to withstand high frequency gradients, grid-supporting requirements, like reactive power control and frequency support must be taken into account in the planning of HVDC systems [75]. Grid-supporting requirements for, and potential limitations of, power electronic systems are explored further in the following sections with reference to [75].

2.3.1.1 Active power control

The following set of requirements are applicable to HVDC systems with respect to control of active power:

If specified by the TSO, an HVDC system shall be capable of providing synthetic inertia in response to frequency changes, activated in low and/or high frequency regimes by rapidly adjusting the active power injected to or withdrawn from the AC network to limit the rate of change of frequency. [75]

- If required, HVDC systems shall be equipped with a power-frequency controller, which modulates the active power output as a function of frequencies at all grid connection points of the HVDC system.
- The provision of frequency sensitive mode depending on the parameters specified by the respective TSO to adjust active power transmission. In addition, Limited Frequency Sensitive Modes –Overfrequency/Underfrequency (LFSM-O/U) must be realized.

2.3.1.2 Reactive power control and voltage support

The following set of requirements are applicable to HVDC systems with respect to control of reactive power and provision of voltage support:

- Capability to provide fast fault current at a connection point in the case of a symmetrical fault and, if specified by the TSO, an asymmetrical current injection in case of asymmetrical faults.
- Thresholds for reactive power capability at the connection point, with different control modes including
  - Voltage control mode
  - Reactive power control mode
  - Power factor control mode

Fault Ride Through (FRT) capability to stay connected to the network and continue with stable operation after a fault occurs.

2.3.1.3 Risks and limitations

In addition to the grid-supporting requirements for an HVDC system and its benefits for the AC system that already exist today, there are, however, some risks which need to be considered. For example, regarding Frequency Containment reserve (FCR), the worst case of active power deficit for the AC grid could be due to failures in the HVDC systems.

Potential limitations in HVDC systems and converters in comparison to synchronous generators must also be taken into account to address security and resilience during planning. Such limitations include:

- Power electronics are not able to withstand high overloads; thus, current limitation needs to be implemented, which leads to a limited capability (and non-linearity) in the provision of short circuit current.
- The behaviour of a converter depends on control and automatic protection at different control levels.
- The risk of control interaction with other converters that are electrically close.
- It is important to ensure that models used for simulation correspond to real device behaviour to ensure predictability and that the models align with different stability phenomena.
- Typically, there is almost no reactance in HVDC circuits or grids, so the propagation of faults is much faster than in AC grids. This means that any DC fault will have an impact on all connected AC systems (with interaction via each converter). This new phenomenon of very widespread fault impact needs to be assessed.

- For the provision of inertia, additional stored energy may be required (e.g., in a supercapacitor).

In the context of R&R-oriented transmission expansion planning, the aforementioned advantages of HVDC systems as well as their limitations must be reflected by appropriate selection of constraints, e.g. to consider the provision of synthetic inertia. In addition, existing assets (e.g. point-to-point HVDC links) must remain operable within their capabilities, which may be an additional requirement for planning of HVDC systems. Furthermore, different requirements for the HVDC system can arise depending on the use cases and HVDC architectures to be considered. This may require prioritizing or weighting the requirements.

At the same time, the planning procedures of hybrid AC/DC systems must be applicable on realistic use cases (e.g. Continental Europe/Great Britain/Nordic), meaning that appropriate simplification of constraints and complexity reductions might be necessary. For example, stability indicators can be used to consider stability aspects within transmission expansion planning formulations. These stability indicators (e.g. Sensitive Factor Index (SFI), Short Circuit Ratio (SCR), modified Multi Infeed Interaction Factor (mMIIF)) can be obtained on the basis of preliminary investigations and static calculations, which require less computational effort compared to full-scale stability analyses. However, this requires detailed investigations of the robustness of these stability indicators.

The effective development of future hybrid AC/DC systems, with HVDC as the dominant sources, will require the updating of codes and standards as well as various other forms of industry collaboration. It may be appropriate for system planning to become more centralized than it has been in recent years as the challenge of coordination and finding the most cost-effective solution becomes more difficult. Effective system planning requires suitable models and data to support simulation and analysis. HVDC schemes connected over long distances are likely to affect multiple TSO areas and it will be necessary that models and data are shared to allow joint assessment of impacts.

2.4 ENTSO-E approach to transmission planning

ENTSO-E (European Network of Transmission System Operators for Electricity) is the organization responsible for the development of the Ten-Year Network Development Plan (TYNDP) [76]. This plan provides an overview of the European energy system and identifies the investments needed to ensure the security of supply, maintain the current level of service, and meet the EU's energy and climate goals. In this way, Transmission Expansion Planning (TEP) at regional and pan-European level is conducted by ENTSO-E following a series of steps, as presented in Figure 4. Note that the planning framework described in section 3 is essentially a cost benefit analysis (CBA).

FIGURE 4: ENTSO-E APPROACH TO TRANSMISSION PLANNING

The first step on TYNP is to establish the scenarios that will be considered over the process. The starting grid is considered as of 2025 (from previous TYNDP and projects under construction), and a Pan-European market modelling database is considered for the planning horizon. The TYNDP 2020 study used three climate years in market simulations. A climate year describes a climate condition. However, ENTSO-E plans to use up to 10 climate year simulations to address the identification of system needs in studies for 2040, recognising the increasingly important role that weather and climate will have in the planning and operation of future power systems.

The identification of system needs is the second step of the TYNDP process [77]. It involves an evaluation of the current and future needs of the electricity transmission network, based on both the electricity market and technical developments. This evaluation is done at both a regional and a European level and takes into account the different scenarios for the development of the electricity markets, the evolution of transmission technologies, and the development of renewable energy sources.

The third step is the collection of projects to produce a final list of candidate options to be analysed in the CBA. When the system needs are identified in step 2, TSOs propose the best alternatives to address those needs. Even though the needs were identified using cross-border capacity and flexible candidates, the solutions for those needs must consider environmental and economic impacts, and non-wire solutions can be suggested. Only when no other alternative is feasible, new investments are considered.

The fourth step is to evaluate projects using four types of indicators: project costs, CBA market indicators, residual impact indicators, and CBA network indicators. CBA market and network indicators are obtained from market and network studies, respectively, while project costs and residual impacts are obtained without the use of simulations. Finally, the selection of candidate projects is conducted based on the assessed performance of all the indicators over the CBA.

3. Conceptual architecture for R&R-oriented planning and operation

3.1 Objective

HVDC-WISE addresses the planning of HVDC links or grids, with suitable consideration of R&R in terms of various techno-economic indices. A major objective is to develop a **methodology and tools for reliability and resilience (R&R)-oriented planning of hybrid AC/DC power systems, including operational aspects**. The aim is to allow for the assessment and comparison of different HVDC architectures[1], accounting not only for typical planning techno-economic indices achieved with long term static simulations, but also security and resilience indices, in addition considering the opportunities and challenges associated with HVDC grids. By elaborating the R&R indices, comprehensive Cost-Benefit Analyses (CBA) of the HVDC projects can be carried out.

The approach must apply to HVDC solutions aimed at (1) connecting asynchronous AC systems, and/or (2) building a DC “overlay” (also referred to as Supergrid) embedded in an existing AC transmission grid.

Overall, the following steps are required:

a) Design an overall approach (architecture) for integrated R&R assessment, by adapting, evolving, and building interactions among existing methodologies adopted for adequacy, security, and resilience assessment. Combine them into a consistent workflow considering the specificities of HVDC in the different stages.
b) Build a high-level platform for the overall process management; update and expand the current tools to implement the workflow: adding new functions and integrating the missing HVDC modelling aspects.
c) Specify how the R&R assessment methodology can be used to assess and compare HVDC architectures in line with CBA approaches.

Concerning item a), elaborating an integrated and consistent view of R&R assessment is a challenge even without considering HVDC, because of the separation that has been maintained so far between different contexts, approaches, and tools. This task took advantage of detailed analysis of the definitions of adequacy, security and resilience, pointing out their relationships and differences, as in [34],which outlines the most recent contributions of the international literature on this topic. The specific focus of HVDC, for bi-terminal and especially multi-terminal grids, adds further complexity to the power system modelling requirements and the way these models are dealt with in R&R evaluations.

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[1] It is recalled that within the scope of the project, “HVDC architecture” refers to the combination of purpose, embedment level (connection), topology and configuration, technological components, operation algorithms (operational functions), deployment plan [78], [34]. Hence, for instance, two solutions only different for a parameter are considered two different architectures.

The two major upgrades with respect to conventional approaches and tools for assessing individual aspects of R&R are thus:

- The development of an integrated view of R&R;
- The specific contribution of HVDC grids considered in each of the R&R aspects.

Items a) and c) above are outlined in the sequel of this section and will be further developed in task 6.1 of WP6. Item b) is broadly addressed in WP5 and by WPs 3 and 4.

Due to the complexities inherent with R&R evaluations in planning, the resulting tool will provide indices which will enable the ranking and comparison of different predefined candidate "HVDC architectures", although it will not consider an automatic selection of candidates. This will be further clarified in the following subsections.

3.2 Design dimensions

DC grid planning includes several technical dimensions, such as (see also [78], [34], [79]):

1. **Grid configuration, connection, rating:**
   - DC grid topology
   - connection to existing AC or DC terminals
   - Voltage and power rating
2. **Technology and configuration of the DC solution:**
   - Converter topology (e.g. full-bridge vs. half-bridge)[2]
   - Circuit configuration (monopole or bipole, earthing arrangements)
   - Components associated with the configuration and protection solution (DC circuit breakers - DCCB, fault current limiters, etc.)
3. **Control, protection, and defense:**
   - Steady state and transient (fault-on: ride through, contribution to the fault; post-fault; for faults on the DC or AC side) control strategies: active and reactive (AC side) power response and allocation among converters, AC and DC voltage regulation
   - DC and AC protection arrangements. As regards DC: fully selective with fast/slow DCCB, non-selective with DCCB or converter fault blocking capability, etc.
   - Anti-cascading control functions (firewall capability) etc.

A combination of design choices for each of the above aspects leads to what is referred to in HVDC-WISE as an "**HVDC architecture**" [78], [34] (see footnote 1 on page 35).

When dealing with HVDC grid planning decisions, the planning and design stages are more interlinked than in conventional AC grids. In fact, design aspects such as those related to protection system strategies may strongly impact on investment and operational costs, thus affecting the CBA outcomes; and different protection strategies may significantly vary from performances and cost standpoints. Hence, detailed analyses have to be performed at the planning and design levels.

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[2] It is assumed that VSC will be the reference technology since LCC presents more issues in multi-terminal grids.

3.3 Types of analysis

An interesting application for grid planners consists of "automatic" expansion planning tools, i.e. tools that select the optimal expansion plan according to specified criteria with little input from the operator, other than, for example, the provision of a list of candidate components. A preliminary objective in power system expansion planning is the identification of the areas that need to be reinforced, i.e. where the capacity should be increased. Moving from aggregated areas (as in most resource adequacy assessments) to a detailed grid (as in Production Cost Modelling or static load flow analysis), a major issue is related to deciding at which of the existing nodes new branches should be connected, or which new substations should be built. This task can be computationally very demanding in that it leads to a "combinatorial explosion" of the solutions to analyse.

Previous projects such as FlexPlan [80] and GARPUR [81] have proposed approaches that tackle this issue. However, as far as the planning of a DC grid is concerned, there may be quite more degrees of freedom, that make the application of similar approaches extremely hard from a computational viewpoint. With a possibly meshed, multi-terminal DC grid, the planning process requires not only the choice of the connection points with the existing AC or DC grid, but also the DC grid topology itself as well as all other design aspects, which may significantly impact on the CBA, hence the need to consider grid aspects in suitable detail.

For these reasons, it is proposed to assess and compare pre-defined DC grid architectures connecting areas identified according to conventional TSO practice. Grid expansion needs can be based on historical and/or prospective analyses of system operation, the latter obtained by applying OPF to simulated time series of future scenarios such as used by some TSOs (though not all - see the work of CIGRE WG C1.24, for example) and advocated by, for example, the GARPUR project[3]. As regards the selection of the specific nodes connecting the DC grid to the AC grid, several solutions can be individually analysed.

Two types of comparison among HVDC architectures can be outlined:

- Given a set of existing or planned (but which can be assumed to exist at the target time horizon) AC or DC nodes, *compare different HVDC architectures connected to these nodes*.
- Given an HVDC architecture, specified in all aspects except for the existing AC grid nodes to be connected to, and related aspects such as line lengths, *compare different solutions of the connection nodes to the existing grid configuration.*

In the former case, only the connection nodes are fixed, whereas all other features of the HVDC grid may vary, including the topology. In the latter case, the planned HVDC grid structure is defined and the comparison is carried out by testing different connection nodes.

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[3] More sophisticated methodologies have also been devised to identify suitable expansion candidates, such as the one developed in [86] that accounts for both the lines congested in the base case and the possible further congestions that would arise in case of reinforcement of the former congested lines.

3.4 Conceptual architecture

The conceptual architecture of the HVDC-WISE tool is depicted in Figure 5. A "Master platform" coordinates the overall process management. It implements the analysis workflow by managing the different analysis modules, suitably preparing their inputs and processing their outputs. The input consists of detailed models and data of the power system, R&R related information, and the predefined HVDC architectures to be analysed. Each architecture is individually assessed, assuming it is connected to the base power system model through the nodes specified by the architecture itself. The output of the platform consists of the list of detailed indicators computed for each analysed architecture. Indicators (KPIs) have been defined in WP2/WP3 [78]. In particular, ranked lists can be obtained by sorting the indicators.

The CBA related indicators are of particular interest for HVDC projects. Both HVDC architecture investment costs (CAPital EXpenditure, CAPEX) and power system operational costs (OPerational EXpenditure, OPEX) must be evaluated. Within the integrated R&R approach pursued in the project, costs related to the "lack" of resilience and security have to be accounted for as well, i.e., costs associated with the loss of supply to customers and infrastructure repair. The differences in operating costs in the cases "without" and "with" the project are usually referred to as benefits in CBA. Other indicators can be included in CBA as recalled in [81] and [78]. All of them can be computed by the different modules.

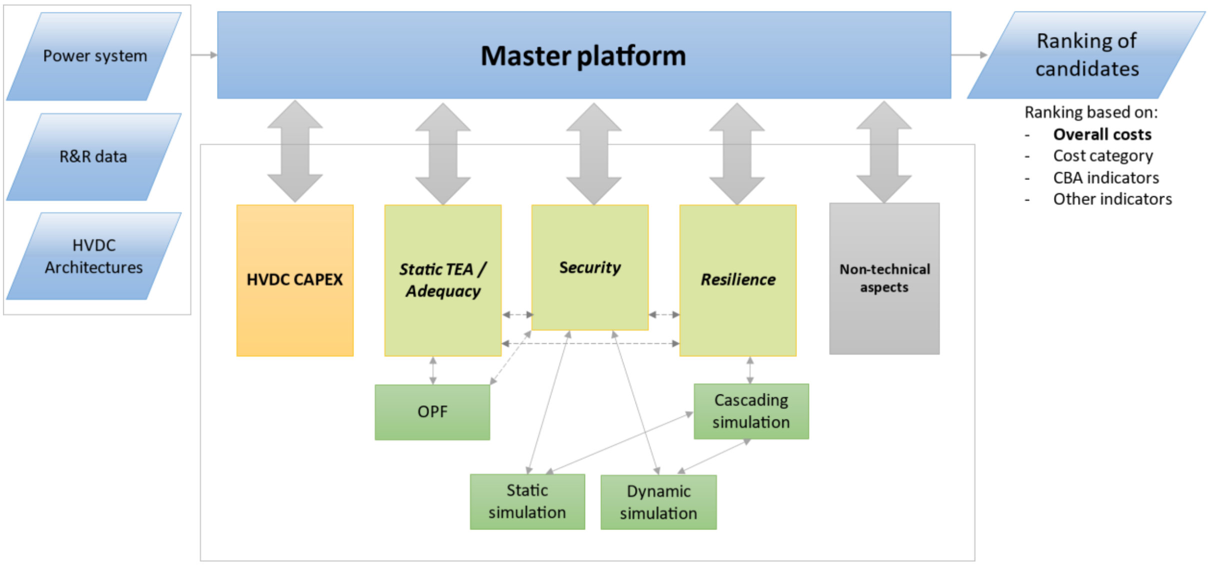

FIGURE 5: HIGH-LEVEL CONCEPTUAL ARCHITECTURE

Investment costs are a major component in CBA. It is straightforward that they depend on "macro" aspects such as overall line length, power and voltage levels, number of nodes, substation configuration, converter configuration, pole configuration, etc. In HVDC grid projects, however, investment costs may be significantly affected also by aspects such as the protection system strategy, in turn impacting on the equipment requirements. The module "HVDC CAPEX" is thus devoted to estimating the investment costs of the HVDC architecture, starting from expected costs of individual equipment or systems, combined with the amount or extent of such equipment as required by the specific architecture under analysis.

Once a HVDC architecture is deemed feasible, operating costs and other KPIs related to power system operation are assessed. Three modules are defined according to the components of R&R: Techno-Economic Analysis (TEA) and adequacy assessment, Security assessment, and Resilience assessment. The R&R modules are described in the next subsection. Table 6 summarizes the salient features of the R&R modules. It is interesting to notice that indicators such as the Expected Energy Not Served (EENS) are computed in more than one module. As described more in detail in next subsections, because the scope, or the events, that are addressed by the three kinds of analyses are mutually exclusive, the relevant indicators are complementary and can be aggregated. For example, EENS can result from lack of, respectively, adequacy, security, or resilience, that are separately addressed.

TABLE 6: SUMMARY OF THE FEATURES OF THE R&R MODULES

	TEA / Adequacy	Security	Resilience
Objectives	Techno-economic and adequacy indices associated with generation and transmission availability, evaluated considering time series of future operation. Show benefit of HVDC due to: - Flexibility of DC grid power flow control - Redundancy of transmission paths - DC reconfiguration options that allow operating at reduced capacity even in case of fault Consider N-k extreme event contingencies considering duration of the event	- Detailed dynamic assessment with focus on (fast) stability phenomena triggered by AC and DC short circuits and subsequent protection and control system action - Validate simplified dynamic models used in resilience analyses - Technical (including monetizable) security indices accounting for system response in case of plausible AC and DC (N-1) contingencies - Determine N-1 secure operating regions (input to TEA) - Feedback on protection and defence (firewall) system design	Technical (incl. monetizable) indices accounting for system degradation and service recovery in case of extreme contingencies (N-k) over long-term horizons
Contingencies	Unavailability due to: • Expected (scheduled) events: Maintenance • Unexpected events: forced outages due to “normal” (independent) AC and DC fault events • optionally, “long-lasting” effects of extreme events (severe infrastructure disruption) (from Resilience module)	N-1, generally associated to short circuits	N-k, possibly common mode, associated to short circuits
Type of analysis / Modelling	Static	Static Dynamic RMS Dynamic phasor	Static Dynamic RMS Cascading, static or dynamic

Notes	Account for HVDC reconfigurations (manoeuvring) during “faulted state” and repair stages Possibly account for ex ante power transfer limits from Security module	Static security assessment and control, considering steady state view of protection, control, defence systems (also in input to Resilience module) Power transfer limits possibly passed to TEA	Includes restoration model List of long-term outages possibly passed to TEA
Time window of analysis	Year, with hourly granularity, possibly iterated within Monte Carlo analysis	For each contingency scenario, interval of unfolding of the contingency effect, i.e. seconds to minutes	For each resilience scenario, interval of scenario unfolding, including multiple contingency occurrences, consequent system degradation and subsequent service recovery, i.e. minutes to few hours
Indicators	Costs of: - Operation: including fuel, losses, CO2 - Lack of adequacy: EENS Other techno-economic indices: • LOLE • LOLP • LOLD • SEW • Transmissible power/energy through the HVDC grid • …	Costs of: - Enforcing security constraints - Lack of security: EENS due to preventive/corrective control	Costs of: - Lack of resilience: EENS Other techno-economic indices: • ENS distribution • LOLD • LOLE • Restoration time • Return periods • …
Tools proposed to be upgraded for usage within the project (see Section 5)	FlexPlan, OpTEA soft	AC-CFM (*), D-CFM (*), DPsim, Market-grid toolchain, HY_ACDC_SIM2, Eurostag/Smartflow (*) exploiting Digsilent PowerFactory.	RESILIENT, RELIEF

It is worth pointing out that all the analyses regarding the planning stage refer to the long-term operation of the system, as depicted in Figure 6:

- **TEA/adequacy analyses** rely on time series of simulated operation of long-term scenarios, typically hourly series of one year each. They are possibly iterated with Monte Carlo simulation. In this way they catch the techno-economic system performances under the variable operating conditions of load/RES and component (un)availability configurations.
- **Security and resilience analyses** regard system evolution over short intervals e.g. minutes to few hours, i.e. the interval over which stability/cascading phenomena unfold, triggered by contingencies. The operating conditions are those foreseen in the long-term. Only a few relevant operating conditions are analysed, due to computational time requirements; results are duly "extrapolated" considering the probabilistic weight of operating conditions. The threat models adopted in resilience analyses account for the whole range of events (spatial-temporal and magnitude evolution) and their probability over the long run.

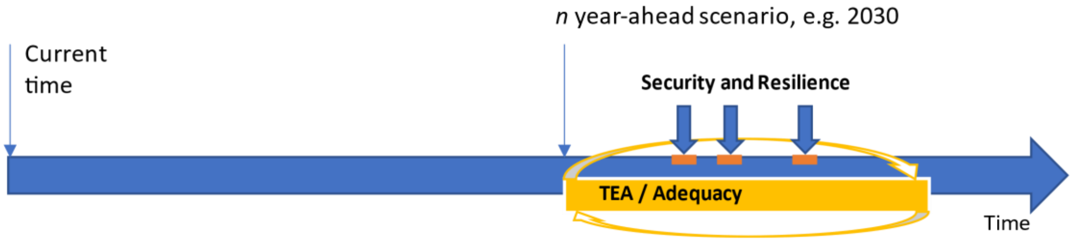

FIGURE 6: TIME HORIZONS OF THE ANALYSES

Besides infrastructure and R&R related costs, other aspects may play a role in investment decision making, such as ease of permission and visual impact of the infrastructure. These factors are to be considered in real life planning processes; however, the project will limit its focus to pure techno-economic analyses.

3.4.1 Techno-economic analysis (TEA) and adequacy assessment

The first module is devoted to the evaluation of adequacy and other techno-economic indices (Techno-Economic Analysis, TEA) typical of planning studies. It relies on static analyses of long-term system operation, performed by an Optimal Power Flow (OPF) routine. A classical approach based on Monte Carlo simulation can highlight some of the benefits of HVDC devices. These benefits include the flexibility provided by power converters (and other HVDC technologies), the ability to control DC power flows, the redundancy offered in transmission paths, and the DC reconfiguration options that allow for operation at reduced capacities, even in the case of component faults (or in the repair stage, after a fault, where reconfiguration may be different).

Monte Carlo simulation allows for the computation of TEA performance indices accounting for the variability of exogenous inputs such as load demand and renewable infeed, as well as scheduled or random unavailability of components. HVDC operating constraints, such as converter capacity and the line current in branches, where this quantity is not directly controlled, need to be accounted for in the OPF. Static constraints assuring dynamic stability, synthesized from the outcome of security analyses, can also be integrated in the OPF.

Consistent with long-term adequacy analyses for planning purposes, contingencies are represented as the unavailability of components, either scheduled (due to maintenance) or "forced" (due to unscheduled outages), extracted within Monte Carlo simulation iterations together with other stochastic quantities of the power system such as load and RES generation. Forced unavailability can be modelled with conventional Mean Time to Failure (MTTF) / Mean Time to Repair (MTTR) parameters relevant to "normal", independent fault events. A suitable estimation of these parameters has to be carried out for HVDC grid components.

The Resilience module can provide sets of multiple contingencies, their occurrence probability (possibly differentiated by time period such as the season or by sampled prevailing weather conditions) and component repair time. These sets of multiple contingencies can be regarded as "long-lasting" effects of extreme events leading to severe infrastructure disruption, with the possible adequacy impacts not accounted for by the Resilience module itself.

The TEA module could be used for a preliminary filtering of the HVDC architectures under analysis: only the candidates ranking first would be retained for subsequent analyses. In fact, the judgement whether a project is relevant from a techno-economic cost-based perspective, is based on socio-economic welfare and other typical benefits evaluated in CBA, which do not explicitly consider power systems operational security. However, due to the integrated R&R approach pursued in the project, combined with the operation challenges associated with HVDC grids, conventional static TEA indicators might not be any longer the most relevant ones to decide about HVDC grid projects. In fact, the techno-economic impact of security and resilience aspects might become comparable to that of adequacy. For example, a candidate that does not perform well in terms of TEA might perform very well from the security and resilience viewpoints, thus impacting on the overall candidate ranking; and vice versa. For this reason, it may be preferable, at least for early applications of the R&R tool, to omit the filtering stage and examine all candidates from the security and resilience standpoints in addition to adequacy.

3.4.2 Security assessment

Static security analyses can be performed by considering the expected steady state of control, protection, and defence systems following N-1 contingencies. This stage is followed by the identification of control actions to relieve static violations. This process can be conducted for all operating points output from the OPF in the TEA module, to provide a rough estimate of the costs associated with the control[4].

Alternatively, it can be applied to the limited set of operating conditions that will undergo resilience analysis, to make sure that resilience is evaluated in situations that are N-1 secure according to the operational practice of TSOs. In general, static security control can be performed by corrective or

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[4] It must be recalled that in conventional TEA / adequacy analyses of the power system, security is not systematically and specifically addressed: not systematically, in that only some random forced unavailabilities are extracted in Monte Carlo simulation; not specifically, in that the system state evolution following sudden events, is not considered. Accordingly, actions and costs associated with maintaining operational security, either in the preventative or corrective domains, are generally not accounted for in TEA. In some approaches, only the costs for reserve are assessed, hence addressing area power balance but not detailed grid constraints.

preventive actions. The former is generally preferred when possible[5] since corrective actions are only applied in case a contingency occurs and hence, they do not imply a guaranteed cost. If preventive actions are needed, the initial operating condition is changed[6].

Dynamic analyses aim at checking stability issues related to DC or AC faults, in particular N-1 faults. In fact, single faults must not result in uncontrolled or cascading instability, even in case of HVDC grids which introduce more complexity and new instability phenomena in system dynamic behaviour.

In particular, dynamic behaviour is more and more determined by controls, that need to be modelled. Therefore, detailed dynamic models (e.g. based on dynamic phasors) are needed to characterise system stability by simulations performed on a reduced grid scale and time horizon, to validate less detailed dynamic models (e.g. phasor domain RMS) adopted in cascading simulation by the Resilience module.

A co-simulation environment can be envisaged to combine the accuracy of dynamic phasor or electromagnet transient (EMT) simulators with the large-scale simulation capabilities of phasor domain simulators. This task requires simulation of different initial operating conditions and fault characteristics (such as affected components, fault location). The analysis needs to address AC and DC faults, with a special focus on DC faults, applied to both “average” and “stressed” initial operating conditions. This task can be exploited to determine N-1 dynamically secure operating limits that could be used as constraints in the OPF described for the TEA module.

Dynamic models must represent in detail features such as HVDC converters controls and protections, as they may strongly impact system response. Of course, dynamic analyses could be used to provide feedback to the protection and defence system design, in order to allow the desired operating conditions (e.g. in terms of a certain amount of power flow through an HVDC grid) to become admissible. This kind of feedback would imply that a new HVDC “architecture” is defined.

3.4.3 Resilience assessment

The Resilience module addresses the evaluation of power system performance indices accounting for system degradation and service recovery in case of extreme contingencies (N-k), e.g., as caused by weather phenomena. System resilience is evaluated as a function both of asset strength and of system responses to disturbances. Damage to the infrastructure and consequent loss of power supply to the users is considered, possibly resulting from common mode multiple contingencies followed by cascade tripping. The power supply recovery process is also assessed, in order to estimate integral indices such

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[5] In order for corrective actions to be viable, the static violations following the contingency must be “mild” enough, to be sure that the post-contingency steady state can be maintained until the corrective action has been activated and the steady state will not degenerate into a subsequent disconnection event. Moreover, enough corrective resources must be available, also meeting activation time requirements which may in turn depend on the magnitude of the violations. Otherwise, some preventive actions are needed to change the initial operating condition.

[6] When dealing with a whole contingency set, preventive actions must be identified, such that the new pre-contingency operating condition can withstand all contingencies of the list, possibly with the support of corrective actions different for each contingency.

as those related to the energy not supplied. Underlying methodologies for resilience in planning horizons have been previously developed by the partners. Cascading simulation tools can be based on static or dynamic simulation. The former can be used for filtering purposes within the Resilience module, the latter for more detailed evaluations of the contingency impact. Due to the complexity and consequent high computational burden of resilience analyses, they will be performed on a limited set of representative operating conditions, selected from the OPF output used in TEA module. Resulting indices will then be suitably post-processed to account for the generality of operating conditions. A by-product of the Resilience module is a set of multiple contingencies that can be used to evaluate the possible impact on system adequacy indices, resulting from long-lasting (e.g. many days, weeks) unavailability of components after an extreme event.

4. Description of the existing tools

In this section, a detailed description of the existing tools in the consortium will be presented. Although the methodology aims to be tool-independent, its implementation will rely on pre-existing tools for the quantification of R&R indicators, which will be suitably upgraded for their use during the project. Most of these tools have been used by the partners in past projects; however, as mentioned in 3.1, they must be upgraded to include the proposed HVDC-based grid architecture concepts. This section thus also identifies limitations and further modelling needs. Finally, in light of the conceptual architecture described in section 3, this section identifies cross-integration opportunities of the existing tool.

4.1 Overview

As mentioned in section 3, a comprehensive assessment is needed to include all the major aspects that affect planning decisions, thus, the tools must be able to appraise these aspects, or be adapted to do so. In this sense, Table 7 gives an overview of the simulation capabilities of the existing tools developed by project partners. Table 7 indicates whether the tool is optimization- and/or simulation-oriented. In this table, with regard to economic analyses, “CAPEX” and “OPEX” stand for CAPital and OPerational EXpenditure, respectively. TEP stands for Transmission Expansion Planning. For environmental analysis “CO2” is related to carbon dioxide emissions, and “RES” stands for Renewable Energy Sources integration. Reliability aspects are handled by adequacy (“Adeq”) and security analysis (“Sec”). Finally, the resiliency aspects deal with static simulations (“Static”), dynamic simulations (“Dyn”) and so-called High Impact Low Probability (HILP) events.

TABLE 7: CAPABILITIES OF CONSORTIUM TOOLS AND CBA

Tool (partner)	Optimisation (O)	Economic		Environmental		Reliability		Resilience		
	Simulation (S)	CAP	OPEX	CO2	RES	Adeq	Sec	Static	Dyn	HILP
OpTEA soft (SGI)	O (TEP of the DC grid)	✓	✓	(✓)*	✓	✓	✓			
FlexPlan (RSE)	O (TEP of AC grid + HVDC links)	✓	✓	✓	✓	✓				
AC-CFM (UCY)	S				✓		✓	✓		
D-CFM (UCY)	S				✓		✓		✓	
HY_ACDC_SIM2 (COMU)	S						✓		✓	
DPsim Tool (RWTH)	S						✓		✓	
Market-Grid Toolchain (RWTH)	O (OPF for congestion management)/S	✓	✓	✓	✓		✓	✓	✓	
RESILIENT (UCY)	O (OPF)/S		✓					✓		✓
RELIEF (RSE)	O/S				✓		✓	✓		✓
Eurostag/Smartflow(ENGIE)	S						✓	✓	✓	✓

*CO2 : This indicator needs CO2 emission for each generator (or zone) and more development within the HVDC-WISE project (see limitation section)

4.2 OpTEA soft Grid (SGI)

4.2.1 Short description

This section presents the high-level functionalities/description of the OpTEA soft Grid tool developed within Supergrid Institute, which is dedicated to techno-economic analyses and optimization of DC electrical networks. The main features, inputs/outputs and key performance indicators (KPIs), based on the business needs, are described.

Unlike planning tools that seek to define a set of grid reinforcements from a generation/demand adequacy and integration of RES perspective, and unlike project assessment tools with the objective of ranking a set of reinforcement projects, the primary focus of OpTEA soft Grid is on providing a ranking of technological solutions. The tool tries to answer the following questions:

- How should a given project be built?
- What are the best architectures, topologies, technologies, components to build this project?

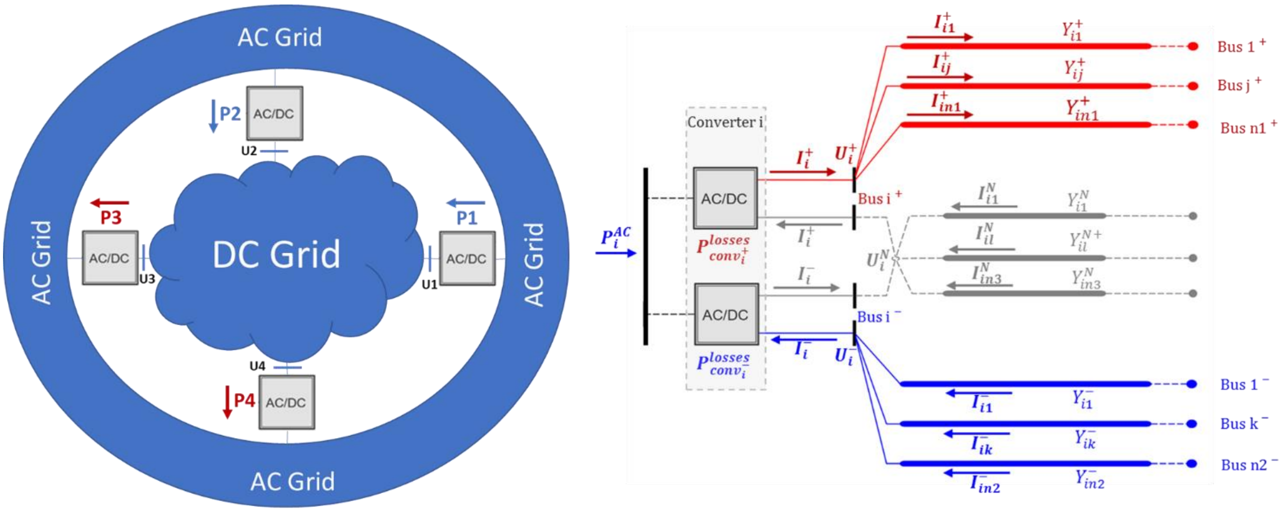
In practice, a DC grid is generally embedded on an AC system. Figure 7-(a) shows such a DC grid in which converter stations exchange power with the connected AC grids. The OpTEA soft Grid tool focuses more on DC grid studies.

The buses where power is exchanged are associated with either a generator/load or a neighbour area whose grid may have power generation capacity and a power demand. Since the study focuses only on the DC part, the converter connected to bounding grid(s) are seen as a generator (injecting node) or load (extracting node) by the AC grid. In Figure 7-(a), the nodes 1 and 2 extract power from the AC grid whereas nodes 3 and 4 inject power into the AC grid. Thus, nodes 1 and 2 are seen as a load by the AC grid whereas nodes 3 and 4 are seen as generators.

Figure 7-(b) shows the way that a converter station is modelled in the OpTEA soft Grid tool (for a bipolar configuration). This figure shows that the paths of the currents could be either on the positive and negative poles or insured by the Dedicated Metallic Return (DMR). This type of modelling allows the user to:

- Take the DMR into account
- Model the power imbalance between poles
- Generate a more realistic representation of N-k contingencies
- Model the cable redundancy
- Model the converter redundancy

Figure 7-(a) and in Figure 7-(b) show an embedded DC grid highlighting the frontiers between DC and AC grids where the active and reactive powers are exchanged through the AC/DC converters, and the converter station modelling respectively. As it can be seen in Figure 7-(a) and (b), only active power injection occurs at the bus connected to a generator in the first case, whereas the second case accounts for the range of routes and DC converter configurations that can be taken into account when modelling DC grids.



(a) **(b)**

FIGURE 7: FRONTIERS OF OPTEA SOFT GRID TOOL (FIGURE A), AND CONVERTER STATION MODELLING WITHIN THE TOOL (FIGURE B)

From a general point of view, the user could use OpTEA soft Grid for the following types of analyses:

- Comparison of the architectural principles of electrical networks with regard to techno-economic criteria or performance indicators
- Optimization of architectures with regard to techno-economic criteria or performance indicators
- Techno-economic and performance assessment of a DC network design

4.2.2 **Functionalities**

The action of comparison implies the decision of stating which candidate is the best suited for specific needs. In such a context, OpTEA soft Grid tool includes a basic feature to provide assessments that can be used as a decision-making support for business experts. The tool also includes more advanced features, including optimization in terms of grid design (grid topology, grid configuration, bus bar design, etc.). Figure 8 shows the main inputs, outputs, and functionalities of the OpTEA soft Grid tool.

The first level of functionality lies in the assessment of a set of indicators. From a high-level point of view, the tool provides automated comparison features.

The scenario involves the definition of time series or distributions of injected and extracted powers at the boundaries of the considered networks. When the techno-economic analysis does not involve time explicitly, the power time series can be replaced by a deterministic or probabilistic power distribution (mainly for offshore wind farms).

Another important input is the lifetime of the project. This data is required for every indicator relying on a time integration over the project.

Some operational constraints, which are strongly related to the key performance indicators, could be required. Optimized power flow calculations can be used to respect the aforementioned constraints. OpTEA soft Grid could take into account the following operational constraints:

- N-1 contingency: The loss of one component in the electrical network involves potential loss of power supply at extraction points. The magnitude of this loss must not be greater than a design margin ΔP_{margin}. This margin guarantees the stability of the AC network behind the extraction point.

- Protection scheme: Implemented protection strategy (fully selective, non-selective, etc.) for the assessed DC grid could impact the choice of its design (configuration, line/converter ratings, etc.) due to the stability of the bounding AC grids. Indeed, the loss of the DC grid during a fault could lead to an excessive maximum loss of infeed, which in turn could lead to the destabilisation of connected AC grids.

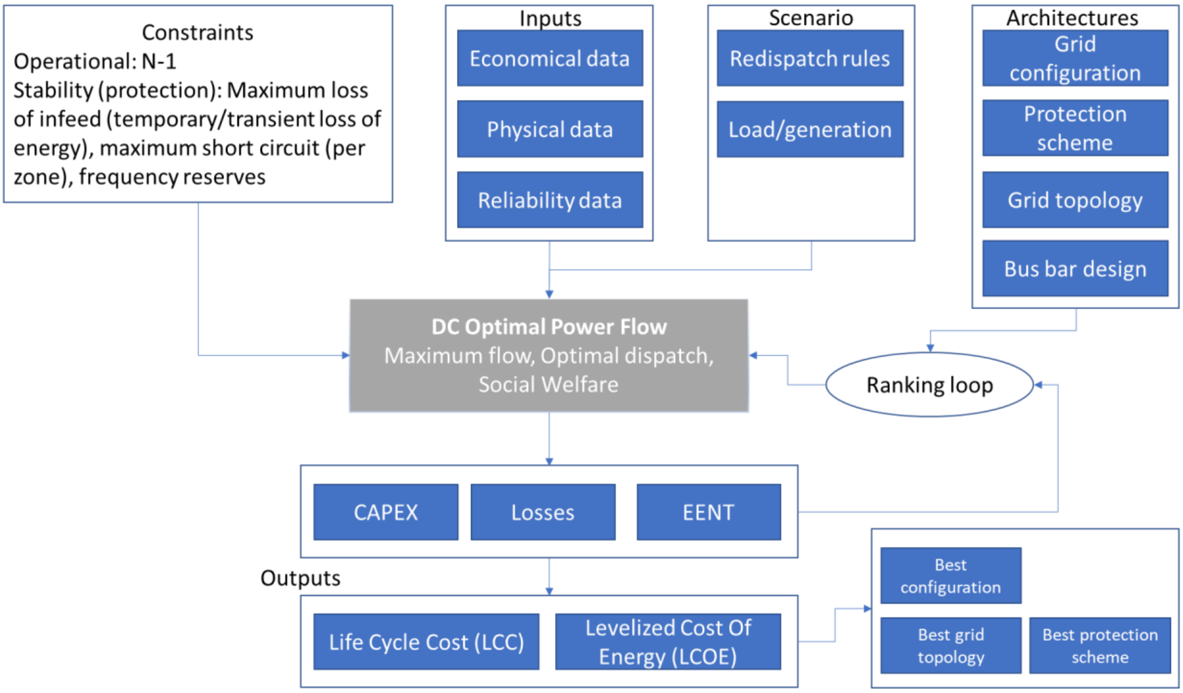


FIGURE 8: GENERAL FRAMEWORK OF OPTEA SOFT GRID TOOL: INPUTS, OUTPUTS AND FEATURES

The tool is developed in Python (an open-source language) and includes the following functionalities:

- Optimal Power Flows: considers line constraints (maximum/minimum current, maximum/minimum power, etc.), node constraints (maximum/minimum voltage, etc.), and a set of objective functions (maximum power flow, cost generation, etc.).
- TEA assessment: including CAPEX (for converters, cables, platforms, transformers, DCCBs etc.), losses (for cables, converters and transformers) and energy curtailment (Expected Energy Not Transmitted (EENT)). This also considers the protection system assessment.
- Busbar topologies/design: performs a busbar topology design (single busbar, double busbar, one and half, etc.)

4.2.3 Specifications

Inputs

From Figure 8, the following inputs are needed by OpTEA soft Grid tool:

- Economic data: Grid asset costs (cables, converters, platforms), discounted rate, project lifetime, energy costs.
- Reliability data: Mean Time to Failure (MTTF) and Mean Time to Repair (MTTR) for each grid asset.
- Optimal Power Flow (OPF) inputs: generation/load profile, re-dispatch rules (in case of contingencies).

- Physical data for component: rated current/voltage, resistivity (conductor & sheath), cable radius, current breaking capabilities, etc.
- Stability data: Maximum loss of infeed (temporary/transient loss of energy), maximum short circuit (per zone), frequency reserves, etc.

4.2.3.1 Outputs

Indicators are used to assess electrical networks or architectures. They are usually adapted and combined in order to emphasize specific aspects. The selection of indicators presented in Figure 7 are available in analyses.

4.2.3.2 CAPEX

The calculation of the CAPEX indicator shall be based upon the following contributions:

- Capital costs
- Installation cost
- Costs for spare devices on period time
- Environmental costs (compliance with environmental regulation)
- Decommissioning & dismantling

Procurement may be integrated; such costs are related to design, production, R&D etc. The cost for spare devices is equal to the expected costs for devices that have to be replaced within the given period (with regard to life-cycles).

Capital and installation costs of a component can stem from a parametric cost model. If so, the software component implementing the model must be interfaced with the tool.

4.2.3.3 OPEX

The calculation of the OPEX indicator for a given grid design is based on the following contributions:

- Maintenance & repair costs
- Cost of energy losses
- Extra charge for expected energy not served (EENS)

Maintenance expenses are the costs incurred to keep an item in good condition or good working order. Repair expenses are the costs incurred to bring an asset back to an acceptable operational condition. The cost of energy losses is the cost of the energy generated that was not transmitted to the point of extraction because it was dissipated by components.

4.2.3.4 Social Economic Welfare (SEW)

The Social Economic Welfare (SEW) problem enables the user to forecast positive and negative economic impacts caused by the implementation of new interconnectors. In other words, this represents a way to address the economic impact of HVDC systems. So, it can be a good indicator to address the target cost computation.

4.2.3.5 Other indicators

From the CAPEX and OPEX (EENT, losses and maintenance costs), a single key performance indicator could be calculated:

- Levelized Cost Of Energy (LCOE): It is a first-order economic assessment of the cost competitiveness of an electricity-generating system that incorporates all costs over its lifetime.
- Life Cycle Cost (LCC): the cost for using a generating system over the full duration of its life.

Currently the tools only outputs indicators used to assess electrical networks or architectures. In the future, this tool could directly output the optimized architecture with other indicators. This could be:

- Grid topology design (monopolar, bipolar, topology, etc.).
- Protection strategy design (fully selective, non-selective, etc.).
- Busbar design (single busbar, double busbar, etc.).

4.2.3.6 **Limitations and modelling needs:**

OpTEA soft implements models for various DC components, such as converters, lines, breakers, and high-speed switches. It can model multi-terminal HVDC systems with no restrictions on topology, including point-to-point, radial, meshed, and configurations with line and converter redundancy. However, the tool has several limitations related to future hybrid AC/DC systems. These limitations are described below and could be addressed by further modelling updates or/and by interfacing with other tools (e.g., Flexplan):

- The tool only models the DC part of the grid and can only compute DC OPF. Section 4.12 of this document describes the possibility of interfacing with FlexPlan to additionally calculate AC/DC OPF.
- The tool only includes static models for VSC AC/DC converters. A first model of a Power Flow Controller is also available. Static models for new components can be added if necessary (e.g. DC/DC converters, other Power Flow Controllers). Integrating such new controller models is a required extension to fully consider the impact of HVDC grids within a hybrid AC/DC grid reliability and resilience assessment framework.
- The tool currently only supports master-slave control for DC grid voltage. Integrating additional control modes, such as droop control, would extend its capabilities. To achieve this, the properties and constraints related to the control mode need to be added to the Optimal Power Flow Engine of OpTEA soft.
- The substation busbar configuration currently only supports single busbar configurations and is an area for improvement. Availability of the AC/DC hybrid grid as well as its security are highly impacted by the busbar configuration. Adding models for more flexible configurations, such as double busbar/double breaker, would expand the range of options that can be modelled.
- OpTEA soft calculates the Expected Energy Not Transmitted (EENT) through the DC grid to the AC grid, taking into account N-1 or N-k scenarios. However, it does not calculate the Expected Energy Not Served (EENS) at the demand side, as simplified AC grid models are used. To calculate the EENS, AC/DC OPF must be performed, considering both AC and DC system scenarios. This can be done by connecting OpTEA soft Grid and FlexPlan. The methodology for defining the N-K scenarios to be considered is crucial and can be done through traditional Monte Carlo simulation, or by using OpTEA soft Grid's alternative semi-analytical method. This proposed method can be applied to the entire AC/DC hybrid system and is a suitable complement to the Monte Carlo method.
- Social Economic Welfare (SEW) including CO_2 emissions, producer/consumer surpluses, and congestion rates could be considered in the calculation of TOTal Expenditure (TOTEX).

4.3 FlexPlan Tool (RSE)

4.3.1 Short description

The network expansion planning tool proposed as a starting point for modification and integration within HVDC-WISE is the tool developed within the FlexPlan European project [80]. The tool builds on open-source packages written in the Julia language, namely *PowerModels* [83] for static analysis of AC power grids and its expansion *PowerModelsACDC* [84] dealing with embedment of DC into AC grids. These two packages are called by the *FlexPlan package* [85], also written in Julia, in order to perform sequential and Monte Carlo simulation.

The tool selects the optimal grid expansion plan out of a set of candidates ("automatic" expansion planning) consisting of:

- AC lines (overhead/cable)
- DC lines (overhead/cable)
- Storage units
- Demand response resources

A "pre-processor" (not included in the open-source project but whose specifications are described in the public document [86]) identifies the list of candidates to be analysed by the main tool. The expansion candidates are characterized both technically (e.g., power ratings), and economically (e.g., CAPEX and OPEX). The network planning is carried out for a number of generation and demand time series. The general procedure of the tool is presented in Figure 9 [82].

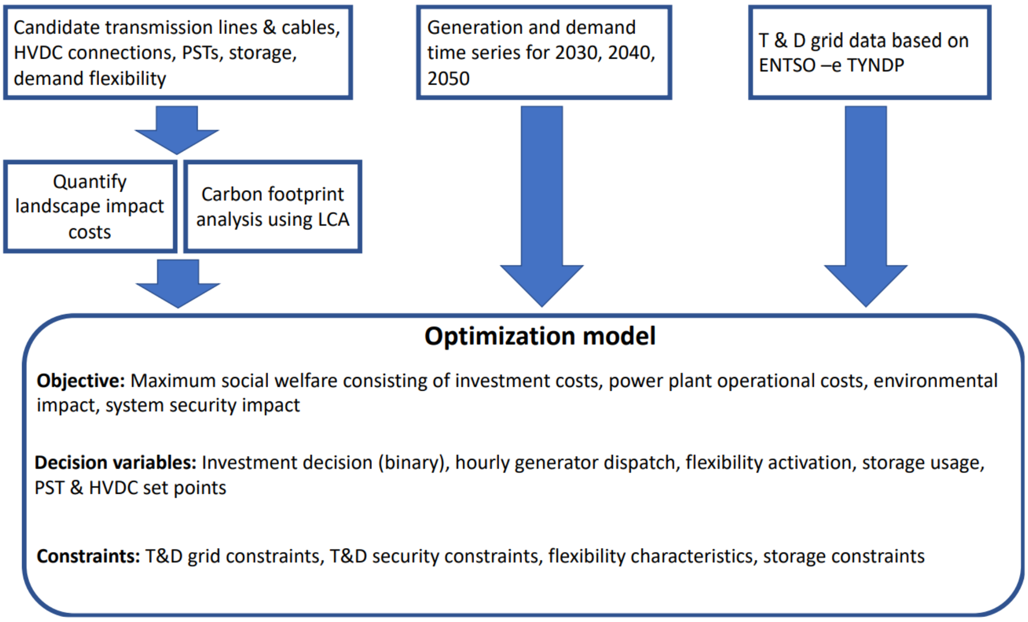


FIGURE 9: HIGH LEVEL OUTLINE OF FLEXPLAN OPTIMIZATION MODEL [82].

As a first step, grid expansion and flexibility candidates are analysed, in order to quantify their costs based on environmental impact (air quality, life-cycle assessment and landscape). These additional costs are included in the objective function of the expansion optimization, such that the best trade-off between T&D system investments and operational costs is found by also considering environmental externalities.

The objective of the optimization is to maximize the system social welfare. This is obtained by minimizing the sum of T&D grid investments, operational costs bound to system dispatch and environmental impact costs, while maximizing the benefits achieved through the use of the flexibility sources and storage.

The optimization is performed jointly for different target years, e.g. 2030, 2040, 2050. Each year is characterized by a continuous time series of ideally 8760 hours (typically, one ‘weather year’), which is necessary to model storage and flexibility activation accurately. As a result, a step-wise investment plan for new grid connections and flexibility investments is obtained. Binary investment decision variables are used for grid and flexibility investments, whereas continuous variables are used for generation dispatch, and the dispatch of flexibility and storage sources.

The power flow equations and technical constraints for flexibility sources and storage are formulated in a linear way, to maintain tractability of the model given its many dimensions. Security constraints for critical contingencies are included in the model. Possible re-dispatch and load curtailment costs stemming from these contingencies are weighted probabilistically. The weighted costs are added into the objective function of the optimization, in order to find the best trade-off between using additional grid and using flexibility investments to avoid congestions during outages.

4.3.2 Functionalities

The open-source tool aims to perform “automatic” expansion planning of large power systems as specified above. Moreover, it can accomplish Technical-Economic Analysis (TEA) of a given expansion configuration. This is the function that will be exploited in HVDC-WISE. FlexPlan already manages DC grids.

4.3.3 Specifications

4.3.3.1 Inputs:

- Planning candidates: techno-economic model.
- Planning horizons (years ahead) and periods within the horizons (e.g. 1 hour).
- Power system technical data.
- Power system economic data: CAPEX, OPEX, environmental costs.
- Time series of RES production and load.

4.3.3.2 Outputs

- Optimal list of candidates and implementation sequence.
- Social welfare.
- OPF of the analysed situations.

4.3.4 Limitations related to hybrid AC/DC systems

- HVDC grid reconfigurations in case of partial unavailability of HVDC components are not modelled. Some of them can be simulated upon external specification of the reconfiguration characteristics.
- In PowerModelsACDC, which FlexPlan builds on, monopolar and bipolar HVDC links are modelled using the same topological configuration (i.e. a DC line connected to one converter at each terminal). The only difference lies in how resistive losses are modelled. Therefore, reconfiguration of the HVDC grid for N-K contingencies can be modelled as full or partial power

derating of the HVDC lines, depending on the configuration, by providing this information as input in the scenario generation. In spite of this, some specific reconfigurations in complex DC grids with metallic return cannot be correctly modelled by PowerModelsACDC.

4.3.5 Further modelling needs

- Currently, neither N-1 nor N-k contingencies are accounted for in FlexPlan. Nevertheless, the FlexPlan tool supports multi-scenario optimization. Hence, by defining contingencies in terms of lines taken out of service (or reduction in DC line ampacity) and associated probability, it is easy to include such information in the EENS computation. Usually, contingencies are drawn independently for each network component, so both N-1 and N-k contingencies can be modelled.
- Accordingly, the availability of components is not managed in sequential OPF. This means that sequential OPF can be performed considering consistent time series of loads and RES, but the out of service and return to service of components according to e.g. Mean Time To Failure (MTTF) / Mean Time To repair (MTTR) is not contemplated. The development outlined above can overcome this limitation.

4.4 AC-CFM (UCY)

4.4.1 Short description

The AC Cascading Failure Model (AC-CFM) [86] is specifically designed for resilience analysis by integrating seamlessly into established resilience metric frameworks. It is stable for very large contingencies or extreme conditions by efficiently addressing convergence issues (e.g., power flow convergence which is dealt with in the tool using specifically designed techniques). The tool follows the approaches developed by the IEEE PES working group on cascading failures [89] and it is compared and cross-tested with other AC-based models, explicitly incorporating dynamic phenomena such as voltage and frequency protection mechanisms in a static representation (depending on values provided by the user, or alternatively automatically estimated by the tool). The tool is computationally faster than dynamic cascading models based on comparisons performed with reported tools in the literature.

4.4.2 Functionalities

- Full AC cascading with protection mechanisms in a static way.
- Simulation and impact assessment of random events (e.g. windstorms).
- N-k security analysis, where k can be in the order of tens or hundreds of assets, still obtaining a feasible power flow solution.

4.4.3 Specifications

4.4.3.1 Inputs

- Network model (e.g. generation and line data).
- Some initial indication of the event to be modelled (e.g., type, intensity, etc.).

4.4.3.2 Outputs

- Cascading visualization with the sequence of protection operation, disaggregation of the network to islands, and resulting load shedding.

- Resilience metric systems, such as the FLEP metric system.
- Load shedding and other performance indicators as a function of time (reflecting the resilience trapezoid or triangle).
- Frequency of operation of protection mechanisms during the simulated scenarios.
- Sensitivity studies for network parameters, e.g., loading level and % penetration of DG buses

4.4.3.3 Prerequisites

- Matlab 2019a or later is recommended to run AC-CFM.
- Matpower 7.1 or later is required to run AC-CFM. Please follow the instructions on the Matpower Website for installation[7].
- IPOPT is recommended to install, as it tends to have higher convergence for AC optimal power flows. Instructions on how to install IPOPT can be found on the Matpower website[8]. The OPTI Toolbox[9] is a simple way of installing IPOPT.

4.4.4 Limitations related to hybrid AC/DC systems

The big limitation is that it does not explicitly include models of multi-terminal HVDC systems, their protection and control. This will require coordination with HVDC expert partners and will be added with the other system inputs (there are some readily available HVDC models in *DigSILENT* which can be used as a starting point).

4.4.5 Further modelling needs

HVDC control, converter and protection modules, and their integration into the AC Cascading Failure Model.

4.5 D-CFM (UCY)

4.5.1 Short description

A dynamic cascading failure model (D-CFM) has been implemented in DIgSILENT PowerFactory via the Python API. It automatically develops cascading mechanisms, simulates sets of failure scenarios and processes results, and has good scalability, such that it can be easily applied to any power system model.

4.5.2 Functionalities

- Implements automation mechanisms for cascading failure analysis, including model development of power system components, assembly of controllers and protection devices, creation and simulation of various network disturbances, and data visualization of obtained simulation results.

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[7] https://matpower.org/about/get-started/

[8] https://matpower.org/download/optional-solvers/

[9] https://www.inverseproblem.co.nz/OPTI/

- It supplements the existing cascading failure models by providing the flexibility to rapidly develop power system models, batch modify system topology and component functions, and examine advanced remedial control measures in different networks.

4.5.3 Specifications

4.5.3.1 Inputs

- Network model (e.g. generation and line data).
- Some initial indication of the event to be modelled (e.g. type, intensity, etc.).

4.5.3.2 Outputs

- Dynamic set-up of power system models (of large size).
- Identification and visualization of cascading mechanisms.
- Common cascading indicators as well as risk-based metrics (e.g. VaR and CVaR).
- Dynamic modelling results of frequency, etc.
- Probability distributions of load shedding and other performance indicators.

4.5.3.3 Prerequisites

- DIgSILENT PowerFactory 2020 SP1.

4.5.4 Limitations related to hybrid AC/DC systems

The big limitation is that it does not explicitly include multi-terminal HVDC system models, their protection and control. This will require coordination with HVDC expert partners and will be added to the necessary inputs (there are some readily available HVDC models in *DigSILENT* which can be the start point).

4.5.5 Further modelling needs

HVDC control, converter and protection modules, and their integration to the Dynamic Cascading Model

4.6 HY_ACDC_SIM2 (COMU)

4.6.1 Short description

PSS/E is a widely used commercial simulation tool for the simulation and analysis of large power systems. In its current version, no model for multi-terminal VSC-HVDC systems (MTDC) is available in PSS/E and only a VSC-HVDC point-to-point model is offered. HY_ACDC_SIM2 is a PSS/E-oriented tool that models MTDC for power flow and dynamic simulations. The tool proposed has been validated against a detailed electromagnetic model in Matlab + Simulink + *SimPowerSystems*, which includes the switching of 3-level power converters, and compared to an existing model in *PowerFactory*.

With respect to modelling for power-flow analysis, each converter is connected to the AC grid and to the DC grid. The AC side is modelled by a voltage source coupled to the AC bus through a phase reactor, a capacitor and a transformer. The DC side of the converter is modelled by a current injection into the DC grid.

4.6.2 Functionalities

- A PSS/E based dynamic model for MTDC systems, intended for electromechanical dynamic simulation, which covers time constants from 0.01 s to 10 s.
- Electromechanical models of a power system, which take into account the slow dynamics of synchronous machines, their controllers and other devices, where AC branches are assumed to be quasi-static.
- Models are split into converter models and the DC-grid models.

4.6.3 Specifications

4.6.3.1 Inputs

- Generation and load dispatch
- Static network model and parameters of the AC and the DC grids
- Dynamic models and parameters of generators, MTDC systems (converters and controls), protections, etc.
- Disturbances (type, location and instant)
- Operational mitigation actions (type, location and instant) (e.g., re-scheduling, line closing, etc.)

4.6.3.2 Outputs

- Power system quantities and states
- Stability assessment

4.6.3.3 Prerequisite

- PSS/E software package
- Python
- Fortran

4.6.4 Limitations related to hybrid AC/DC systems

HY_ACDC_SIM2 focuses on short-term dynamics, involving simulation times up to 100 s. It uses a very simple dynamic DC-grid model, where a lumped RLC model is used to represent DC line dynamics. In addition, no DC-side protections are modelled. With respect to the converter stations, HY_ACDC_SIM2 assumes that converters are operated in grid following mode. In this regard, the current control loops are simplified and approximated by a first-order system, being a valid assumption for relatively strong AC systems.

4.6.5 Further modelling needs

HY_ACDC_SIM2 will be expanded to model converters operating in grid forming mode. Unlike the operation in grid following mode, requiring the existence of an AC grid and a sufficiently robustly tuned PLL, a grid forming converter imposes a voltage and a frequency by making use of appropriate power controls.

HY_ACDC_SIM2 will also model the consequences of DC-side faults (line tripping, etc.). Finally, it is planned to update the tool to handle long-term dynamic simulations. This can be achieved by converting the models for long-term simulations or by establishing sequential runs of short-term dynamic simulations followed by quasi-steady state simulations.

4.7 DPsim Tool (RWTH)

4.7.1 Short description

Most system-level (non-commercial) dynamic simulation tools do not consider electromagnetic dynamics when the primary goal is to increase the simulation speed and efficiently simulate power systems. Dynamic phasors (DP) enable the simulation of large-scale system dynamics in an efficient manner by reducing the high sampling rates of electromagnetic transient (EMT) simulations and using the frequency shift introduced by the DP approach to simulate the envelope of the signal instead of the instantaneous quantities. It can be seen as Intermediate between detailed time-domain EMT circuit representation and the quasi-static sinusoidal steady-state approximation [90]. This can have several advantages for co-simulation applications and large-scale scenarios [91], as well as power electronics simulation [92].The tool [88] is capable of running detailed dynamic simulations on commercial off-the-shelf hardware without neglecting electromagnetic dynamics. It also enables larger simulation steps compared to EMT simulations by using dynamic phasors according to shifted frequency analysis.

4.7.2 Functionalities

- Dynamic phasor, EMT, RMS and power flow solver library.
- C++ for high-performance simulation.
- Parallelization methods, e.g., for the computation of higher order harmonics to accurately represent switching power electronics.
- Python interface for simulation management and analysis.
- Distributed simulation via integration with VILLASframework.
- Fully open-source code.

4.7.3 Specifications

4.7.3.1 Inputs

- Network topology and parametrization (e.g., via CIM or CGMES).
- Network state (e.g., via CIM or CGMES).

4.7.3.2 Outputs

- Electrical network quantities and power system component states.

4.7.4 Limitations related to hybrid AC/DC systems

- The inverter models developed so far in DPsim consider only the AC side dynamics and neglect the dynamics of the DC side (by assuming a large DC link capacitor).
- The available models are Averaged Value Models (AVM) and no switching semiconductor models are available. Two types of AVM including control loops for grid forming and grid following inverter are available:
    - AVM with switching function: the inverter is modelled as controlled AC source with switching and grid harmonics.
    - Simplified AVM: the inverter is modelled as controlled AC source with quasi-stationary assumption considering only the fundamental frequency of the grid.

- DC line modelling is limited to a simple lumped parameters π-line model.

4.7.5 Further modelling needs

- Extend the tool capabilities by implementing additional models of DC components, control and protection to allow the consideration of DC side dynamics.

4.8 Market-Grid Toolchain (RWTH)

4.8.1 Short description

The Market-Grid Toolchain developed by RWTH is a scenario generation and market simulation toolchain that can derive power plant dispatches, by considering exchange capacities, load and RES feed-in time series. Hybrid AC/DC power flow calculations and congestion management are available in this toolchain in order to avoid or remedy grid congestions. Afterwards, system stability analysis with an RMS time domain simulation for different event cases is carried out, as presented in Figure 10 below:

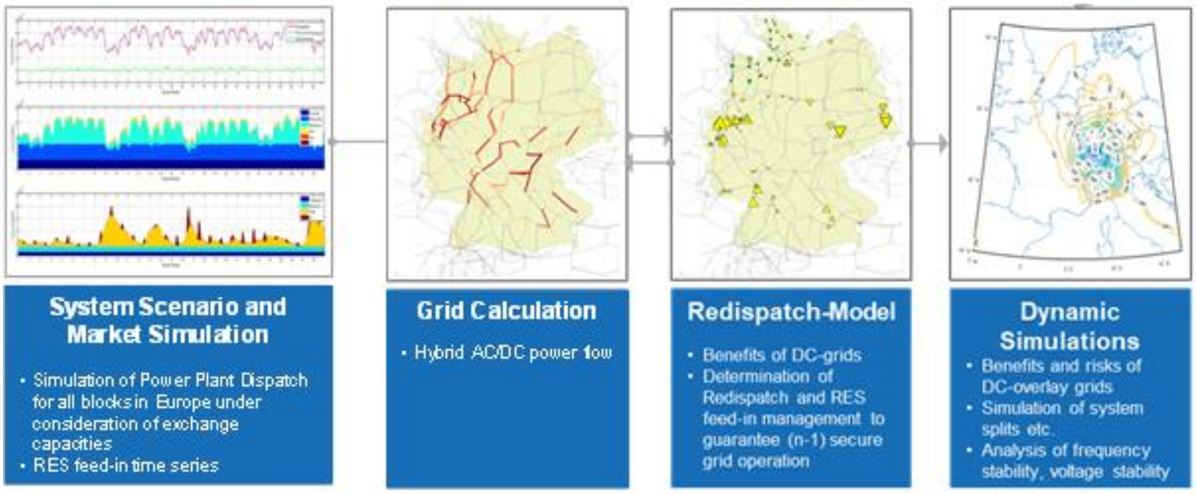


FIGURE 10: MAIN CAPABILITIES OF THE MARKET-GRID TOOLCHAIN.

4.8.2 Functionalities

- Based on future scenarios (load and RES feed-in time series), simulations of power plant dispatches in Europe considering increasing penetrations of renewable energies, exchange capacities, and different market coupling approaches (Flow-Based Market Coupling, NTC) can be conducted.
- Hybrid AC/DC power flow for each hour (DC point to point connection).
- Congestion management optimization to determine the redispatch and RES feed-in management to guarantee (N-1) secure grid operation.
- Plausibility checks regarding system stability, post redispatch, for different event cases (short circuit, generator outage, system split), with respect to grid-forming control of power electronic interfaced devices.

4.8.3 Specifications

4.8.3.1 Inputs

- Scenarios (2045 based on national development plans, TYNDP, etc.).
- Power system model.
- Parameters for dynamic models.

4.8.3.2 Outputs

- Power plant dispatch under consideration of exchange capacities which benefits from HVDC lines between market regions.
- Hourly AC/DC power flow results.
- Current related optimal redispatch and RES feed-in management regarding congestions within the grid.

4.8.4 Limitations related to hybrid AC/DC systems

- Congestion management optimization with respect to multi-terminal DC systems
- Current- and voltage-related redispatch optimization (Optimal Power Flow)
- Identification of critical hours regarding stability issues based on power flow and congestion management results
- Consideration of stability requirements within Optimal Power Flow
- Plausibility check of grid-forming control and interaction with multi-terminal DC systems on large scale networks

4.8.5 Further modelling needs

- Hybrid AC/DC Optimal Power Flow.

4.9 RESILIENT (UCY)

4.9.1 Short description

RESILIENT stands for Realistic Event Simulator for International Location-Independent Energy Network Testing. RESILIENT is being developed in the H2020 EUniversal project [89] and it is a fully flexible and modular simulation tool capable of spatio-temporal modelling of extreme weather across transmission and distribution networks. This is coupled with fragility-based models and multi-temporal/multi-spatial OPF models for capturing and quantifying the impact of the event on the network using different risk and resilience metrics.

4.9.2 Functionalities

- Automatic geographical projection of any power system to real coordinates.
- Spatial and temporal modelling of extreme weather, with existing focus in the tool on windstorms but it can be expanded to other events.
- Fragility-driven assessment of the event impact on power system assets (e.g., lines, towers/poles).
- Coupled with AC-OPF models for quantifying the spatial and temporal load shedding.

4.9.3 Specifications

4.9.3.1 Inputs

- Network data, including coordinates (if available – if not, coordinates can be generated by the tool.)
- Ideally some historical weather data to better calibrate the event generation.

4.9.3.2 Outputs

- Spatial and temporal profiles of windstorms, including wind gust speed, coordinates, etc.
- Set of risk and resilience metrics as a function of the event characteristics (e.g., wind intensity)

4.9.4 Limitations related to hybrid AC/DC systems

- Depending on the weather event of interest, RESILIENT may need to be updated.
- Incorporation of HVDC models in the spatial simulators.

4.9.5 Further modelling needs

- Hybrid AC/DC power flow.

4.10RELIEF (RSE)

4.10.1 Short description

RELIEF is a tool for resilience assessment and enhancement, which supports both **long-term planning** and **operational planning** analyses. It allows for probabilistic modelling of different types of threats, vulnerability of grid components to the same threats, as well as various countermeasures used for mitigation purposes. Combining threat and vulnerability models allows for the identification of the components with the highest failure probabilities, as well as the multiple, dependent, contingencies affecting these components. The tool calculates risk and resilience indicators and provides useful information, such as indications of the grid portions where interventions are needed in long-term planning contexts, or anticipation of critical situations in operational planning contexts.

The operational planning application works on specific forecast situations of the power system and weather conditions for the next hours. The planning application considers few representative operating conditions associated to future scenarios and applies a list of multiple contingencies whose probabilities have been computed from the failure probabilities of components, in turn derived from the combination of vulnerability curves and probabilistic threat models based on historical series of weather events. Hence, probabilities are expressed in terms of return periods. Their probability can change in future due to climate changes which can be accounted for in the model. Operators' response time is modelled in the operational planning application, while cascading outages are simulated in both long-term and operational planning applications.

4.10.2 Functionalities

- **Long-term:** Efficient **selection** of the set of the most representative multiple, dependent **contingencies**, accounting for the extension of past weather events; evaluation of contingency probability (applicable to planned lines as well); evaluation of **long-term resilience indicators**
- **Operational planning:** Anticipation of critical grid situations, by identification of both the components with the highest failure probabilities ("critical" components) and the riskiest **contingencies** based on weather forecasts; evaluation of **risk/resilience indicators**

- **Long term / Operational planning:** Quantification of the **benefits** brought to resilience metrics by **countermeasures** that mitigate the effects of different threats (e.g. anti-torsional devices and superhydrophobic coatings against wet snow, tower support hardening against wind and/or snow)
- Probabilistic modelling for a wide range of threats (wet snow, strong wind, floods, debris-flows, etc.)
- Probabilistic modelling of component vulnerability to threats
- Probabilistic modelling of the processes for the recovery of grid infrastructure and electric service considering weather forecasts and organizational uncertainties (in particular, for operational planning application)

4.10.3 Specifications

4.10.3.1 Inputs

- Electrical and physical data of network components (including geographical coordinates, component design), environmental data (e.g. orography, tree coverage, etc.) with possible application of standard data.
- **Operational planning**: Weather forecasts.
- **Long-term:** probability distributions of maximum values of exogenous (e.g. weather) stress variables (these can be derived from weather/environmental historical data sets); other information about past weather events (extension of threat, etc.).

4.10.3.2 Outputs

- **Long-term:**
  - Set of the most representative, dependent **contingencies** and their probabilities (applicable to planned lines as well).
  - EENS and outage return period of the most critical substations (i.e. those with highest EENS and/or lowest outage return periods).
- **Operational planning:**
  - Component outage probability for the most critical components.
  - List of the riskiest contingencies affecting the power system in the next hours, and their probability.
  - Risk and resilience metrics (e.g. risk of loss of load) as a function of the event characteristics (e.g., intensity, extension and duration).
- **Operational planning / Long-term:** Benefits brought by the application of specific countermeasures, in terms of improvement of resilience metrics.

4.10.3.3 Prerequisites

- MATLAB environment.
- Inputs for probabilistic modelling of threats (e.g., parameters for Generalised Extreme Value -GEV- distributions of the maximum values for stress variables of a threat, such as wind speed, wet snow load, mean time between subsequent occurrences of a threat with specified intensity, the simultaneity of the weather events on grid components).
- Inputs for probabilistic models of component vulnerability (at least, essential parameters for standard models).

4.10.4 Limitations related to hybrid AC/DC systems

- Incorporation of HVDC models.

- Incorporation of HVDC vulnerability models.
- Hybrid AC/DC power flow.

4.10.5 Further modelling needs

- Depending on the weather events of interest, RELIEF could require an update.

4.11 Eurostag/SmartFlow (ENGIE)

4.11.1 Short description

Eurostag is a dynamic power system simulator (RMS/phasor) developed by Tractebel Engineering, capable of considering multi-terminal and meshed HVDC systems. It is coupled with the SmartFlow toolbox, comprising AC/DC power flow and Security Constrained OPF modules. Eurostag is already used for probabilistic security and resilience assessment, with the consideration of dynamic cascading outage phenomena (including the action of protection systems).

4.11.2 Functionalities

- Power flow for hybrid AC/DC systems (PLAIRE module).
- Security Constrained Optimal power flow (OPF) for hybrid AC/DC systems (IPSO module).
- Dynamic simulations of hybrid AC/DC systems (Eurostag)
- Can run on high-performance computers for probabilistic risk assessments (e.g., using Monte Carlo simulation).

4.11.3 Specifications

4.11.3.1 Inputs

- Electrical network static and dynamic data (for Eurostag/SmartFlow)
- Probabilistic characterization of hazards and fragility curves for power equipment (for security/resilience assessments based on these tools)

4.11.3.2 Outputs

- Security/Resiliency KPIs such as the amount of unsupplied power

4.11.4 Limitations related to hybrid AC/DC systems

- Simplified representation of DC cables
- No restoration process assessment/methodology included

4.11.5 Further modelling needs

- Simulation of the restoration process based on the IPSO module to estimate additional resilience KPIs such as the unsupplied energy

4.12 Opportunities for cross-tool integration

In section 3, a methodology for reliability and resilience (R&R)-oriented planning of hybrid AC/DC power systems has been proposed. A top-down approach has been proposed, where techno-economic (adequacy-like) analyses are performed first and are followed by respective security and resilience analyses for a subset of operating states, possibly feeding back results to the techno-economic analysis (e.g., admissible operating regions according to security analyses). The proposed top-down approach makes use of the previously presented techno-economic analysis (TEA) tools, cascading simulation tools, and static and dynamic power system simulation tools. This section identifies cross-integration opportunities of the existing tools that allow for mapping of the conceptual architecture to the available tools.

Table 8 marks with a tick the capabilities of the tools with respect to economic analysis, linear load flow, non-linear load flow, dynamic RMS analysis, EMT simulations, N-1 and N-k contingencies. Further, capabilities that can be added to the existing tools (e.g., by including existing libraries and models) or that will be developed in the project (e.g., dynamic phasor models for DC systems) are marked with a tick within parenthesis, too. It also shows to what extent each tool can handle AC or DC systems. Table 8 also shows the opportunities for cross-tool integration by linking the missing capability to one or several of the existing tools. The link is highlighted in green and by indicating the name of the corresponding tool.

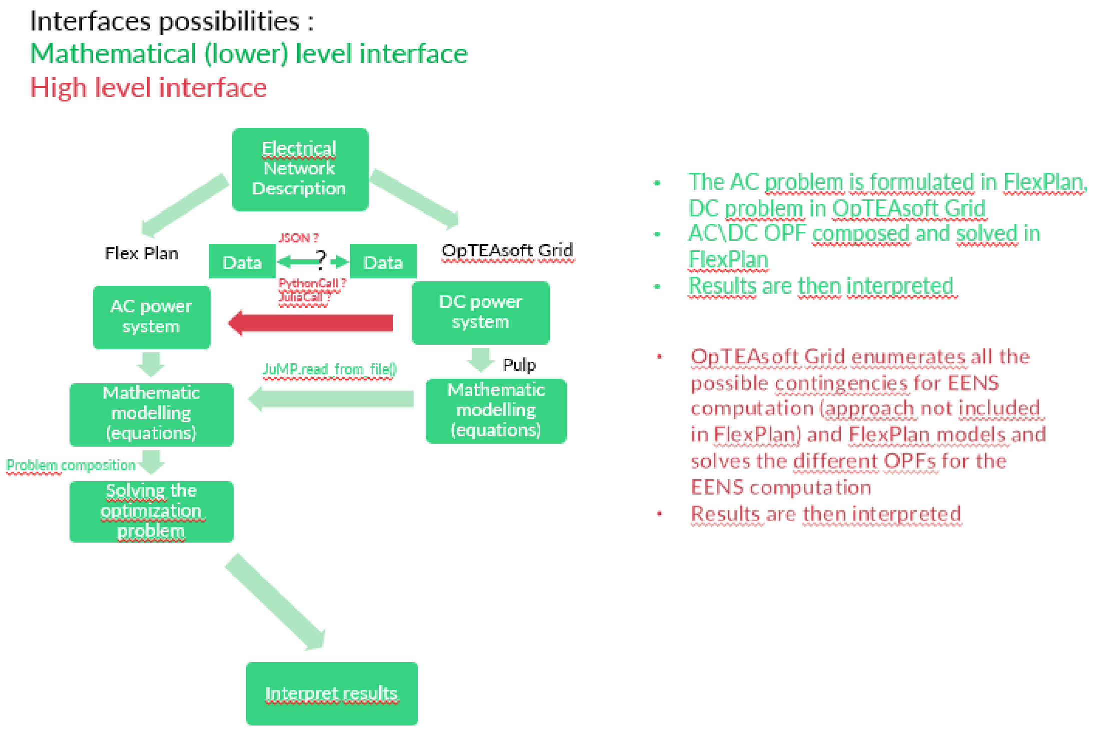
TABLE 8: CAPABILITIES OF TOOLS AND OPPORTUNITIES FOR CROSS-TOOL INTEGRATION.

		OpTEA soft	**FlexPlan**	**AC-CFM**	**D-CFM**	**HY_ACDC_SIM2**	**DPsim**	**Market-Grid Toolchain**	**RESILIENT**	**RELIEF**	**Eurostag/ Smartflow**
Economic analysis	**AC**	FlexPlan	✓	FlexPlan	FlexPlan	FlexPlan		✓	FlexPlan	FlexPlan	FlexPlan
	DC	✓	✓	FlexPlan	FlexPlan	FlexPlan, OpTEA soft		✓	FlexPlan, OpTEA soft	FlexPlan, OpTEA soft	FlexPlan
Linear load flow	**AC**	FlexPlan	✓				FlexPlan, Market-Grid toolchain	✓	✓		✓
	DC	✓	✓				FlexPlan, Market-Grid toolchain	✓	(✓)		✓
Non-linear load flow	**AC**	FlexPlan	✓	✓	✓	✓	✓	✓	✓	✓	✓
	DC	✓	✓	(✓)	(✓)	✓	FlexPlan, Market-Grid toolchain	✓	✓		✓
RMS-type dynamic analysis	**AC**		HY_ACDC_SIM2, DPSim, Market-Grid Toolchain		✓	✓	✓	✓		HY_ACDC_SIM2, DPSim, Market-Grid Toolchain	✓
	DC		HY_ACDC_SIM2, DPSim, Market-Grid Toolchain		(✓)	(✓)	(✓)	(✓)		HY_ACDC_SIM2, DPSim, Market-Grid Toolchain	✓
Dynamic phasor	**AC**		DPSim	DPSim	DPSim		✓				DPSim
	DC		DPSim	DPSim	DPSim		(✓)				DPSim
N-1		✓	(✓)	✓	✓	✓	D-CFM	✓	AC-CFM, D-CFM	✓	✓
N-k		✓	RELIEF, RESILIENT	✓ RELIEF, RESILIENT	✓ RELIEF, RESILIENT	D-CFM	D-CFM	D-CFM	AC-CFM, D-CFM	✓	✓

4.12.1 AC and DC planning tool cross-integration opportunities

According to Table 8, there exist cross-integration opportunities for the planning tools. OpTEA soft DC modelling capabilities are advanced, whereas FlexPlan excels in AC modelling. The integration of both tools would combine the strengths of both and realize the benefits of a comprehensive AC/DC solution.

Two potential interface levels can be identified: one at the mathematical problem formulation level (low level interface), and one at the tool level where functions from each tool are simply called from within the other tool (high level interface). Figure 11 illustrates both interfacing approaches.



Interfaces possibilities :
Mathematical (lower) level interface
High level interface

- The AC problem is formulated in FlexPlan, DC problem in OpTEAsoft Grid
- AC\DC OPF composed and solved in FlexPlan
- Results are then interpreted

- OpTEAsoft Grid enumerates all the possible contingencies for EENS computation (approach not included in FlexPlan) and FlexPlan models and solves the different OPFs for the EENS computation
- Results are then interpreted

FIGURE 11: LOW & HIGH LEVEL INTERFACE APPROACH.

The mathematical problem interface would be preferred for AC/DC Optimal Power Flow (OPF) computations, where the DC part would be handled by the SGI tool (OpTEA soft) and the AC part by the RSE tool (FlexPlan). The RSE tool would receive both the AC and DC mathematical problem formulations and compose the problems, then solve it. The discussion is still ongoing as to testing the feasibility of such an option.

Additionally, the already implemented N-k resilience computation of the SGI tool can be leveraged. OpTEA soft computes the EENT (Expected Energy Not Transmitted (to the AC Grid) but not the EENS (Estimated Energy Not Served), but by feeding the N-k contingencies to FlexPlan, AC/DC OPF computation could be performed, and EENS could be computed.

4.12.2 Cascading simulator and power system simulator cross-integration opportunities

According to Table 8, there exist cross-integration opportunities for cascading simulator and power system simulator. Whereas Market-Grid Toolchain and HY_ACDC_SIM2 are able to run static and dynamic security analyses considering fundamental frequency models and RMS-type network representations, DPsim represents and simulates dynamic phasor models of both the network and elements. Dynamic phasors do not require the high sampling rates EMT simulations do. The Market-Grid Toolchain also carries out network constraint management.

Currently, AC-CFM uses MatPower and IPOPT to run AC power flow and to solve optimal AC power flows. AC-CFM could be interfaced with HY_ACDC_SIM2 and the Market-Grid Toolchain. Indeed, the Matlab system command interface can execute external software such as PSS/E, that HY_ACDC_SIM2 is based on.

An even more straightforward connection can be made with the D-CFM which utilizes DigSilent PowerFactory building on Python APIs. Currently, D-CFM builds on DigSilent PowerFactory, which is able to represent MTDC systems, but it can be also interfaced with HY_ACDC_SIM2 through Python APIs. Similarly, D-CFM can be interfaced with DPsim through a Python module. In this regard, existing power system simulators can be used to simulate the power system response to N-k contingencies with both static (AC-CFM) and dynamic (D-CFM) cascading models. The cascading models in turn can be connected to an event generator that simulates extreme HILP events and provides the set of outage scenarios to be considered as an input to the cascading models. Particularly, RESILIENT can simulate the spatial and temporal trajectory of the event (e.g., windstorms) as it moves across the network, and assess its stochastic impact on power system assets. Either historical events of interest with high accuracy or random events driven by the input data defined by the end-user can be generated. The weather- and time-dependent status of the assets is then fed as an input to AC-CFM and D-CFM to assess and quantify the performance of the network under stressed conditions, and also evaluate the benefits of different mitigation strategies (e.g., controlled islanding).

Finally, and in view of the challenges for the R&R assessment in a system with HVDC architectures due the fast DC-side dynamics, a co-simulation environment that will consist of different solvers for the different layers of the grid (HVAC, HVDC) can be envisaged to maintain sufficiently high accuracy in the R&R assessment while being able to simulate large-scale power systems.

4.12.3 Planning tool and power system simulator cross-integration opportunities

For a subset of operating states, the planning tools, among others, provide the set points of AC and DC-system elements (e.g., generator active power set point, converter station active and reactive power set points, etc.). Together with the planning options, these set points serve as an input to the power system simulators, which directly evaluate static and dynamic security of an expanded power system or which indirectly, through the cascading simulators, contribute to the quantification of resilience indices.

FlexPlan and OpTEA soft, according to their interfacing, will provide set points to Market-Grid Toolchain and HY_ACDC_SIM2 for static and dynamic security assessment based on fundamental frequency, RMS-type simulations. They can also provide the set points for the DPsim tool for dynamic phasor simulations.

5. Summary of work requirements

This section summarizes the overall work requirements for the tool set for the operation and planning of hybrid AC/DC power systems. The High-level architecture is summarized first, highlighting the methodology for resilience- and reliability-oriented planning and operation of hybrid AC/DC power systems. Secondly, further development needs of the involved tools are addressed, before discussing data models and data exchange. Finally, the testing of the tools involved in the methodology requires suitable test systems.

5.1 High-level architecture

Section 3 outlines the proposed methodology for reliability- and resilience-oriented planning of hybrid AC/DC power systems. First of all, adequacy, security and resilience must be evaluated to compare and rank different predefined candidate HVDC architectures. A comprehensive cost-benefit analysis (CBA) of HVDC architectures can then be carried out by making use of R&R indices.

The two major upgrades with respect to conventional approaches and tools for assessing individual aspects of R&R will be:

- the integrated view of R&R;
- the specific contribution of HVDC grids considered in each of the R&R aspects.

Figure 12 shows the high-level conceptual architecture. A Master platform implements the analysis workflow by managing the different modules, suitably preparing their inputs and processing their outputs. The input consists of the detailed models and data of the power system, the R&R evaluation data, and of the predefined HVDC architectures to be analysed. The output of the platform consists of the list of detailed indicators computed for each analysed architecture, and of synthetic indicators obtained from the aforementioned ones. In particular, ranked lists can be obtained by sorting the indicators.

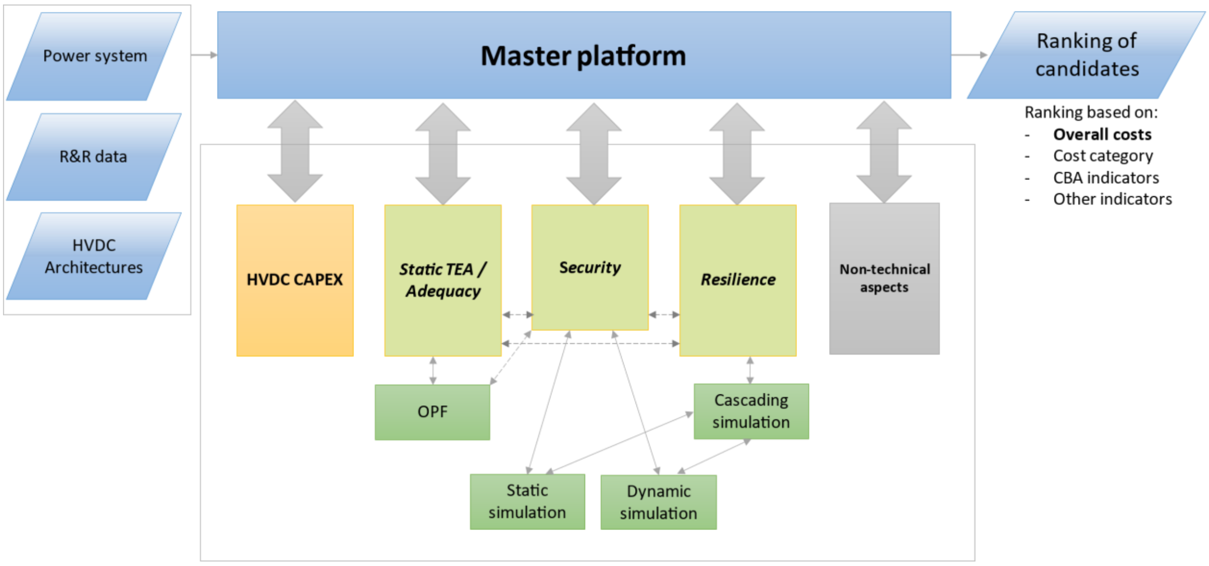


FIGURE 12: HIGH-LEVEL CONCEPTUAL ARCHITECTURE

Investment costs are a major component in CBA. The module “HVDC CAPEX” in Figure 12 is devoted to estimating the investment costs of the HVDC architecture, starting from expected costs of individual equipment or systems, combined with the amount or extent of such equipment as required by the specific architecture under analysis.

Operational costs and other KPIs related to power system operation are assessed by three modules related to static TEA and adequacy, security, and resilience. A top-down approach has been proposed, where techno-economic adequacy-oriented analyses are performed first, and security and resilience analyses for subsets of operating states follow.

The evaluation of adequacy and other techno-economic indices relies on static analyses performed by an Optimal Power Flow (OPF) routine. Security analyses are aimed at checking possible stability issues related to DC or AC faults, in particular N-1 faults. Electrical variables need to be within certain limits after single faults.

The Resilience module addresses the evaluation of power system performance indices accounting for system degradation and service recovery in case of extreme contingencies (N-k) over long-term horizons, caused by weather phenomena, for example. Damage to the infrastructure and consequent loss of power supply to the users is considered, possibly resulting from multiple contingencies followed by cascade tripping. Static security analyses can be performed prior to the dynamic security and resilience analyses, considering the expected steady state of control, protection, and defence systems following N-1 contingencies to make sure that the considered subsets of operating states are N-1 secure.

Table 6 in Section 3.4 summarizes the objectives, contingencies, type of analysis and modelling, time window of analysis, and indicators for the three R&R modules.

5.2 Challenges and further development needs

Reliability and Resilience (R&R) assessment in power systems is very critical for evaluating the robustness of a power system under different contingencies. To have a credible R&R assessment, an accurate modelling of the system is needed to run several what-if scenarios and apply mathematical tools for assessing the R&R of the system.

In bulk power systems with AC generation, the modelling of the whole system is a well-established task since there are not only accurate models that one can use for modelling the system but there are also advanced simulators that can mimic quasi-realistic operating conditions. Furthermore, most power system models used for R&R assessment in AC grids are solved using a phasor domain solver, ignoring the electromagnetic transient (EMT) behaviour of the system, given that the AC grid operating conditions of interest can be represented accurately in phasor domain.

Nevertheless, such studies are critically important at the system-wide operational and planning stages. The integration of HVDC architectures poses, then, a challenge in relation to R&R assessment with respect to cascading failure simulations, since the use of phasor domain simulation models alone may be insufficient given the fast dynamics of HVDC systems.

Accordingly, Sections 3 and 4 have highlighted further development needs. These can be classified in three groups: enabling the interaction and interfacing of the tools needed as by the conceptual architecture (see Section 5.1); adding new functionalities to tools; and modelling needs.

With respect to the interaction of the tools, a challenge for the R&R assessment in a system with HVDC is the selection of an appropriate simulation framework that can give inputs to the R&R assessment tools. A possible approach to maintaining a high degree of accuracy in the R&R assessment is to create a co-simulation environment that will consist of different solvers for the different layers of the grid

(HVAC, HVDC). Using this approach, one should consider that the different simulators that will be used in the co-simulation environment should communicate in a seamless fashion overcoming the incompatibilities which could arise between them.

Nevertheless, since in time domain simulations the delay of the solvers is critical, the co-simulation environment requires accurate coordination between the timings of the different solvers (used in different simulators), so as not to compromise the accuracy of the results. A key aspect is then the fluent interchange of information (outputs from one tool, serving as inputs to the subsequent tool, modelling parameters, etc.) among the tools. This requires that the information is available in a format or formats readable by the different tools (see also Section 5.3).

With respect to new functionalities, Section 4 has identified limitations and new functionalities to be included within the different tools available in the consortium. In this regard, OpTEA soft, focusing on DC grid planning, seeks to extend its DC OPF functionality to hybrid AC/DC OPF by interfacing it with FlexPlan. FlexPlan will include N-1 and N-k contingencies in the planning process. HY_ACDC_SIM2 will be adapted for long-term simulation. Market-Grid Toolchain seeks to extend its congestion management functionality to MTDC, to implement current- and voltage-related re-dispatch, requiring the adoption of a hybrid AC/DC OPF. Inclusion of stability constraints within the OPF will also be considered. RESILIENT will consider HILP events other than windstorms and implement a hybrid AC/DC power flow. A first proposal of how all these tools can be applied to the analysis blocks in Figure 5 can be found in Table 9.

TABLE 9: FRAMEWORK AND TOOLS APPLICABLE.

Framework part	Tool/s applicable
Static TEA/Adequacy	OpTEA soft, FlexPlan
Security	DPsim, HY_ACDC_SIM2, Market-Grid Toolchain, Eurostag/Smartflow
Resilience	AC-CFM, D-CFM, RESILIENT, RELIEF

In Deliverable D4.1 [79], key technologies, potential benefits and restrictions have been identified. The concept of building blocks has been introduced, to describe an element that can be considered in the planning process. Building blocks have been grouped in three categories: building blocks enabling DC architectures; building blocks for the AC system; and other building blocks. Within the first category, building blocks enabling DC architectures, MMC modelling and control, DC circuit breaker, DC fault current limiting devices, energy dissipating systems, energy storage, DC/DC converters, DC Power flow controllers, and DC cables and overhead lines (including superconducting lines) are included. With respect to the building blocks for AC system, AC current limiting devices, grid-forming controls, energy storage, and superconducting AC cables and overhead lines have been listed. Finally, other building blocks include LCC converters, AC circuit breaker, and FACTS.

Some of these building blocks have been identified as further modelling needs in Section 4. OpTEA soft intends to include DC Power Flow Controllers, DC/DC converters, different control strategies of converter stations, and additional substation busbar configuration. FlexPlan will consider different converter station topologies. AC-CFM and D-CFM must be updated to consider MTDC grids in general, and their protection and control systems. This can be partially achieved by interfacing the cascading failure models with other power system simulators. The PSS/E-based HY_ACDC_SIM2 will consider grid-forming control strategies for the converter stations, and the explicit representation of consequences of DC-side faults. DC Power Flow Controllers may also be implemented. Grid-forming control strategies will also be included within Market-Grid Toolchain. Since phasor domain simulation is not suitable, a priori, to represent the fast dynamics of an HVDC system, HVDC models can be simplified to be somehow integrated into the already existing phasor domain simulations, suitable for large-scale system analysis. It is, however, necessary to check that the simplified representations are accurate enough.

5.3 Data models and exchange

In Section 3, a top-down methodology for reliability and resilience (R&R)-oriented planning of hybrid AC/DC power systems has been proposed. It uses the Techno-Economic Analysis (TEA) tools, cascading simulation tools, and static and dynamic power system simulation tools presented in Section 4. These tools have different data requirements, although some of the data will be shared among them. Apart from the HVDC architectures, the following data are needed:

- Time series of demand and renewable infeed
- Maintenance programs and MTTF and MTTR indices for normal events
- OPF economic parameters
- Static AC/DC network data, and steady-state operation strategies of renewable infeed and MTDC
- Dynamic AC/DC element data (including models and parameters for physical, control and protection responses)
- Weather and vulnerability models for HILP events
- Infrastructure restoration (repair) and service restoration (recovery) models for HILP events

TEA tools require data corresponding to the first four items. Static security analysis requires static network data, generation and load dispatches, the operation strategies, and optionally OPF parameters, which are necessary when considering operator intervention. Note that the generation and load dispatch are selected from a subset of operating states, generated by the TEA tools. Dynamic security analysis requires dynamic element data in addition to the static security analysis data. Finally, resilience analyses need dynamic or static security analysis data, data related to weather and vulnerability models, and data related to repair and recovery models.

TEA tools, cascading simulation tools, and static and dynamic power system simulation tools have their own underlying data models. The required data will be mainly modelled by making use of the software-imposed models (e.g., FlexPlan uses a Julia package called *PowerModels*, which reads MATPOWER and PSS/E input formats; the dynamic cascading failure model calls upon DigSilent PowerFactory). The principal users of the tool set have data available in one of the software-imposed data models. Many of the tools available within the consortium can read different, commercially available data formats. Some tools can convert the data from one format to another. Care must be taken that data conversion is exact. In a second step, the use of ENTSO-E’s Common Grid Model Exchange Standard (CGMES) [92] will be investigated and, if appropriate, this standard will be implemented.

Whereas the use of a software-imposed data model avoids the need to first set up a common data model, the sharing of data among the different tools involved in the tool set needs to be guaranteed. This does not only affect parameters but also those outputs that serve as inputs for other tools (e.g., the operating states including generation and load dispatches needed for security analyses).

The interfaces, guaranteeing data exchange, can be either intra-software or inter-software. The former relates to those tools than are based on a common coding or scripting language such as Python and thus can make use of software-related objects. Inter-software interfaces refer to readable data files, containing the necessary information for consecutive executions of tools.

5.4 Test Systems

Test systems will be used to test and validate the different approaches for operating and planning of hybrid AC/DC power systems. Test systems have been developed with specific purposes in mind. For instance, some test systems have been set up to analyse low-frequency oscillations and their damping solutions, whereas other test system have been developed for voltage stability, planning or algorithmic scalability purposes.

Whereas the methodology and tool set will be applied to realistic, large-scale use cases in WP 6, smaller scale test systems should be used initially to analyse the efficacy and efficiency of the tools, and their underlying solutions including re-dispatches, protections, controls, etc. For this purpose, two test systems have been proposed in WP5:

- The first test system is a three-area test system, being an extension of Kundur’s two-area power system [93]. This test system also includes a proposal for a MTDC grid. The purpose of this test system is mainly to validate controls and protections to mitigate technical problems such as low-frequency oscillations, transient stability, converter-driven stability, etc.
- The second test system is the IEEE 39 (see, for example, [94] where the data were obtained from [95] and [96]), which is mainly used for planning purposes, but which can also be used for the analysis of low-frequency oscillations. This test system does not include a candidate for a MTDC grid. Among given candidates, this is an output of the planning methodology.

More information on the test systems can be found in Deliverable D5.2 [97].

6. Conclusions

Modern electric energy systems have the challenge of expanding their energy-handling capability to satisfy a continuously-increasing demand while guarantying the sustainability of this growth by boosting the application of renewable energy sources to the generation mix. All this without jeopardising (and hopefully improving) current levels of reliability, resiliency and quality of service. This scenario requires the improvement of the flexibility of bulk power systems, the application of new technologies and the development of analysis and design tools capable of dealing with these new aspects. On the one hand, HVDC is one of the technologies with enormous potential to make this future possible because it can more easily deal with generation from various sources (e.g., non-dispatchable ones), can provide flexible power flow control, has a great transport capability, and can easily and actively participate in frequency and voltage support. On the other hand, modern analysis and design tools for power systems are not fully ready to deal with hybrid HVAC/HVDC systems, comprehensively.

Firstly, a literature review on resilience, its definition and evaluation, and on techno-economic planning (TEP) including HVDC and resilience has been carried out. Resilience can be quantified by evaluating the area of the resilience triangle or trapezoid, describing the evolution of a resilience metric. Performance-based metrics such as available generation, served load, etc. could be particularly useful for cost-benefit and planning analyses. The consideration of cascading outages in resilient TEP is the subject of current research, and should include aspects such as congestion management and operator responses, etc. TEP involving HVDC must consider grid-connection requirements as well as the inherent risks, particularities and limitations of HVDC within the modelling approaches. Characteristics of HVDC systems significantly differ from the characteristics of AC systems. The control capabilities of HVDC systems should be considered as well as their DC protection systems. The complexity of large-scale TEP has led ENTSO-e to analyse candidate projects through a cost-benefit analysis (CBA) with four types of indicators: project costs, CBA market indicators, residual impact indicators, and CBA network indicators. The candidate projects respond to identified system needs for the regional and pan-European networks.

Secondly, this document has outlined a general framework in which this analysis could be carried out in the future. The main challenges relate to the consideration of both reliability and resiliency, and its extension to hybrid HVAC/HVDC systems. This general framework enables assessing and comparing different HVDC architectures, by considering not only typical TEP indices quantified by long term static simulations, but also security and resilience indices. By elaborating the R&R indices and in line with the ENTSO-e TEP approach, comprehensive CBA of the HVDC architectures can be carried out. The general framework makes use of a top-down approach where techno-economic (adequacy-like) analyses are performed first and are followed by respective security and resilience analyses for a subset of operating states. The input consists of detailed models and data of the power system, R&R related information, and the predefined HVDC architectures to be analysed. Each architecture is individually assessed, assuming it is connected to the base power system model through the nodes specified by the architecture itself. The framework will provide a list of detailed indicators computed for each architecture analysed.

Thirdly, this deliverable has identified the main software tools, the consortium is acquainted with, that will be used within the framework. In fact, the consortium members have already been applying these tools to traditional power systems for partial analysis of the kind to be addressed in the current project. A review of the tools included in this document has shown many gaps to be filled before accurate reliability and resilience analysis of hybrid HVDC/HVDC can be carried out. For each tool, its objective, functionalities, input and outputs, limitations with respect to hybrid AC/DC systems and further modelling needs have been described. In addition, the review of the tools together with the general framework has identified cross-integration opportunities of the tools. Such opportunities arise between:

- the two planning tools, FlexPlan and OpTEA soft,
- the above planning tools and power system simulators (Market-Grid Toolchain, HY-ACDC-SIM2, Eurostag/Smartflow, and DPsim),
- cascading failure models (AC-CFM and D-CFM) and the above power system simulators.

This document has also emphasised why the achievement of the R&R-oriented planning and operation of hybrid AC/DC power system will require, first of all, the development of new models and functionalities for well-known software tools (some of them developed by members of the consortium before), secondly, the interaction and interfacing of these already existing tools according to the general framework, setting-up a co-simulation environment and, finally, the adoption of protocols and data models to make this interaction and interfacing seamless and efficient. With respect to the interaction of the tools, a challenge for the R&R assessment in a system with HVDC is the selection of an appropriate simulation framework that can give inputs to the R&R assessment tools. A co-simulation environment, that will consist of different solvers for the different layers of the grid (HVAC, HVDC), can be envisaged to combine the accuracy of dynamic phasor or electromagnet transient (EMT) simulators with the large-scale simulation capabilities of phasor domain simulators. With respect to data models and exchange, planning tools, cascading failure models, and power system simulation tools have their own underlying data models. The required data will be initially modelled by making use of the software-imposed models. As far as possible, intra-software data exchange will be sought for those tools based on a common coding or scripting language such as Python and thus can make use of software-related objects.

Finally, the models and tools to be improved or newly developed in this project will be first tested on a few artificially designed test systems but will later on be taken to more realistic scenarios to validate their contributions.

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