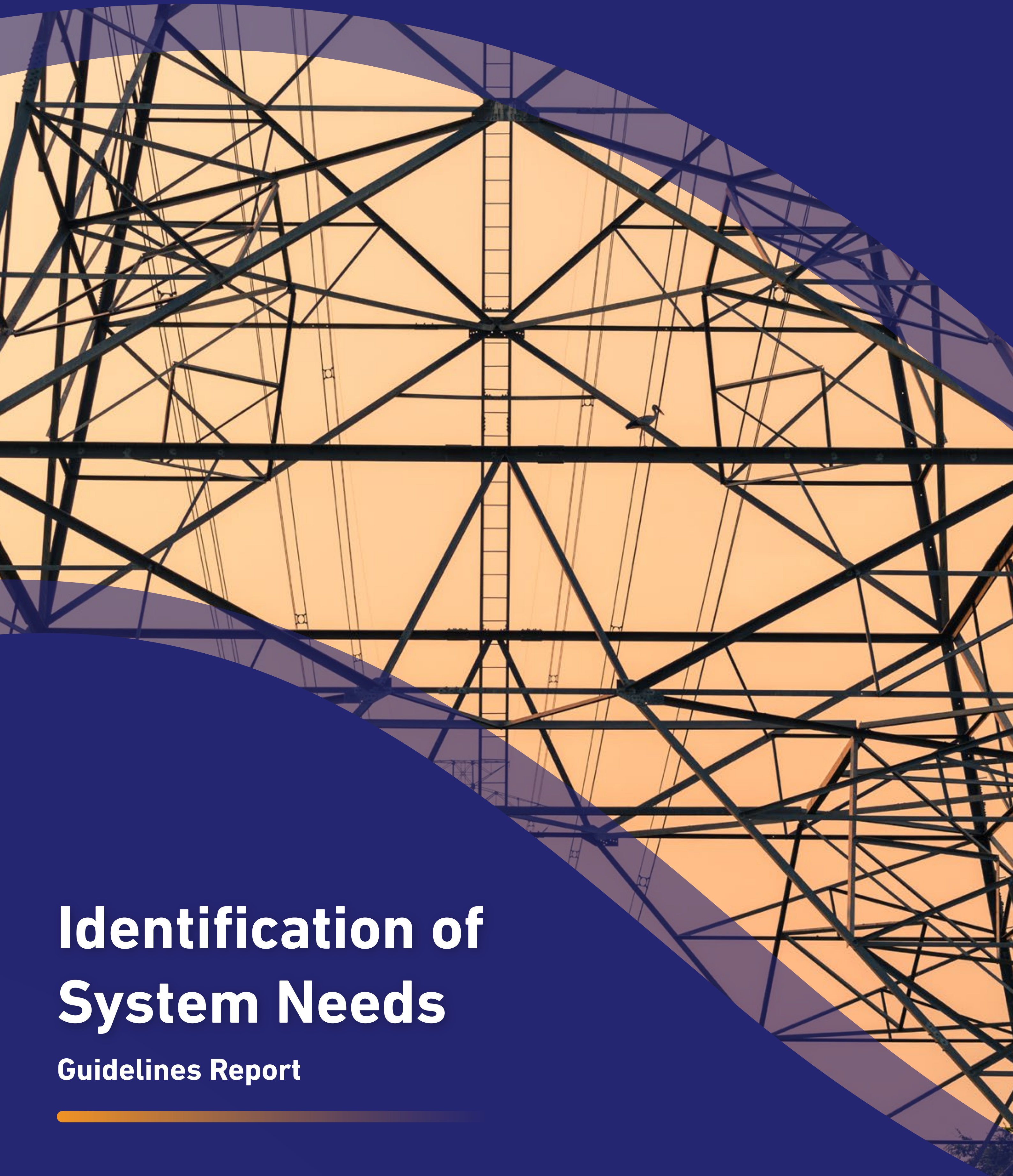

Identification of System Needs

Guidelines Report

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Abbreviations

BESS	Battery Energy Storage System
CAPEX	Capital Expenditure
CBA	Cost-Benefit Analysis
OCGT	Open-Cycle Gas Turbine
CESA	Continental Europe Synchronous Area
DSF	Demand-Side Flexibility
ENS	Energy Not Served (adequacy metric)
ENTSO-E	European Network of Transmission System Operators for Electricity
EV	Electric Vehicle (context: smart charging in DSF)
FO&M	Fixed Operation and Maintenance (cost)
GW / MW / MWh	Gigawatt / Megawatt / Megawatt-hour (power/energy units)
HVAC	High-Voltage Alternating Current (interconnection line)
HVDC	High-Voltage Direct Current (interconnection line)
IoSN	Identification of System Needs (Med-TSO planning framework)
LOLE	Loss of Load Expectation (adequacy metric)
Med-TSO	Mediterranean Transmission System Operators association
MEIP	Mediterranean Electricity Interconnections Perspectives
NDP	National Development Plan (national grid plan)
NTC	Net Transfer Capacity (cross-border transfer limit)[1].
O&M	Operation and Maintenance (costs of activities)
OPEX	Operating Expenditure
PCI	Project of Common Interest (EU energy-infrastructure list)
PMI	Project of Mutual Interest (EU–non-EU infrastructure label)
PtX	Power-to-X (e-fuels, hydrogen, etc.)
RES	Renewable Energy Sources
TYNDP	Ten-Year Network Development Plan (ENTSO-E)
TSO	Transmission System Operator
DSO	Distribution System Operator (appears in some comments/metrics)

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[1] Net Transfer Capacity (NTC) refers to the maximum amount of electricity that can be transmitted across a border between two countries or regions without jeopardizing the security of the electricity system. It is calculated by considering the physical limitations of the transmission network and the need to maintain a balance between supply and demand. NTC is crucial for ensuring that electricity markets can operate efficiently, and that power can be traded across borders to meet varying demand and supply conditions.

1

Executive Summary

Introduction and strategic rationale

The Mediterranean region stands at a critical point in its evolution towards a resilient, efficient, and future-proof electricity transmission framework. In this context, the IoSN presents a study designed to align the region's transmission infrastructure with the challenges and opportunities presented by an evolving energy landscape. The Med-TSO IoSN report looks at the regional electricity grid infrastructure, presents an analysis of capacity limitations, and assesses opportunities in the region. A forward-thinking transmission network is key to supporting energy transition policies; the system operators from the Mediterranean region have committed to developing a system that is both robust and agile enough to incorporate future developments in the region. This study addresses current system limitations whilst aligning with regional energy policies and best international practices, paving the way for harmonised cross-border initiatives and sustainable long-term investments. To manage this, Med-TSO has established a unified framework to ensure that regional transmission infrastructure evolves in alignment with this transformation. This report presents the process used to develop, for the first time, an Identification of System Needs (IoSN) guidelines set out in Chapter 2 for the Mediterranean perimeter.

The IoSN methodology: a unified playbook

The IoSN study is an important step in the planning of a resilient, efficient, and integrated power system. By systematically assessing and addressing key infrastructural challenges. The study is expected to enhance grid efficiency, promote market integration, reduce congestion, improve energy security, and lower overall system costs. The approach facilitates the optimisation of existing transmission assets, the identification of bottlenecks, and targeted investment in renewable energy and BESS. The study is poised to create significant benefits throughout the Mediterranean region, serving the evolving needs of member countries and supporting a forward-looking energy system. This study focuses on the year 2040.

Market simulations are run to identify benefits. These simulations focus on:

1. Economic gains: Assessing the economic benefits of proposed infrastructure projects, including cost savings and efficiency improvements across the power system.
2. Renewable Energy Source (RES) Integration: Evaluating the capacity of the grid to incorporate renewable energy sources, ensuring that infrastructure developments support increased RES penetration.
3. CO_2 emission reductions: Estimating the potential decrease in carbon dioxide emissions resulting from infrastructure enhancements and greater use of renewable energy.
4. Security of supply: Analysing the reliability and stability of the energy supply, identifying measures to prevent shortages and ensure consistent energy availability.

The Guidelines Report establishes a multi-scenarios-driven planning cycle designed to identify infrastructure gaps that could impede effective interconnected network performance.

- Integrated optimisation: The framework uses Antares-Xpansion to simultaneously evaluate a diverse portfolio of investments: transmission, storage, and peaking units, identifying the most economically efficient combination rather than assessing projects in isolation.
- Alignment with European standards: The process is harmonised with ENTSO-E’s TYNDP cycles, ensuring the use of consistent datasets and methodological compatibility for North-South and East-West exchanges.
- Stochastic modelling: By incorporating multiple “climate years,” the methodology ensures that recommended infrastructure is robust against weather-driven uncertainty in renewable generation and demand.

The IoSN process is structured in five main steps:

1. Development of market models for 2040. This first step involves constructing market models for 2040 based on predefined Med-TSO scenarios, which set the foundation for assessing future network needs, including the definition of the starting grid.
2. Collection of expansion candidates. In this phase, potential projects, ranging from new interconnections to flexibility and security of supply solutions, are gathered from Med-TSO members to form a comprehensive pool of candidate investments.
3. Integration of candidate project parameters. The collected candidates are then parameterised and integrated into the Antares-Xpansion tool, ensuring that technical, economic, and scenario-specific data are accurately reflected in the model.
4. Optimisation execution. Antares-Xpansion is run to determine the optimal expansion strategy. This step identifies the most cost-effective investments among the candidates for each scenario.
5. Market simulations and benefit analysis.

Practical implementation: The 2040 dry run

The practical implementation tested the methodology across three scenarios: Inertial (IN), Proactive (PR), and Mediterranean Ambition (MA). Even under conservative assumptions, the region needs a coordinated package of cross-border reinforcements, plus targeted storage, to move low-cost renewables, keep security of supply, and improve price convergence. Using a simulation planning workflow (scenarios, Antares market simulations and Antares-Xpansion for least-cost investment), the study finds that by 2040, the current and planned grid is insufficient to support the Mediterranean energy transition.

Key economic and environmental findings include the following:

- High return on investment: Every euro invested in the transmission grid returns approximately four to five euros in avoided system costs.
- System cost savings: The identified infrastructure reduces annual operating costs by €7.4 billion to €10.2 billion (a reduction of 6% to 9%).
- Decarbonisation impact: The IoSN Grid cuts annual CO2 emissions by 25 to 41 million tonnes.
- Renewable integration: The plan reduces renewable energy curtailment by 31 to 37 TWh annually.

Priority infrastructure requirements

The dry run identified a cumulative need for 38 to 43 GW of new cross-border capacity across the three scenarios we studied.

The key result is a corridor-based map with five strategic corridors:

1. **Adriatic and Balkan Corridor:** the single largest corridor representing about 41% of all capacity needs (around 20.5 GW), with two-thirds clearly no-regret (i.e. common to the three scenarios); it is indispensable for north-south and east-west exchanges.
2. **West Mediterranean Corridor:** 26% of all capacity needs (12.6 GW), linking Iberia with France (scenario dependent) and North Africa.
3. **Central Mediterranean and North Africa Backbone:** 100% no-regret (6.2 GW), as North African system must better connect to the rest of Mediterranean in every scenario.
4. **Middle East Mediterranean Integration:** around 6.3 GW, ~80% no-regret, giving the Eastern Mediterranean a stable internal backbone (between Egypt and Türkiye, connecting Jordan, Palestine, Syria, and Lebanon).
5. **East Mediterranean Interconnectors:** about 3.7 GW and 100% scenario-dependent (only in the Mediterranean Ambition scenario), creating direct Egypt-EU/Levant links when high-RES integration is pursued.

Across all three transition narratives: Inertial, Mediterranean Ambition, and Proactive, the model selects 38 to 43 GW of new cross-border capacity on 31 to 38 borders.

A net-beneficial portfolio

The total surplus analysis confirms that all Med-TSO countries stand to gain positive economic returns from this infrastructure portfolio. The implementation of the IoSN Guidelines has successfully moved regional planning from ad-hoc bilateral discussions to a coherent, evidence-driven roadmap.

By 2040, these strategic reinforcements will become the foundation of a resilient, low-carbon, and deeply interconnected Mediterranean power system.

2

Introduction and Purpose of Med TSO IoSN

The Mediterranean Transmission System Operators play a crucial role in ensuring a reliable and efficient energy transition across the region. The Identification of System Needs (IoSN) framework is a structured approach to planning and optimising energy infrastructure investments to support this transition. This document outlines the purpose and methodology of IoSN, emphasising its role in enhancing cross-border electricity transmission, integrating renewable energy sources, and improving overall grid reliability. IoSN aims to foster regional cooperation and create a robust and resilient energy network.

2.1. Key stakeholders and participants

The implementation of the IoSN framework brings together a diverse array of stakeholders whose collective efforts form the backbone of a modern, resilient, and integrated grid. At the core of this ecosystem are the Transmission System Operators: The 20 Med-TSO members entrusted with the planning, operation, and integration of power systems in the Mediterranean region. Their role is critical, as they ensure that grid operations remain reliable even as renewable energy sources gradually increase their share of the energy mix.

Supporting the TSOs are regulatory agencies such as MEDREG, which work in tandem to harmonise standards, enforce legal compliance, and promote effective market integration. This collaboration is formalised through initiatives like the trilateral Memorandum of Understanding signed with the European Commission and MEDREG in 2014. The European Commission, in turn, not only helps co-fund projects aimed at sustaining regional development but also recognises Med-TSO as a “long-term partner”.

International cooperation is reinforced through partnerships with organisations like ENTSO-E. A significant agreement reached in 2017 between Med-TSO and ENTSO-E, aimed at enhancing collaboration through the exchange of data, methodologies, and models, underscores both parties’ commitment to a unified and innovative approach to grid management.

2.2. Background and rationale for IoSN

As the Mediterranean energy landscape evolves, the Med-TSO IoSN study provides a technical baseline for developing a resilient transmission framework. This study assesses the current regional grid, quantifies capacity bottlenecks, and outlines strategic infrastructure opportunities. To support decarbonisation and policy shifts, Mediterranean TSOs are prioritising a dual-capability system: one that offers structural robustness alongside the agility required for future load shifts. This framework aligns regional operations with international standards, facilitating the interoperability and long-term capital investment necessary for a unified energy market.

2.3. Scope and objectives of IoSN

The precursor to the IoSN is the Scenario Development Process, conceived as the foundation for assessing future energy requirements. It is designed to provide a quantitative basis for infrastructure assessment and network planning, thereby establishing a set of plausible futures against which system performance can be evaluated. In practice, scenarios are crafted to capture the dynamic uncertainties of the energy transition, exploring variations in demand and supply patterns. This should allow assessment outcomes based on the scenarios to remain robust in the face of evolving market conditions and policy adjustments. The scenarios inform studies that examine future needs for system reinforcement and infrastructure gap identification.

Once the scenarios are developed, they serve as the input for the IoSN Process. While the Scenario Development Process offers a high-level, strategic perspective on the future of the energy system, IoSN drills down into the operational realities, pinpointing specific infrastructure gaps that could impede effective interconnected electricity network performance.

The IoSN Process builds on the quantitative outputs provided by the scenarios, analysing aspects such as potential interconnection congestion, and the feasibility of integrating additional solutions like BESS, hydrogen electrolysers, and peaking units.

The aim of this report is the development of guidelines for the IoSN, with a view to identifying and quantifying critical infrastructure needs associated with a growing share of variable renewables. The evaluation refines targets for infrastructure investment through rigorous, data-driven assessments of future system needs. The analysis also highlights the role of interconnectors, BESS, electrolysers, and peaking units in integrating power systems across the region. The primary objectives are to enhance supply security by anticipating future grid challenges and to optimise transmission infrastructure investments through interconnection investment modelling.

IoSN vs. CBA

The IoSN process differs significantly from the Cost-Benefit Analysis (CBA) conducted within the Mediterranean Electricity Interconnections Project (MEIP) framework. The MEIP CBA is primarily a project selection tool designed to assess individual candidate projects rigorously against a consistent set of standardised economic and strategic criteria. Each proposed project within MEIP undergoes a detailed assessment, weighing anticipated benefits such as enhanced reliability, increased cross-border energy exchanges, operational cost reductions, and environmental improvements against the total investment costs.

In contrast, the IoSN economic optimisation model goes beyond individual project assessment, adopting a broader systemic view. It simultaneously evaluates a diverse portfolio of potential investments, optimising across multiple scenarios and interdependent factors to determine the most economically efficient combination of projects. Rather than focusing solely on discrete projects, IoSN addresses the broader question of infrastructure strategy and long-term network planning, incorporating the interplay between renewable energy growth, grid flexibility, BESS solutions, and cross-border interconnection capacity.

Furthermore, while the MEIP CBA enforces a centralised methodology and strict evaluation guidelines to ensure transparency and fairness, the IoSN economic optimisation employs advanced optimisation algorithms to dynamically identify infrastructure pathways that minimise overall system costs and maximise system-wide reliability. The MEIP CBA approach ensures fairness and transparency at the project level, while IoSN strategically guides holistic infrastructure planning decisions to deliver integrated, cost-effective outcomes aligned with the region's long-term energy transition objectives.

2.4. Expected outcomes and benefits

The IoSN study is an important step in the planning of a resilient, efficient, and integrated power system, systematically assessing and addressing key infrastructural challenges. This study is expected to enhance grid efficiency, promote market integration, reduce congestion, improve energy security, and lower overall system costs. The approach facilitates the optimisation of existing transmission assets, the identification of bottlenecks, and targeted investments in renewable energy and BESS. Taken together, these measures are set to create significant benefits throughout the Mediterranean region, serving the evolving needs of member countries and supporting a forward-looking energy system. The study focuses on the year 2040.

Market simulations are run to identify benefits, focusing on:

1. **Economic gains**: Assessing the economic benefits of proposed infrastructure projects, including cost savings and efficiency improvements across the power system.
2. **RES integration:** Evaluating the capacity of the grid to incorporate renewable energy sources, ensuring that infrastructure developments support increased RES penetration.
3. **CO_2 emission reductions:** Estimating the potential decrease in carbon dioxide emissions resulting from infrastructure enhancements and greater use of renewable energy.
4. **Security of Supply:** Analysing the reliability and stability of the energy supply, identifying measures to prevent shortages and ensure consistent energy availability.

3

Overview of the Process

The IoSN process is a multi-step methodology that guides Med-TSO members in assessing system needs, identifying investment candidates, and optimising expansion solutions. This section provides a high-level overview of the key phases involved in the implementation of IoSN. An illustration of the process flow is provided below

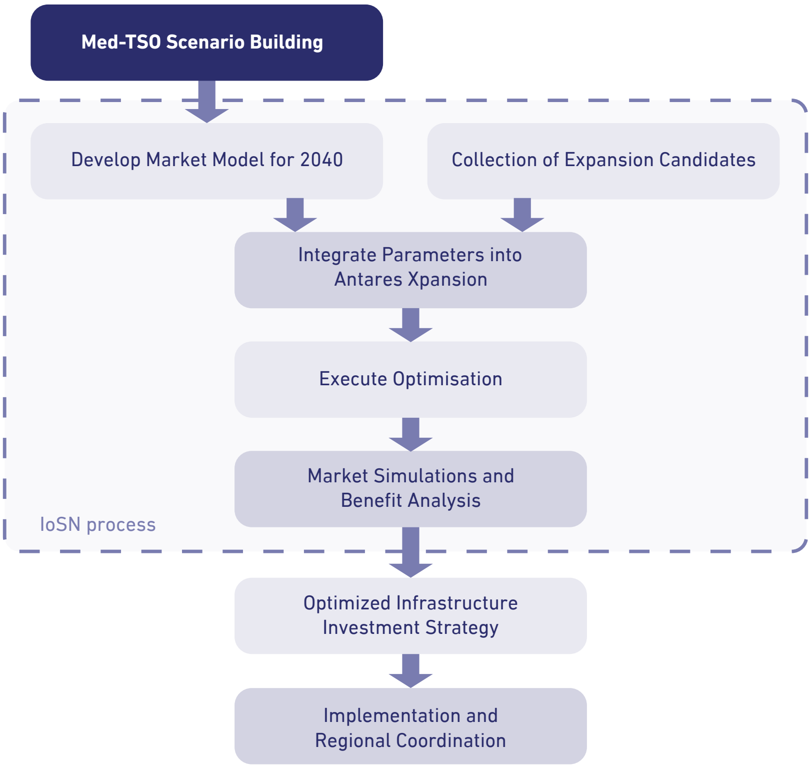


Figure 1 - IoSN process flow diagram

3.1. Key steps in IoSN implementation

In establishing a structured roadmap for identifying system needs within the Med-TSO region, it is critical to ensure that the process is both consistent and transparent at every step. Drawing inspiration from ENTSO-E's approach for its Ten-Year Network Development Plan and adapting it to the unique characteristics of the Mediterranean power system, the following outline of the essential phases that form the backbone of the identification process can be established.

The first phase involves framing the future energy landscape by using tailored scenarios that consider local energy supply and demand trends, the integration of renewable energy sources, and potential technological developments. This is followed by a comprehensive analysis of the power systems and the transmission network, using modelling tools to assess the impact of different future scenarios on electricity supply, and grid infrastructure. The objective is to determine the operational demands and network characteristics required to support a balanced and robust energy system, particularly under conditions of increased cross-border electricity exchange.

A crucial component of the process is identifying where current infrastructure may fall short in meeting future needs, with a focus on pinpointing potential gaps related to cross-Mediterranean electricity flows. Given the ambitious renewable energy targets across the region, existing infrastructure presents certain limitations, highlighting the need for strategic and economically optimised investments. By explicitly pinpointing these infrastructure gaps, especially those related to interconnection capacity, grid flexibility, and BESS solutions, the IoSN process can more effectively inform economic optimisation decisions. This ensures that future investments are not only technically feasible but also economically efficient, aligning infrastructure development with the region's long-term energy transition goals.

The IoSN Process is structured in five main steps:

1. **Development of market models for 2040:** This first step involves constructing market models for 2040 based on predefined Med-TSO scenarios, which set the foundation for assessing future network needs, including the definition of the starting grid.
2. **Collection of expansion candidates:** In this phase, potential projects, ranging from new interconnections to flexibility and security of supply solutions, are gathered from Med-TSO members to form a comprehensive pool of candidate investments.
3. **Integration of Candidate Project Parameters into Antares-Xpansion:** The collected candidates are then parametrised and integrated into the Antares-Xpansion tool, ensuring that technical, economic, and scenario-specific data are accurately reflected in the model.
4. **Optimisation Execution:** Antares-Xpansion is run to determine the optimal expansion strategy. This step identifies the most cost-effective investments among the candidates for

each scenario.

5. **Market simulations and benefit analysis:** Finally, unit commitment and economic dispatch simulations are performed to evaluate the benefits of the proposed expansion portfolio. This analysis quantifies improvements in system performance, reliability, and economic efficiency. After the capacity-expansion run, unit commitment and economic-dispatch simulations are executed for every Monte Carlo year. These market runs translate the raw build-out into hourly production costs, price signals and security-of-supply metrics (LOLE, ENS, NTC utilisation). The outcome is a system-wide benefit stack, rather than a project-by-project CBA, including:
    - total-system-cost variation versus the “no-investment” case
    - reduction in curtailment and congestion hours
    - price-convergence across bidding zones
    - avoided CO_2 emissions

These steps provide a systematic roadmap for identifying and prioritising infrastructure investments, ensuring that the IoSN framework supports a resilient and integrated energy network.

3.2. Regulatory and technical considerations

Compliance with regulatory and technical standards is essential for identifying system needs and ensuring the success of cross-border transmission and grid modernisation efforts in the Med-TSO region. A complex interplay of national policies, and regional cooperation shapes this landscape, demanding harmonised approaches that promote operational efficiency and the effective integration of renewable energy sources.

The regulation governing Projects of Mutual Interest (PMIs) plays a pivotal role. PMIs are key energy infrastructure projects promoted by the European Union in cooperation with third countries, aiming to enhance cross-border energy connectivity and market integration between EU and non-EU nations. These projects benefit from streamlined planning and permit approvals, as well as increased visibility to investors, facilitating their timely and efficient implementation. It should be noted that ENTSO-E is legally responsible for performing the cost-benefit analysis (CBA) for submission to the PMI process.

The integration of PMIs within the Med-TSO region requires addressing both regulatory and technical challenges. Differences in national regulatory frameworks can lead to suboptimal use of existing interconnections and hinder the development of new infrastructure. The absence of a uniform investment framework for cost allocation and benefit sharing further complicates the financing of cross-border initiatives. On the technical side, aging infrastructure and the integration of variable renewable energy sources require investments in modern transmission systems, BESS solutions, and advanced digitalisation to maintain grid stability and manage congestion.

Addressing these challenges requires sustained and coordinated efforts among all stakeholders. Harmonising regulations, streamlining approval processes, and investing in resilient, modern grid infrastructure will facilitate the successful implementation of PMIs, thereby enhancing cross-border energy cooperation and contributing to a secure, efficient, and sustainable energy system across the Mediterranean region.

3.3. Interlinkages between ENTSO-E and Med-TSO processes

The ENTSO-E and Med-TSO IoSN processes are both central to understanding and planning future transmission needs in Europe and the Mediterranean. While they serve similar objectives, ensuring security of supply, market integration, and energy transition, they are organised within different institutional frameworks and across different geographic scopes. Nonetheless, coherence and coordination between them is essential, especially as Mediterranean countries are increasingly integrated with the EU energy system.

3.3.1.Timeline alignment between Med-TSO and ENTSO-E IoSN

The Med-TSO IoSN is organised around a three-year planning loop that starts with Mediterranean-specific scenario design and ends with the publication of a region-wide system-needs report and investment roadmap. The ENTSO-E IoSN, which runs on a separate two-year cadence, provides useful upstream data points such as Pan-European demand trajectories, technology costs, and cross-border bottlenecks. The two timelines interact as follows:

- **Year 1 (Med-TSO):** update the Mediterranean starting grid and collect data from all member TSOs.
- **Mid-Year 1:** ENTSO-E publishes its draft IoSN outputs; Med-TSO screens them for items relevant to North–South and East-West Mediterranean exchanges and imports relevant elements into its database.
- **Year 2:** Med-TSO runs the expansion and market-simulation suite, using refreshed data plus Mediterranean-specific parameters supplied by each national TSO.
- **Year 3:** results are consolidated, reviewed with the member TSOs, and issued as the Mediterranean System-Needs Report.

This interaction between timelines of ENTSO-E IoSN (part of the TYNDP process) is illustrated

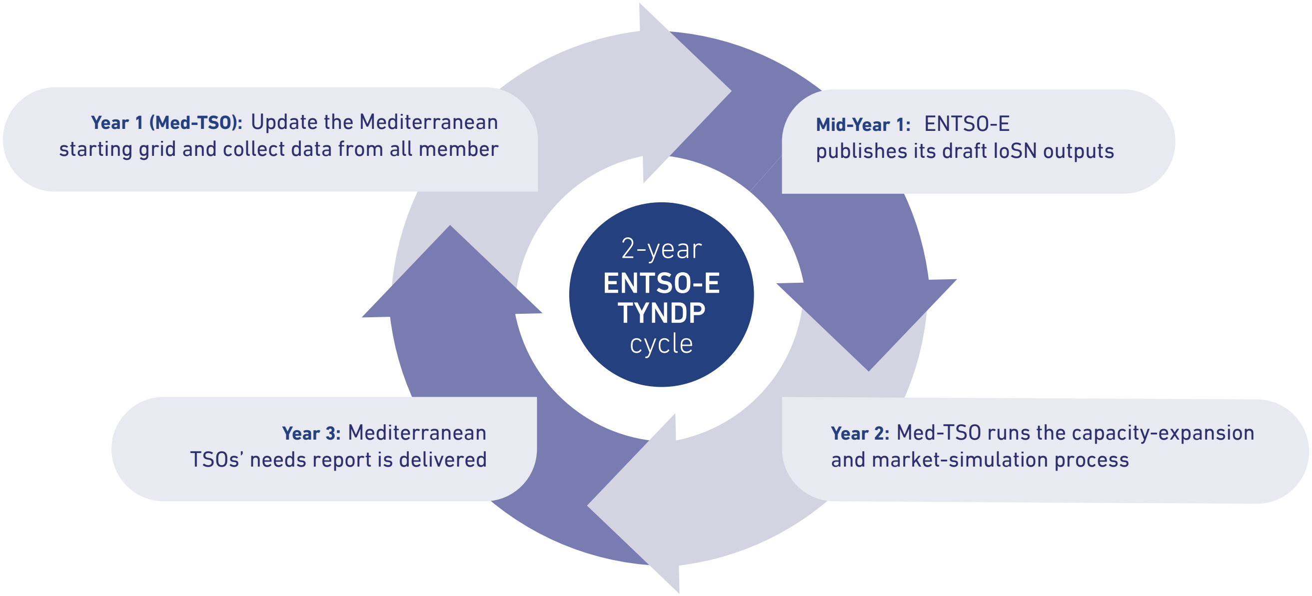


Figure 2: Timeline alignment between Med-TSO and ENTSO-E IoSN

Scheduling Med-TSO scenario work to begin after ENTSO-E's scenario freeze (around month six of their cycle) ensures that Mediterranean planners can:

- reuse vetted macro-assumptions where relevant
- customise parameters (e.g., North-African RES build-out, gas-price paths) without time pressure
- publish their findings one year after ENTSO-E, giving national TSOs ample time to feed conclusions into their own development plans

Country-level engagement is embedded throughout: each TSO submits data packs, reviews intermediate results, and co-chairs corridor-specific task groups. This bottom-up process keeps the three-year calendar realistic, fosters ownership of the final portfolio, and limits duplication with the ENTSO-E exercise.

3.3.2.Conditions and mechanisms for incorporating ENTSO-E IoSN outcomes into Med-TSO IoSN

The incorporation of ENTSO-E IoSN outcomes into the Med-TSO process depends on several strategic and methodological conditions. First, scenario alignment is essential. Med-TSO should begin by mapping ENTSO-E's TYNDP scenarios to its own Mediterranean context scenarios. This involves reviewing assumptions related to energy demand, renewable integration, electrification, and policy targets. Where relevant, these assumptions can be adapted to reflect regional circumstances, such as a higher reliance on natural gas or different electrification trajectories in North African countries.

Second, Med-TSO should review ENTSO-E's identified system needs to determine whether any of the projects or bottlenecks analysed are relevant to Mediterranean interconnections. Cross-border interconnectors such as Italy–Tunisia or Greece-Egypt may be partially covered in the ENTSO-E analysis, and Med-TSO can build upon these findings by conducting more regionally detailed assessments. If projects are already flagged in ENTSO-E but not sufficiently analysed from the Mediterranean side, Med-TSO's IoSN can provide complementary insights. Section 4.2 provides a more detailed examination of how the ENTSO-E perimeter can be integrated into the Med-TSO IoSN framework.

Third, modelling interoperability between the two processes is critical. This includes ensuring technical compatibility of the tools and assumptions used in the assessment (e.g. hourly dispatch modelling, climate input data, and network topology). Data sharing agreements and collaborative modelling efforts are key mechanisms for achieving consistency.

Fourth, project prioritisation can benefit from ENTSO-E's findings. Med-TSO can use the ENTSO-E IoSN results as a baseline or filter for highlighting projects of mutual interest or trans-regional relevance. However, prioritisation must be conducted using a cost-benefit analysis (CBA) framework adapted to the Mediterranean context, potentially derived from the ENTSO-E CBA guidelines but modified to account for local socio-economic and technical conditions.

4

Software Tools for IoSN

A variety of software tools support the IoSN studies, informing decision-making around network design, adequacy and flexibility capacity expansion, market behaviour, and system operation under different future scenarios. These tools, used both in academic literature and by TSOs, allow for the simulation and optimisation of energy systems under multiple technical and economic assumptions.

Among the tools currently used for the IoSN are PLEXOS, a commercial software suite widely used for power system modelling and market simulations, valued for its high temporal and spatial resolution capabilities, and its flexibility in representing generation, BESS, and transmission constraints. PLEXOS has been applied in several large-scale planning studies, particularly where detailed operational modelling and market dispatch optimisation are required.

The primary tool used in this study is Antares-Xpansion, an open-source capacity expansion module developed to complement the Antares Simulator, a platform extensively adopted by Med-TSO, ENTSO-E, and European TSOs for long-term adequacy and planning assessments. Antares-Xpansion supports multi-scenario optimisation and integrates investments in transmission, generation, and BESS infrastructure, making it particularly well-suited for complex, cross-border studies like IoSN.

4.1. General description of the optimisation challenge

This section introduces the core optimisation issue that Antares-Xpansion aims to solve, centred on investment planning and cost minimisation.

Antares-Xpansion minimises the following cost:

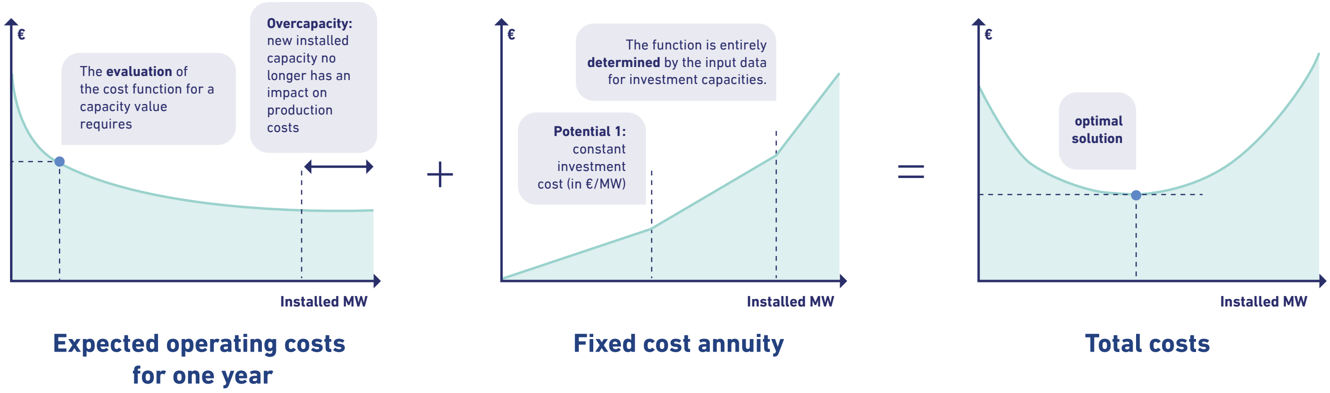
(expected operating costs for one year + fixed cost annuity)

Over a set of investment variables specified by the user.

The anticipated operating costs for one year, calculated by Antares, include the variable costs of thermal generation (fuel and CO2 costs), penalties in case of unsupplied energy, interconnection line transit costs (where applicable), and where the expansion_accurate mode is used, the start-up costs of thermal generation units. Production costs are calculated over the entire geographical perimeter of the Antares study, and in expectation over the probabilistic scenarios defined therein.

The fixed-cost annuity includes the fixed operating and maintenance costs of the generation and transit costs and, in the case of new units, the annualised investment cost.

Where the problem involves a single investment variable, the cost function described above can be represented graphically in Figure 3.



Expected operating costs for one year

Fixed cost annuity

Total costs

Figure 3: Objective function of the Antares-Xpansion optimisation problem for one candidate

Expected operating costs for one year decrease as installed capacities increase. New generation or transmission capacities indeed reduce the variable operating costs of the power system by substituting "higher-cost" generation (or unsupplied energy penalties) with output from a cheaper source. The marginal contribution of investment to this component of the cost function is decreasing: the first installed MW offers the greatest economic potential and the greater impact on generation costs, whilst the last installed MW yields a lower economic utility, or even none in the case of over-investment. These characteristics ensure that the expected operating cost is a convex function of the installed capacity.

In Antares-Xpansion, fixed-cost annuities are considered piecewise linear. Different potentials are defined, each of which is characterised by a fixed annuity in €/MW installed and corresponds to one of the slopes of the function (see Figure 3). A particular case of this representation of fixed annuities is a fully linear function characterised by a single fixed cost (in €/MW installed).

The resulting total cost is a convex function and therefore has a minimum solution plateau (see Figure 4), which in most (but not all) real-world applications is reduced to a single point (see Figure 3). In some cases, there are several points leading to the optimal cost. Antares-Xpansion seeks an optimal solution, i.e. the point that minimises the total cost, or any point of the minimum plateau in the case of a so-called degenerate problem.

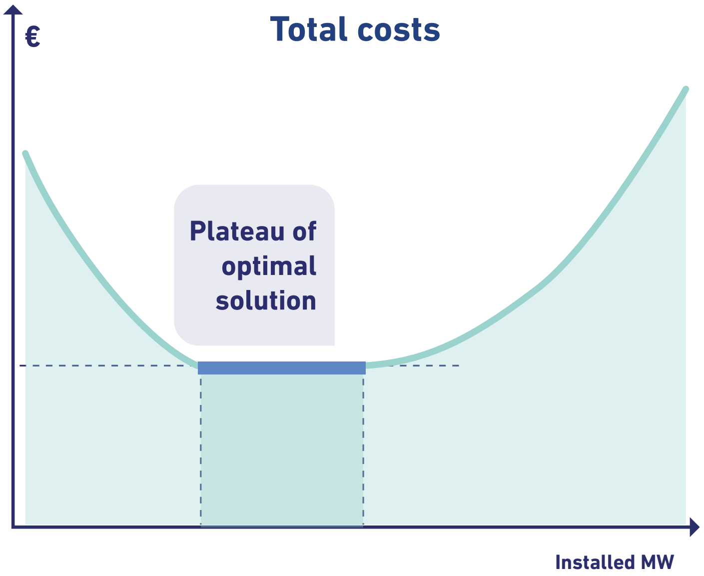


Figure 4: Generic case (uncommon in practice) with a set of optimal solutions (a plateau)

4.2. Investment variables and parameters

Investment decisions are based on several key variables, including costs, capacities, and technical constraints. This subsection explains the critical parameters that influence the optimisation process. The investment variables are the installed capacities (in MW) of the generation and/or transmission assets defined in the Antares-Xpansion input as candidates for investment.

The cases shown in Figure 3 and Figure 4 contain only one investment variable. The search for the optimal solution is carried out over the interval [0, available potential], bounded on the left by zero and on the right by the maximum available potential of the investment under consideration. The available potential is one of the input parameters of Antares-Xpansion.

In the more general case of several investment candidates, Antares-Xpansion determines the optimal investment combination, i.e. the combination *(c1,c2,..,cn)* of capacities of the *n* investment candidates that minimises the cost function.

The search for the optimal combination is conducted simultaneously across all investment candidates, rather than evaluating each one in isolation. This joint optimisation approach allows Antares-Xpansion to identify and evaluate both synergies and competitions between infrastructure options. For instance, it can detect synergies such as an interconnection line between nodes A and B that only becomes beneficial once an interconnection line between B and C is also in place. Similarly, it can reveal competitive dynamics, such as when two alternative corridors offer parallel routes that compete with each other.

4.2.1.Types of investment considered

Transmission infrastructure

Within the IoSN methodology, transmission projects are classified as first- or second-step projects, depending on their maturity, feasibility, and role in transmission system planning.

First step projects are concrete, planned, or already proposed infrastructure investments identified by TSOs through their national or regional planning processes. These projects are technically feasible, have defined costs and locations, and are either under regulatory assessment or already included in planning frameworks like the TYNDP. Their key characteristics are:

- Identified and developed by TSOs
- Supported by detailed technical and economic feasibility studies.
- Included in institutional plans (NDP, TYNDP, PCI).
- May already be in the permitting phase.
- Address clearly defined system needs (e.g. congestion relief, security of supply, market integration).

Second-step projects are hypothetical investment candidates not yet present in national or TSO planning, introduced within the IoSN process to explore new grid expansion possibilities.

These projects help assess alternative scenarios, long-term needs, and emerging technologies before formal project development begins. Their key characteristics are:

- Used to test the system-wide impact of new interconnections or grid reinforcements.
- Explores innovative solutions, such as offshore grids, sector coupling, or HVDC corridors.
- Help to compare different investment pathways in the CBA.
- Capable of transitioning into real projects if justified by the analysis.

Criteria	**First-step Projects**	**Second-step Projects**
Definition	Already planned or under development	Hypothetical projects for scenario testing
Approval process	Underway or completed	Not yet proposed
Purpose	Solve existing system needs	Explore new investment pathways
Example	Egypt-Greece	Italy-Tunisia (2nd/3rd project)

Table 1 First- vs. second-step projects in IoSN

Flexibility and security of supply investments

The approach to proposing these investment candidates differs from that used for interconnection projects, as it does not distinguish between first- and second-step candidates. Instead, flexibility and security of supply options are classified solely on the basis of economic and technical parameters defined during the data collection phase. Where no specific geographical differentiation is available, a standardised set of expansion parameters is applied to ensure consistency.

4.2.2. Economic and technical parameters

Economic parameters play a critical role in determining the financial feasibility of infrastructure investments. A key factor is Capital Expenditure (CAPEX), which represents the initial investment required for expanding transmission capacity, installing power generation assets, or deploying BESS solutions. Transmission infrastructure, such as high-voltage alternating current (HVAC) and high-voltage direct current (HVDC) lines, typically incur CAPEX costs ranging from €500,000 to €3 million per kilometre, depending on the voltage level and installation method (overhead, underground, or submarine). Generation assets such as Combined Cycle Gas Turbines (OCGTs) carry CAPEX of €500,000 to €1.2 million per MW, whereas BESS investments can vary significantly based on technology and scale. Utility-scale lithium-ion BESS systems typically cost €200 to €500 per kWh, depending on size, duration, and integration needs. Longer-duration systems (2-4 hours) benefit from economies of scale, with costs trending downward as technology matures.

In addition to initial investment costs, Operation and Maintenance (OandM) expenses influence the overall economic viability of an expansion candidate. Fixed OandM costs, measured in €/MW per year, cover routine maintenance, inspections, and system management; variable OandM costs, expressed in €/MWh, account for operational expenses related to electricity generation and transmission. For transmission projects, annual OandM costs typically range from 1% to 3% of CAPEX; thermal generation plants, such as OCGTs, incur fixed OandM costs of €10,000 to €30,000 per MW per year and variable OandM costs from €2 to €10 per MWh.

To ensure a fair evaluation of long-term investments, Antares-Xpansion applies a discount rate to calculate the present value of future expenditures and revenues. Discount rates generally range from 5% to 7% for regulated infrastructure projects, with higher values (up to 10%) applied to merchant power plants or projects subject to market risks. The economic assessment also considers the investment lifetime, which varies depending on the asset type: 40 to 50 years for interconnection lines, 25 to 40 years for thermal power plants, and 15 to 20 years for BESS.

Asset type	**CAPEX (€/unit)**	**Fixed OandM**	**Variable OandM**	**Discount rate**	**Lifetime**	**Second-step Projects**
Interconnection line (HVAC/HVDC)	0.5-3.0 M/km	1-3 % of CAPEX / yr.	-	5-7 % (regulated)	40-50 yr.	Overhead, underground, or submarine
OCGT (peaking units / mid-merit)	0.5-1.2 M/MW	€10-30k per MW/yr.	€2-10 / MWh	5-7 % (up to 10 % merchant)	25-40 yr.	Not yet proposed
BESS (Li-ion, 2-4 h)	€200-500/ kWh	1-2 % of CAPEX / yr.	≈ €0-5 / MWh	5-7 %	15-20 yr.	Longer duration → lower €/kWh

Table 2: Standard Economic Parameters for Expansion Candidates

Beyond financial considerations, technical parameters define the performance characteristics, operational feasibility, and system impact of expansion candidates. One of the most fundamental aspects is Transfer Capacity (MW), which represents the additional power transfer capability provided by a new transmission corridor or interconnector.

Another potential parameter in evaluating expansion projects is transmission efficiency, shaped by energy losses along interconnection lines. HVAC systems typically experience losses of 5% to 10% per 1,000 km, whilst HVDC lines incur lower losses of approximately 3% per 1,000 km, making them more suitable for long-distance energy transport. These efficiency metrics directly impact system reliability and cost-effectiveness.

For generation expansion, technical specifications include installed capacity (MW), availability factor (%), and minimum stable generation levels (MW). An OCGT power plant, for instance, typically has a capacity of 800 MW, an availability factor of 85%, and a ramp rate of 50 MW per minute, enabling flexible dispatch during peak demand periods. Start-up costs, which reflect the expenses associated with restarting thermal plants, are also factored into investment modelling, often reaching €50,000 per start for large-scale units.

For BESS and flexibility assets, Antares-Xpansion requires parameters such as BESS capacity (MWh), charge/discharge power (MW), and round-trip efficiency (%). Lithium-ion BESS solutions typically exhibit charge/discharge capacities of 200 MW, with a round-trip efficiency of 90%, whereas pumped hydro storage systems operate at lower efficiencies of 75% to 85%.

4.3. Mathematical problem formulation

Antares-Xpansion uses mathematical equations and constraints to evaluate the total cost of expanding and operating an energy system across various future scenarios, encompassing both infrastructure investments and day-to-day operational costs. This section explains how investment decisions and operating performance are represented within the model. A more detailed mathematical construction of the optimisation problem is provided in Appendix 10.1.

Investment decisions and capital costs

At the heart of Antares-Xpansion are investment decisions: how much capacity to build for each potential project, whether interconnection lines, BESS, or generation facilities.

Each project or “candidate” has:

- A maximum allowable capacity (how much can be built).
- A cost per unit of capacity installed (€/MW).

- decision variable specifying how much of it to build.

Projects are divided into two categories:

- Continuous investments: capacity can be added in any amount (e.g. interconnection line upgrades).
- Discrete investments: capacity is added in fixed units (e.g. modular BESS or entire power plants).

Total investment cost is calculated as the sum of all built capacities multiplied by their respective costs.

Estimating the costs to run the system

In addition to investment costs, Antares-Xpansion calculates the annual operating cost of running the system, considering:

- Electricity demand.
- Availability of renewable sources.
- Generation costs (fuel, maintenance).
- System constraints (e.g. network bottlenecks).

These costs are estimated through hour-by-hour and week-by-week simulations under different future conditions. To reflect uncertainty (e.g., weather or demand fluctuations), the model uses Monte Carlo simulations, running the system multiple times with different assumptions.

For each simulated year and week in the simulation, Antares solves a sub-problem to determine how best to operate the system based on the current investment plan.

Weekly decomposition

Because simulating an entire year of hourly data is computationally intensive, Antares divides the year into 52 separate weekly problems, each solved independently. This structure significantly reduces computation time while preserving operational realism. Each week is optimised separately, the results are aggregated to estimate the total annual operating cost, and the final cost reflects both investment decisions and the expected performance of the system across many scenarios.

Total system cost: investment + operation

The goal is to minimise total system cost, which includes:

- Investment cost: What it costs to build new infrastructure.
- Operating cost: What it costs to run the system each year under different scenarios.

The total cost is calculated as the addition of investment costs and expected operating costs. This provides a holistic view of the financial trade-offs between building more infrastructure versus relying more heavily on operations.

4.4. Benders Decomposition Algorithm

In large-scale energy planning, such as the development of future electricity networks, decision-makers must find the right balance between long-term investment costs (e.g. building new infrastructure) and short-term operational costs (e.g. daily power generation and dispatch). Further details on the mathematical formulation are provided in Appendix 10.2.

To address this complexity, Benders Decomposition is used within Antares-Xpansion to split this complex problem into two parts:

- A Master problem, which focuses on long-term investment decisions (e.g. what infrastructure to build).
- Subproblems, which evaluate how the system operates under specific future conditions, given the investments proposed in the master problem.

This separation simplifies the problem and makes it computationally feasible to analyse very large systems with many uncertainties.

How It works

The decomposition process is iterative:

- Initial investment plan: the model proposes an initial investment plan without considering all detailed operational constraints.
- Simulation of future operations: the system is simulated under various scenarios (e.g. each week and year), assessing operational performance and cost.
- Feedback and correction: if the proposed investment leads to inefficient or expensive operation, the model adds a “correction” (known as a Benders cut) to improve the next

investment decision.

- Iteration to convergence: this cycle repeats, improving the investment plan step-by-step until both investment and operational performance are optimal, or within an acceptable margin of error.

Why it matters

This method is particularly useful for large-scale models involving:

- Many years of uncertainty (e.g. 100+ Monte Carlo years),
- Detailed temporal granularity (e.g. weekly operations),
- Multiple infrastructure choices (e.g. lines, BESS, generation).

Without Benders decomposition, solving such a model directly would require enormous computational power and time.

The "Benders by Batch" variant

Whilst Benders Decomposition improves efficiency, evaluating every operational scenario in every iteration can still be too slow. The Benders by Batch variant addresses this by assessing only a subset of future scenarios at each step, introducing new scenarios only when necessary. Although this requires more iterations, it reduces the time needed per step and often results in faster overall performance.

4.5. Antares-Xpansion investment candidate set-up

4.5.1.Overview

This chapter presents a comprehensive guide to the configuration required for various technologies within the Antares-Xpansion framework. It serves as a reference for understanding the techno-economic parameters associated with different investment candidates and their role in the Med-TSO IoSN process.

The Med-TSO IoSN framework primarily focuses on two key investment areas: transmission infrastructure, (encompassing both electric power and hydrogen networks), and flexibility and security of supply investments. Guidance on modelling infrastructure retirements is also included to ensure the framework remains adaptable to evolving energy transition needs.

4.5.2.Investment in transmission capacity between two areas

In Antares-Xpansion, investment in transmission capacity is evaluated by assessing interconnections between regions.

- New interconnection line construction: when adding a completely new interconnection line, an additional link must be introduced in the Antares study to connect the two areas concerned.

- Grid reinforcement: where reinforcement is required between already-interconnected areas, the existing link in the Antares study remains unchanged. Instead, the already-installed-capacity parameter in the candidates.ini file is used to specify the pre-existing transmission capacity. Antares-Xpansion then determines whether increasing this capacity is economically justified.

In all four cases (transmission, thermal, renewable, and flexibility investments), the investment candidate link must fulfil the following conditions:

1. **Transmission capacities setting:** the link's transmission capacity parameter must be set to "use transmission capacities" and must not be set to null or infinite.

2. **Hurdle costs:** where applicable, a hurdle cost can be assigned to the link and will be incorporated into economic optimisation calculations.

3. **Binding constraints**: binding constraints can be applied but require Antares version v6.1.3 or later. These constraints influence system operation simulations and can be constructed using the Kirchhoff constraint generator or impedance, loop flow, and phase shift parameters.

4. **Transmission capacity adjustments:** direct and indirect transmission capacities are dynamically modified by Antares-Xpansion. Initial values in the Trans. Capacity Direct and Trans. Capacity Indirect fields are overridden when solving the expansion problem; existing capacity values should therefore be specified via the already-installed-capacity parameter in candidates.ini.

4.5.3.Investment in flexibility and security of supply

Traditionally, peaking units such as open cycle gas turbines and light or heavy oil generation plants are considered well-suited for adequacy purposes, given that their low capital costs can be offset by operating during periods of high demand or peak load. These units are designed to be flexible, ramping up quickly to provide additional power during spikes in electricity usage, making them valuable for maintaining grid stability and reliability. When planning investments in thermal generation capacity, the infrastructure is typically assigned to a single area. However, since Antares-Xpansion performs investments through study links, a virtual node (e.g. invest_semibase) must be created and connected to the physical node (area). The investment candidate link is then established between these two nodes.

The thermal generation candidate must be modelled as a thermal cluster, defined by the following technical and economic parameters:

1. **Location:** Assigned to the virtual node (invest_semibase).
2. **Market bid:** The bid price corresponds to its marginal cost, equivalent to the variable operating cost (€/MWh).
3. **Availability time-series:**
    - If using predefined time series, they must always exceed the candidate's potential (i.e. the maximum investment allowed by the user).
    - If using a stochastic time series, parameters must be adjusted to ensure availability exceeds potential (e.g. number of units × nominal capacity > potential, with no outage rate).
4. **Additional parameters:** Other variables like minimum power (pmin) and start-up costs can be specified but will only be considered by Antares-Xpansion if the unit-commitment type is set to expansion_accurate.

Flexibility assets such as BESS require specific modelling within Antares-Xpansion, typically represented as transmission capacity between a set of virtual nodes and links, constrained by operational limits.

- Defining flexibility as an investment candidate: a transmission link in Antares must be identified whose capacity corresponds to the flexibility potential (e.g. maximum power output or BESS volume).
- Example: Battery Energy Storage Systems (BESS):
- The charging and discharging capacity of the BESS system is represented by the link between an area and a virtual hub.
- Investment in BESS is determined based on the maximum possible flow across this link.
- Additional binding constraints (e.g. negative ROW balance in BESS-in, positive ROW balance in BESS-out) must be defined to simulate BESS dynamics correctly.

4.6. Uncertainty consideration in problem formulation

Energy investment decisions must account for uncertainty in demand, generation, and policy. The stochastic nature of the Monte Carlo years in Antares reflects the impact of uncertainties in key system parameters, including:

- thermal generation availability, influenced by unplanned outages and maintenance schedules,
- electricity demand variations, driven by temperature fluctuations and economic factors,
- renewable energy generation, particularly wind and solar power fluctuations,
- hydraulic inflows, affecting hydroelectric generation potential.

These uncertainties are incorporated into the problem formulation described in Appendix 10.1 as:

$$C(x) = c^T x + \sum_{l=1}^{l=N} p_l * \sum_{s=1}^{s=52} \Theta_{l,s}(x)$$

where $c^T x$ represents the total investment cost, computed as the dot product of the investment cost vector c and the investment decision vector x and $\Theta(x)$ denotes the expected yearly operating cost, determined through Antares simulations. The probability weight p_l is assigned to Monte Carlo year l, and $\Theta_{l,s}(x)$ is the weekly operational cost.

This formulation closely resembles a two-step stochastic optimisation problem, a widely used approach to decision-making under uncertainty in energy systems planning, comprising:

1. **First-step (investment) decisions:** made before the uncertainty is realised, covering capital allocation for new generation assets, grid infrastructure, and demand-side management strategies.
2. **Second-step (operational) decisions:** made after the uncertainty is realised., involving operational cost minimisation given the first-step decisions and observed stochastic outcomes, such as fuel costs, demand levels, and renewable generation fluctuations.

Mathematically, a two-step stochastic optimisation problem can be formulated as

$$c^T x + E_\xi \left[Q(x, \xi)\right]$$

where:

- x represents the first-step decision variables (e.g. capacity expansion choices).
- $Q(x,\xi)$ is the second-step recourse function that adjusts operational decisions based on uncertainty realisation ξ.
- $E_\xi[\cdot]$ denotes the expectation over the probability distribution of ξ.

The second-step recourse function also incorporates a Monte Carlo year-dependent set of constraints, represented as:

$$Ax = b$$

These constraints ensure operational feasibility across stochastic realisations. Essentially, a unique set of expansion decisions is optimised to best fit multiple operational scenarios, each reflecting a different Monte Carlo year. This allows for a flexible and robust investment plan that accommodates variations in system conditions, ensuring feasibility across diverse operational conditions.

From an energy system planning perspective, this means that each Monte Carlo scenario introduces specific constraints on generation capacity, network limitations, and demand-supply balancing. The optimisation process must therefore account for these scenario-dependent variations while maintaining overall system reliability and economic efficiency.

4.6.1. Stochastic vs deterministic approaches

Deterministic and stochastic optimisation approaches differ fundamentally in how they handle uncertainty:

Feature	**Deterministic optimisation**	**Stochastic o ptimisation**
Treatment of uncertainty	Ignores uncertainty or assumes fixed values	Explicitly models uncertainty using probability distributions
Solution robustness	Solutions are optimal for assumed conditions but may perform poorly under uncertainty	Solutions are designed to be robust under different uncertainty realisations
Computational complexity	Generally simpler and faster	More complex due to scenario generation and probabilistic modelling
Application for energy investment	Used when future conditions are assumed to be known or predictable	Used when uncertainty in demand, generation, or policies must be explicitly considered

Table 3: Comparison of stochastic and deterministic approaches

4.6.2. Handling demand and generation variability

The stochastic nature of the Antares-Xpansion problem only arises when more than one Monte Carlo year is selected; otherwise, the problem is deterministic. The Med TSO IoSN allows for up to 35 Monte Carlo years to be introduced, derived from the PECD data, with climate years ranging from 1982 to 2017.

In practical terms, solving an Xpansion problem for 35 Monte Carlo years simultaneously is neither computationally feasible nor technically advisable for several reasons:

- Climatically similar years add unnecessary mathematical burden without significantly improving solution accuracy.
- Certain climatic years might require a higher weight to ensure the planning of a more robust system.
- Computational complexity increases exponentially with the number of Monte Carlo years, leading to longer solution times and potential convergence issues.
- Monte Carlo year selection must balance representativeness and efficiency, capturing key scenarios without overloading the model.
- Strategic selection of representative years can yield near-identical investment decisions with significantly lower computational costs.
- Aggregation techniques, such as clustering similar climate years, can help reduce problem size while preserving variability.
- Sensitivity analysis on Monte Carlo year weighting can refine the investment strategy, improving resilience to extreme weather conditions.

4.6.3. Analysis methodology for the definition of representative climate years

The primary goal of this methodology is to define representative climate years that accurately reflect historical climate variability and its impact on the energy system, enabling an efficient yet comprehensive analysis of different climatic scenarios, and ensuring the feasibility of the Antares-Xpansion problem.

The methodology encompasses three primary steps:

- **Residual load distributions:** the residual load for each region is calculated on an hourly basis by subtracting RES infeed, such as solar, wind, and hydro, from the system load. This calculation captures the temporal and spatial variability of the system state due to climatic conditions.

- **Delta indicators:** to evaluate how individual years compare to the 35-year average on a regional level, delta indicators are computed. These indicators assess deviations in parameters like demand, RES generation, and temperature, providing insights into the representativeness of each year concerning long-term climatic trends. To compare the residual load distributions, two primary statistical indicators are employed: the mean $\mu_{r,g}$, which represents the overall energy content of the annual distribution, and the standard deviation $\theta_{r,g}$, which reflects the variability within the distribution. Each candidate combination is evaluated based on how closely its statistical properties approximate those of the aggregate distribution $\Omega_{r,g\in G}$. This is assessed by computing the differences between the mean and standard deviation of each $\in G$ and those of the aggregate distribution, thereby determining the extent to which each candidate captures the central tendency and dispersion of the overall residual load profile.

$$\Delta\mu_{r,g} = mean\left(\Omega_{r,g}\right) - mean(\Omega_{r,g\in G})\ \text{(mean)}$$

$$\Delta\theta_{r,g} = std\left(\Omega_{r,g}\right) - std(\Omega_{r,g\in G})\ \text{(standard deviation)}$$

- **Selection of candidate combinations**: based on the residual load distributions and delta indicators, a combination of three climate years is selected to represent a range of climatic conditions effectively, ensuring that the analysis encompasses diverse uncertainties, enhancing the robustness of the system needs assessment.

Each TYNDP cycle, ENTSO-E's identifies a set of climatic years that are most representative for energy system modelling, selected based on their ability to capture a wide range of weather variability, renewable energy availability, and demand patterns, ensuring robust scenario analysis. This dataset has also been incorporated into ENTSO-E's IoSN process, where it is used in conjunction with Antares-Xpansion for system optimisation studies.

For the Med-TSO IoSN framework, the selection of representative climatic years will undergo further validation and testing. Alternative combinations of climatic years will be assessed to determine their impact on system expansion and flexibility needs. This process will follow the methodology outlined in Section 4.2, to ensure that the most suitable climatic scenarios are used for Mediterranean-specific energy planning and grid development.

5

Data Collection and Optimisation Execution

5.1. Data collection and preparation

The identification and assessment of expansion candidates are carried out in collaboration with Med-TSO members, ensuring a comprehensive and standardised approach to data gathering. This process relies on structured data templates designed for both flexibility and security of supply and transmission technologies, capturing essential technical and economic parameters.

Entry	Description
Node	Physical node/country name
Scenario	Scenario name
Technology	Investment candidate type. The user can only select between four options: BESS, peaking units, electrolyser, or SMR

CAPEX (€/MW)	Investment capital expenditure cost
FOandM (€/MW/a)	Fixed operational cost
Capacity (MW)	Maximum investable capacity
Discount rate (%)	Reflects the time value of money, which means that a euro today is worth more than a euro in the future because it can be invested and potentially earn a return. The higher the discount rate, the lower the present value of the annuity, because future payments are discounted more heavily. Conversely, a lower discount rate results in a higher present value for the annuity, because the future payments are discounted less heavily.
Lifetime (a)	The number of periods over which investment payments are made.

Table 4: Data Collection template for generation technologies

Entry	Description
Line	Interconnector name
Type	HVDC or HVAC
Voltage Level	Transmission network voltage level
From Node	Starting physical node for interconnector
To Node	Ending physical node for interconnector
Sector	The commodity (electricity or hydrogen) into which the interconnector is placed.
Scenario	Scenario name
CAPEX (M Eur)	Investment capital expenditure cost
FOandM (M Eur)	Fixed operational cost
Capacity A→B (MW)	Direct transmission capacity (from starting to ending node).

Capacity B→A (MW)	Indirect transmission capacity (from ending to starting node).
Discount rate (%)	Reflects the time value of money, which means that a euro today is worth more than a euro in the future because it can be invested and potentially earn a return. The higher the discount rate, the lower the present value of the annuity, because future payments are discounted more heavily. Conversely, a lower discount rate results in a higher present value for the annuity, because the future payments are discounted less heavily.
Lifetime (a)	The number of periods over which investment payments are made.

Table 5: Data Collection template for transmission technologies

Standardised data templates are used to facilitate consistency and comparability across different scenarios. The predefined templates include:

1. Generation technologies: covering power sources such as BESS, peaking units, and electrolysers.
2. Transmission technologies: encompassing high-voltage interconnection lines and hydrogen pipelines.

Each template captures the required input parameters necessary for Antares-Xpansion to formulate expansion candidates effectively. The templates capture both technical and economic attributes which are critical for evaluating expansion options:

- **Technical data**
  - Capacity (MW): maximum output of the generation asset or transmission capability.
  - Grid connection requirements: connection points.
- **Economic data**
  - Capital Expenditure (CAPEX) (€/MW or M€): initial investment costs, including construction, permitting, and infrastructure development.
  - Operational and Maintenance Costs (OPEX) (€/MW/year): ongoing costs for operation and maintenance.
  - Discount rate (%): the time value of money, which means that a euro today is worth more

than a euro in the future because it can be invested and potentially earn a return. The higher the discount rate, the lower the present value of the annuity, because future payments are discounted more heavily. Conversely, a lower discount rate results in a higher present value for the annuity, because the future payments are discounted less heavily.

- Expected lifetime (years): the number of periods over which investment payments are made.

Data is gathered directly from national TSOs and regional grid planners, ensuring alignment with ongoing infrastructure projects and regulatory constraints. Once collected, the technical and economic datasets are structured for integration into the Antares-Xpansion framework, where expansion candidates are generated based on predefined investment decision rules and feasibility constraints ensuring technical compatibility with the existing and planned grid.

5.2. Optimisation execution

The execution of the Med-TSO study depends on a series of critical decisions, which are systematically incorporated into the simulation framework outlined below.

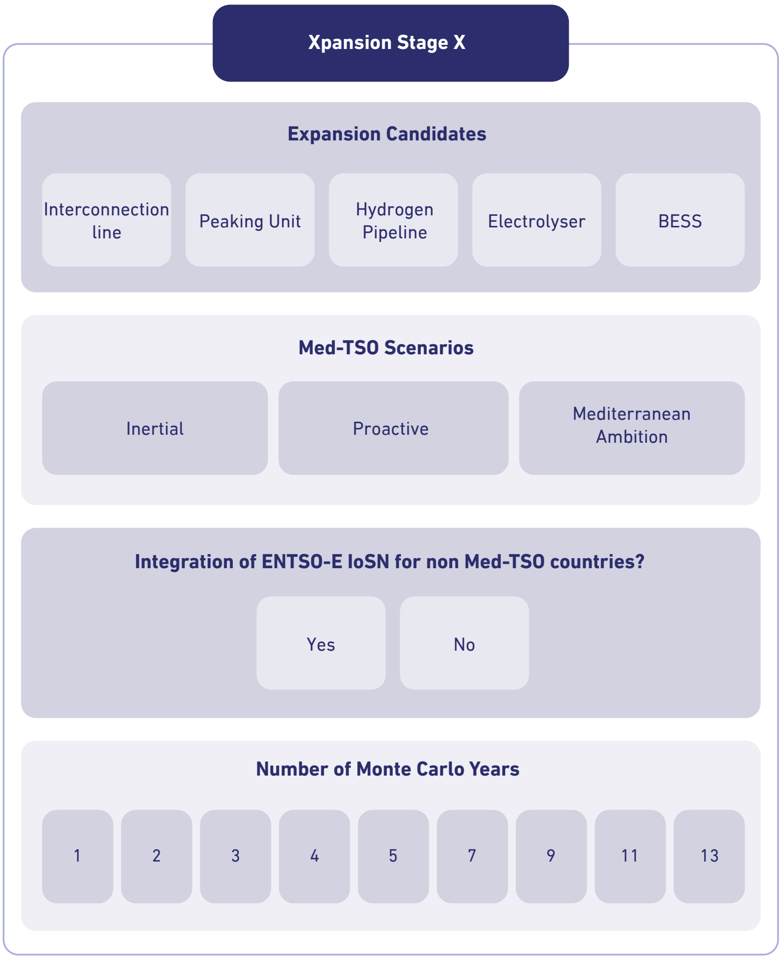


Figure 5: Med-TSO IOSN Simulation Framework

This framework consists of several hyperparameters that influence both the scope of the problem and the implications of the study. The decision layers are categorised as follows:

- **Xpansion step X:**
  - Traditionally, the ENTSO-E IoSN is divided into two steps, distinguished by the type of interconnector candidate projects the optimiser may invest in. The number of optimisation steps helps prioritise certain investments based on their maturity and alignment with a region's energy strategy whilst preserving overall system optimisation.
  - Default selection: 2 expansion steps.
- **Expansion candidates:**
  - The selection of permissible technologies in the expansion problem serves as a crucial hyperparameter. It helps analyse the system's investment preferences and quantify correlations between different technologies. For example, transmission investment levels may vary between a scenario that allows only power transmission investments and one that includes both power transmission and hydrogen infrastructure investments.
  - Default selection: interconnection lines, peaking units and BESS.
- **Med-TSO scenarios:**
  - The Med-TSO framework includes three scenarios, Inertial, Proactive, and Mediterranean Ambition, which reflect potential future interactions among national power systems, ultimately leading to a coordinated Mediterranean power system. These scenarios outline pathways from the present to diverse possible future trends in energy demand, electricity generation, sector coupling, technology evolution, policies, and decarbonisation targets, providing a robust foundation for grid development studies.
  - Default selection: inertial scenario.
- **Integration of ENTSO-E IoSN for non-Med-TSO countries:**
  - The Med-TSO IoSN study must logically integrate with ENTSO-E's IoSN framework. Two reconciliation approaches are possible: aligning the starting point with ENTSO-E's IoSN, ensuring that the Pan-European geography begins from its starting grid or incorporating ENTSO-E's IoSN results into non-Med-TSO countries while focusing on expansion paths specific to the Med-TSO region.
  - Default selection: No.

- **Number of Monte Carlo years:**
  - As discussed in Section 3.6.1, the number of Monte Carlo years significantly impacts expansion modelling. This parameter must balance uncertainty management with computational feasibility to ensure an efficient and reliable analysis.
  - Default selection: 3.

The following three examples illustrate possible hyperparameter combinations within the presented framework to help familiarise the reader with the practicality of the presented options.

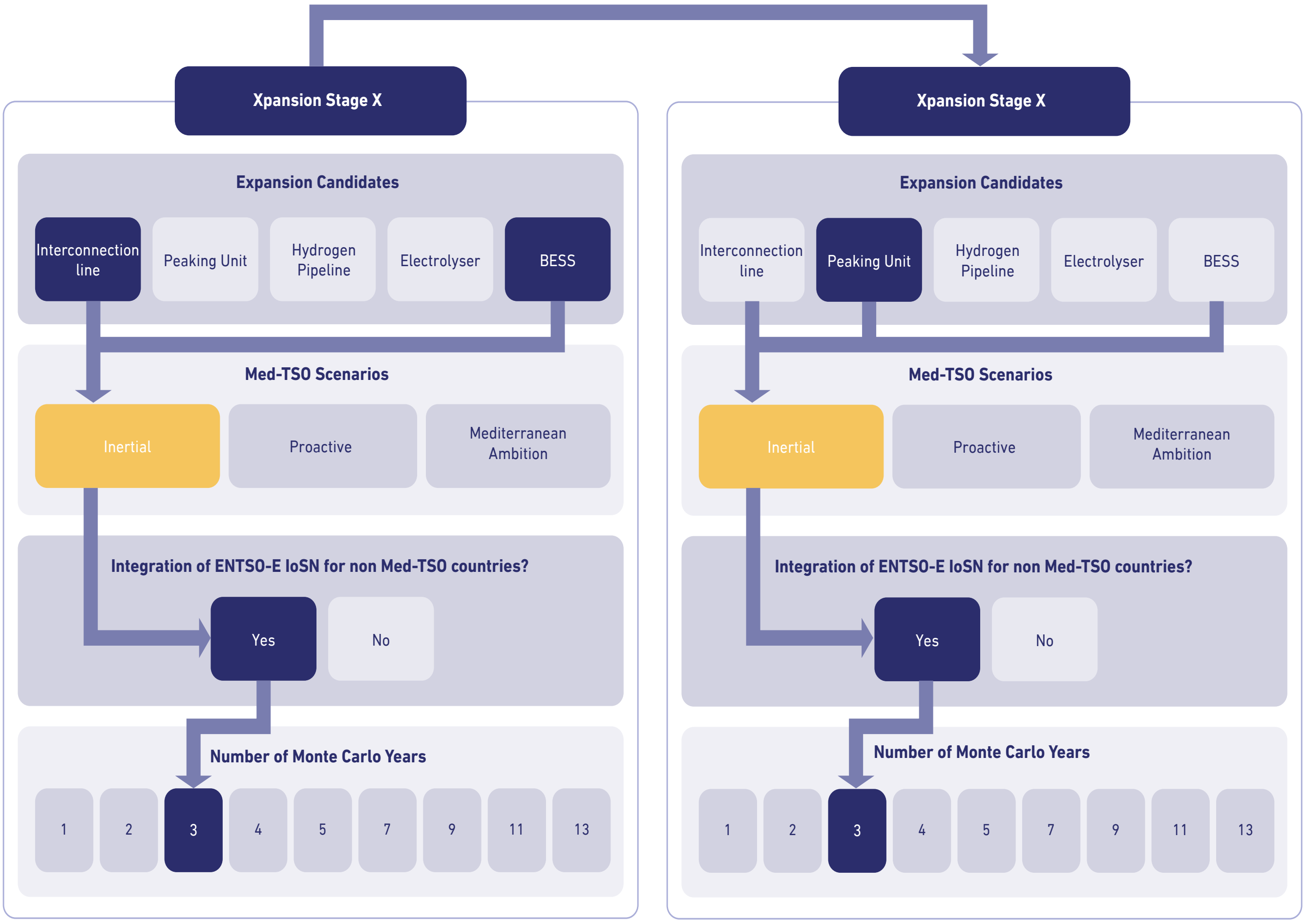


Figure 6: Example Framework 1

Example Framework 1 (EF1) presents an IoSN divided into two expansion phases, distinguished primarily by the assigned expansion candidates in each step.

- **Step 1:** expansion is limited to interconnection lines and BESS, with further differentiation of candidates is made, as detailed in Section 3.2.1
- **Step 2:** the expansion scope broadens to include peaking units as security of supply measures.

Both steps incorporate predefined commitments tied to energy and environmental policies, such as Fit-for-55 and RePowerEU for EU-27 member states. In this framework, the expansion strategy prioritises the Med-TSO region. To address the stochastic nature of the expansion problem, the study employs three Monte Carlo years.

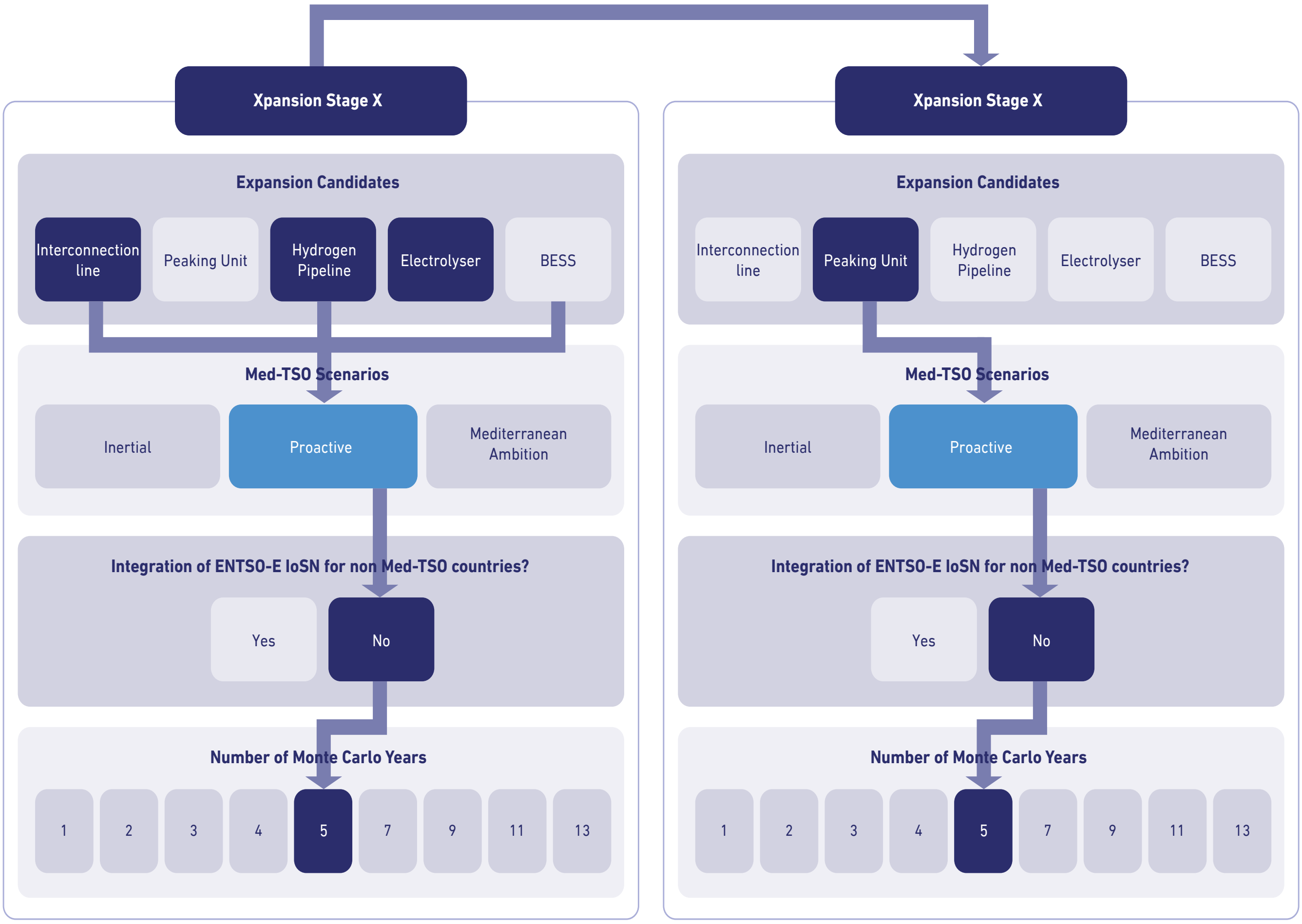


Figure 7: Example Framework 2

Example Framework 2 (EF2), like EF1, is structured into two expansion phases but with a broader scope in the second step.

- **Step 1**: as in EF1, expansion is limited to interconnection lines and BESS.
- **Step 2:** the candidate pool expands to include additional flexibility options, such as sector coupling technologies (electrolyser) and hydrogen pipelines.

This approach aligns with the Med-TSO Proactive scenario, which emphasises accelerated renewable energy development, driven by localised solutions and investment incentives at consumer and prosumer levels. The inclusion of hydrogen technologies reflects this scenario' prioritisation of green hydrogen strategies alongside other energy efficiency measures.

At European level, the Proactive scenario is not merged with ENTSO-E IoSN expansion results. This allows for a unified expansion strategy encompassing both Med-TSO and Pan-European countries.

To account for uncertainty, three Monte Carlo years are considered, each weighted according to the methodology outlined in the study.

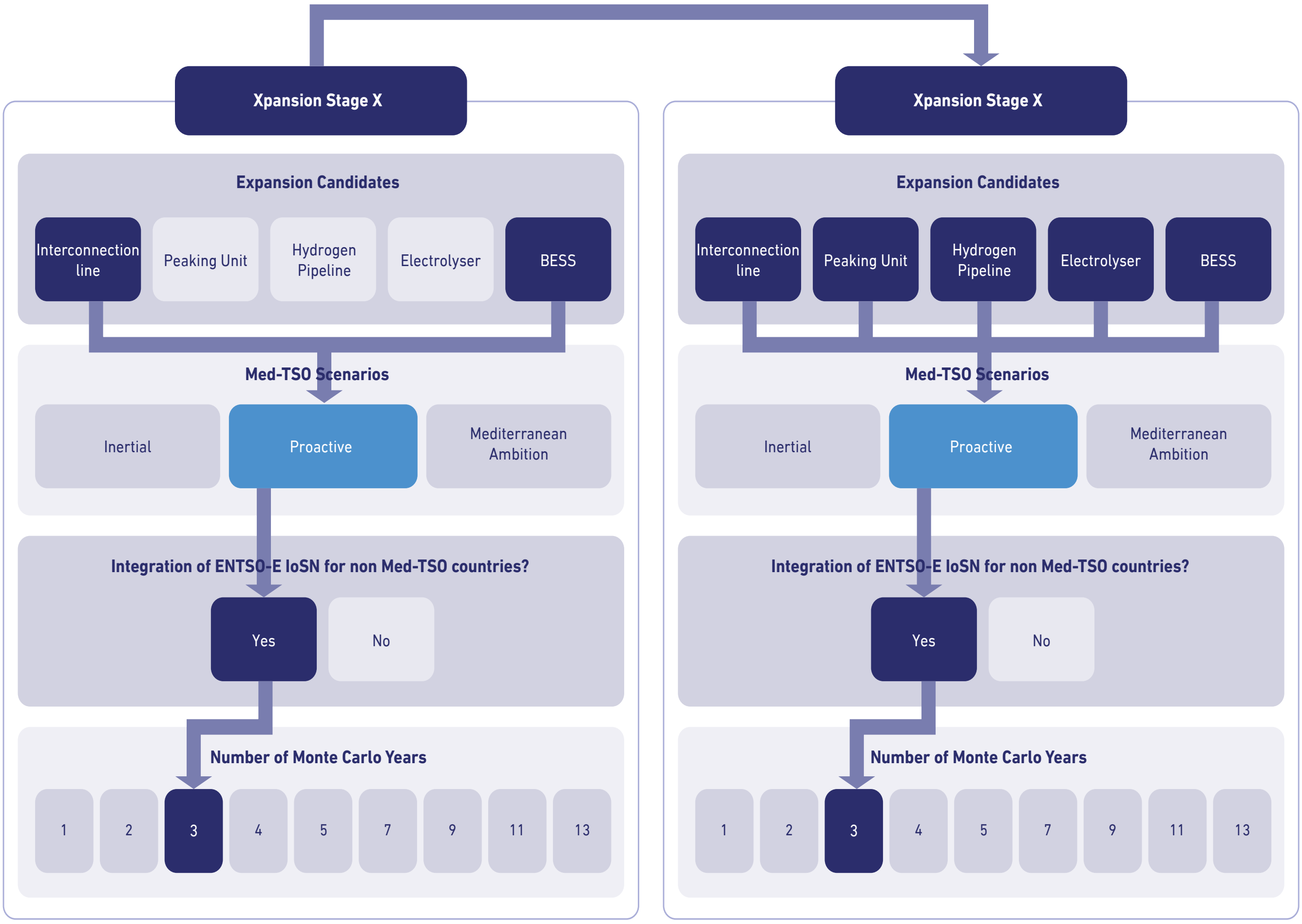


Figure 8: Example Framework 3

Example Framework 3 (EF3) functions as a sensitivity analysis for EF 1 and EF 2, assessing the robustness of investment decisions and exploring correlations between technologies.

- **Step 1:** prioritises high-potential investments in interconnection lines and hydrogen infrastructure with reduced emphasis on flexibilities such as BESS.
- **Step 2:** introduces security of supply as the sole expansion measure, focusing on evaluating the reliability of the initial investment phase.

The primary objective of EF3 is to validate the investment resilience while examining technological interdependencies. The focus remains on the Med-TSO region, with scenario reconciliation achieved by incorporating ENTSO-E IoSN investment results into the analysis. Since the expansion is restricted to the Med-TSO region, a larger set of Monte Carlo years is used to better assess the impact on the updated investment pool.

The three frameworks described above are illustrative and may be adjusted during the simulation phase to accommodate the experimental nature of the study. Each framework will be reviewed and approved by Med-TSO members throughout the simulation process to ensure consistency and relevance.

Analysis of frameworks and results

The frameworks described above represent distinct sensitivities, each reflecting alternative assumptions and trajectories. As such, the results derived from them must be interpreted with the same methodological rigour and contextual understanding applied to scenario-building. These simulations offer multiple insights, with a primary focus on assessing the robustness of investment decisions across different Med-TSO scenarios. We evaluate whether specific investment decisions, such as the reinforcement of particular interconnections or the deployment of new infrastructure, remain consistent across a range of scenario narratives. Robustness in this context implies that the investment retains its strategic value under varying future conditions.

A further critical aspect of the analysis involves assessing the competition and potential bias in infrastructure development when different technology expansion options are permitted. For instance, we compare investment pathways under scenarios that allow the deployment of hydrogen infrastructure, such as pipelines and electrolysers, against those that do not. This approach enables us to identify whether certain technologies systematically crowd out others, or whether the inclusion of specific assets leads to significantly different system configurations. Such insights are essential for understanding not only the cost-efficiency of alternative expansion strategies but also their alignment with broader policy objectives, such as decarbonisation, flexibility, and security of supply.

5.3. Assessment of economic viability of non-selected projects

Whilst the IoSN process focuses on identifying and prioritising the most promising infrastructure projects based on predefined scenarios and cost-benefit criteria, exclusion of certain projects from the final list does not inherently imply a lack of economic value. To ensure a comprehensive and future-resilient planning process, it is recommended to conduct a systematic post-assessment of non-selected projects. This involves evaluating their economic viability through targeted sensitivity analyses, standalone cost-benefit appraisals, and post-processing of large-scale system simulations. Such an approach can help identify projects whose benefits may become substantial under alternative assumptions or in combination with other investments.

This post-evaluation should begin with the application of a consistent CBA methodology, such as that outlined in the ENTSO-E CBA Guidelines, adapted where necessary for the Mediterranean context. Sensitivity analyses should test project performance across a range of variables, including demand growth, renewable penetration, fuel and CO_2 prices, and discount rates. Sensitivity analyses may be performed to study different incrementally changeable project costs (CAPEX, OPEX etc.) to identify the gap between the initially estimated costs and the cost assumptions under which the candidate project may be selected within the optimisation. Furthermore, insights from system-wide simulations can be mined to quantify the marginal benefits of non-selected projects, such as congestion reduction, enhanced system adequacy, or flexibility contributions. Where relevant, project clustering analysis may reveal synergies not evident in isolated assessments. This extended analysis not only increases transparency and robustness in the planning process and supports the strategic monitoring of projects that could become viable in future planning cycles or policy contexts.

6

Model Requirements

Effective investment planning relies on accurate data and robust modelling techniques. This section outlines the necessary input data, sources, and model requirements.

6.1. Input data and related sources

Key data sources, including network topology and market projections, are discussed below. The starting grid construction is critical in establishing a starting point for the market models.

6.1.1. Starting grid and IoSN starting point

The Pan-European starting grid developed within ENTSO-E's TYNDP follows a comprehensive review of the infrastructure projects considered for inclusion. These starting networks serve as the foundation for the Cost-Benefit Analysis (CBA) of infrastructure projects and as the starting point for ENTSO-E's IoSN process.

During this review, project promoters were contacted and asked to review and update their proposed projects and provide clear justifications for inclusion in the starting networks. This approach ensured that only relevant, technically and economically viable projects were retained in the system development framework.

ENTSO-E assessed three starting network configurations. The 2030 starting grid constitutes the starting point for the IoSN process, with eligibility criteria as follows:

1. Projects must be in the construction phase; or

2. Projects must have successfully completed environmental impact assessments.

For any project meeting these criteria, proof of maturity was required in the form of a study demonstrating compliance. Final approval for inclusion remained at ENTSO-E's discretion.

To ensure realistic commissioning timelines, project promoters were required to submit written justifications for expected commissioning years. The validation process involved:

- Agreement between TSOs and National Regulatory Authorities (NRAs) in the respective countries.
- Inclusion in the latest National Development Plan (NDP) at the time of project data collection.
- Use of recent agreements (e.g. quarterly monitoring updates) if available.
- Cross-checking against average lead times of similar infrastructure projects in cases where direct evidence was unavailable.

Where a project lacked a formal agreement between the promoter, TSO, and NRAs regarding its commissioning date, or was not included in any country's National Development Plan (NDP), ENTSO-E applied the CBA 3.0 Guidelines to assess the feasibility of the proposed timeline. Where the stated commissioning date was deemed unrealistic, ENTSO-E reserved the right to exclude the project from the starting grid.

The **Med-TSO Starting Grid** outlines the existing and planned interconnections among Mediterranean countries, serving as a foundation for coordinated infrastructure development and system planning.

To ensure a cohesive starting point for the IoSN, it is essential to reconcile and harmonise the different transmission grid frameworks. This includes adapting existing interconnections, such as those between Med-TSO countries like Spain and France (ES-FR), to reflect a 2030 baseline. This will enable the integration of relevant transmission expansion candidates identified during ENTSO-E's IoSN process.

Existing Transmission Capacities

The Med-TSO starting grid is provided in Appendix 10.3.

6.1.2. Market definition

The IoSN process relies on a structured dataset to ensure consistency, accuracy, and compatibility with the Med-TSO study framework. The required data inputs cover generation, fuel pricing, hydro constraints, renewable energy sources, load time series, and network expansion potential. These datasets are integrated into the Antares-Xpansion for the 2040-time horizon, serving as the foundation for the optimisation.

The generation dataset follows the PEMMDB 2.5 format, ensuring compatibility with market modelling and capacity expansion tools, and includes:

- **Common generation dataset:** standardised capacity, efficiency, and availability data for generation units.
- **Fuel prices:** extracted from the published dataset in the Scenario Building report, reflecting market-based pricing assumptions.
- **Maintenance and forced outage profiles:** outage probability distributions and planned maintenance schedules for conventional generation units.
- **Hydro constraints and inflow data:** parameters for hydropower generation availability, water inflows, and seasonal constraints.
- **RES full-load hourly time series:** sourced from the Pan-European Climatic Database, providing hourly generation profiles for solar, wind, and other RES technologies.
- **Load time series:** demand profiles based on historical consumption patterns and future projections.

7

Setting the List of IoSN Investment Candidates

Investment candidates are evaluated based on technical and economic feasibility. This section explains the selection criteria following the logic described in Section 3.2.1.

7.1. Transmission candidates

7.1.1. Corridor-specific considerations

- **West Mediterranean Corridor:** emphasis is on integrating the Iberian market with Maghreb countries to reduce price disparities and enhance bilateral exchanges.
- **Central Mediterranean Corridor and North Africa Backbone:** these projects focus on linking Maghreb nations with Italy, ensuring that the abundant renewable potential in North Africa and the region's growing demand are efficiently integrated into European networks.
- **East Mediterranean Interconnectors:** the priority here is to create new corridors connecting countries on both shores of the Eastern Mediterranean, fostering a more balanced and secure regional grid.

- **Adriatic and Balkan Corridor:** projects in this corridor aim to boost the Net Transfer Capacity between Türkiye and the Continental Europe Synchronous Area (CESA), enhancing the flexibility and reliability of the interconnected grid.
- **Middle East Mediterranean Integration:** this cluster targets enhanced connectivity among Eastern Mediterranean countries (e.g. Jordan, Syria, Türkiye, Lebanon, Palestine, and Egypt), addressing regional isolation and increasing overall interconnection capacity.

7.1.2. List of corridors

The Med-TSO region's strategy for enhancing grid integration and securing a sustainable energy future is organised around five key corridors. These serve as clusters for interconnection projects, each tailored to the unique geographical, technical, and market conditions of its area. Collectively, they support energy security, renewable integration, and foster regional market coupling. The corridors are defined as follows:

- **West Mediterranean Corridor:** bringing together projects that involve Algeria, Morocco, Portugal, and Spain. Its primary objective is to integrate the Iberian electricity market with the Maghreb region, enhancing cross-border energy exchanges and reducing price differentials between northern and southern shores of the Mediterranean. By strengthening these links, the corridor supports increased renewable energy flows and reduces the risk of supply disruptions.
- **Central Mediterranean Corridor and North Africa Backbone:** focusing on the core of the Mediterranean, this corridor strengthens interconnections among Maghreb countries and forges robust links to the Italian transmission network. Projects in this cluster typically span Algeria, Tunisia, Libya, and Italy, facilitating the exchange of renewable energy resources and reinforcing grid reliability across a critical north-south axis.
- **East Mediterranean Interconnectors:** dedicated to forging new electricity corridors along the eastern shores of the Mediterranean, this corridor connects countries such as Egypt, Türkiye, Israel, Cyprus, and Greece. The projects in this cluster are designed to create asynchronous interconnections that enable the efficient transfer of energy between the two shores, balancing supply and demand and supporting the broader integration of diverse renewable energy sources.
- **Adriatic and Balkan Corridor:** comprising interconnection projects such as those between Bulgaria, Türkiye, and Greece, as well as between Italy and Greece. It aims to boost the existing Net Transfer Capacity (NTC) between Türkiye and the Continental Europe Synchronous Area (CESA). Enhancing these links improves the overall operational flexibility of the network and paves the way for a more integrated European electricity market.

- **Middle East Mediterranean Integration:** focusing on the eastern Mediterranean region, this corridor targets the reinforcement of connections among countries such as Jordan, Syria, Türkiye, Lebanon, Palestine, and Egypt. Projects in this cluster are vital for overcoming regional isolation, improving system adequacy, and ensuring that energy generated in one country can be efficiently and reliably shared with neighbouring countries.

Together, these corridors provide a structured approach for clustering interconnection projects in the Med-TSO region. They support a coordinated effort to modernise grid infrastructure, harmonise technical standards, and facilitate the exchange of renewable energy across borders, ultimately contributing to a more secure, resilient, and sustainable power system throughout the Mediterranean. The integration of renewable energy sources into power grids increases the need for enhanced flexibility and resilience. In the Med-TSO region, the growing share of variable renewable energies drives system operators to explore innovative solutions that ensure grid stability. BESS systems play a critical role by bridging supply and demand gaps; they absorb excess generation during low-demand periods and release stored energy during peak times, thereby smoothing fluctuations. These systems also enhance grid stability by responding quickly to frequency changes and abrupt variations in generation or consumption. As renewable capacities expand, BESS solutions facilitate higher renewable penetration and align with regulatory frameworks that encourage market-based flexibility.

Demand response programmes complement these efforts by allowing consumers to modify their electricity usage in response to grid signals, which is essential for balancing supply and demand under variable renewable generation. Participation across residential, commercial, and industrial sectors continues to grow, supported by the adoption of smart metering and advanced energy management systems. Recent regulatory developments at EU level aim to integrate demand response more fully into the broader energy system, further promoting non-firm connection agreements and flexible market mechanisms. Together, BESS and demand response are crucial for reducing congestion, increasing operational flexibility, and maintaining overall grid stability in the Med-TSO region. As investments in flexible technologies and regulatory reforms progress, these approaches are well placed to support a more balanced and sustainable energy ecosystem.

7.1.3. Potential for hydrogen and power-to-X integration

Hydrogen and power-to-X (PtX) solutions are rapidly emerging as critical pillars of the Mediterranean energy transition, complementing traditional electricity interconnections with flexible, low-carbon energy pathways. Green hydrogen is produced by electrolysers that use renewable electricity to split water into hydrogen and oxygen. The strategic placement of these electrolysers is vital: new electrical interconnections can harness surplus renewable or nuclear power to boost low-carbon hydrogen production, while also potentially influencing local generation balances.

In many MENA countries, hydrogen production is primarily oriented towards export to Europe, often in the form of hydrogen gas or after conversion into ammonia. Although some of the hydrogen produced is intended for domestic use, the prevailing strategy is to build export capacity that supports Europe's decarbonisation efforts. This dual focus is integrated within European planning models, where dedicated hydrogen grids operate alongside traditional electricity networks, ensuring that hydrogen production is closely linked to the overall energy system.

A key element of the Mediterranean strategy is sector coupling, which links electricity and hydrogen systems through electrolysers. By converting excess renewable energy into hydrogen, these systems provide a flexible load that can help stabilise the grid whilst enabling the storage and subsequent use of energy in industrial processes or as a feedstock for further chemical conversion. This approach, often referred to as PtX, transforms surplus electricity into valuable chemical energy, reducing renewable curtailment and enhancing overall energy efficiency.

Infrastructure plays a decisive role in this transition. Decision-makers are evaluating whether to retrofit existing gas pipelines for hydrogen transport or to invest in new, dedicated hydrogen pipelines. Such infrastructure is essential to establish reliable hydrogen corridors that connect production hubs in North Africa and the Eastern Mediterranean with the growing European market. These corridors are envisioned as key enablers of cross-border energy trade, ensuring that hydrogen produced from abundant renewable sources reaches its intended markets at competitive costs.

Furthermore, the integration of hydrogen production facilities with the electricity grid is designed to be both smart and flexible. Facilities may operate either on-grid or off-grid, with dedicated wind and solar capacities ensuring that electrolysis is triggered only during periods when renewable or nuclear power is marginal. This careful control of electrolyser activation helps maintain competitive production costs, positioned between nuclear and combined cycle gas turbine prices, and avoids unintended increases in fossil fuel generation.

Med-TSO's modelling and planning efforts explicitly incorporate hydrogen and PtX considerations. Although current scenarios do not call for a dramatic expansion of electrolyser capacity, the models integrate hydrogen production and grid interactions by using detailed data supplied by transmission system operators. For example, under the Mediterranean Ambition scenario, which envisions full decarbonisation for European countries by 2050, centralised low-carbon solutions including hydrogen are favoured. At the same time, the planning differentiates between the grid dynamics within European countries and those related to interconnections with North Africa and the Middle East, highlighting the need for tailored approaches across different regions.

In short, hydrogen and PtX are not merely complementary to conventional electricity interconnections; they are fundamental to creating a flexible, resilient, and decarbonised energy system in the Mediterranean. By integrating renewable hydrogen production into the broader grid strategy, the region is poised to enhance energy security, support cross-border trade, and drive the transition toward a sustainable future.

8

Common Metrics Used to Assess Needs

To assess the needs identified during the simulation process, several metrics can be used to ensure that energy infrastructure projects contribute meaningfully to the energy and climate objectives. The evaluation framework is structured around four main dimensions: technical reliability, economic efficiency, market integration and flexibility, and environmental sustainability. A more detailed description of each metric is provided in Appendix 10.5.

8.1.Technical metrics

Technical metrics are used to assess whether the electricity system can reliably meet demand across different scenarios, including periods of peak consumption or system stress. Among the most critical indicators is the Loss of Load Expectation (LOLE), which quantifies the expected number of hours per year during which electricity supply may fall short of demand. A LOLE of fewer than three hours per year is generally considered acceptable. Complementing this, the Energy Not Served (ENS) indicator measures the total volume of electricity demand that remains unmet, helping assess the socio-economic impact of potential outages.

Another key indicator is the system adequacy reserve margin, which represents the buffer between available generation capacity and expected peak demand. Maintaining a reserve margin in the range of 15-20% is commonly recommended to ensure reliable operations, although this figure can vary with system characteristics and the level of renewable energy integration. Furthermore, grid congestion, measured as the percentage of hours per year during which interconnection lines are heavily loaded, is used to assess the efficiency of electricity flow across regions and to identify where reinforcements may be needed.

In a decarbonising and increasingly integrated power system, expanding and reinforcing electricity grids is essential. A primary indicator used to evaluate this dimension is the transmission grid reinforcement need, expressed in gigawatts (GW). This metric helps estimate the additional grid capacity required to accommodate growing electricity consumption, high shares of renewables, and increased cross-border flows. Such assessments are typically based on power flow simulations and long-term energy system modelling.

8.2. Economic metrics

From an economic perspective, infrastructure projects are evaluated on their contribution to minimising total system costs whilst meeting future electricity needs. Total system cost includes expenditure related to electricity generation, transmission, distribution, and system flexibility services. This indicator supports comparisons between different system configurations and investment pathways.

8.3. Market and flexibility metrics

Market integration and system flexibility are essential for ensuring that electricity is delivered at the lowest possible cost while maintaining reliability. Market integration is often assessed through price convergence between countries, indicating how effectively different national electricity markets are interconnected. Higher levels of price alignment suggest efficient cross-border exchanges and well-functioning market coupling.

8.4. Environmental and sustainability metrics

To ensure that infrastructure development aligns with climate targets, the renewable energy share measures the proportion of total energy consumption met by sources such as wind, solar, and hydro. A further key indicator is the carbon intensity of power generation, expressed in grams of CO_2 per kilowatt-hour.

The curtailment of renewables, which captures the amount of clean energy that cannot be used due to grid limitations or lack of demand, highlights the need for improved infrastructure and flexibility. High curtailment rates signal inefficiencies and missed opportunities for clean energy use.

9

Conclusion

The IoSN Guidelines set out in this report constitute Med-TSO's first common, end-to-end playbook for planning a future-proof regional grid. They clarify why system-wide coordination is essential, how needs are to be uncovered, and what analytical and organisational building blocks are required to turn needs into bankable, policy-aligned projects. In doing so, the Guidelines deliver on the objectives first articulated in Chapter 1: to strengthen cross-border power flows, integrate ever-larger shares of renewables and bolster regional security of supply while keeping total system costs in check.

At the heart of the framework is a five-step process that moves seamlessly from 2040 scenario definition to candidate collection, Antares-Xpansion optimisation, and pan-regional benefit assessment. This transparent, scenario-driven loop ensures that every investment decision is tested against multiple futures and that regulatory, technical and cost–benefit considerations are captured from the outset, underpinned by an open-source toolchain anchored in Antares-Xpansion.

The Guidelines translate this methodology into concrete portfolio logic. Five priority transmission corridors, from the West Mediterranean to the Middle East Mediterranean Integration cluster, provide a structured map for interconnector expansion, targeting the cross-border routes that unlock the greatest security-of-supply and market-coupling benefits. The document elevates BESS, peaking units, and emerging demand-side resources to equal footing with physical infrastructure, recognising that flexibility is now central to balancing high-RES systems.

Robust metrics ensure that each candidate is screened on an equal, transparent footing. Technical adequacy indicators such as LOLE and ENS are paired with total system cost, price convergence, and carbon intensity metrics, while congestion and curtailment serve as early-warning signals for under-investment or misallocation of capacity. Applying these indicators consistently across scenarios provides a traceable audit trail for regulators, funders and the broader stakeholder community.

Taken together, the Guidelines yield four headline outcomes for the Med-TSO community:

1. A shared analytical language that aligns national studies with ENTSO-E practice yet remains tailored to Mediterranean specifics, including higher RES shares in North Africa and differing regulatory cultures.
2. A prioritized “investment funnel” that channels resources first to corridor backbones and proven flexibility technologies.
3. A repeatable process that can be rerun with modular updates to scenarios, cost data and regulatory assumptions, thereby institutionalising continuous learning.
4. A clear line-of-sight to system benefits, lower congestion, deeper market integration, reduced curtailment and measurable CO_2 savings, quantified through harmonised metrics and benefit-analysis workflows.

By institutionalising this Guidelines-based process, Med-TSO and its members can move from ad-hoc bilateral planning to a coherent, evidence-driven roadmap that underpins a resilient, low-carbon, and deeply interconnected Mediterranean power system that is ready to meet the region’s 2040 ambitions and beyond.

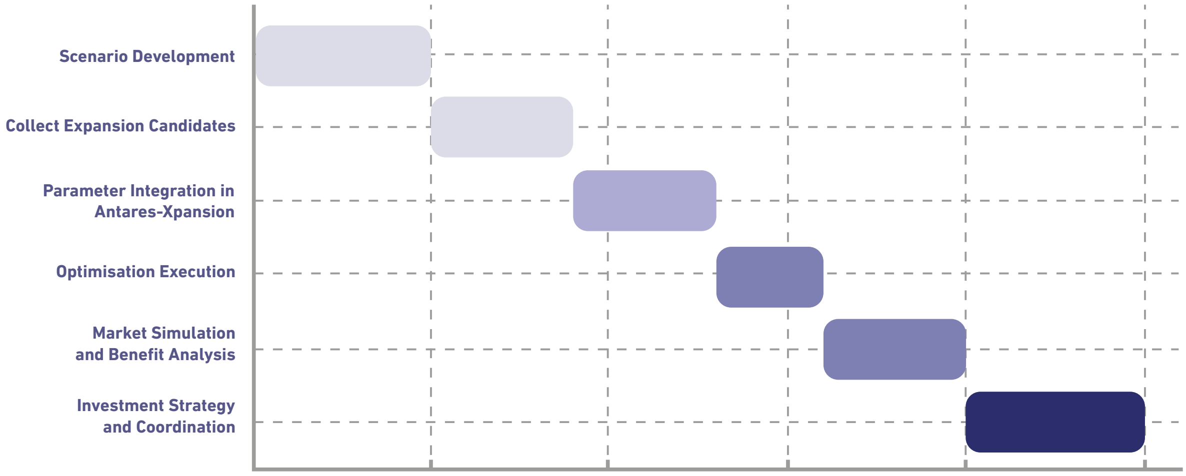


Figure 9: IoSN Process Generic Gantt Chart

10

Appendices

The appendices provide supporting information, including data on the Med-TSO grid and investment assumptions.

10.1. Mathematical problem formulation

Precise mathematical formulation is essential for achieving reliable results. This section provides an overview of the equations and constraints used in Antares-Xpansion.

10.1.1. Variables and costs

Investment capacity and investment cost

In the context of investment modelling for expansion planning, the decision variables represent the invested capacities (in MW) of the different candidate projects. These investments can be either continuous or integer-valued, depending on the nature of the technology and infrastructure in question.

For investment options that allow for **continuous expansion**, the invested capacity for candidate i, denoted as x_i , falls within a predefined range:

$$x_i \in \left[0, \underline{x_i}\right]$$

where x_i represents the **maximum allowable investment** for candidate i, also referred to as **max-investment.** The set of candidates that allow for continuous investment is defined as:

$$R = \left\{i \mid \underline{x_i}\ is\ continuous\right\}$$

where R **(for real)** denotes the indices of candidates with continuous investment decisions.

For investment projects where capacity expansion occurs in discrete steps (e.g. construction of power plants, modular BESS), the investment variable x_i takes values that are multiples of a predefined unit size u_i :

$$x_i \in \{0, u_i, 2u_i, \dots, K_i u_i\}$$

where:

- $u_i \in R$ is the unit size, representing the minimum expansion step.
- $K_i \in N$ is the maximum number of units that can be installed.
- The total investment for candidate i is bounded by:

$$\underline{x_i} = K_i u_i$$

which represents the **maximum investment capacity**, determined by the **maximum number of units** multiplied by the **unit size.** The set of integer investment candidates Is defined as:

$$I = \{i \mid x_i\ is\ integer\}$$

where I (**for integer**) denotes the indices of candidates subject to discrete investment decisions. Since every investment candidate falls into either the **continuous or integer category**, the total set of investment candidates is:

$$\cup_R^I \{1,2, \dots, n\}$$

ensuring that all candidates are accounted for in the optimisation framework.

Each investment candidate is characterised by an annualised **investment cost per MW installed**, denoted as:

$$c_i \in R_+$$

where C_i is **non-negative** and represents the **unit cost** of investment (e.g., €/MW). The investment vector x, containing the decision variables for all candidates, is as:

$$x = (x_1, x_2, \dots, x_n)$$

Similarly, the **cost vector** C, containing the cost per MW for each candidate, is:

$$c = (c_1, c_2, \dots, c_n)$$

The **total investment cost** can be expressed in matrix notation as:

$$c^T x$$

which represents the **dot product of the cost and investment vectors**, yielding the total monetary investment required for system expansion.

Operating cost

Total system cost is determined not only by investment expenditures but also by expected yearly operating costs, denoted as $\Theta(x)$. This cost represents the financial requirement to operate the electricity system under different investment scenarios and is obtained as an output of an Antares simulation, which evaluates system performance at a given investment level x.

The operating cost as the solution of an Antares simulation

In Antares-Xpansion, the expected operating cost is estimated using a Monte Carlo approach, where N stochastic scenarios (Monte Carlo years) are considered. The total expected operating cost is computed as:

$$\Theta(x) = \sum_{l=1}^{l=N} p_l * \Theta_l(x)$$

where:

- p_l represents the probability weight assigned to each MC year l.
- $\Theta_l(x)$ is the operating cost computed for scenario l at investment level x.

Each $\Theta_l(x)$ corresponds to the solution of a relaxed yearly Antares problem, which can be formulated as follows:

$$\Theta_l(x) = g_l^T y$$

subject to:

$$Wy = d_l - T_l x$$

where:

- y represents the set of decision variables in the Antares optimisation problem.
- Y is the admissible solution set, defining feasible operational conditions.
- g_l is the cost vector, representing operational expenses such as fuel, maintenance, and startup costs.
- W is a constraint matrix that ensures system balance.
- d_l represents demand levels, renewable generation availability, and other stochastic parameters for year l.
- T_l is a matrix that models investment-dependent constraints, which vary across MC years due to changing link profiles for expansion candidates.

The optimisation problem solved within Antares-Xpansion is a relaxed version of the full Antares problem. In particular, unit-commitment constraints such as minimum on and off times for thermal generators are not explicitly included. This relaxation simplifies computational complexity while still providing a robust approximation of expected system costs.

Splitting the weeks

In Antares, the decision variables representing system operation are defined at an hourly resolution, meaning that the variable set can be expressed as:

$$y = (y_1, y_2, \dots, y_{8760})$$

where y_h corresponds to all decision variables at hour h of the year. Given that Antares performs weekly-based simulations, each optimisation problem only considers the variables of a single week. Consequently, for a given week s, where $s \in [1,52]$, the corresponding variable subvector is:

$$y_s = \left(y_{168(s-1)+1}, \dots, y_{168s}\right)$$

This formulation ensures that each weekly problem is solved independently, capturing system behaviour within a constrained timeframe. Throughout this appendix, the index s will consistently denote subvectors corresponding to a specific week.

A key assumption in Antares-Xpansion, is that weekly problems are treated as independent from each other. This simplification means that no inter-week coupling constraints are allowed, leading to a mathematical structure where the constraint matrix W is diagonal block:

$$W = diag(W_1, W_2, \dots, W_{52})$$

Additionally, the remaining elements of the problem formulation, including cost vectors, demand vectors, and investment-dependent constraint matrices, are decomposed as follows:

$$g_l = \left(g_{l,1}, g_{l,2}, \dots, g_{l,52}\right)$$
$$d_l = \left(d_{l,1}, d_{l,2}, \dots, d_{l,52}\right)$$
$$T_l = \left(\frac{T_{l,1}}{T_{l,2} \ \dots \ T_{l,52}}\right)$$

This decomposition allows the yearly Antares problem for a given Monte Carlo year $\boldsymbol{l}$ to be split into 52 independent weekly problems. The optimisation problem for a given week s in Monte Carlo year $\boldsymbol{l}$ is thus formulated as:

$$\Theta_{l,s}(x) = g_{l,s}^T y_s$$

subject to:

$$W_s y_s = d_{l,s} - T_{l,s} x$$

where $\Theta_{l,s}(x)$ represents the operational cost for week s of Monte Carlo year l, and y_s defines the admissible solution set for the weekly variables. By structuring the optimisation problem in this way, each week is solved separately, significantly reducing computational complexity while preserving the system's operational behaviour.

Given that the full-year optimisation is decomposed into weekly problems, the total expected operating cost over all Monte Carlo years and weeks is computed as:

$$\Theta(x) = \sum_{l=1}^{l=N} p_l * \sum_{s=!}^{s=52} \Theta_{l,s}(x)$$

where p_l is the probability weight assigned to Monte Carlo year l, and $\Theta_{l,s}(x)$ is the weekly operational cost. This formulation ensures that the total yearly cost is an aggregate of all independent weekly cost calculations, weighted by the likelihood of each Monte Carlo scenario.

Summary of costs

The total cost of the energy system for a given investment level x consists of two primary components: the capital investment cost and the expected yearly operating cost. Mathematically, the overall system cost is expressed as:

$$C(x) = c^T x + \Theta(x)$$

where:

- $c^T x$ represents the total investment cost, computed as the dot product of the investment cost vector c and the investment decision vector x.
- $\Theta(x)$ denotes the expected yearly operating cost, determined through Antares simulations.

The computation of $\Theta(x)$ involves solving a set of weekly optimisation problems over multiple Monte Carlo years. Specifically, for each given investment level x, the expected operating cost is obtained from the solution of $52N$ linear weekly Antares problems, where N represents the number of Monte Carlo years considered in the simulation. This formulation accounts for the stochastic variations in demand, renewable generation availability, and system constraints, ensuring a comprehensive evaluation of the system's economic performance under uncertainty.

10.1.2. Constraints

The capacity expansion planning process requires ensuring that the invested capacities of different candidates adhere to predefined constraints. These constraints, specified by the user through the additional-constraints parameter, are represented as a system of linear equations:

$$Ax = b$$

where:

- $A \in R^{m \times n}$ is the constraint matrix,
- $b \in R^n$ is the right-hand side vector,
- m is the number of constraints imposed on the investment decisions.

This formulation ensures that investment decisions account for both technical feasibility and economic efficiency, balancing infrastructure expansion with system operating costs. The inclusion of linear constraints allows for the incorporation of practical investment limitations, such as regional capacity limits, interconnection reinforcement priorities, or policy-driven

10.2. Benders reformulation and decomposition algorithm

The structure of the investment problem, where investment decisions form the first step and optimal dispatch decisions form the second step, naturally aligns with a Benders decomposition approach. This method separates investment planning from operational dispatch, improving computational efficiency. The following sections outline the Benders reformulation, and the Benders decomposition algorithm applied to the investment problem.

10.2.1. Rationale for Benders decomposition

To facilitate decomposition, the dual form of the weekly Antares problem is derived. By applying duality, the operating cost for week s in Monte Carlo year l, denoted as $\Theta_{l,s}(x)$, is expressed as:

$$\Theta_{l,s}(x) = \pi_{l,s}^{T} * \left(d_{l,s} - T_{l,s}x\right)$$

subject to:

$$W_s^{T}\pi_{l,s} \geq g_{l,s}$$

where:

- $\pi_{l,s}$ represents the dual variables associated with the operational constraints,
- $\Pi_{l,s}$ is the feasible set of dual solutions,
- W_s^T is the constraint matrix,
- $g_{l,s}$ is the cost coefficient vector,
- $d_{l,s}$ represents system parameters such as demand and renewable generation availability,
- $T_{l,s}$ accounts for investment-dependent system constraints.

An important property of the dual formulation is that the feasible region of the problem:

$$F_{l,s} = \left\{\pi_{l,s} \mid W_s^{T}\pi_{l,s} \geq g_{l,s}\right\} \cap \ \ \Pi_{l,s}$$

forms a polyhedron that is independent of the investment decision variable x.

Since weekly Antares problems are always feasible, achieved by penalising infeasibility in their objective function, the feasible set $F_{l,s}$ is always non-empty and bounded. Consequently, the optimal solution to the dual problem corresponds to one of the extreme points of $F_{l,s}$. This p allows us to reformulate $\Theta_{l,s}(x)$ as:

$$\Theta_{l,s}(x) = \pi_{l,s}^T * \left(d_{l,s} - T_{l,s}x\right)$$

where $extr\left(F_{l,s}\right)$ represents the set of extreme points of the feasible region $F_{l,s}$. Using the above expression, the original investment problem can be rewritten as:

$$c^T x + \sum_{l=1}^{l=N} p_l * \sum_{s=1}^{s=52} \pi_{l,s}^T * \left(d_{l,s} - T_{l,s}x\right)$$

subject to:

$$Ax = b$$

where:

- $c^T x$ represents the investment cost,
- $\sum_{l=1}^{l=N} p_l * \sum_{s=1}^{s=52} \pi_{l,s}^T * \left(d_{l,s} - T_{l,s}x\right)$ represents the expected operational cost,
- $Ax = b$ ensures that investment decisions satisfy system constraints,
- x is the set of admissible investment levels, incorporating both continuous and discrete investment options.

Since this formulation includes nested maximisation operations, it is computationally complex. To simplify, an equivalent linearised formulation is introduced by defining auxiliary variables $\Theta_{l,s}$, where:

$$\theta_{l,s} \geq \pi_{l,s}^T * \left(d_{l,s} - T_{l,s}x\right) \forall\, l, s, \pi_{l,s}^T \in extr\left(F_{l,s}\right)$$

The investment problem is then reformulated as the **Benders master** problem:

$$c^T x + \sum_{l=1}^{l=N} p_l * \sum_{s=1}^{s=52} \theta_{l,s}$$

subject to:

$$Ax = b$$

$$\theta_{l,s} \geq \pi_{l,s}^T * \left(d_{l,s} - T_{l,s}x\right) \forall\, l, s, \pi_{l,s}^T \in extr\left(F_{l,s}\right)$$

The constraints of the form $\theta_{l,s} \geq \pi_{l,s}^T * \left(d_{l,s} - T_{l,s}x\right)$ are referred to as Benders cuts and iteratively refine the solution space by incorporating information from the operational problem into the investment decision-making process.

10.2.2. Master problem and subproblem

In practical applications, the number of extreme points in the feasible region $F_{l,s}$ is often very large. Consequently, the full Benders master problem includes a significant number of constraints, making it computationally challenging to solve directly. To address this, the Benders decomposition algorithm is implemented as an iterative approach that progressively refines the solution by solving a sequence of smaller problems.

Step 1: Solve the master problem without Benders cuts

The algorithm begins by solving a relaxed version of the master problem, where all Benders cuts have been removed. The optimal solution to this problem, denoted as $\underline{x}$, is used as a trial investment value for subsequent steps.

Step 2: Solve the subproblems for Each Monte Carlo year and week

For each Monte Carlo year l and each week s, the dual formulation of the weekly Antares problem, referred to as the subproblem, is solved with the investment value set to $\underline{x}$:

$$\pi_{l,s}^{T} * \left(d_{l,s} - T_{l,s}\underline{x}\right)$$

subject to:

$$W_s^{T}\pi_{l,s} \geq g_{l,s}$$

There is a total of 52N subproblems to solve, where N is the number of Monte Carlo years. The optimal solution of each subproblem is denoted as $\underline{\pi_{l,s}}$, with its corresponding optimal objective value:

$$\underline{\pi_{l,s}} * \left(d_{l,s} - T_{l,s}\underline{x}\right)$$

Step 3: Add Benders cuts to the master problem

For each Monte Carlo year l and each week s, a new Benders cut is introduced into the master problem:

$$\theta_{l,s} \geq \underline{\pi_{l,s}} * \left(d_{l,s} - T_{l,s}\underline{x}\right)$$

This adds 52N additional constraints to the master problem, progressively refining the solution space by incorporating information from the subproblems.

Step 4: Solve the Updated Master Problem

At iteration k, the updated master problem takes the form:

$$c^T x + \sum_{l=1}^{l=N} p_l * \sum_{s=1}^{s=52} \theta_{l,s}$$

subject to:

$$Ax = b$$

$$\theta_{l,s} \geq \pi_{l,s}^{i} * \left(d_{l,s} - T_{l,s}x\right) \; \forall \, l, s, i < k$$

where $\pi_{l,s}^{i}$ represents the solution of the subproblem for Monte Carlo year l at week s at iteration i. The updated master problem is solved, and the new optimal investment decision is denoted as $\underline{x}$. The process then returns to Step 2, and the algorithm continues iterating.

Step 5: Convergence check

At each iteration, an optimality gap is computed to determine whether the algorithm has converged. The lower bound of the optimal cost is provided by the solution of the master problem, as it is a relaxation of the full investment problem.

For a given investment level $\underline{x}$, a feasible solution can be obtained by summing up the investment cost and the optimal subproblem costs:

$$c^T \underline{x} + \sum_{l=1}^{l=N} p_l * \sum_{s=1}^{s=52} \underline{\pi_{l,s}}$$

This value serves as a valid upper bound for the investment problem. The optimality gap is defined as the difference between the upper and lower bounds, either in absolute or relative terms. The algorithm terminates once the optimality gap falls below a user-specified threshold or a default value. These thresholds are controlled by the parameter's optimality_gap and relative_gap in Antares-Xpansion.

10.2.3. The Benders by Batch algorithm

The classical Benders decomposition algorithm involves solving all subproblems at each iteration, resulting in 52N subproblem resolutions per iteration, where N represents the number of Monte Carlo years. As a result, an equal number of Benders cuts are introduced into the master problem during each iteration. Whilst this approach ensures a direct path to convergence, it can be computationally intensive and time-consuming, especially for large-scale energy system models.

To address this computational challenge, an alternative approach known as the Benders by Batch algorithm has been introduced. This method reduces the number of subproblem resolutions per iteration by grouping subproblems into batches. Rather than solving all subproblems at every iteration, only a subset of subproblems is processed, with additional subproblems solved only when necessary to refine the solution. The process is terminated early once it is determined that the current solution of the master problem is not yet optimal, avoiding unnecessary computation.

By limiting the number of subproblem resolutions in each iteration, the Benders by Batch algorithm introduces fewer cuts into the master problem at each step. This results in a greater number of iterations being required for full convergence. However, the overall computational burden is often reduced, as solving a large number of subproblems at every iteration in the classical approach is significantly more time-consuming.

In practice, the trade-off between fewer subproblem resolutions per iteration and a greater number of iterations leads to improved performance. Studies have shown that the Benders by Batch algorithm generally outperforms the classical Benders method in terms of total computation time, particularly for large-scale energy system planning problems.

10.2.4. Iterative convergence

The Benders decomposition method converges towards the optimal solution of the investment problem described above and is commonly used to solve large stochastic problems. The number of iterations required depends strongly on the structure of the problem and on the variants/algorithmic parameters used. In general, it strongly increases with the number of defined investment variables.

Number of investment candidates	Order of magnitude of the number of iterations
5	10
10	40
25	100
50	300
100	800

Each iteration of the Antares-Xpansion algorithm includes an Antares simulation. However, the simulation of "operational" studies across several tens of nodes and with several hundred Monte Carlo scenarios requires a significant amount of computing time, sometimes several hours. Finding the optimal solution to the problem solved by Antares-Xpansion can therefore be a lengthy process and in some cases requires simplification of the problem being solved.

10.2.5. Walkthrough a basic example

The following example illustrates the optimal allocation of generation capacity while minimising total system costs, which include both fixed investment costs and variable operating costs.

The optimisation problem is formulated as follows:

$$\sum_{i=1}^{n} \left(I_i * x_i + \sum_{j=1}^{m} C_i * T_j * y_{ij} \right)$$

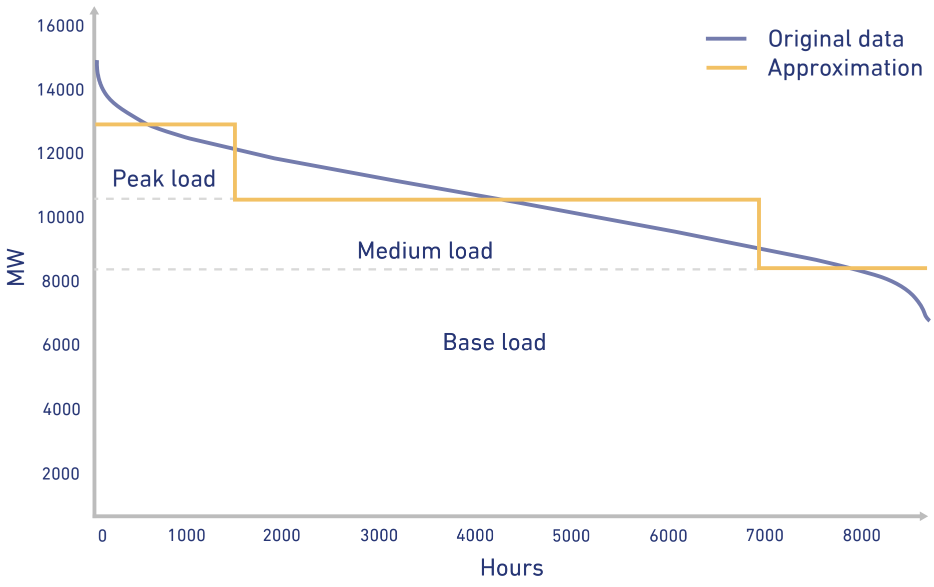
subject to:

$$\sum_{i=1}^{n} y_{ij} = D_j, \qquad \forall j = 1, \dots, m$$

$$\sum_{j=1}^{m} y_{ij} \leq x_i, \qquad \forall i = 1, \dots, n-1$$

where:

- x_i represents the installed capacity of technology i,
- y_{ij} represents the capacity of technology i allocated to load block j,
- I_i and C_i denote the investment and operational costs of technology i, respectively,
- D_j represents the demand level for load block j,
- T_j represents the duration of load block j.



The table below summarises the cost parameters of different generation technologies:

Technology	Fuel cost (€/MWh)	Investment cost (€/MW)
Coal	24	17
Gas	82	6
Nuclear	6.2	33
Oil	165	3

System demand is divided into load blocks, characterised by different durations and power levels:

Load type	Duration (hours)	Load level (MW)
Base load	8760	0 - 4230
Medium load	7000	4230 - 7498
Peak load	1500	7498 - 10400

Since capacity expansion involves long-term investment decisions (first step) and short-term dispatch optimisation (second step), it is naturally suited for Benders decomposition.

The master problem determines the optimal investment in new generation capacity while relaxing the operational constraints:

$$M : \sum_{i=1}^{n} (I_i * x_i + \theta)$$

subject to:

$$\theta \geq \sum_{j=1}^{m} \lambda_j^k * D_j + \sum_{i=1}^{n} \rho_i^k * x_i \geq 0 \quad (\lambda^k, \rho^k) \in V_k$$

where:

- θ represents the expected operational cost,
- λ^k and ρ^k are dual multipliers from the subproblem,
- V_k is the set of previous optimal dual solutions from the subproblem.

The master problem initially ignores operational feasibility, which is introduced iteratively via Benders cuts obtained from the subproblem.

Once an investment decision x is made, the subproblem determines the optimal dispatch of generation units to meet demand:

$$\sum_{i=1}^{n} \sum_{j=1}^{m} C_i * T_j * y_{ij}$$

subject to:

$$\sum_{i=1}^{n} y_{ij} = D_j, \qquad \forall j = 1, \ldots, m$$

$$\sum_{j=1}^{m} y_{ij} \le \underline{x_i}, \qquad \forall i = 1, \dots, n-1$$

where $\underline{x_i}$ is the trial investment decision from the master problem. The dual multipliers from the subproblem λ_j^k and ρ_i^k are used to generate Benders cuts, refining the master problem iteratively.

The Benders decomposition algorithm proceeds iteratively, refining the investment decision at each step. The process involves:

1. Solving the master problem without operational constraints to obtain an initial investment decision.
2. Solving the subproblem for a given x to determine the operational feasibility and compute operational costs.
3. Extracting dual multipliers from the subproblem and adding new Benders cuts to the master problem.
4. Updating the master problem and repeating the process until convergence.

The following table illustrates how investments evolve over successive Benders iterations.

Iteration	Coal (MW)	Gas (MW)	Nuclear (MW)	Oil (MW)
1	0	0	0	0
2	0	0	0	8735.6
3	0	0	0	18565.1
4	0	14675.8	0	0
5	10673.3	0	0	0
6	0	0	7337.9	3063.1
7	0	1497.7	7337.9	732.2
8	0	1497.7	7337.9	2033.3
9	0	0	8966	1435
10	2850.8	2189.2	5360	0

The results suggest that early iterations favour low investment-cost technologies such as oil, before transitioning to more capital-intensive long-term options such as coal and nuclear.

10.3. Med-TSO starting grid

The following grid serves as the baseline infrastructure for assessing transmission expansion needs and form the starting point for future system development and optimisation.

From	To	Direct NTC (MW)	Indirect NTC (MW)
AL00	RS00	250	250
AL00	MK00	500	500
AL00	GR00	400	400
AL00	ME00	400	400
AT00	ITN1	875	695
AT00	SI00	950	950
BA00	ME00	500	500
BA00	HR00	900	800
BE00	FR00	2800	4300
BG00	RS00	380	350
BG00	MK00	400	400
BG00	RO00	2190	2190
BG00	TR00	900	500
BG00	GR00	1700	1400
CH00	FR00	2200	4500
CH00	ITN1	5772	3110
DE00	FR00	4800	4800
DZ00	TN00	250	250
DZ00	MA00	1000	1000
EG00	LY00	240	240
EG00	SD00	300	0
EG00	JO00	550	550
EG00	SA01EG	3000	3000
EG00	JOIN	0	0
ES00	MA00	900	600
ES00	PT00	4200	3500
ES00	FR00	5000	5000
FR00	LUF1	380	0
FR00	IE00	700	700
FR00	UK00	5600	5600
FR00	ITN1	4485	2160
FR15	ITCO	120	150
GR00	ITS1	500	500
GR00	TR00	660	580
GR00	GR03	800	800

GR00	MK00	1100	850
HR00	SI00	1500	1500
HR00	RS00	300	400
HR00	HU00	800	1000
HU00	SI00	1200	1200
IL00	PS00	10000	0
ITCN	ITCO	400	400
ITCN	ITN1	4500	5300
ITCN	ITCS	4650	5350
ITCO	ITSA	420	480
ITCS	ME00	600	600
ITCS	ITSA	720	900
ITCS	ITVI	0	0
ITCS	ITN1	0	0
ITCS	ITS1	3100	5700
ITN1	SI00	1080	1153
ITS1	ITCA	3250	2000
ITSA	ITVI	0	0
ITSI	ITVI	0	0
ITSI	ITCA	2000	2000
ITSI	MT00	225	225
JO00	JOIN	0	0
JO00	SY00	0	0
JO00	LB00	0	0
JO00	SA01JO	0	0
JOIN	SA02	0	0
LY00	TN00	500	500
ME00	RS00	540	1140
ITSI	TN00	600	600
GR03	CY00	1000	1000
CY00	IL00	1000	1000

10.4. Decommissioning decisions for thermal capacities

Antares-Xpansion also supports decommissioning decisions, in which existing power generation assets are classified as decommissioning candidates. These differ from investment candidates primarily in the way fixed-cost annuities are calculated.

Fixed-cost annuity for Investment candidates

For investment candidates, the annuity consists of:

1. Annualised investment costs.
2. Fixed annual operation and maintenance (OandM) costs.

Antares-Xpansion makes economic decisions by comparing the sum of these costs against the expected reduction in variable operating costs, such as fuel expenses and penalties associated with loss of load.

Fixed-cost annuity for decommissioning candidates

For decommissioning candidates, the annuity only includes fixed OandM costs, as there are no new investment costs, the decision revolves around whether to continue operating the asset or shut it down.

- Antares-Xpansion determines whether the OandM costs justify keeping the asset operational relative to potential variable cost savings if the unit is decommissioned.
- Investment costs are considered stranded and do not influence the economic decision.
- The potential decommissionable capacity (i.e., max-investment or max-units × unit-size) is equal to the asset's already-installed capacity that can be retired if deemed unprofitable.

Modelling decommissioning candidates in Antares-Xpansion

Since Antares-Xpansion cannot directly decommission generation units located at physical nodes, decommissioning must be modelled using the same virtual node logic as investment in thermal generation.

Example:

- If decommissioning is being considered for thermal generation in area1, the unit must be moved to a virtual node (e.g., invest_semibase).
- The hourly availability time-series for the decommissioning candidate must exceed its decommissionable capacity.
- The decommissioning decision is controlled via the capacity of the link between area1 and invest_semibase.
  - Invested capacity on this link represents the portion not decommissioned by Antares-Xpansion.

10.5. Common metrics to assess needs

10.5.1. Technical metrics

Security of supply metrics

Security of supply metrics are critical indicators used to evaluate the ability of the electricity grid to consistently meet demand under various conditions, including peak loads and unforeseen contingencies. These metrics guide policymakers and system operators in maintaining grid reliability and avoiding power shortages.

Loss of Load Expectation (LOLE) [hours/year]

- Definition: LOLE quantifies the expected number of hours in a year where electricity demand surpasses supply due to inadequate generation or transmission capacity. It reflects the system's ability to meet peak demand under normal and stressed conditions.
- Importance: a lower LOLE indicates a more reliable system, with less risk of power shortages.
- Applications: used in system adequacy assessments to inform capacity planning and grid investments.
- Energy Not Served (ENS) [MWh/year]
- Definition: ENS measures the total electricity demand (in megawatt-hours) that cannot be fulfilled due to system constraints or failures, such as insufficient generation or transmission capacity.
- Importance: a lower ENS signifies a more resilient grid with fewer disruptions in supply.
- Impact on stakeholders: high ENS can result in significant economic losses for industries and reduced quality of service for consumers.
- Use in decision-making: ENS data supports investment prioritisation in infrastructure and technology to enhance grid reliability.
- System adequacy reserve margin [%]
- Definition: the reserve margin represents the percentage difference between the total available generation capacity and peak demand. It acts as a buffer to handle unexpected surges in demand or generation outages.
- Optimal range: a reserve margin of 15-20% is generally considered sufficient for reliable operations, though the exact value may vary depending on system characteristics and renewable energy penetration.

- Significance: insufficient reserve margins can lead to reliability risks, whilst excessive margins may indicate overinvestment.
- Grid congestion [% of hours]
- Definition: grid congestion is measured as the percentage of hours in a year when interconnection lines operate at or near full capacity, limiting the ability to transmit electricity between regions.
- Implications: high congestion levels indicate inefficiencies and the need for grid upgrades or expansions to improve interconnection capacity.
- Consequences: persistent congestion can lead to price disparities between regions, renewable energy curtailment, and increased operational costs for system operators.
- Mitigation: infrastructure investment in transmission corridors and grid optimisation technologies (e.g. dynamic line ratings) are key strategies for reducing congestion.

Grid expansion and interconnection metrics

The expansion and interconnection of electricity grids play a crucial role in enhancing energy security, enabling cross-border electricity trade, and integrating renewable energy sources into the power system. The European Commission uses various metrics to assess the adequacy of transmission infrastructure and the effectiveness of interconnection projects. These metrics help determine whether additional investments are needed to improve grid capacity and reliability.

Transmission grid reinforcement needs [GW]

- Definition: this metric quantifies the additional transmission capacity required to support growing electricity demand, accommodate higher shares of renewable energy, and enhance cross-border power flows.
- Key drivers:
  - Growth in renewable energy generation (onshore and offshore wind, solar PV).
  - Increase in electricity consumption due to electrification of transport and heating.
  - Need to reduce grid congestion and improve security of supply.

Cross-border transfer capacities (NTC) [% of demand]

- Definition: Net Transfer Capacity (NTC) measures the maximum amount of electricity that can be exchanged between two interconnected power systems under normal operating conditions. This metric is expressed as a percentage of peak electricity demand.

- Benefits of higher NTC:
  - Enhanced competition in electricity markets, leading to lower prices.
  - Greater integration of renewable energy sources, reducing curtailment.
  - Improved energy security through access to diversified power sources.
- Challenges: increasing NTC requires significant investment in interconnectors and cross-border coordination among Transmission System Operators (TSOs).

10.5.2. Economic metrics

Investment and cost efficiency metrics

Investment and cost efficiency metrics provide a financial perspective on energy system planning, ensuring that infrastructure development is economically viable whilst maintaining system reliability. The European Commission evaluates total system costs, grid investment needs, and congestion costs to optimise expenditures and improve cost-effectiveness in electricity markets.

Total system cost [€]

- Definition: total system cost encompasses all financial expenditures associated with electricity generation, transmission, distribution, and flexibility services.
- Components:
  - Generation costs: capital and operational expenses for power plants.
  - Transmission and distribution costs: infrastructure investments, maintenance, and grid reinforcement.
  - Flexibility costs: investments in demand response, BESS, and grid-balancing mechanisms.
- Significance: helps policymakers and regulators assess the financial burden of different energy pathways and design cost-effective solutions for system expansion.

Grid Investment needs [Billion €]

- Definition: this metric estimates the capital required for new transmission and distribution infrastructure to support electrification, renewable energy integration, and interconnection improvements.

- Investment drivers:
    - Expansion of interconnectors for cross-border electricity trade.
    - Upgrades to accommodate high renewable penetration.
    - Reinforcement of ageing infrastructure to enhance reliability.

10.5.3. Market and flexibility metrics

Market efficiency and flexibility are crucial for ensuring stable and competitive electricity markets. The European Commission evaluates market integration, demand-side flexibility, and BESS utilisation to optimise system operations and enhance resilience.

Market Integration (% of price convergence across the EU)

- Definition: this metric assesses how well electricity prices align across different Med-TSO markets, reflecting the effectiveness of market coupling and cross-border interconnections.
- Target: a higher percentage of price convergence indicates better market integration, leading to reduced electricity price volatility.
- Barriers to integration:
    - Transmission congestion between market zones.
    - Regulatory differences across EU member states.
    - Limited cross-border interconnection capacity.

Demand-side Flexibility (DSF) [GW available]

- Definition: The volume of flexible electricity demand that can be adjusted in real-time to balance supply and demand fluctuations.
- Key applications:
    - Industrial demand response: large-scale consumers adjusting consumption based on market signals.
    - Smart grids and digitalisation: enabling real-time control of household appliances and EV charging.
    - Dynamic tariffs: incentivising consumers to shift electricity usage to off-peak hours.
- Benefits:
    - Reduce reliance on costly peaking units.

- Enhance system reliability without new infrastructure investments.

Storage utilisation [%]

- Definition: measures the share of grid-scale BESS capacity used to balance supply and demand.
- Types of storage:
  - o Pumped hydro storage: the most widely used form of large-scale storage.
  - o BESS: increasingly deployed to support renewables and grid stability.
  - o Hydrogen storage: emerging as a long-term storage solution.
- Impact on the power system:
  - Supports the integration of variable renewables.
  - Reduces reliance on fossil fuel backup generation.
  - Enhances energy security by providing backup supply during peak demand periods.

10.5.4. Environmental and sustainability metrics

Renewable integration and emission reduction

These metrics assess progress in increasing the share of renewables, reducing greenhouse gas emissions, and optimising the efficiency of renewable energy utilisation. These indicators help ensure that the Mediterranean power systems meet climate targets whilst maintaining energy security and affordability.

Renewable Energy Share [%]

- Definition: measures the proportion of total energy consumption met by renewable sources (wind, solar, hydro, biomass, and geothermal).
- Key drivers:
  - Expansion of wind and solar capacity.
  - Electrification of heating, transport, and industrial processes.
  - Improved grid flexibility and interconnections to support variable renewables.
- Challenges:
  - Variability of renewable energy sources requiring enhanced grid management.

  - Need for significant investment in BESS and demand response.

Curtailment of renewables [% of total generation]

- Definition: represents the percentage of renewable electricity generation that is lost due to grid constraints, lack of BESS, or insufficient demand.
- Implications: high curtailment levels indicate inefficiencies in the grid and the need for better energy management strategies.
- Solutions to reduce curtailment:
  - Grid upgrades: reinforcing interconnection lines and interconnectors.
  - Storage: deploying BESS and pumped hydro storage.
  - Market-based flexibility: implementing demand-side response programmes to shift consumption patterns.

Energy efficiency metrics

Improving energy efficiency is essential to reducing energy demand, lowering costs, and decreasing emissions. The energy efficiency metrics evaluate the effectiveness of energy-saving initiatives and infrastructure efficiency improvements.

Demand reduction potential [TWh]

- Definition: the volume of electricity consumption that can be reduced through energy efficiency programmes, including industrial efficiency improvements, building retrofits, and smart energy use.
- Key drivers:
  - Adoption of energy-efficient appliances and lighting.
  - Building insulation and HVAC optimisation.
  - Smart energy management and automation.
- Impact:
  - Lowers overall electricity demand, reducing the need for fossil fuel-based backup power.
  - Enhances energy security by decreasing reliance on imports.
  - Reduces consumer electricity costs.

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