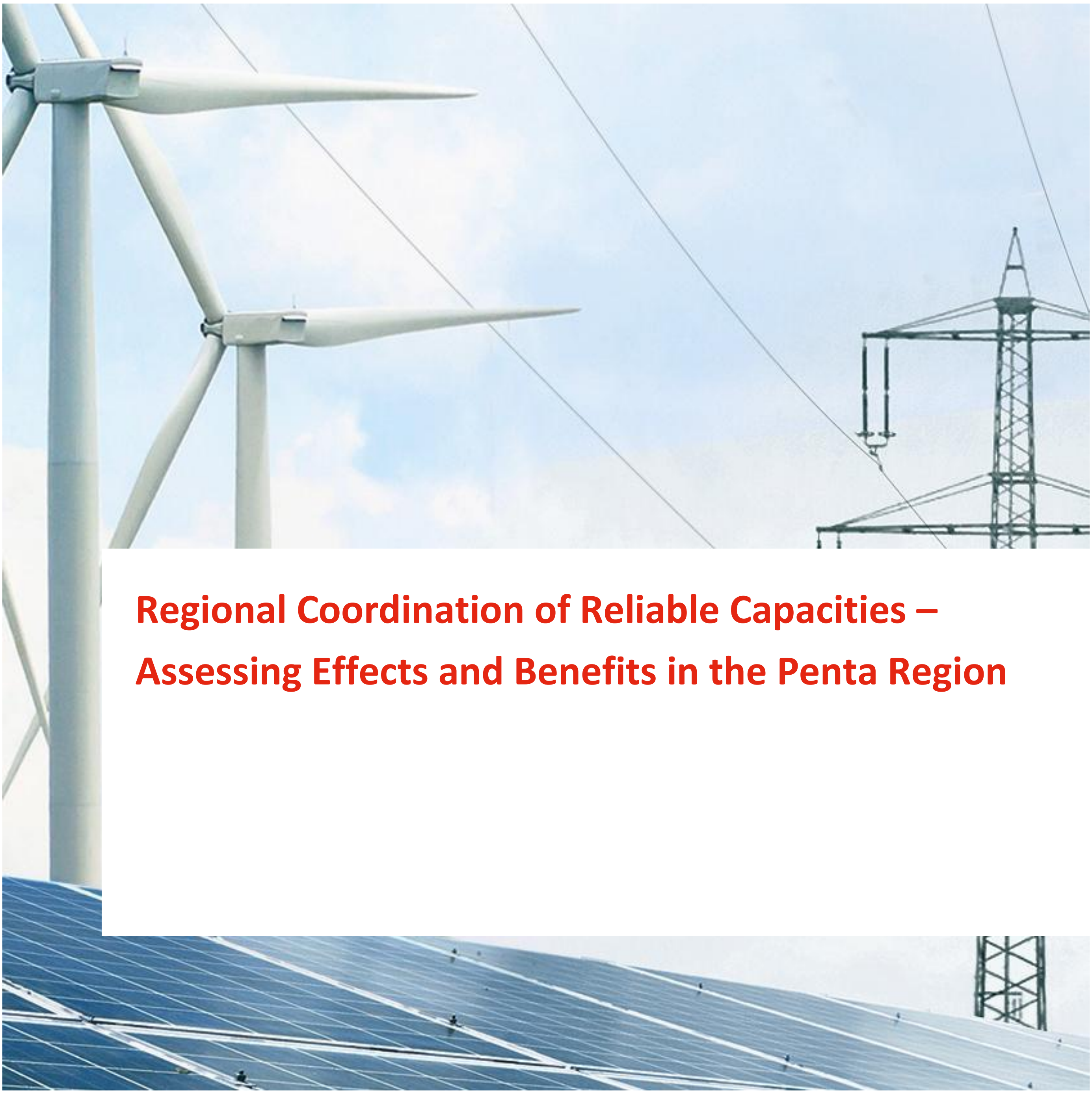

Regional Coordination of Reliable Capacities – Assessing Effects and Benefits in the Penta Region

Final Report

Commissioned by the

Federal Ministry for Economic Affairs and Energy (BMWE)
with expert support from the Pentalateral Energy Forum

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energy consulting

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Executive Summary

The study analyses the possible added value of cooperation in driving capacity expansion in the region of the Pentalateral Energy Forum ("Penta region"). The analysis contributes to a better understanding of how coordinated approaches to resource adequacy and cross-border resource sharing can enhance system resilience, particularly under stressed and crisis conditions. Reliable capacity in this context may be provided through different adequacy instruments, including capacity mechanisms or strategic reserves. The analysis shows that a demand-oriented and coordinated expansion of capacities in the Penta region can achieve a comparable level of security of supply with less installed capacity for those scenario variations compared to the reference scenario. These benefits of coordination are observed not only under normal conditions but also in crisis scenarios. The modelling approach is built on a European reference scenario that ensures resource adequacy, complemented by several stylized variations that deliberately tighten adequacy conditions (e.g., through reductions in available capacity).

Over the past decades, short-term electricity markets in Europe have become increasingly integrated. However, decisions affecting resource adequacy and the expansion of generation capacities remain largely national topics and are hence shaped by individual policy objectives. This misalignment between market integration and national resource adequacy assessments can lead to inefficiencies. Some countries may pursue strategies aimed at a high degree of national self-sufficiency, resulting in structural overcapacity at the system level when followed by all countries. At the same time, countries may rely excessively on free riding by imports, leading to structural undercapacity and increased vulnerability to supply shortages, especially during periods of stress or crisis when reliable capacity instruments beyond market-based outcomes may play an important role. As a result, the overall system may face both redundant investments or insufficient firm capacity in critical situations. A more efficient approach would consider the physical interconnectedness of the European power system and the potential benefits of coordinated planning. Leveraging cross-border synergies can reduce total capacity requirements and costs while maintaining, or even improving, security of supply.

This study was commissioned and funded by the German Federal Ministry for Economic Affairs and Energy (BMWE) and was developed in close cooperation with the Pentalateral Energy Forum. It follows the *Penta statement on the need to ensure a resilient electricity system for future electricity crises*, in which the Penta region agreed to assess the economic costs and benefits of reliable capacity provision (e.g., via capacity mechanisms or reserves) and cross-border cooperation in electricity crisis situations. The study design was developed in collaboration with experts from the Penta region. [1]

This study investigates whether a sweet spot exists between the two extremes described above, i.e., a level of coordinated planning that reflects realistic expectations of cross-border support. It should be demonstrated whether it would be theoretically possible to achieve a high level of resource adequacy through cooperation and joint coordination, while at the same time avoiding the redundant capacities and investments.

Study design

[1] The contents of the study reflect solely the views of the authors and do not necessarily represent those of the BMWE or the Pentalateral Energy Forum. The results were extensively discussed with experts from the Pentalateral Energy Forum.

The analysis focuses on the region covered by the Pentalateral Energy Forum (AT, BE, CH, DE, FR, LU, NL) and is based on a 2040 electricity system aligned with assumptions taken based on TYNDP 2024. Whilst such long-term planning scenarios have the advantage of providing a commonly agreed and consistent input dataset, they ensure resource adequacy by design. Hence, to make the effects of alternative capacity expansion approaches observable, this study applies stylized capacity reductions as variation to this scenario, deliberately inducing scarcity situations characterized by Energy Not Served (ENS) and Loss of Load Expectation (LoLE) within the Penta region and hence providing an exemplary foundation to assess capacity needs.

Based on this, the capacity requirements aiming to reach a level of ENS of 0 MWh/a, are determined under three distinct cooperation assumptions, allowing for a systematic assessment of how different degrees of cross-border coordination affect overall capacity needs, free-riding incentives, and security of supply.

1. In the "Import Dependency" approach, each country minimizes its domestic capacity investments assuming sufficient support from neighboring systems, only limited by available transmission capacities, to be available during periods of scarcity. As a result, countries only build the capacity that is strictly necessary to cover demand while implicitly relying on imports. Consequently, this approach leads to minimal domestic capacity levels.
2. In the "Autarky Plus" approach, each country plans its capacity expansion under the assumption that it must be able to support all shortages in neighboring systems up to the level of transmission capacities available. This effectively eliminates all adequacy risks from a national perspective, as sufficient capacity is ensured even under stressed system conditions and widespread scarcity events. However, if all countries follow this approach simultaneously, it leads to systematic redundant capacities, as multiple countries build capacity to cover the same potential shortage events.
3. The "Coordination" approach represents an intermediate. It assumes a coordinated, system-wide optimization of available capacities, in which countries support each other based on solidarity principles, while respecting their own adequacy constraints. In this framework, cross-border exchanges are determined endogenously: countries provide support to neighboring countries whenever they have available capacity, but only to the extent that this does not create or exacerbate scarcity within their own system (i.e. no additional loss of load is induced domestically). In case of simultaneous scarcity in two or more neighboring countries, a country portions its support equally. In other words, shortages are not exported, and mutual support is limited by the physical and adequacy constraints of each system.

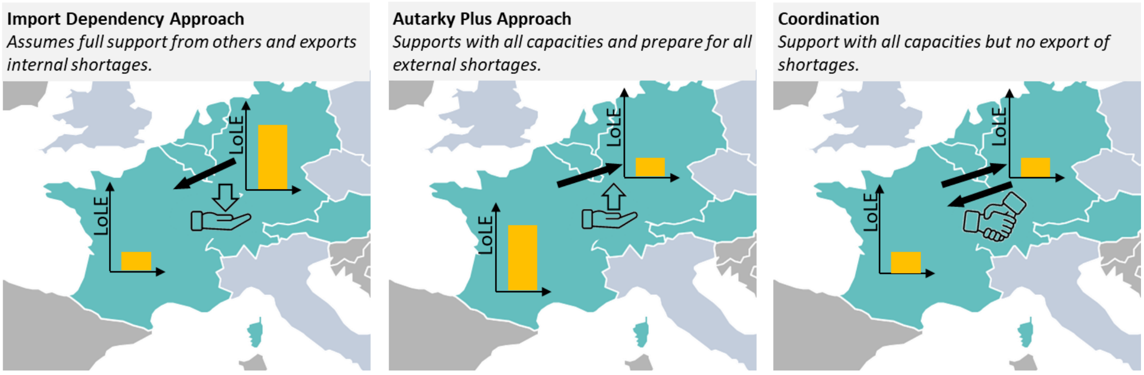

Figure 1 *Illustration of the three cooperation cases for France (FR) as the country under consideration. In the first case, shortages are exported; in the second, shortages are imported. In the third case, no shortage is exchanged.*

Moreover, the study systematically evaluates the different scenario variations across both dimensions of cooperation and system conditions. Each scenario variation is analyzed under the three approaches described above and for the two system states

- normal conditions, and
- a crisis setting.

The crisis setting is represented by a uniform and significant reduction in import capacities from non-Penta countries into the Penta region, thereby limiting external support to the Penta region and increasing stress on the internal system.

Findings

The study shows that across all scenario variations, the assumption of the Import Dependency approach leads to the lowest capacity investments hence leading to the lowest level of resource adequacy for the Penta region. In contrast, assuming the Autarky Plus approach results in substantially higher capacity expansion. The Coordination approach consistently lies between these extremes, showing a high level of resource adequacy with a reduced amount of capacity investments. Whilst the absolute values of capacity needs provide a wide range across scenario variations, as shown in Figure 2, the relative order of the cooperation cases remains robust across all scenario variations investigated. National individual countries' assumptions on cooperation and external support during scarcity situations significantly influence overall system capacity.

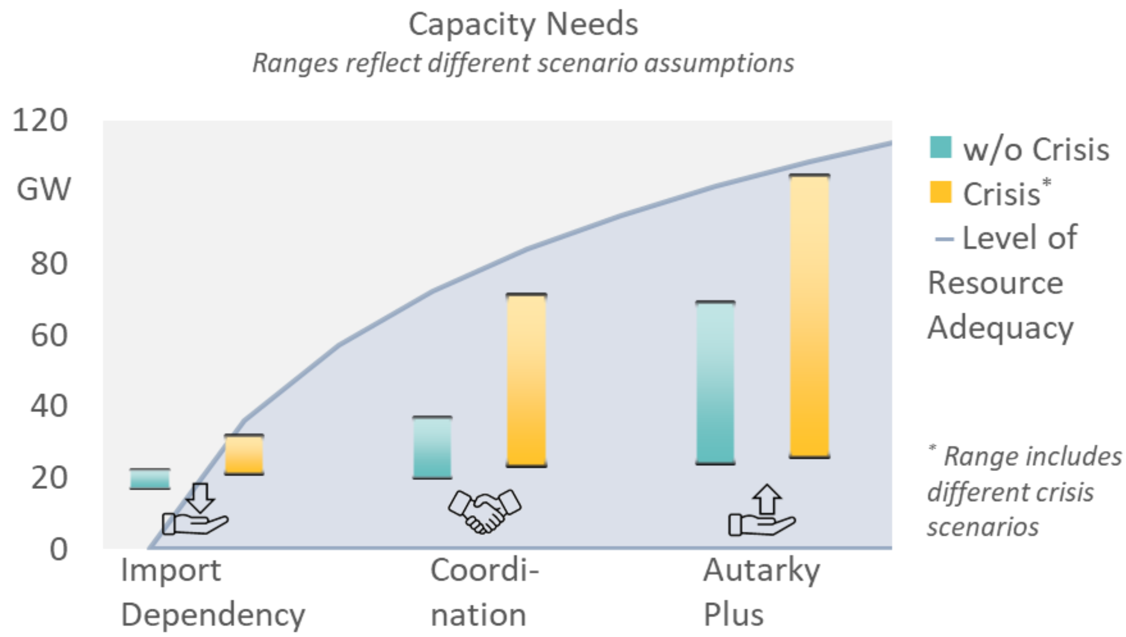

Figure 2 *Ranges of Capacity Needs across scenario variations and per cooperation assumption (left) without crisis and (right) including crisis scenarios*

Higher capacity does not translate proportionally into higher resource adequacy per se. The Coordination approach achieves resource adequacy comparable to the conservative Autarky Plus approach, with a LoLE close to zero across all scenarios. By contrast, the Import Dependency approach, while minimizing capacity needs, leaves small residual adequacy risks.

These trends are also observed in the crisis state, characterized by restricted exchange between the Penta and non-Penta regions. While the relative effects and patterns compared to the normal state remain largely consistent, significantly higher capacity requirements emerge under crisis conditions. For the set of investigated scenario variations and crisis assumption, capacities required to ensure adequacy in the crisis state are also sufficient under normal conditions. Consequently, and non-surprisingly, planning for crisis scenarios inherently provides robustness for non-crisis situations across the scenario variations under consideration. However, no conclusions can be drawn regarding the economic efficiency of such a crisis-oriented planning approach, as this requires assumptions about the probability and frequency of crisis events, which are beyond the scope of this study.

Conclusion

Coordination improves efficiency without compromising resource adequacy in the Penta region and can help avoid unnecessary capacity expansion. Overall, the analysis indicates that uncoordinated, conservative national capacity expansion strategies tend to create overcapacity without delivering significant additional reliability benefits at regional level. In contrast, overly optimistic assumptions about external support can undermine adequacy. Coordinated capacity expansion emerges as a robust and efficient approach in interconnected systems, achieving a high resource adequacy with lower overall capacity requirements. While the absolute figures depend on the underlying scenario assumptions, the structural conclusion is clear: The results highlight the potential value of regional coordination when designing adequacy instruments in interconnected electricity systems.

The results highlight that coordination is not only a key element of “normal” adequacy planning but becomes even more critical in the context of risk preparedness. Given the higher capacity needs in crisis scenarios, effective cross-border cooperation is particularly essential for developing credible and efficient risk preparedness strategies. This suggests a need to better align existing frameworks for adequacy and risk preparedness. In particular, it is recommended, when updating the requirements under the Risk Preparedness Regulation and while mandating EU Member States to prepare for electricity crisis situations, to consider how these requirements may align with the design and implementation of capacity remuneration mechanisms, where relevant. The results indicate that current arrangements, including existing provisions for cross-border participation in capacity mechanisms, may not be sufficient to fully capture the benefits of coordinated planning. Therefore, further work is needed to assess how coordination can be implemented more effectively in practice, for example through a stronger integration of regional perspectives in ERAA processes and national risk preparedness plans.

Contents

1 Background and Introduction

The European energy sector is undergoing a transformation driven by decarbonization. The reduction of controllable generation capacity and the increasing share of renewable energy are leading to increasing relevance of resource adequacy. This transformation is accompanied by the continued development of the European internal electricity market, including market coupling and expanding interconnections. The resulting regulatory and technical challenges raise the question of how today's high level of resource adequacy can be maintained in individual EU Member States and across interconnected, more integrated regions such as the region of the Pentalateral Energy Forum, hereinafter referred to as the Penta region.

While electricity markets in Europe are becoming increasingly integrated, the assessment and regulation of resource adequacy and the design of capacity remuneration mechanisms (CRMs) remain largely national. National assessments still rely on heterogeneous assumptions and methodologies. As a first step towards a more coordinated approach to maintaining resource adequacy, the EU established the European Resource Adequacy Assessment (ERAA) as a common monitoring framework. The ERAA is conducted by ENTSO-E under the oversight of ACER. Within the ERAA, resource adequacy is assessed in a coordinated manner. However, when problems are identified, measures to ensure resource adequacy, such as capacity mechanisms and off-market reserves, are mainly implemented at national level. In each such implementation, assumptions must be made about other countries' behavior. This can lead to inefficiencies when European markets are considered from an integrated perspective.

Given this background, the Penta-countries, consisting of Austria, Belgium, France, Germany, Luxembourg, the Netherlands and Switzerland, seek to examine whether benefits of cooperation in terms of resource adequacy, which so far have mainly been shown in scientific theory, can also be demonstrated empirically using a probabilistic resource adequacy model.

This study, jointly conducted by Consentec GmbH and r2b energy consulting GmbH, analyses the effects of coordinated measures to maintain resource adequacy, with a focus on capacity expansion. It assesses resource adequacy paradigmatically in all countries of the Pentalateral Energy Forum under various conditions and compares coordinated and uncoordinated approaches for adding capacities in scarcity scenarios. Still, the objective of this study is not to carry out a detailed resource adequacy analysis that derives country-specific probabilistic figures or capacity requirements. Instead, the study aims to illustrate the general effects of cooperation by evaluating a set of exemplary future scenarios. The study was commissioned and funded by the German Federal Ministry for Economic Affairs and Energy of the Federal Republic of Germany (BMWE) and was supported by experts and representatives of the Pentalateral Energy Forum. Despite extensive discussions of all results with the stakeholders involved, the contents of the study reflect solely the views of the authors and do not necessarily represent those of the BMWE or the Pentalateral Energy Forum.

The study is based on the TYNDP 2024 scenario NationalTrends+ and applies a probabilistic modelling approach. To provide a suitable reference point for assessing the impact of adequacy-increasing measures, a scenario is required in which adequacy is clearly not ensured. None of the publicly available 2040 scenarios meet this condition. Therefore, as a first step, capacity is reduced in a simplified and uniform manner. This makes the effects of cooperation on resource adequacy more visible and supports a relative comparison across the scenarios considered.

However, the resulting absolute values should not be interpreted as directly meaningful and no conclusions on resource adequacy are to be drawn from these results.

Based on TYNDP assumptions, installed capacity is reduced across several standard scenarios as well as selected crisis scenarios. These scenarios form the starting point for analyzing the value of coordination of capacity needs. Across the cooperation cases considered, the allocation of Energy Not Served (ENS) is varied, and the resulting capacity needs are determined for each country. In a final step, the derived capacity additions are applied, and resource adequacy is reassessed. Against this backdrop, the following section situates the study within the broader academic and policy debate on adequacy coordination in interconnected electricity systems. It reviews existing literature to provide a conceptual and empirical foundation for understanding how cross-border cooperation can influence capacity needs, system reliability, and overall efficiency in regional electricity markets.

2 Conceptual Background

The existing literature on coordination of capacity needs to support resource adequacy includes conceptual discussions on the prerequisites for cooperation, quantitative modelling of adequacy outcomes, and case studies on operational integration. All these contributions reveal a consistent tension between the logic of integrated electricity markets and the continued treatment of resource adequacy as a national responsibility.

Cherp and Jewell (2011) provide a useful framework for understanding the development of this tension. They distinguish between sovereignty, robustness, and resilience as three perspectives on resource adequacy, each reflecting different historical priority. Sovereignty reflects a longstanding focus on national control shaped by geopolitical considerations. Concerns about robustness grew with the rise of complex systems analysis and a focus on reliability under non-geopolitical stresses. A resilience perspective became more central following market liberalization and increasing interdependence.

From this perspective, adequacy coordination appears economically attractive because it enables efficiency gains from integration. Politically, however, it remains contentious, as sovereignty-oriented approaches still shape national policymaking and limit the willingness to share responsibility for resource adequacy. Moreover, one could argue that such inefficiencies, which may result in overcapacity, can, at least in the short term, support resource adequacy by providing an additional buffer. Building on this, the following section reviews the conceptual and theoretical foundations of adequacy coordination, focusing on how literature defines the preconditions for successful cooperation.

Conceptual and theoretical foundations

Several studies highlight how national adequacy policies clash with the efficiency logic of integrated markets. In a qualitative assessment of EU-level coordination Hawker, Bell and Gill (2017) show that despite increased coupling, capacity mechanisms remain designed around national priorities. This division undermines price signals, distorts trade and investment, and ultimately reduces system-wide efficiency. Even if short-term effects on prices and dispatch may be limited, significant distortions and inefficiencies are likely to arise in the long run. Such outcomes reflect a sovereignty-oriented approach to security, in which national control takes precedence over integration.

Other contributions emphasize that nationally determined reliability standards can themselves become problematic in integrated systems, as they were developed in largely self-sufficient systems. Typically, cross-border adequacy externalities are ignored in increasingly interconnected markets and may lead to inefficient capacity investments at the system level. Astier and Ovaere (2022) argue, however, that if adequacy is assessed holistically across regions and these external benefits are internalized, nationally determined reliability standards can still yield efficient allocations in integrated systems. Under these conditions, coordination enables risk pooling and reduces additional capacity needs, thereby lowering costs. Their analysis shows that regional coordination of needs produces particularly large welfare gains, compared to the full internalization of all cross-border effects. This suggests a non-linear relationship between efficiency gains and the depth of coordination. Moreover, they identify interconnector reliability as a fundamental parameter in adequacy assessments, underlining the importance of system flexibility. This reasoning reflects a resilience-oriented perspective, in which security arises from interdependence and flexible use of shared resources.

Henriot and Glachant (2014) complement these arguments by outlining the conditions for the successful integration of capacity remuneration mechanisms. They emphasize three requirements: consistent adequacy assessments across countries, transparent allocation of risks and remunerations for cross-border contributions, and clear definitions of rights over resources. These conditions address distribution and incentive challenges that are identified in economic theory as barriers to cooperation. While Henriot and Glachant view full integration as most consistent with market coupling, they note that national adequacy policies can remain viable if foreign resources are explicitly valued in procurement. Like Astier and Ovaere, they conclude that harmonized standards and shared definitions can bring greater marginal benefits than full system integration.

Overall, these conceptual contributions highlight key predictions from economic theory. Cross-border cooperation should enable risk diversification and reduce adequacy requirements when demand patterns and supply shocks differ across countries. This can lower system costs and avoid redundant capacity investments. Larger integrated market areas are also expected to benefit from economies of scale and greater operational flexibility. At the same time, literature underlines that these gains are not automatic. Distributional effects arise when benefits and costs are unevenly distributed across countries, raising questions of fairness. Different adequacy standards and institutional arrangements complicate coordination, while governance structures become more complex as responsibilities are shared across borders. Ultimately, the larger the coordination area, the greater both the potential efficiency gains and the risks of political controversy and implementation complexity. These dynamics mirror the tension between sovereignty, which emphasizes national control, and resilience, which frames resource adequacy as emerging from interdependence.

Coordination Benefits Quantified

Building on these conceptual insights, a second strand of literature quantifies the efficiency gains and risks of coordination. Using a range of modelling approaches, these studies compare various degrees of cooperation in adequacy mechanisms to estimate how theoretical benefits translate into system-wide outcomes.

Hagspiel et al. (2018) solve a long-term optimization model to compare self-sufficiency and joint adequacy in multi-regional power systems. They estimate that coordination can reduce the required generation capacity by 6.4%, equivalent to around USD 14.5 billion savings in investment costs, when targeting a perfectly reliable system, compared with isolated regional approaches. Beyond overall reductions, their framework highlights that the value of individual technologies, and interconnectors in particular, increases with deeper cooperation. However, these effects are highly sensitive to the assumed reliability targets. Even small changes affect region-specific gains and the implicated value of individual technologies. Overall, the results illustrate both the efficiency potential of coordination and the fairness concerns arising from uneven distributions of costs and benefits across countries.

Similar patterns emerge in studies on capacity market design. Bucksteeg et al. (2019) argue that national mechanisms operating in parallel can be inefficient and can invite free riding, thereby threatening long-term adequacy. Their probabilistic modelling suggests that a fully integrated EU capacity market would reduce overall capacity requirements by about 10%, improve investment signals, and increase consumer surplus. However, they note that while full coordination offers the greatest gains, a more feasible second-best option may be regional coordination of national mechanisms, given lower political and institutional hurdles. This reinforces earlier arguments about a potentially non-linear relationship between cooperation and efficiency gains, in which harmonized standards and regional cooperation often deliver larger marginal benefits than full system integration.

Cepeda (2018) reaches similar conclusions using a dynamic model comparing national capacity mechanisms, unilateral cross-border participation, and regional integration. While national mechanisms increased reliability in relative terms, they also created distortions, by incentivizing implicit export bans during scarcity. Uncoordinated participation resulted in significant social welfare losses due to free riding and flawed adequacy estimates. By contrast, integrated regional mechanisms produced consistent welfare gains, with interconnectors serving as substitutes for capacity. Cepeda underscores the importance of common evaluation rules and fair cost allocation. Without this, the expected efficiency gains cannot be sustained in practice.

Evidence from Switzerland further illustrates these dynamics. Zimmermann et al. (2021) show that capacity mechanisms in neighboring countries initially lowered Swiss wholesale prices and improved stability, but in doing so reduced domestic investment incentives. While short-term outcomes appeared favorable, the long-term risks included underinvestment and reliance on foreign resources, creating opportunities for free riding. This case demonstrates how asymmetries between coordinated and non-coordinated systems can destabilize system adequacy and distort investment signals.

Together, these studies suggest that coordination reliably reduces system costs, avoids redundant investments, and strengthens reliability by exploiting risk pooling and scale effects. At the same time, they highlight the uneven distribution of benefits across regions, the sensitivity of results to reliability targets, and the persistent governance challenges of aligning market designs.

Coordination in Operational Contexts

Finally, we consider literature that focuses on operational and design-level choices, examining how coordination shapes balancing, reserve sharing, and fairness in system operation. Baldursson et al. (2018) provide one of the clearest demonstrations of the benefits of cross-border cooperation in this area. Using a comparison between self-sufficiency, reserve exchange, and full reserve sharing, they show that the welfare effects of cooperation depend on cost structures and the pattern of imbalances between countries. When procurement costs are highly asymmetric, but imbalances are strongly correlated, reserve exchange is most beneficial. By contrast, when costs are similar, but imbalances differ across space and time, full reserve sharing delivers greater gains. Their simulations based on 2015 market data suggest annual efficiency improvements of EUR 165 million for reserve exchange and up to EUR 500 million for full sharing.

However, they also stress that such outcomes remain conditional on institutional design. Weak incentives for TSOs to cooperate, risks of strategic behavior, and limited cost transparency currently hinder integration. To address these issues, the authors propose binding cooperation agreements, transparent cost reporting, and the allocation of reserve costs according to each participant’s marginal impact on overall needs.

Questions of fairness are taken further by Fraunholz et al. (2025), who argue that distributive effects must be explicitly addressed in adequacy and reserve allocation decisions. Their framework introduces spatial and temporal fairness into demand curtailment and offers two design routes. Either dispatch outcomes are adjusted ex post to achieve a fairer distribution across regions, or penalties for inequality are embedded directly in the optimization process to improve both spatial and temporal fairness. They caution against overreliance on single reliability indicators and instead advocate a mix of measures that better capture heterogeneous system conditions. In doing so, they highlight that efficiency-oriented coordination must be balanced against fairness and equity to ensure political legitimacy and long-term sustainability.

Van den Bergh et al. (2017) add another dimension by exploring how coordination interacts with physical system constraints. Using unit commitment and dispatch simulations, they show that coordinated reserve sizing, allocation, and activation can reduce operational costs and enhance system stability. They also highlight a non-linear relationship between the depth of coordination and efficiency gains. If network constraints are internalized realistically, coordination yields consistently positive outcomes. However, if these constraints are underestimated, the expected gains may be offset by inefficiencies during activation. This illustrates the risks of inadequate modelling and underscores the need for transparent and realistic consideration of physical system limits.

Synthesis

The reviewed literature concludes that coordination of capacity needs across countries yields efficiency gains, reduces costs, and improves total-system reliability compared with nationally isolated approaches. At the same time, the relationship between the degree of integration and the magnitude of benefits appears to be non-linear. Several contributions emphasize that the largest marginal gains are not necessarily achieved under full integration, but rather through consistent assessment standards, harmonized reliability targets, and transparent valuation of interconnectors. Therefore, optimal design requires balancing potential efficiency gains against the political and institutional feasibility of deeper integration. Distributional and fairness concerns are central to this balance and may aggravate sovereignty and trust issues between cooperating countries.

A recurring theme is the growing role of interconnectors. Their reliability and economic value are identified as key parameters in adequacy assessments and investment decisions. Accurate and transparent modelling is therefore critical for guiding efficient capacity allocation. Yet outcomes remain highly sensitive to reliability standards, the contributions of individual technologies, and heterogeneity in procurement costs and demand imbalances across countries. As a result, the effectiveness of coordination depends strongly on the structural characteristics of the participating systems.

The literature also highlights important uncertainties and gaps. Most contributions focus on efficiency gains from risk pooling, economies of scale, and interconnector use. However, economic theory suggests an additional channel via specialization: Countries could focus on technologies or resources in which they have comparative advantages and rely on coordinating partners for complementary capacity. This dynamic is rarely explored, likely due to the high levels of trust required and the governance complexity it entails. Long-term modelling to date has primarily addressed aggregate efficiency outcomes, with limited attention to more nuanced dynamics such as evolving risk profiles or technology pathways.

Finally, despite broad consensus on the potential of coordination, the level of actionable design guidance differs across the literature. While suggestions for cooperation in generation adequacy assessments are often readily implementable, research on capacity mechanisms remains more stylized. The case for efficiency gains is well established, but limited guidance is provided on how proposed “balanced” solutions could be designed in practice.

To address this gap, this study investigates the concrete effects of regional cooperation on resource adequacy indicators within a larger interconnected system such as the Penta region. This enables an assessment of potential non-linear benefits and broader system effects of coordinated approaches compared with national, uncoordinated strategies.

3 Overview of the Study's Methodology

The literature review above demonstrates that the advantages of coordinated capacity planning are well established in theory. Numerous studies report efficiency gains, cost reductions, and improved system security when adequacy is assessed at a regional level rather than at the level of individual countries in isolation. At the same time, the specific form of cooperation is critical for the actual outcome. However, it often remains unclear how these conceptual arguments translate into a concrete and realistically modelled system.

To complement the theoretical background and analyses available in the literature, this study conducts a quantitative resource adequacy assessment for the Penta region. It examines different cooperation concepts based on alternative allocation approaches for ENS, with a focus on the Penta region. The objective is not to derive specific national capacity targets or to perform a comprehensive resource adequacy analysis. Instead, the study aims to illustrate the system effects of different approaches in a comparable manner and to complement the theoretical discussion with an empirical perspective. To this end, the potential benefits of coordinated capacity expansion in the Penta region are assessed using stylized scenarios and representative case studies.

Applying existing resource adequacy tooling, we follow a four-step approach. First, an investment model that mimics the TYNDP National Trends scenario (based on TYNDP 2024) is set up to provide a consistent input dataset for the target year 2040. This step yields efficient investment decisions; therefore, the initial system reflects a high level of resource adequacy, as is typical for publicly available 2040 datasets. As a result, no additional capacity is required to ensure resource adequacy in the Invest/Dispatch based NT+-scenario.

In a preparatory second step, capacity is removed in a simplified way to induce hours with ENS within the Penta region, thereby creating a case in which resource adequacy is clearly not maintained and which can hence be used for further analysis. This provides the basis for the subsequent modelling steps that analyze the effects of coordination. In the third step, capacity needs are identified via a resource adequacy analysis by determining the additional capacity required to cover peak hourly ENS per zone. Depending on the design of the coordinated expansion and the underlying assumptions, there are various capacity needs. We represent various coordination approaches by running the model setup multiple times with various ENS penalty costs in the Penta countries, as outlined in more detail in the next paragraphs.

To evaluate the consequences for resource adequacy, the fourth step reruns the resource adequacy model after applying the capacity additions derived in Step 3. The resulting workflow is illustrated in Figure 3.1.

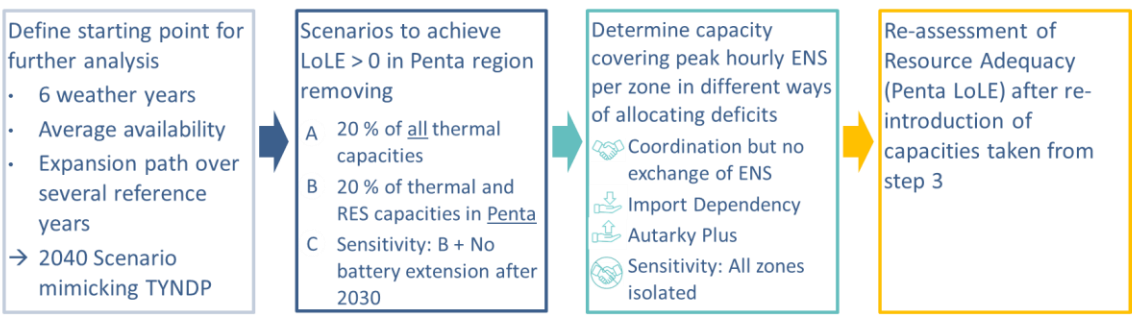

Figure 3.1 Workflow in this study

The following sections outline the exact method and toolchain used for the resource adequacy analysis. Section 3.1 provides a general overview of the applied resource adequacy modelling tools that form the basis of the analysis framework. Section 3.2 describes the initial step, in which a scenario based on the TYNDP is defined using the investment model to establish consistent input data and boundary conditions. Section 3.3 describes how capacity reductions are applied to selected technologies or regions to simulate stress conditions and test system resilience. Section 3.4 presents the resource adequacy assessment, which evaluates resource adequacy after the implementation of capacity expansion measures for each cooperation case and scenario. Finally, section 3.6 provides an additional summary and an overview of the model runs.

3.1 Toolchain for Resource Adequacy Analysis

The probabilistic resource adequacy model aims to compute probabilistic indicators that describe resource adequacy as prescribed by European legislation:

- **LoLE (Penta): Loss of Load Expectation (h/a)** – a reliability metric for the entire Penta region, measuring the average number of hours per year during which load cannot be fully served in region under investigation.
- **EENS: Expected Energy Not Served (MWh/a)** – the expected amount of unserved energy in this region.

When applied to a "standard" resource adequacy analysis, these indicators are computed per bidding zone. Hence, it is assumed that there is no congestion within zones. In this study, however, the focus is on the effects concerning the Penta region rather than on distinctions between individual bidding zones. Accordingly, while maintaining the individual bidding-zone setup and cross-border exchange limitations between all those bidding zones in the modelling toolchain, we additionally compute a "Penta LoLE" which focuses on an evaluation of this region as a whole, accounting for LoLE whenever ENS occurs in at least one of the respective bidding zones within the Penta region: We evaluate hours during which at least one country in the Penta region experiences a loss of load. For the set of the Penta counties C_{penta} the Penta LoLE is given by

$$LoLE_{penta} = \frac{1}{|Y|} \sum_{y \in Y} \left(\sum_{t \in T} \mathbf{1} \exists c \in C_{penta} : ENS_c(y,t) > 0 \right)$$

with set of weather and outage years Y, set of all hours in a year T, and $ENS_c(y,t)$ Energy Not Served in country c, year y and hour t. The indicator function **1**{}, equals 1 if the condition is true and 0 otherwise, for example, the Penta LoLE counts for each year the number of hours in which at least one of the Penta countries has ENS > 0, and takes the average across all years.

The resulting distribution reflects variations in load, the availability of generation units, and the availability of primary energy sources (for renewables, mainly driven by weather conditions). These variables are used to evaluate whether electricity demand can be met in the market.

Monte-Carlo Simulation

Since no analytical methods are available to calculate these indicators while accounting for all interdependencies, a Monte Carlo approach is applied. For each reference year, the model generates distributions of Loss of Load Hours (LoLH) and ENS to estimate expected values in line with the law of large numbers.

For the analysis in this study, six historical weather years (2009–2013 and 2017) are combined with 350 randomly drawn outage years each, resulting in 2,100 "Monte Carlo years". For each Monte Carlo year, the tool tests whether the generation stack (for example, derived from the initial scenario after capacity reducing adjustments) can meet demand. Based on the results the model determines the resulting LoLE, Penta LoLE, and Expected Energy Not Served (EENS).

In this context, a weather year is defined by time series for renewable generation, inflows to hydropower reservoirs, and electricity demand. An outage year is characterized by stochastic sampling of outages for thermal plants, hydropower plants, and battery storage facilities. Each outage year therefore includes a time series of plant availability based on the assumed outage probabilities. The selected weather years correspond to those available in the European electricity market model to ensure consistency with European regulatory requirements. All weather and outage years are weighted equally when deriving probability values. The number of weather years is limited to six to maintain computational feasibility, as multiple model runs are required for this study.

The Monte Carlo simulation approximates the underlying distribution using randomly generated samples. Still, with a sufficiently large sample size, reliable estimates of means and expected values can be obtained. In practice, around 350 samples are deemed sufficient for model convergence.

Coverage of Demand per Monte-Carlo Year

A closed linear optimization model with perfect foresight is used to analyze each Monte Carlo year deterministically, covering all 8,760 consecutive hours of a year. The model minimizes energy shortfalls (i.e., ENS) within each Monte Carlo year. To ensure computational efficiency, only parameters essential for determining the probabilistic reliability indicators are included. The modelling approach is simplified compared with a full market simulation. It is assumed that, in scarcity situations, all available resources (generation units and storage) are dispatched in response to high price signals, preventing shortages. This implies a perfectly functioning and efficient market. Accordingly, all technically available capacities are assumed to participate during scarcity periods.

In this study, models assume cross-zonal trade based on today's existing bidding zone configuration. For the sake of simplicity, countries with multiple bidding zones, such as Italy and Sweden, are aggregated into a single zone. Cross-border exchanges are constrained by Net Transfer Capacities (NTCs), which are also taken from the TYNDP dataset.

When identifying hours with energy not served, it is not necessary to track which specific units serve demand. In the objective function, dispatchable power plants are therefore assigned identical cost coefficients. During scarcity hours, all available plants are dispatched. During non-scarcity hours, it is sufficient that at least one feasible dispatch combination meets demand and storage constraints.

If a demand shortfall occurs in any hour within a Monte Carlo year, it is recorded as ENS and characterized by its duration and magnitude. From the collection of such events across all Monte Carlo years, the key indicators LoLE and EENS are calculated.

The core analytical tasks for determining these probabilistic reliability metrics are:

- Identifying hours per bidding zone in which market-available generation cannot meet any demand, and
- quantifying the amount of unserved energy during those hours.

Storage and pumped-storage operation are modelled analogously to a power market model, using intertemporal constraints to ensure energy balance over time and compliance with storage capacity limits. Energy withdrawal from storage therefore cannot exceed the amount previously stored or added through inflows. A similar approach is used for demand-side flexibility (DSM) to ensure that postponed demand is recovered within the modelled time horizon.

The geographical scope of the probabilistic resource-adequacy model corresponds to the one of the European electricity-market model. Without penalty costs, the model would be indifferent with respect to the allocation of EENS to bidding zones. The total amount of ENS does not vary between the cooperation cases; differences pertain solely to its allocation across zones and hours. To define how ENS is distributed across zones, a penalty term is introduced to simulate different allocation mechanisms for resource adequacy deficits. To assess the influence of Coordination of Capacity Needs serving resource adequacy, three distinct cooperation cases are defined within the probabilistic resource-adequacy model: *Coordination*, *Import Dependency Approach and Autarky Plus Approach*. However, for a fixed demand/supply and weather set, the total ENS summed over all zones and hours is invariant across cooperation cases.

3.2 Step 1: Define TYNDP-based scenario as a starting point

For this study, we use the existing multi-model toolchain and interfaces developed at r2b and Consentec to build on previous work. We rely on our established interfaces, weather years as well as our proprietary outage and maintenance data. To establish a consistent starting point, the selected scenario is hence first processed through the existing toolchain.

Against this background, scenario assumptions for the analysis of coordinated capacity expansion across the Penta region are based on the "National Trends +" (NT+) scenario of ENTSO-E's TYNDP 2024. Based on these assumptions, a closed investment and dispatch modelling is carried out over the entire time horizon and for six different climate years (2009–2013, 2017) using a perfect foresight optimization approach. Policy-driven capacity (i.e., renewables and nuclear) is set exogenously, while the decommissioning and expansion of market-driven capacity is modelled endogenously. The model determines, based on the economic viability of a given asset, whether it is commissioned (gas-fired plants) or decommissioned (coal-, oil-fired plants).

Using an integrated investment and dispatch modelling tool chain is necessary to ensure that the analysis of coordinated capacities in the Penta region is based on an efficient system. In this system, adequacy issues (i.e., loss-of-load events) occur only after targeted reductions in capacity or interconnection. This ensures that the resource adequacy assessment is not driven by structural overcapacity within the modelling framework.

Figure 3.2 provides an overview of the detailed model regions, the Penta region and its satellite regions depicted in this analysis.

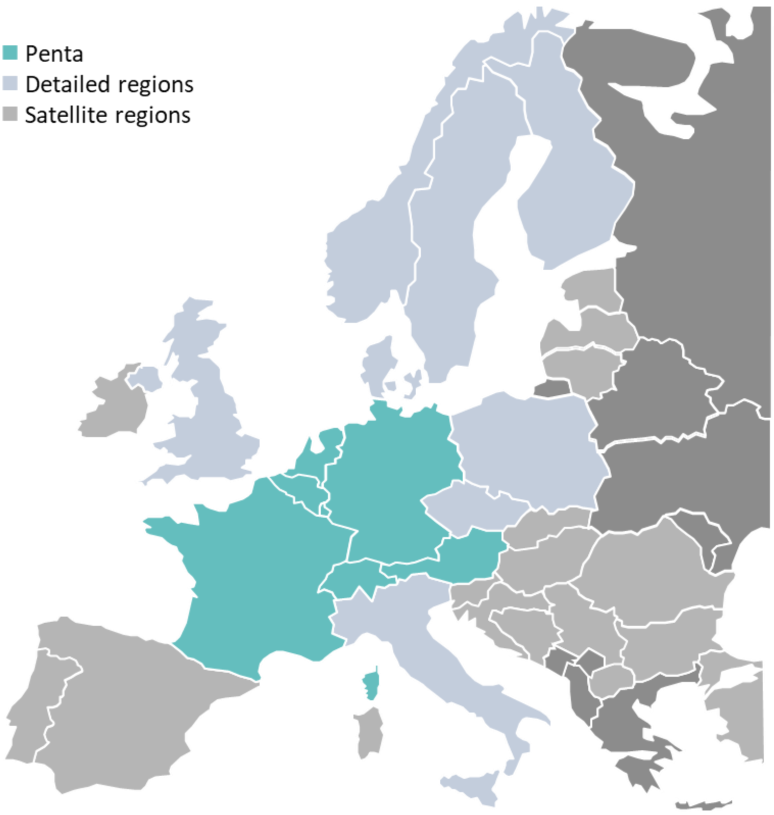

Figure 3.2 Overview of model regions

The capacities after invest- and dispatch-modelling deviate from those of the original TYNPD NT+ scenario. The following figure compares the installed capacities of the scenario for the Penta countries (i.e. Austria, Belgium, France, Germany, Luxembourg, Netherlands and Switzerland) before (TYNDP NT+) and after the investment-modelling (Invest/Dispatch based NT+) performed by r2b.

2040	**Capacities in Penta**	
Type	**TYNDP NT+ ov in GW**	**Invest/Dispatch based NT+ in GW**
Nuclear	63	63
Lignite	-	-
Hard coal	-	-
Gas	65	81
OCGT	2	69
Hydro PSP	55	50
Hydro RoR	29	28
BESS	153	150
Other RES	11	11
Other non-RES	8	4
DSR	29	23
Sum	415	480

Table 1: Comparison of installed capacities before and after invest- and dispatch-modelling

The key difference between the initial scenario and the scenario after the investment and dispatch modelling is the substantial investment in open-cycle gas turbines (OCGTs) amounting to 67 GW, and in combined-cycle gas turbines (CCGTs) amounting to 16 GW across the Penta region. We assume this outcome is mainly driven by the TYNDP assumption that residential and commercial heat pumps are not flexible.

In the model used for this study, demand-side response (DSR) is represented as a potential that is deployed endogenously, with marginal costs increasing as more DSR is activated. As a result, the model does not necessarily deploy the full DSR potential available. Additional deviations stem from differences in hydropower modelling, including assumptions and a more conservative commissioning of new plants, as well as smaller differences in other non-RES technologies and battery energy storage systems (BESS).

3.3 Step 2: Apply Capacity Reduction

The TYNDP based scenario is based on a market equilibrium framework and implies a high level of resource adequacy across the Penta region bidding zones. Hence, applying a resource adequacy model using this scenario would not show any adequacy concerns, meaning no ENS or LoLE values will occur. This would not be a valid starting point for the question under investigation. To establish a baseline from which the effects of alternative capacity expansion conditions on resource adequacy can be observed, a scenario is required in which resource adequacy is not granted.[2] Therefore, in the second step, capacities are removed from the system with a simplified cross-the-board approach. This allows us to investigate the effects of various capacity expansion strategies on resource adequacy and will make them more visible; however, the

[2] If we did not do so, we could achieve an increased level of resource adequacy, as no LoLE 0 h/a or EENS < 0 MWh/a is possible.

absolute figures for capacity needs derived in this study should therefore not be taken at face value, given the methodological approach applied. The study is mainly designed to demonstrate the effects of cooperation in stylized examples than providing political guidance on the capacity needs or resource adequacy concerns for specific countries.

Hence, to assess the value of the Coordination of Capacity Needs serving resource adequacy, we consider scenarios that provide significant resource adequacy concerns. This implies restricting available capacity such that unserved energy occurs in the Penta region. We define three stylized scenarios for reducing the installed capacity. The scenarios are chosen so that the effects of cooperation are clearly visible. The reduction is applied proportionally for each bidding zone and defines the following set of scenarios:

Set of scenarios under investigation

A. All 20: In the first scenario, 20% of thermal capacities are withdrawn in the model area, corresponding to 214 GW (approximately 111 GW within the Penta).

B. Penta 20: The second scenario removes 20% of both thermal and renewable[3] capacities in the Penta region, corresponding to 111 GW non-RES and 290 GW RES.

C. B + No battery extension: In a sensitivity case, additional to the reduction described in scenario B, we assume no further battery storage expansion beyond 2030, leading to an additional reduction of 133 GW of non-RES capacity, mainly affecting Germany.

The capacity reductions induce ENS and hence the occurrence of LoLH. Due to the different assumptions, both the frequency LoLH and the resulting level of ENS vary across scenarios. In scenario A: Capacity is reduced throughout the entire model region, which not only reduces the ability to cover domestic load but also restricts import options. In scenario B: capacity reductions are confined to the Penta region, allowing continued imports from the non-Penta regions. These different starting conditions allow for a robust evaluation of the Coordination of Capacity Needs, independent of the initial generation park.

3.4 Step 3: Define Capacity Needs for each Cooperation Case

In the third step of the analysis, the capacity requirements for each Penta country are determined for the different cooperation cases (see below). While the previous step deliberately introduced capacity shortages to create scarcity situations in the system, this step quantifies how much additional capacity would be required in each bidding zone and in the Penta region to restore resource adequacy. The target is a LoLE of 0 h/a, achieved by adding capacity equivalent to the peak hourly ENS identified in each zone. To capture the potential benefits and risks of coordinated capacity expansion, several variants of cooperation ("cooperation cases") are defined. Each variant represents a specific assumption regarding how the Penta countries determine their capacity needs, depending on the level of support expected from other countries in the system.

The set of cases ranges from complete isolation, in which neither cross-border electricity exchange nor ENS sharing is allowed, to Import Dependency approach. The latter assumes that support from neighboring countries would be available, even if this implies ENS in those countries, and therefore defines the minimum national capacity level that would not be regrettable if such support materialized. Between these extremes, two intermediate cases are considered:

[3] Including both, onshore and offshore wind as well as photovoltaics.

Coordination Case (allowing full cross-border sharing) and Autarky Plus approach. In the latter case, each country must also cover potential shortfalls in neighboring zones, resulting in a capacity level that does not rely on external support and avoids adequacy risks arising from cooperation. Each case is implemented mathematically by adjusting the penalty cost for ENS in the objective function of the optimization model, thereby simulating different incentives to share or withhold capacity. By performing separate resource adequacy analyses for each cooperation case, the model identifies the maximum hourly ENS per zone and scenario. These values form the basis for deriving the additional capacity requirements of each country within the Penta region under the respective cooperation assumptions.

Adding capacity equal to the peak hourly ENS corresponds to sizing capacity to cover the worst-case shortage hour for each country in the simulation. Thus, this approach implicitly targets a LoLH value of 0. The choice of 0 is primarily methodological and ensures comparability across cooperation cases. Determining the corresponding capacity level would be more complex and less transparent when choosing another figure.

In all Coordination Cases, the same NTC values are applied, limiting the cross-zonal exchanges between the bidding zones, also for bidding zones within the Penta region. For the first three approaches to allocating deficits, the total amount of ENS is invariant between the cooperation cases, with differences arising solely from its distribution.

The following sections describe the three cooperation cases in a more detailed manner.

Cooperation Case: Coordination approach

In the Coordination Case ("Coord"), all available generation capacities can provide cross-border support. However, cross-border exchanges are penalized such that a country will never provide support if this would lead to ENS in its own bidding zone. Therefore, if a country can fully meet its own demand with domestic generation, no ENS will occur in that country. Any remaining capacities (from renewable energy sources, thermal units, batteries, demand-side management, etc.) are then used to support neighboring countries.

To achieve this, cross-border exchanges are penalized with a cost lower than the penalty cost for ENS ensuring that

1. each country serves its own demand first,
2. subsequently imports electricity if possible, and
3. imports only in the event this does not cause ENS and hence a LoLH in another country.

Exchange across each individual border is penalized such that direct neighboring countries receive support first. Only afterwards is support provided to second- and third-tier neighbors. In this case, support needs to be provided to two or more zones leading to indifferent results, a LoLH is assumed for both countries.

This yields the following simplified formulation of the problem:

Parameters:

Z: Set of zones (countries)
T: Set of hours
Y: Set of weather and outage years (scenarios)
$L \subseteq Z \times Z$: Set of transmission links between zones

D_{zty} : Demand in zone z at hour t in year y
G_{zty} : Available generation and flexibility capacity in zone z, hour t, year y

$F_{ij,ty}$: Transmission capacity on interconnection (i,j) in hour t, year y
c^g_{zty} : Generation cost in zone z, hour t, year y (usually small)
$c^{exchange}$: Cost for cross-border electricity exchange (lower than ENS cost)
c^{ENS} : Penalty cost for ENS, where $c^g_{zty} \ll c^{exchange} \ll c^{ENS}$

Variables:

$g_{zty} \in [0, G_{zty}]$: Generation or flexibility used in zone z, hour t, year y
$f_{ij,ty}$: Power flow from zone i to zone j in hour t, year y
$ENS_{zty} \geq 0$: Energy not served (Loss of Load) in zone z, hour t, year y

Objective Function

$$\min \sum_{y \in Y} \sum_{t \in T} \left[\sum_{z \in Z} c^g_{zty} g_{zty} + c^{exchange} \sum_{(i,j) \in L} |f_{ij,ty}| + \sum_{z \in Z} c^{ENS} ENS_{zty} \right]$$

Cooperation Case: Import Dependency approach

In the Import Dependency approach ("Import Dep.") variant, each bidding zone assumes that it will receive full support from neighboring countries. When determining its capacity needs, a zone assumes that neighboring zones will provide cross-border exchanges if interconnector capacity is available, even if this creates additional ENS in the neighboring zone. This minimizes the capacity need in the zone under consideration.

To mimic this behavior, the zone being analyzed minimizes ENS allocated to itself by pushing ENS to other zones, resulting in the lowest possible peak hourly ENS for that zone. In other words, whenever ENS can be transferred to another zone, it is not assigned to the zone being analyzed. This approach therefore assumes that neighboring zones provide support even if this causes ENS in their own zones. Therefore, the estimated capacity needs are required as a minimum, and we refer to this as no-regret capacity expansion. The shift of ENS is implemented by increasing the penalty cost for ENS only in the zone under consideration.

To determine capacity needs for each bidding zone in the Penta region, each zone is analyzed once as the zone that shifts ENS to all others.

The mathematical formulation changes to

$$\min \sum_{y \in Y} \sum_{t \in T} \left[\sum_{z \in Z} c^g_{zty} g_{zty} + c^{exchange} \sum_{(i,j) \in L} |f_{ij,ty}| + \sum_{z \in Z} c^{ENS}_z ENS_{zty} \right]$$

where

$$c^{ENS}_{without\ analyzed\ zone} \ll c^{ENS}_{analyzed\ zone}$$

Increasing c^{ENS}_z shifts ENS away from the analyzed zone, assuming full support from neighboring zones.

We expect this case to lead to undercapacity, as all countries prepare only for the potential issues in their country and not for simultaneous scarcity in the neighboring countries.

Cooperation Case: Autarky Plus approach

The Autarky Plus approach ("Autarky+") case assumes the opposite of the previous variant. Each bidding zone assumes that it must cover not only its own ENS but also the ENS of neighboring zones. De facto, neighboring zones are supported first whenever this is possible using the cross-border exchange capacities. Accordingly, the zone being analyzed maximizes ENS allocated to itself by pulling ENS from other zones, resulting in the highest possible peak hourly ENS for that zone. In effect, each zone ensures export capability even under the assumption that all other zones reallocate ENS away from their own systems. Consequently, the capacity need calculated does not include any risks stemming from external support assumptions.

The pull of ENS is implemented by lowering the penalty cost for ENS only in the zone under consideration. To determine the capacity need for each bidding zone in the Penta region, each zone is analyzed once as the zone that pulls ENS from all others.

The cost for ENS is changed to

$$c^{ENS}_{without\ analyzed\ zone} \gg c^{ENS}_{analyzed\ zone}$$

Decreasing c^{ENS}_{z} shifts ENS to the analyzed zone, assuming no cooperation with neighboring zones.

We expect this case to lead to overcapacity, as all countries prepare simultaneously for the potential issues in the neighboring countries as well.

Cooperation Case: Isolation

Besides the cooperation cases, we run the model in a setup where all countries are fully isolated. This case of isolation serves as an extreme example illustrating the importance of exchanges. In the Isolation case it is assumed that no exchange is possible, neither of ENS nor of regular capacities. The transmission capacity is zero for all zones.

$$F_{ij,ty} = 0$$

The resulting capacity needs are not explicitly determined or put back into the modelling loop. Rather, the figures provided by this analysis aim to illustrate the extent to which the 2040 under investigation scenarios rely on cross-border trade and exchange.

Capacity Need Determination

The resource adequacy modelling approach aims to determine the peak hourly ENS for each bidding zone to define the additional capacity required to achieve a level of resource adequacy without significant amounts of ENS for each Penta country and each cooperation case. The assessment focuses on identifying the maximum hourly ENS per bidding zone across all Monte Carlo years and cooperation cases.

For each scenario, six Monte Carlo simulations, one per Penta country, are conducted for the cooperation cases Import Dependency approach and Autarky Plus approach. In each simulation, one country acts as the reference zone in which ENS is either minimized or maximized, consistent with the variants described above. The capacity need for each country is derived from the simulation in which that country is the reference zone. By contrast, the Coordination and Isolation cases require only a single Monte Carlo simulation.

$$CapNeed^{coop}(z) = \max_{y \in Y} \max_{t \in T} ENS_{zty}^{coop}$$

$$CapNeed^{No-Regret}(analysed\ zone) = \max_{y \in Y} \max_{t \in T} ENS_{ty}^{No-Regret}(analyzed\ zone)$$

$$CapNeed^{No-Risk}(analysed\ zone) = \max_{y \in Y} \max_{t \in T} ENS_{ty}^{No-Risk}(analyzed\ zone)$$

$$CapNeed^{Iso}(z) = \max_{y \in Y} \max_{t \in T} ENS_{zty}^{Iso}$$

3.5 Step 4: Updated resource adequacy assessment to check resource adequacy after capacity reintroduction for each cooperation scenario

By comparing the results of these cases, the analysis captures a range of capacity needs between optimistic and conservative cooperation assumptions. This step serves to verify whether the additional capacities identified in Step 3 are sufficient to restore the desired level of resource adequacy across the Penta region. For each cooperation case, Coordination, Import Dependency approach, Autarky Plus approach, a new resource adequacy assessment is conducted using the updated capacity configurations. The analysis determines the remaining LoLE and EENS for each bidding zone as well as for the Penta region considered as a whole.

By comparing these outcomes across the different cooperation cases, the approach provides insights into how varying assumptions on cross-border support and cooperation influence overall system adequacy. This step closes the modelling loop: After defining, stressing, and adjusting the system, the updated adequacy assessment quantifies the effectiveness of coordinated capacity expansion in improving resource adequacy within the Penta region.

It is important to note that the key outcome of this step is the estimated capacity addition required under each cooperation assumption, not the confirmation that LoLE will effectively be 0 h/a after expansion. The added capacities are subject to forced outage rates and maintenance schedules in the model. Therefore, a residual risk of scarcity may remain even after the calculated capacity additions.

3.6 Summary of all Model Runs

To conclude this section, a graphical summary, provided in Figure 3.3, illustrates the structure and dependencies of the various scenarios, cooperation cases, and corresponding model runs considered in this analysis.

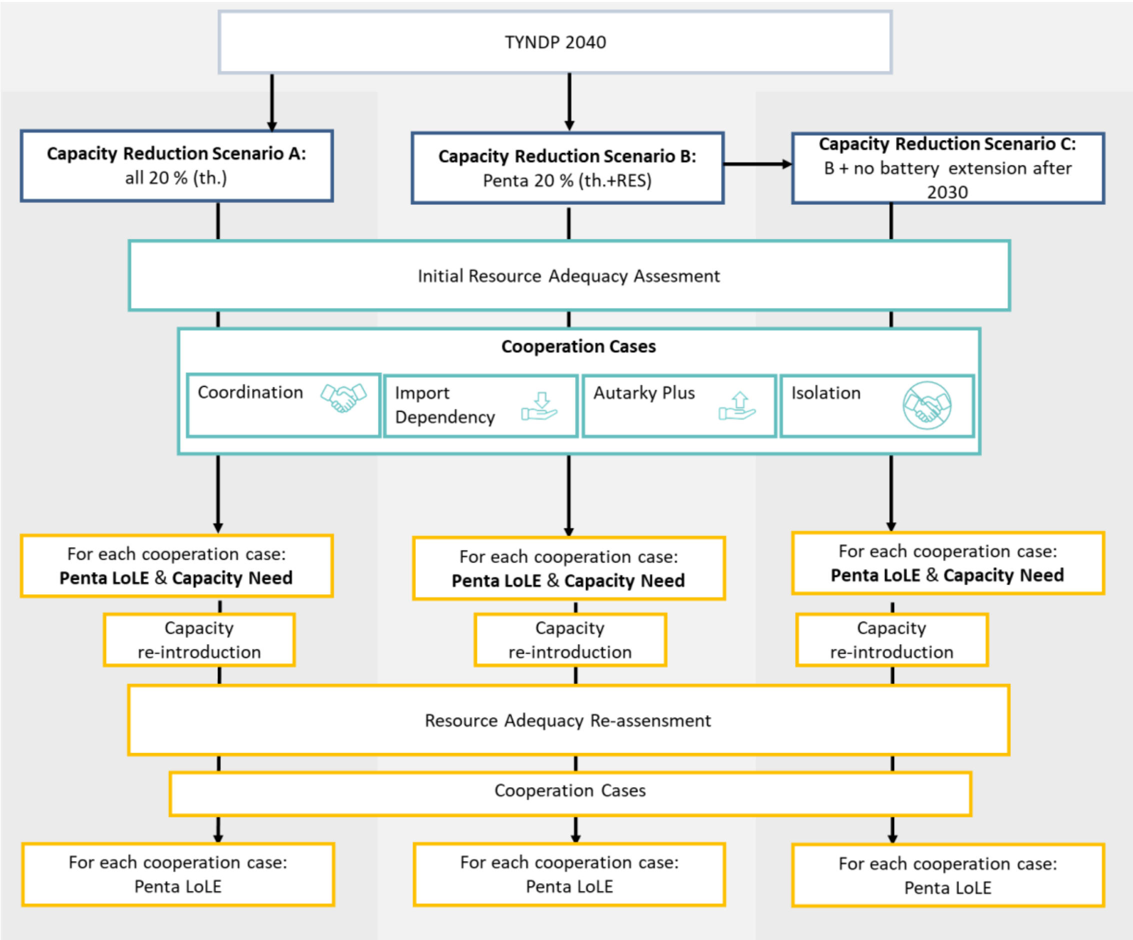

Figure 3.3 Overview of Model Runs

3.7 Methodology to define Crisis Scenarios

In addition to assessing the value of coordinated capacity planning under normal system conditions, this study also aims to show how the results change under stressed system conditions. The crisis analysis addresses two questions:

- whether capacity re-introduction can be designed to improve the Penta LoLE during a crisis, and
- whether coordination-based sizing better safeguards the Penta region when conditions deteriorate.

A crisis can be represented in different ways, for example, by selecting an adverse weather year to focus on extreme and rare weather conditions, increasing residual load to simulate a demand or generation shock, or restricting interconnection to investigate impact of reduced availably of interconnection infrastructure. In this study, the crisis is modelled as a reduction of external (non-Penta) exchange capacities. This focuses the stress test on limited external support while keeping internal exchanges within the Penta region unchanged. To keep the statements as general as possible, the crisis scenarios have been chosen so that all countries in the Penta region are equally affected, and no individual states are disproportionately impacted by the crisis.

Because the crisis assumption is imposed deterministically and its occurrence probability is set to 100% for the respective analyses, the expected-value logic of the ERAA methodology is no longer met. The resulting LoLE and ENS indicators are therefore conditional values. Thus, they cannot be compared directly with the unconditional expected values derived from a standard ERAA assessment.

Definition of Crisis Scenarios

The crisis scenarios are implemented as exogenous constraints on cross-border exchange capacities between the area under consideration and zones outside the Penta region. The crisis does not modify internal exchange capacities between the Penta’s bidding zones. Instead, it reduces the ability of the Penta region to rely on imports from, or export surpluses to, non-Penta zones. This represents a situation in which the wider system is simultaneously strained, or external transmission availability is reduced, thereby limiting support from neighboring areas.

Figure 3.4 illustrates the implementation of the crisis scenarios as a reduction of external (non-Penta) exchange capacities, while internal exchanges within the Penta region remain unchanged.

Two crisis levels are considered:

- **Crisis 30%**: External (non-Penta) exchange capacities are reduced to 70% of their initial TYNDP-based values.
- **Crisis 50%**: External (non-Penta) exchange capacities are reduced to 50% of their initial TYNDP-based values.

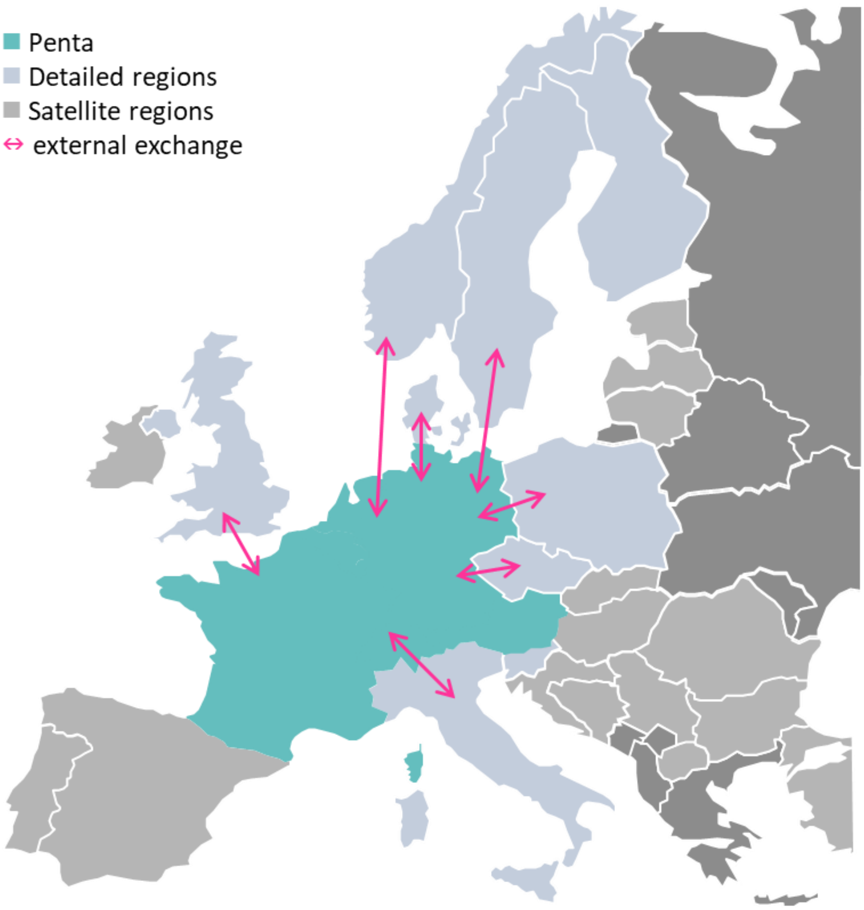

Figure 3.4 *The crisis scenarios affect the exchange capacities to the simulated non-Penta countries.*

Implementation in the modelling workflow

The crisis runs follow the same stepwise procedure as the core methodology, with the crisis constraint added as an additional modelling layer. For each scenario without crisis and each cooperation case defined in the preceding sections, the scenario is recalculated under the respective crisis setting. Resource adequacy is then assessed, and capacity needs are derived from the resulting deficit patterns, consistent with the approach applied throughout the report.

In a subsequent step, the derived capacity needs are reintroduced into the model to reassess adequacy outcomes under crisis conditions, with a focus on the Penta LoLE. This serves as a consistency check of whether the deficit-based sizing is sufficient to restore resource adequacy in the stressed system. Finally, the same capacity needs are also evaluated in the corresponding scenarios without crisis to assess whether crisis-based sizing remains sufficient under normal conditions.

4 Results

This section provides the results of our analyzed effects of coordinated measures to maintain resource adequacy. The following section will focus on resource adequacy in all Penta countries under various conditions and compare them for coordinated and uncoordinated approaches of the study's methodology outlined in section 3.

4.1 Resource Adequacy Figures in the Initial Scenario before Capacity Reduction

Our analysis is based on an investment model outcome, which ensures adequacy by design (see Chapter 3). This starting point for the capacity-needs assessment reflects the TYNDP 2024 National Trends+ scenario. In this configuration, installed non-RES capacity after maintenance amounts to approximately 730 GW across Europe, of which around 440 GW is located within the Penta region. The scenario assumptions lead to efficient investment decisions and therefore ensure a high level of resource adequacy.

Accordingly, an initial resource adequacy assessment carried out for verification shows no LoLE or EENS in the Penta region and almost zero values in all other countries, except for a marginal LoLE of 0.01 h/a in Poland. This outcome is consistent with expectations, as the investment model is designed to maintain adequacy by construction.

4.2 Results after Capacity Reduction

To identify a baseline where we can reach observable adequacy effects by capacity expansion, be it coordinated or non-coordinated, generation capacities are reduced based on the scenarios defined in 3.3.

All scenarios that are subsequently analyzed derive their capacity needs using the cooperation cases introduced in Chapter 3.1:

- Coordination Case ("Coord")
- Import Dependency approach ("Import Dep")
- Autarky Plus approach ("Autarky+")
- Isolation

Figure 4.1 shows the Penta LoLE for different cooperation cases across the three different scenarios A, B, and C. Across all scenarios, the capacity reduction leads to a noticeable Penta LoLE, making the scenarios suitable for further investigation in this study.

Across all scenarios, the LoLE values in the Coordination Case are consistently lower than in the Import Dependency approach. This is because, in the Import Dependency approach, each country assumes support from all other Penta countries. As a result, ENS can be shifted across zones, which may increase the number of hours in which at least one zone experiences ENS compared with the Coordination Case, where ENS is not shifted between zones.

The Penta LoLE counts those hours with loss of load in at least one country in the Penta region. Therefore, a single hour with ENS in multiple Penta countries is counted as one loss-of-load hour for the region. This definition ensures that the indicator reflects system-wide scarcity rather than the sum of national shortages.

In the Autarky Plus approach, the LoLE differs significantly across scenarios A, B, and C. In scenario A, the effect on LoLE is pronounced, with the lowest value of 3.7 h/a in the Coordination Case and the highest value of 6.3 h/a in the Autarky Plus approach. When only Penta capacities are reduced (scenario B), differences between the Coordination (3.8 h/a), Import Dependency approach (4.5 h/a), and Autarky Plus approach (4.5 h/a) cases are relatively small. This indicates that LoLE depends strongly on how and where capacity is removed, as well as on the underlying base scenario.

Notably, the additional reduction of 85 GW of battery capacity relative to scenario B approximately doubles the LoLE. The ordering remains consistent, with the lowest LoLE in the Coordination Case and the highest in the Autarky Plus approach. This highlights that, while the underlying effects and interdependencies are robust, the numerical values are sensitive to modelling assumptions.

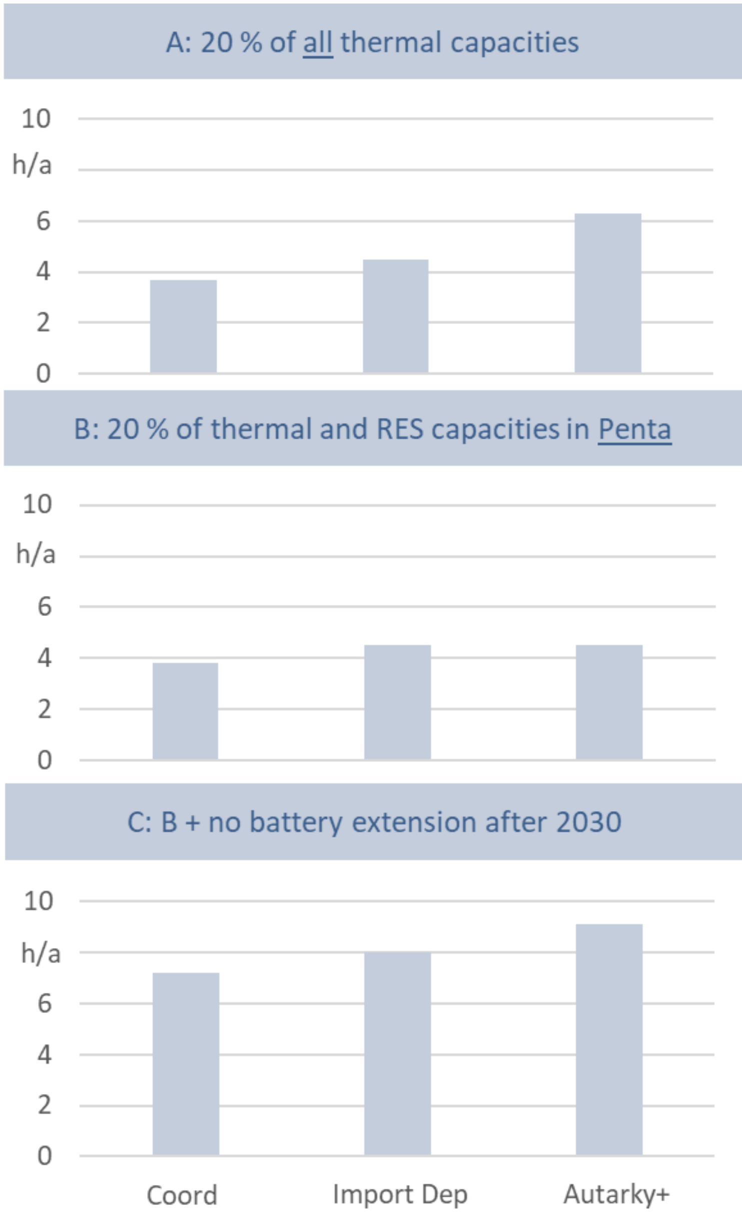

Figure 4.1 Penta Loss of Load Expectation for the different cooperation cases. Each graph shows a different scenario.

Isolation Case

The Isolation case should be considered separately, as it provides specific insights. In this case, no exchanges between zones are allowed, resulting in much higher LoLE values across all scenarios (LoLE > 2,000 h/a). This highlights the importance of interconnection and coordinated operation, particularly in a highly meshed grid such as the one envisaged for 2040. A LoLE at this level would correspond to several months per year with loss-of-load hours, drastically demonstrating how interconnection serves resource adequacy even without further improvements in terms of cooperation in this TYNDP future scenario.

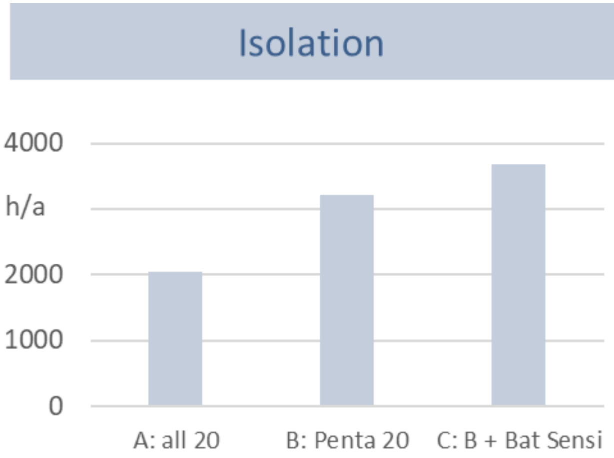

Figure 4.2 Penta LoLE across all three scenarios in Isolation case.

4.3 Identification of Capacity Needs for the Different Cooperation Cases

After evaluating the LoLE results, the next step is to determine the highest hourly ENS across all six weather years and cooperation cases to derive the corresponding capacity needs per bidding zone.

Figure 4.3 shows the capacity needs for scenarios A, B, and C. The different cooperation cases are displayed as stacked bars, with the Penta countries shown separately. Country-level values should be interpreted as illustrative, as they can vary between scenarios. For example, consider the emerging capacity need in Germany after the reduction of battery capacity. These differences mainly reflect interconnector capacities and local generation mixes rather than national adequacy targets.

In scenario A, the additional capacity requirement is smallest in the Import Dependency approach, at about 17 GW, around 10 GW lower than in the Coordination Case. The Coordination Case requires 27 GW of additional capacity, while the Autarky Plus approach yields around 37 GW, implying roughly 10 GW of overcapacity relative to Coordination. The Isolation case again illustrates how much additional capacity would be required if there were no interconnection within the Penta region. Under ERAA 2024 assumptions, a difference of 10 GW in capacity could translate into EUR 5 to 10 billion in additional capital expenditure. This highlights the potential economic benefits of coordinated capacity planning, where joint adequacy targets can significantly reduce total system costs.

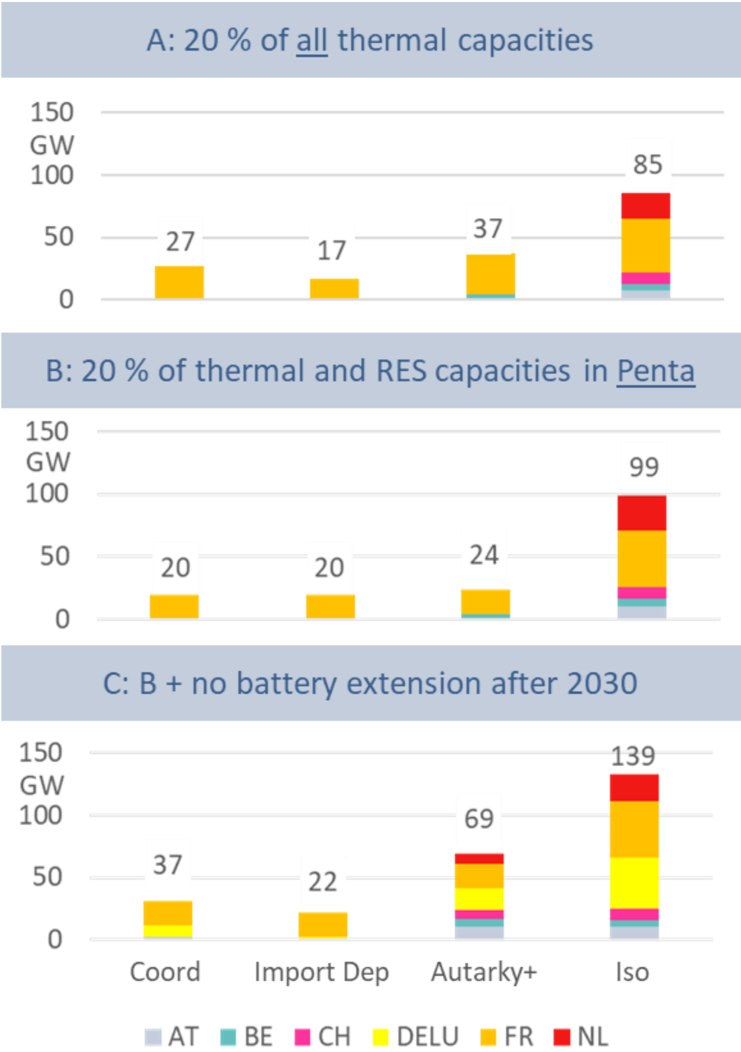

Figure 4.3: *Capacity Need per cooperation case per bidding zone in the Penta region. The countries' specifics should be seen as examples but do not allow for conclusion on individual countries.*

Due to the lower capacity reduction in scenario B, the relative differences between the Coordination, Import Dependency, and Autarky Plus cases are smaller. However, the Isolation case again shows higher capacity needs due to lower overall available generation within the Penta region.

In scenario C, reducing available battery capacity in Germany and Luxembourg to 2030 levels approximately doubles the LoLE and creates additional capacity needs in both countries across all cooperation cases. In the Autarky Plus approach, additional capacity is required in all zones except France. Based on ERAA assumptions on investment costs, 32 GW of additional capacity could imply EUR 17 to 32 billion in CAPEX, depending on the technology added.

Finally, the effect of re-adding the calculated capacity needs on resource adequacy is assessed. For this purpose, the calculated capacities are reintroduced as gas-fired power plants in each zone, and a subsequent resource adequacy analysis is performed. This serves as a validation step to test whether the identified capacity additions restore the desired adequacy level, which is close to zero for all cases (see Figure A.1 Loss of Load Expectation after re-adding the capacity needs.Figure A.1).

4.4 Interpretation of Results

The findings show a systematic difference between the analyzed cooperation cases in terms of both required capacity needs and resulting resource adequacy in the Penta region after reintroduction of capacity needs. Although the capacity of the Penta LoLE will be significantly reduced for all cooperation cases after the reintroduction of capacities, it could be expected that the Coordination Case and the Import Dependency approach will lead to a significantly lower Penta LoLE.

Across all analyzed scenarios, coordinated capacity expansion emerges as the most balanced solution. It consistently achieves a very low Penta LoLE while avoiding the excessive capacity needs observed in the more conservative Autarky Plus approach, which leads to significantly higher capacity needs without providing additional improvements in regional resource adequacy. The Import Dependency approach, on the other hand, results in systematically lower capacity additions but fails to fully restore the adequacy target in several scenarios, leaving residual Penta LoLE. These results show that the Import Dependency approach, which is optimistic from an individual country perspective because it implicitly assumes that neighboring countries will always provide support, could lead to adequacy risks while overly conservative assumptions would primarily increase system costs without resulting in higher resource adequacy.

It is important to note that the differences between the cooperation cases are not driven by changes in the total amount of energy not supplied (ENS), but by its temporal and geographical distribution. Depending on the way of cooperation, ENS can be concentrated in a single hour and country in one case, whereas in another case it may be distributed across several hours and multiple countries. Although the adequacy model minimizes total ENS, the Penta LoLE indicator counts the number of hours in which ENS occurs anywhere in the Penta region. As a result, different distributions of the same total ENS can lead to different LoLE outcomes.

The isolation scenario illustrates the extreme consequences of no cross-border exchange, where LoLE rises to a level that would be incompatible with acceptable resource adequacy standards. Coordination enables the system to make more effective use of the interconnected structure of the Penta region and reduce the need for redundant national capacity expansions. This empirical finding supports the view discussed in Chapter 2 that interconnection is a structural element of adequacy provision and not a secondary option.

While the absolute gains from coordination might depend on the specific scenario and the numerical results should not be interpreted as fixed capacity targets, the underlying structural effects and trends are robust across all scenarios. In particular, the results consistently indicate the advantages of cooperation. In scenarios with high scarcity, the differences between the cooperation cases become more pronounced. This suggests that coordination becomes increasingly important as system margins decline. Overall, the results of this study are consistent with the literature presented in Chapter 2.

4.5 Investigation of the Crisis Scenarios

This chapter presents the results of the crisis runs based on the methodology described in section 3.7. Two crisis levels are considered implemented as reductions of external (non-Penta) exchange capacities while keeping internal exchange within the Penta unchanged: Crisis 30% reduces external exchange capacities to 70% of their initial values, and Crisis 50% reduces them to 50%. The following sections report the adequacy impact after the initial capacity reduction and then discuss capacity needs and adequacy outcomes after capacity re-introduction.

Results after Capacity Reduction

Figure 4.4 compares the Penta LoLE under the two crisis conditions investigated with the corresponding non-crisis scenario after the initial capacity reduction. Across all scenarios, restricting external exchange options increases the Penta LoLE relative to the non-crisis case, with the magnitude depending on the underlying reduction setting. In scenarios A and B, the crisis effect is broadly similar across cooperation cases, indicating that the loss of external support affects the region in a comparatively uniform way. Increasing the severity from Crisis 30% to Crisis 50% amplifies the adequacy impact, with Penta LoLE rising by roughly a factor of 1.5 in both scenarios.

Scenario C shows an even higher crisis sensitivity. Under the assumptions of scenario C, Penta LoLE responds much more strongly to crisis severity: Moving from Crisis 30% to Crisis 50% approximately doubles the Penta LoLE. This emphasizes, consistent with the non-crisis results, the dependence of LoLE on the initial system conditions, now under stressed assumptions.

Differences between cooperation cases (Coordination, Import Dependency approach, Autarky Plus approach) also remain scenario dependent. In scenario B, the difference between Coordination, Import Dependency approach, and Autarky Plus approach is comparatively small, whereas larger differences emerge in scenario C. This pattern is consistent with a non-linear relationship between LoLE and ENS: Different ENS allocations can shift deficits between fewer hours with larger shortfalls and more hours with smaller shortfalls, resulting in noticeable LoLE differences.

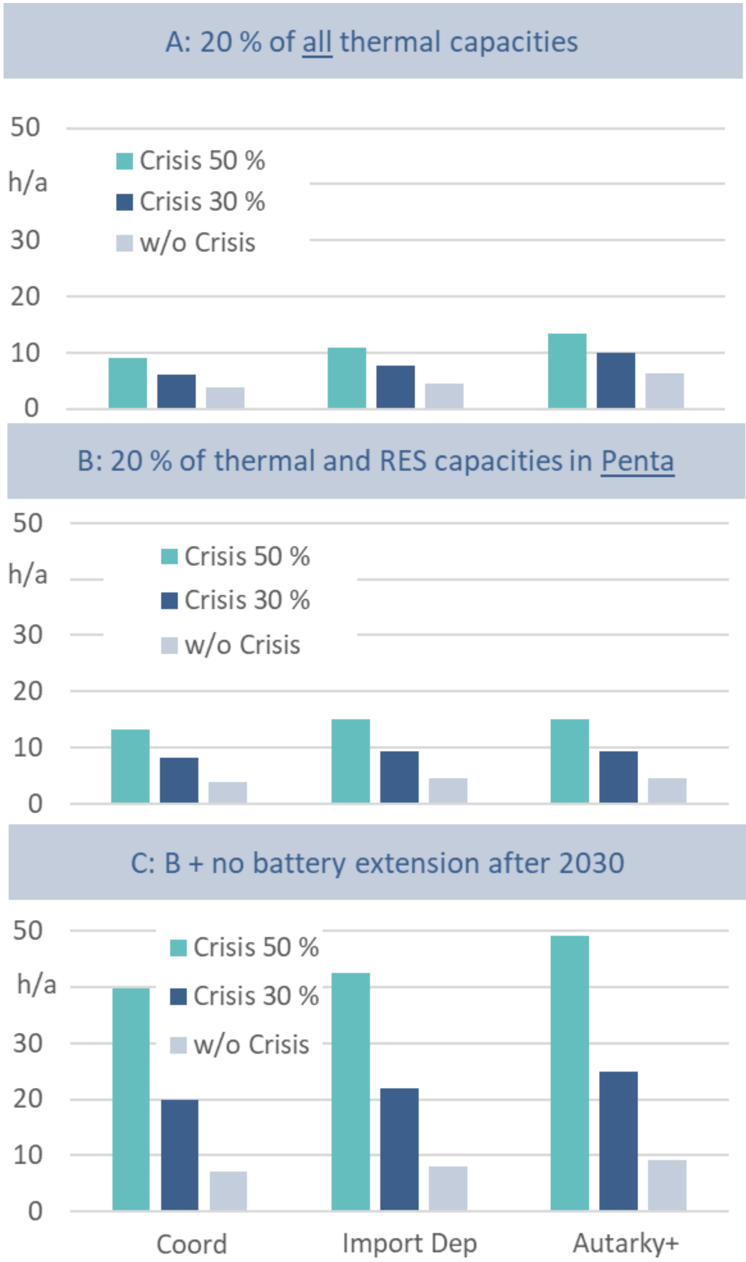

Figure 4.4 *Penta LoLE after initial removal of capacities, for the different scenarios (A-C) and different cooperation cases. All scenarios considered without crisis, crisis 30% and crisis 50%.*

Identification of Capacity Needs

Figure 4.5 shows the capacity need in the Penta region for the scenarios without crisis and under Crisis 30% and Crisis 50%, differentiated by cooperation case. Overall, restricting external exchange options increases the required additional capacity, but the magnitude and the pattern across cooperation cases differ markedly by scenario.

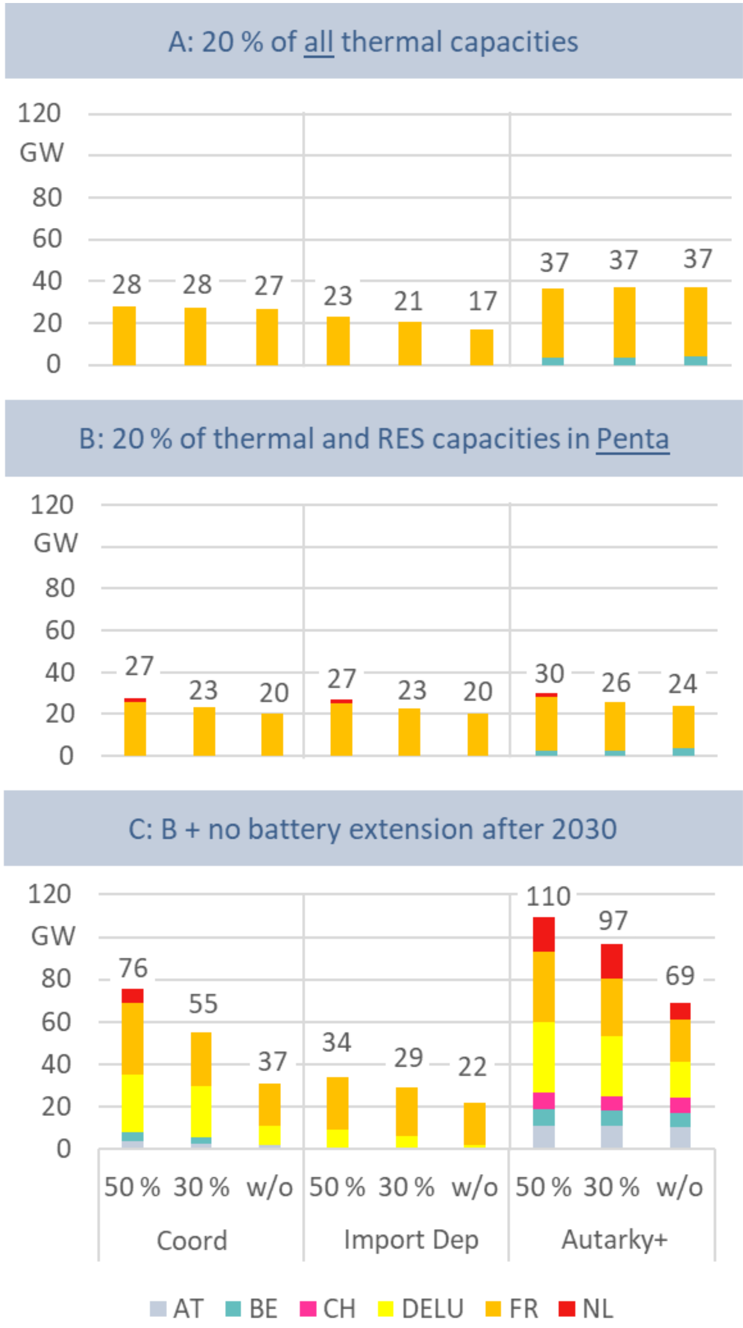

Figure 4.5 Capacity Needs under Crisis 50%, Crisis 30% and without crisis.

In scenario A, the crisis scenarios have only a limited effect on regional capacity needs. The Solidarity Coordination Case result remains almost unchanged compared with the non-crisis case (27 GW without crisis versus 28 GW under both Crisis 30% and Crisis 50%). The Autarky Plus approach is unaffected and remains at 37 GW across all conditions. Only the Import Dependency approach responds more visibly: The capacity need increases from 17 GW without crisis to 21 GW under Crisis 30% and 23 GW under Crisis 50%. Overall, the crisis mainly raises capacity needs in the Import Dependency approach, while leaving the Coordination and Autarky approach results largely unchanged since the interdependence in Penta is increasing.

In scenario B, the crisis leads to a more systematic upward shift across cooperation cases. For Coordination and Import Dependency approach capacity needs increase from 20 GW without crisis to 23 GW under Crisis 30% and 27 GW under Crisis 50%. In the Autarky Plus approach, capacity needs rise from 24 GW without crisis to 26 GW under Crisis 30% and 30 GW under Crisis 50%.

The strongest crisis impact is observed in scenario C. Here, capacity needs increase sharply with crisis severity, and the absolute differences between cooperation cases become large. In the Coordination Case, capacity needs rise from 37 GW without crisis to 55 GW under Crisis 30% and 76 GW under Crisis 50%. The Import Dependency approach increases from 22 GW to 29 GW (Crisis 30%) and 34 GW (Crisis 50%). The Autarky Plus approach increases from 69 GW to 97 GW (Crisis 30%) and 110 GW (Crisis 50%).

Across all scenarios, with and without crisis, the derived capacity needs are much smaller than the capacities removed in the Penta region. Note that in scenario A, an additional 59.1 GW is removed in non-Penta countries. As a result, import possibilities are already reduced in the non-crisis case due to lower available capacity outside the Penta region. Therefore, the additional effect of reduced exchange capacity in the crisis scenarios is limited.

In summary, the crisis scenarios show that reducing external (non-Penta) exchange capacities worsens resource adequacy in all scenarios, but the magnitude depends strongly on the underlying assumptions. This underlines the importance of interconnection and cooperation in general. Although the Penta LoLE increases in all scenarios as crisis severity rises, the fundamental benefits of coordination remain.

Coordinated capacity expansion can achieve the same or even a higher level of resource adequacy with less overall capacity than uncoordinated approaches, even under crisis conditions. The effects are non-linear: A crisis tends to affect a region more strongly when coordination is weaker, both in terms of capacity utilization and capacity expansion. The results also indicate that a system dimensioned conservatively for crisis conditions through coordination performs robustly in non-crisis situations. Nevertheless, deciding on the appropriate level of “crisis preparedness” and selecting the underlying scenario assumptions is not straightforward.

5 Summary and Conclusion

Across all analyzed scenarios, the results reveal a consistent and robust ordering of the cooperation cases. The Import Dependency approach, which assumes full external support, yields the lowest additional capacity requirements but leaves residual adequacy risks in several scenarios. In contrast, the Autarky Plus approach, under which each country must also cover potential external shortfalls, results in the highest capacity requirements without delivering proportionally higher regional resource adequacy. The Coordination Case lies systematically between these extremes and achieves adequacy levels close to the target with significantly lower overall capacity requirements than conservative national approaches.

The crisis scenarios implemented as a 30% and 50% reduction in external (non-Penta) exchange capacities, reinforce these findings. Limiting external support through reductions in cross-border exchange capacities increases adequacy risks across all scenarios, particularly in low-flexibility settings. At the same time, coordinated capacity sizing proves robust under such stress conditions, maintaining low levels of loss of load expectation (LoLE) in both crisis and non-crisis situations. By contrast, capacity sizing based on optimistic assumptions about external support remains more vulnerable under stressed conditions. This highlights the importance of aligning adequacy planning with realistic assumptions on cross-border availability, especially in the context of risk preparedness.

The analysis also confirms that higher capacity requirements do not necessarily translate into improved regional reliability for all scenarios. Differences in adequacy outcomes across cooperation cases are primarily driven by the temporal and spatial distribution of shortages rather than their overall magnitude. This underlines the structural nature of the observed effects and further supports the case for coordinated approaches.

Overall, the results confirm that coordinated capacity expansion in interconnected systems can achieve high levels of resource adequacy with lower total capacity requirements than uncoordinated strategies. While overly conservative approaches risk creating inefficiencies and unnecessary costs, overly optimistic strategies may undermine adequacy. In line with the findings of the previous section, this points to the importance of strengthening regional coordination frameworks, including their integration into adequacy assessments and risk preparedness planning. Enhancing the consistency between these frameworks and existing instruments, such as capacity remuneration mechanisms and ERAA processes, could help to better capture the benefits of coordinated planning in practice.

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A Appendix

Penta LoLE after capacity re-introduction

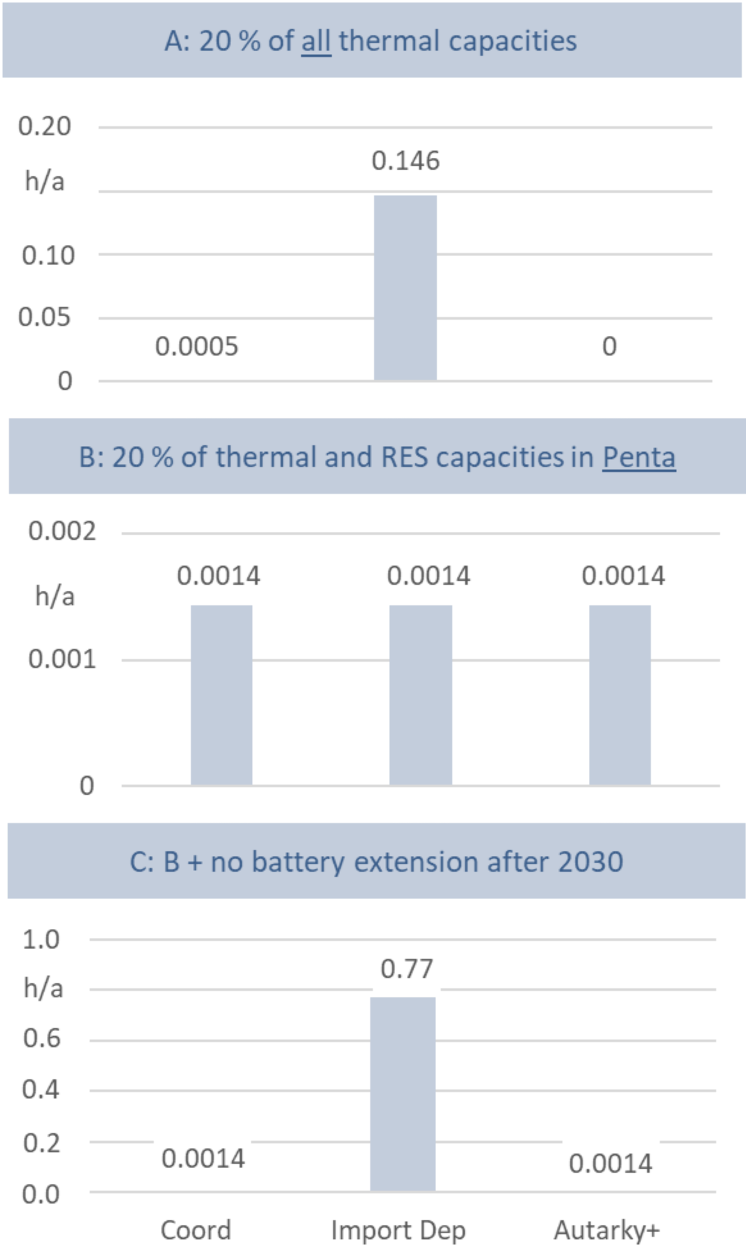

Figure A.1 Loss of Load Expectation after re-adding the capacity needs.

Figure A.1 shows the updated LoLE values by scenario, with the bars representing the different cooperation cases. In all scenarios, LoLE is reduced substantially reaching the resource adequacy close to the TYNDP basis before capacity reduction with significantly less capacities installed. In scenario A (20% reduction of all thermal capacities), adding 17 GW reduces LoLE in the Import Dependency approach from 3.8 h/a to 0.15 h/a. This remains higher than in the Coordination Case, where adding 27 GW results in a LoLE below 0.01 h/a. The additional capacity in the Coordination Case is therefore sufficient and remains close to the level required to restore adequacy.

By contrast, the Autarky Plus approach, where 37 GW is added, also achieves a LoLE below 0.01 h/a, indicating that around 10 GW is added in excess relative to the Coordination Case. In scenario B, all cooperation cases achieve a LoLE below 0.01 h/a, and the differences in capacity additions between the Coordination, Import Dependency and Autarky Plus cases are negligible. The sensitivity case shows a similar pattern to scenario A, but at a larger scale.

Crisis scenario

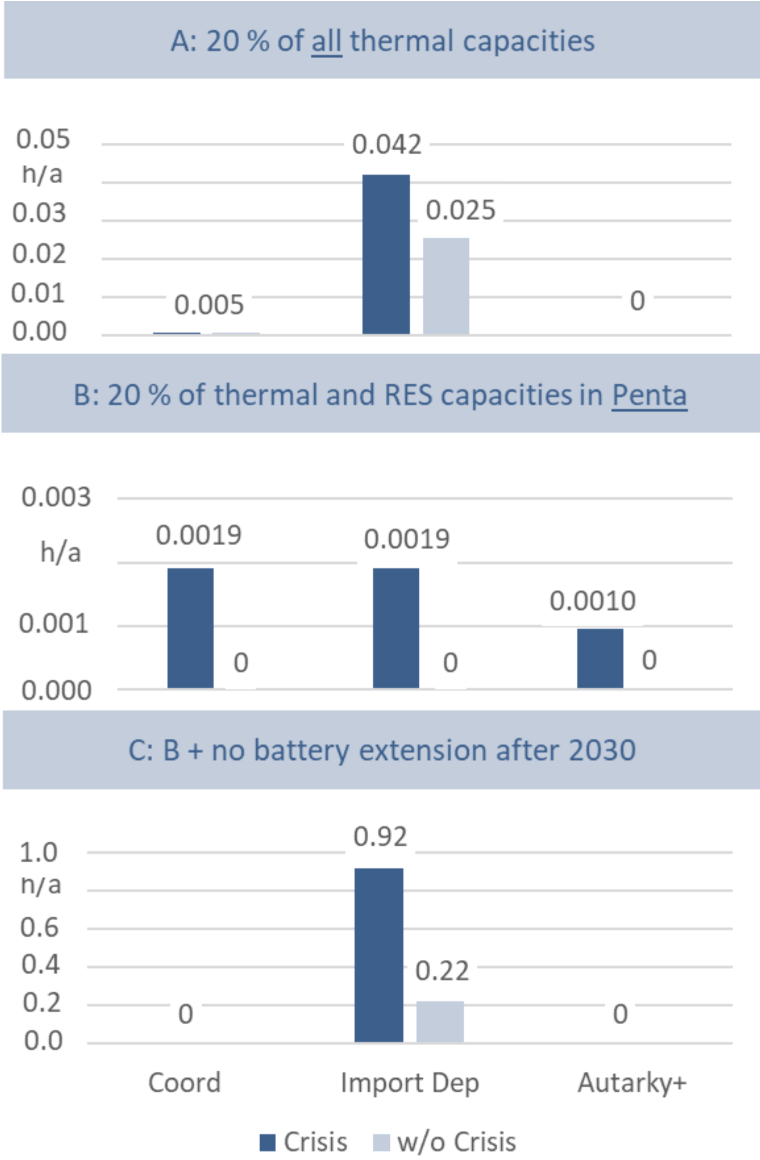

Figure A.2 *Penta LoLE after re-introduction of the capacity need from the Crisis 30% scenario under two sets of conditions: Crisis 30% conditions (blue) and no-crisis conditions*

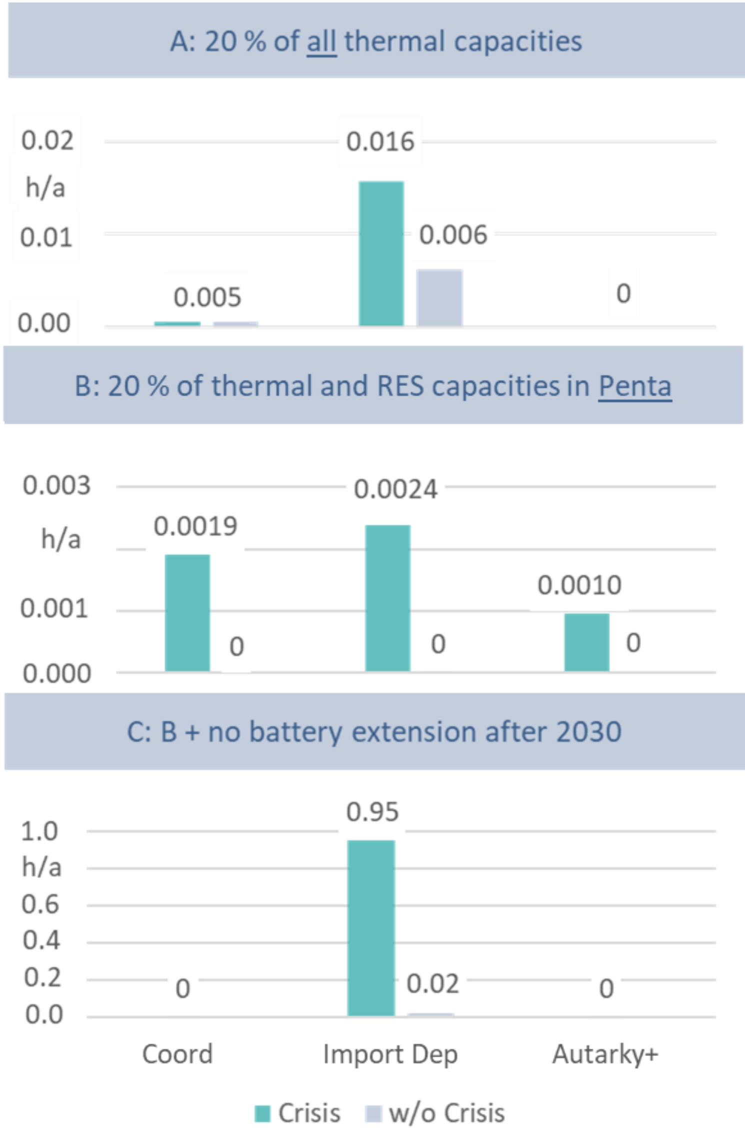

Figure A.3 *Penta LoLE after re-introduction of the capacity need from the Crisis 50% scenario under two sets of conditions: Crisis 50% conditions (blue) and no-crisis conditions (grey).*

Figure A.2 and Figure A.3 show the Penta LoLE after reintroducing the derived capacity needs under Crisis 30% and Crisis 50%, respectively, and compare the results with the corresponding non-crisis scenario. Overall, reintroduction reduces the Penta LoLE substantially across all scenarios.

In scenario A, reintroduction reduces the Penta LoLE to very low levels close to zero in the Coordination Case and zero in the Autarky Plus approach under both crisis severities. By contrast, the Import Dependency approach remains above the <0.01 h/a range after reintroduction. Exactly zero will not be achieved in all cases, as outages are also assumed for the gas-fired power stations that have been built.

In scenario B, reintroduction reduces the Penta LoLE close to zero across all cooperation cases under both Crisis 30% (Figure A.3) and Crisis 50% (Figure A.3). At this level, differences between Coordination, Import Dependency and Autarky Plus approaches are negligible. In the corresponding non-crisis scenario, the Penta LoLE is eliminated or remains negligible after reintroduction.

Scenario C follows a similar pattern to scenario A, but with higher LoLE after reintroduction, on the order of 1 h/a in the Import Dependency approach.

Comparing crisis-based sizing with the non-crisis scenario indicates that dimensioning capacity under crisis conditions improves robustness outside of crises as well. Even with the lowest dimensioning (Import Dependency), LoLE is reduced to a very low or negligible level in the non-crisis scenario. By contrast, dimensioning based only on the non-crisis scenario would leave a substantially higher residual LoLE.