Investment Coupled Whole-System Planning

Milestone Report 1: 28/11/2024

Report for C4NET

Project Consortium

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Acknowledgement

- This research is part of a program of fourteen projects, which have variously been funded and supported under C4NET's Enhanced System Planning collaborative research project. While conducted independently, the authors acknowledge the funding and in-kind support of C4NET, its members and supporters, and its ESP project partners.

Executive Summary

The widespread deployment of small-scale assets (e.g., electric vehicles, distributed storage, distributed generation) is increasing the controllability within distribution networks along with the ability of customers to take control over their own energy demand, opening new value streams for them. These new interactions and the transition from passive to active distribution networks are spreading decision-making across multiple levels, increasing the complexity of power system planning. A clear example of this trend is the Australian power system, where the Australian Energy Market Operator (AEMO) expects that if Consumer Energy Resources (CER) are effectively orchestrated, up to $4.1 billion in large-scale investments could be avoided.

However, most system planners neglect decision-making over Distributed Energy Resources (DER) and/or CER, usually considering them as an inherent feature of analysed scenarios, as well as the limitations and investments needed within distribution networks to support such technologies. In turn, this could lead to inaccurate assessments on the value provided by DER, as well as in inefficient and conflicting investments across the system, and although joint planning arrangements between transmission and distribution systems are encouraged in the Australia under the National Electricity Rules, such a process comes after the ISP optimally decides the transmission augmentation needs.

Hence, *decision-making over transmission and distribution system is an independent process* and thus, to make better and more efficient investment decisions across the whole system and truly capture the value of CER, the coordination within planning must be improved. In this sense, a literature review was conducted in this report to analyse the proposed methodologies to coordinate integrated planning frameworks between transmission and distribution systems.

Centralised	Multi-level	Iterative	Decoupled
Centralised objective	Multi-objective	Individual objectives	Individual objectives
Full knowledge of networks across levels	KKT conditions and strong duality theorem	TSO-DSO communicate through variables	Decentralised decision - making
Difficult real-world applications	Full knowledge of networks across levels	Improves solving efficiency	TSO-DSO communicate decisions

Figure 1-1: Integrated planning methodologies

As depicted in Figure 1-1, four main methodologies were identified. A **centralised approach** hinges on one entity having full knowledge over the whole system (e.g., resources, constraints, etc.) and thus, has the potential to find the best possible solution. A **duality-based approach** considers a multi-objective problem, leveraging Karush-Kuhn-Taker (KKT)[1] conditions and strong-duality theorem to reformulate it into a single-level one but it does not remove the need for having full knowledge of the

[1] Corresponds to a set of mathematical conditions for a solution to be optimal in a constrained optimisation problem. These conditions generalise the Lagrange method to handle inequality constraints.

system. However, both approaches are the most difficult to apply in a real-world context due to the huge amount of data that needs to be exchanged, resulting in high computational burden.

Such aspect is removed with an **iterative approach** by communicating transmission and distribution planning problems through a reduced set of variables at the interface, such as power, cost, voltages, etc. However, it considers a simultaneous solving methodology (both problems are solved at the same time) and thus, such approach would require multiple instances for coordination and data exchange which may hinder real-world applications. Finally, a **distributed approach** is an emerging methodology that decouples integrated frameworks in a sequential decision-making process, allowing for coordinating system operators with a reduced set of variables or even, surrogate representations (e.g., distribution planning model within transmission planning problem).

In this context, distributed approaches have the potential to provide efficient coordination and scalable formulations for integrated planning problems without compromising the quality of solutions and thus, appear as the most suitable methodology for real-world applications.

For this reason, a distributed approach is proposed in this work package. This methodology aims at providing a ***parametric representation of the investments required (e.g., active network management, distributed storage, network reinforcements) in active distribution networks to support DER adoption***. By minimising investment and operational costs from a distribution system operator (DSO) perspective, the optimal portfolio of investments and associated costs for varying levels of CER adoption could be obtained, resulting in a parametric cost function.

In this context, such representation could be produced by any DSO with their own tools and use them to inform the power system planner (e.g., AEMO in the Australian case), enhancing the planning coordination in an efficient manner. In turn, this would help in making better investment decisions across the whole system without detailed distribution network modelling.

Glossary of Terms / Abbreviations

AEMO	Australian Energy Market Operator
ISP	Integrated System Planning
CER	Consumer Energy Resources
DER	Distributed Energy Resources
TNSP	Transmission Network Service Provider
DNSP	Distribution Network Service Provider
ADN	Active Distribution Networks
TEP	Transmission Expansion Planning
DEP	Distribution Expansion Planning
ITDEP	Integrated Transmission and Distribution Expansion Planning
EV	Electric Vehicles
DR	Demand Response

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1. Project Overview

Background

Power system planning aims to find cost-effective and reliable investments for the future development of power systems. However, this problem is increasing in complexity due to new interactions and the integration of new technologies that increase the variability of supply, flexibility requirements, and spread decision-making across multiple levels. In particular, the widespread deployment of small-scale assets is increasing the controllability within distribution networks (e.g., demand response, electric vehicles, distributed storage) and the ability of customers to take control over their own energy demand. Consequently, there is a transition from passive to active distribution networks that will decentralise and impact the planning of power systems worldwide [1].

A clear example of this trend is Australia's case. The Australian Energy Market Operator (AEMO), as depicted in Figure 1-1, is expecting that a big portion of the available assets by 2050 will be in distribution networks in the form of CER storage, rooftop and distributed solar, and demand-side participation. In addition, AEMO estimates that $4.1 billion in large-scale investments could be avoided if such resources are effectively orchestrated [2].

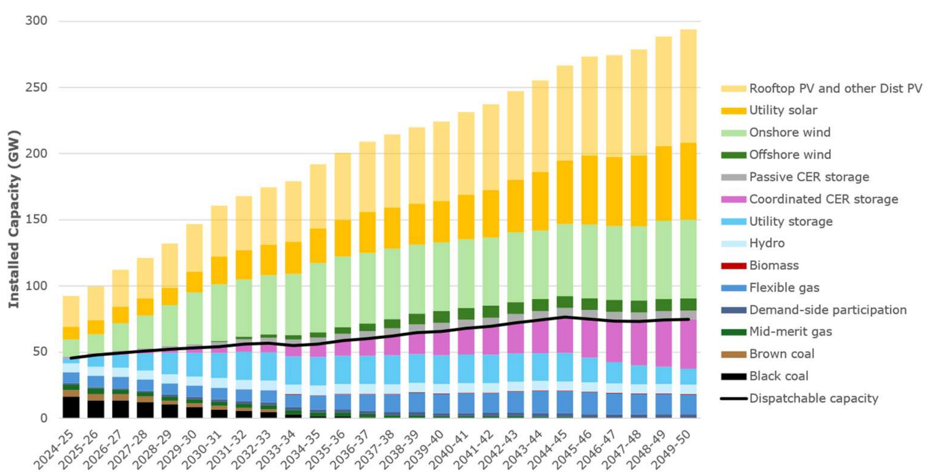

Figure 1-1: Expected Installed Capacity, ISP Step-Change Scenario [2]

In this regard, consumer energy resources (CER) and distributed energy resources (DER) have the potential to impact planning, deferring or complementing costly infrastructure investments, as assets like demand response (DR), electric vehicles (EV), distributed generation (DG), storage, and aggregated resources as virtual power plants (VPP) increase the controllability coming from the demand side, enhancing the whole-system flexibility [3], [4], [5]. Consequently, active distribution networks (ADNs) will be key to facilitating strong supply-demand linkages through proper investment decisions to support CER, and its orchestration.

Nevertheless, current power system planning practices often neglect decision-making over DER by considering them as an inherent feature of the analysed scenarios in planning processes, and the limitations and investments within distribution networks [6]. Thus, mechanisms to adequately assess and quantify the investments needed at the distribution level to unlock DER's operational flexibility are not accounted for, missing out on trade-offs between large- and small-scale investments. In turn, this may lead to inaccurate assessments on the value provided by these resources, and inefficient and conflicting investments across the system [7]. Moreover, although these challenges have been identified by power system planners across the world, particularly in the UK and Australia [8], [9], there is yet to be found an integrated planning framework within the real real-world.

In this vein, a paradigm shift is needed in planning frameworks and integrating ADNs as investment opportunities within an integrated planning process could be key to providing insights on where is more convenient to develop power systems (e.g., large- or small-scale developments). Nevertheless, the lack of coordination and standardised data exchange protocols due to differing scales and scopes between system operators, and the computational challenges of large-scale optimisation formulations, hinder an integrated planning process.

Therefore, to bridge this gap, regulators must improve the planning of transmission and distribution systems aiming at finding more robust and cost-effective solutions [10]. Thus, alignments between decision-makers, improved coordination schemes, and new planning tools and methodologies will be crucial to find more efficient development paths for the future and in turn, orchestrate an *integrated transmission and distribution expansion planning* (ITDEP) framework.

Based on this, this report seeks to outline and identify the key challenges of coordination methodologies from the literature that may have potential for practical implementation of an ITDEP in the context of the Enhanced System Planning (ESP) project from C4NET, and particularly for work package 3.13, Investment Coupled Whole-System Planning.

Aims and Objectives

WP3.13 "Investment Coupled Whole-System Planning", as part of C4NET Enhanced Systems Planning (ESP), aims to:

- Develop a methodological framework that integrates the planning of transmission and active distribution systems
- Asses large- and small-scale investment trade-offs across the whole-system in the presence of active distribution systems.

Overall, WP3.13 will provide methodological steps to represent the planning of active distribution systems within a whole-system planning framework. In this sense, any DNSP, will be able to replicate this methodology using their own tools and in turn, provide investment paths with a reduced amount of information to AEMO, facilitating the decision-making process of the whole-system. This in turn, will allow identification of the main drivers that shift the development of the Australian power system towards large- and small-scale developments.

Key Milestones

The key milestones of this work package, their timelines, and the corresponding contents are further detailed bellow.

Milestone 1: Literature Review (September 2024)

Overview of approaches for coordinating the planning of transmission and distribution systems, providing recommendations on the methodology to be adopted for Milestone 2

Milestone 2: Modelling and Planning Methodologies (November 2024)

A detailed presentation is expected, showing the methodological principles in place for this work package, that allow for efficient coordination of transmission and distribution networks within planning

Milestone 3: Assessment of trade-offs (January 2025)

A detailed presentation is expected, highlighting the potential of multiple technologies to reduce the impact of electrification by supporting the adoption of DER and its controllability, improving decision-making across the whole system

Milestone 4: Final Report (March 2025)

A final report presenting the findings of the 10-month project WP 3.13, including a summary of inputs and assumptions, as well as results from case studies.

2. Integrated Whole-System Planning

Real-world Context

Integrated planning frameworks are challenging to orchestrate mainly due to computational burden (e.g., increasing variables and constraints), the lack of coordination, and vast differences in scale and scope between transmission and distribution systems, but have the potential to truly achieve better techno-economic value. However, there are no real-world examples where such framework is in place, nevertheless there is increasing interest in improving this coordination as well as allowing DER to participate in whole-system markets.

In the USA, the Federal Energy Regulatory Commission (FERC) oversees wholesale electricity markets and investments in transmission systems, where the latter is carried out by Regional Transmission Organisations and Independent System Operators for at least three distinct long-term scenarios and no less than a 20-year planning horizon [11]. However, there is no coordination with distribution systems, as the planning of these is regulated within each state independently by Public Utility Commissions. Despite that, the FERC has arrangements in place for DER to participate in electricity markets through aggregators, who share compensation back to individual DER [12].

A similar situation can be found across Europe. The European Network of Transmission System Operators for Electricity coordinates the transmission planning across Europe through the Ten-Year Network Development Plan, working closely with TSOs to ensure that investment portfolios meet national and EU-wide goals, while DSOs are responsible for distribution planning at a local level [13]. Moreover, in terms of coordination, the Clean Energy Package identified the need for improving coordination mechanisms due to the growth of DER and extend this to planning [14].

Under this context, UK is one of the most advanced countries in Europe regarding regulatory aspects for DER adoption. Even though distribution planning is handled locally by DSOs, the Office of Gas and Electricity Markets, entity that regulates the planning of transmission networks, increased the emphasis on flexibility services and cooperation between system operators to manage DERs and demand response, identifying the need for improving the coordination within planning [15], [16].

Furthermore, in Australia, the Integrated System Planning (ISP) serves as a roadmap for the energy transition of the National Energy Market (NEM). It outlines a clear path for infrastructure investments at the transmission level to meet future energy needs. The ISP adopts an iterative and multi-module approach with interactions between modelled inputs, gas supply model, engineering assessments, capacity outlook model (e.g., generation and transmission expansion, dispatch, retirements, etc.), time-sequential model, and cost-benefit analyses to test scenarios and development plans [17].

Particularly, AEMO expects a huge uptake of CER within their projected scenarios and quantified that, if such resources are properly orchestrated, up to $4.1 billion in large-scale infrastructure could be saved. Nonetheless, the ISP focusses on transmission-level investments, neglecting the investments needed in distribution networks to support these scenarios, nor the investment and operational costs associated to DER and CER.

Such aspect creates a gap where trade-offs between large- and small-scale assets are not properly captured. Despite the encouragement of joint planning arrangements between Transmission Network Service Providers (TNSPs) and Distribution Network Service Providers (DNSP) under the National Electricity Rules in the form of Regulatory Investment Test (RIT)[2] [18], such a process comes after the ISP as shown in Figure 2-1, meaning that distribution planning is assessed independently and hence, such process may potentially lead to suboptimal investment decisions across the power system. Therefore, improving the coordination between transmission and distribution planning processes could be key to achieving more efficient and cost-effective outcomes in the context of Australia's energy transition.

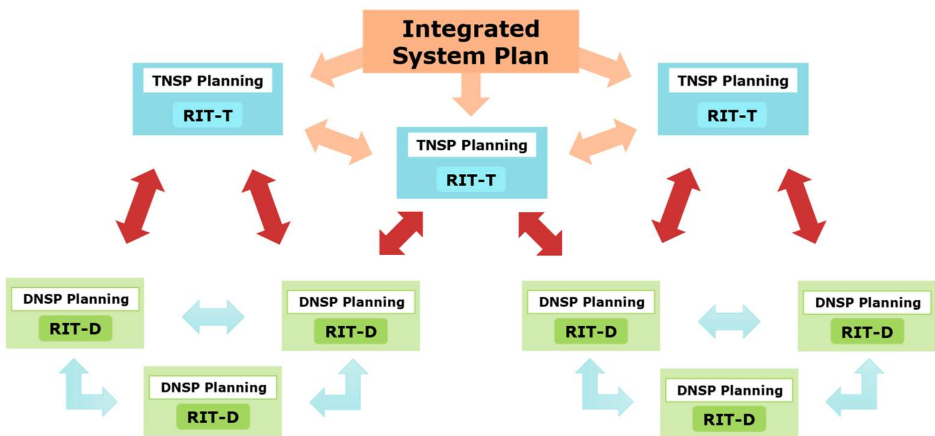

Figure 2-1: Coordination within planning of Australian power system. Red arrows indicate possible coordination between TNSP and DNSP planning

From an operation perspective, various Australian projects have aimed at enhancing the integration and market participation of DER, making significant efforts to advance this topic from a whole-system point of view. **Project EDGE** focused on aggregating DER as VPPs to provide services into the NEM, conducting live trials in Victoria's Hume region that allowed enhancing customer participation [19]. Likewise, **project Edith** offers a path for fairer pricing for customers by proposing a dynamic pricing methodology based on network charges on the actual conditions for a particular customer at a specific time and location [20], [21]. Using the same VPP aggregation strategy, **project Symphony** was designed to orchestrate approximately 900 DER assets within 500 households and businesses in Western Australia [22]. Furthermore, **project Converge** is an initiative that focussed on improving DER integration to provide network support services through enhanced data and communication

[2] Process to identify the investment option that maximises net economic benefits, from the TNSP or DNSP perspective, according to the augmentation needs that were optimally found in the ISP

technologies, maximising their value in energy and Frequency Control Ancillary Services (FCAS) markets [23].

Despite Australia being one of the most advanced countries in DER adoption, these projects have identified several challenges such as technical integration, market and regulatory frameworks, consumer engagement, data communication, and stronger connections between industry needs and trial learnings [24]. All these need to be addressed for enhancing the coordination and shift towards a whole-system perspective, and truly value DER services, open market-based opportunities, and find a cost-effective development for the future system [25].

Overview of Coordinated Planning Methodologies

Having a clear understanding that planning of transmission and distribution networks are often independent and lack decision-making coordination within a real-world context, the objective of this section is to overview the modelling approaches proposed in the literature to tackle ITDEP with particular focus on how system operators coordinate and solve such problems, identifying the most suitable approaches for real-world implementation.

a. Centralised Scheme

This approach is formulated with a single objective function that minimises investment and operational costs of the whole system and therefore, it works under the key assumption that the planning entity has full knowledge over networks and allocation of resources across all levels of the system. In this sense, it is suitable when the system planner entity has jurisdiction over the whole-system.

The most common analysis under this approach is a comparison with uncoordinated approaches (independent planning processes), concluding potential reductions on the total network expansion costs. Such insights have been provided with deterministic formulations that include the impact of battery energy storage system (BESS) as investment options [26], [27], while stochastic formulations have been proposed as well to account for degrees of uncertainty, analysing additional benefits with decision-making over distributed generators (DGs) [28], and improvements in reliability indicators [29].

However, the effectiveness of centralised approaches hinge on perfect data availability across the whole-system, which is often not feasible nor within regulatory frameworks and hence real-world applications leveraging this methodology would be difficult to achieve. What is more, this approach usually comes at the expense of complex and intractable formulations, often needing assumptions on uncertainty and temporal granularity. In this sense, important operational conditions due to variable renewable energies (VRE) intermittency, unit-commitment constraints, and flexible investment alternatives (e.g., storage) are often not captured in the literature. Consequently, this may result in an inefficient portfolio of investments that are not suitable for different realisations of the future.

b. Multi-level Scheme

This methodology is based on formulating integrated planning as a multi-level optimisation problem, where the upper-level refers to transmission system planning, which is subject to technical constraints and the lower-level problems usually representing distribution systems planning. Such an approach is typically solved by leveraging KKT conditions and strong duality theorems to reformulate the lower-level problem, enabling the upper-level to consider the follower's optimal response within a single-level optimisation problem. In this sense, the different interests from agents involved in decision-making can be accounted for.

Similar to centralised approaches, benefits in investment and operational costs for the whole system can be found. For instance, these conclusions have been found while analysing the impact of distributed energy resources (DER) in decision-making over the transmission network [30], nevertheless, the impact of distribution networks constraints is neglected and thus, benefits may be inaccurate. This has been further analysed, but works only account for the available flexibility of distribution networks, neglecting investments within them, not capturing trade-offs between large- and small-scale [31], [32], and although network reinforcements on both transmission and distribution systems have been accounted for, only a one-year planning horizon is modelled due to the complex formulation of the equivalent single-level problem [33].

In this sense, following up on a duality approach to reformulate a tri-level problem into a bi-level model (transmission and distribution planning) and to manage the complexity of this equivalent model, multi-parametric programming has been employed to DSO planning problems to produce a set of single-level problems that are easier to solve than the initial bi-level formulation [34]. However, this is still challenging since to find the optimal solution, all single-level problems must be solved which would be difficult for problems with extended planning horizons and more technologies as investment options.

In this context, limitations remain for this method. Even though multiple interests are being captured, full knowledge of transmission and distribution networks is also assumed to reformulate the equivalent single-level problem, as otherwise KKT conditions and duality theorem cannot be utilised and thus, making its real-world applicability difficult.

c. Iterative Scheme

The aim of this methodology is to consider communication variables (e.g., target and response) between TSOs and DSOs planning problems, and solve them iteratively until a stopping criterion is met. In this vein, this methodology removes the need for having full knowledge over the whole system by communicating both problems with reduced information [35].

A common approach is coordinating decision-making between TSO and DSO through the purchase and selling costs at the interface [36]. Recent studies have explored this by analysing the impact on investment decisions when including DER [37], and transmission cost allocation [38], [39], concluding potential benefits in terms of cost reduction, resource allocation, and computational efficiency. However, these studies focus on short-term planning horizons and overlook the long-term implications of investment decisions.

This aspect has been covered by considering 10-year planning horizons [40], [41], however the complexity of the ITDEP formulations limits the ability to account for flexible investment options, such as storage and demand-side response. In this context, these limitations have been addressed by introducing flexible investment options within distribution systems in the form of energy production and conversion technologies such as DGs, combined heat and power units, boilers, and heating and cooling pipelines [42]. However, time blocks to represent the operation are assumed to keep tractability of the problem and thus, intermittency of VRE and DER, and the potential needs and value of flexible investment options (at both levels) are not properly captured.

Finally, even though data exchange between system operators is reduced, both planning problems must be solved simultaneously to communicate key variables and meet any convergence criteria, which means having multiple instances of data exchange that may hinder real-world applications.

d. Heuristic Decoupled

This is an emerging approach in which planning problems are also communicated with a reduced set of variables and/or constraints but differs from the previous approach in that the problems can be solved in a decentralised order rather than iteratively coordinated, decoupling the decision-making process by agents. In this context, it could improve scalability and enhance privacy as the need for having full knowledge of networks and simultaneous planning are avoided, solving more manageable planning problems.

A clear example is proposed through a top-down multi-stage approach (e.g., from transmission to distribution) based on heuristic methods, where network and storage are considered as investment options across all levels [43]. Results show potential cost-reductions from storage expansion and curtailment management at the distribution level, contributing to the overall system's operation. However, a case study on the German power system revealed only marginal cost reductions, suggesting that there might be limitations in the broader applicability of the observed benefits or potential issues with the specific solving method.

Furthermore, an ITDEP is proposed by decoupling decision-making problems, representing ADNs with a surrogate single-bus model based on a generator, load, and storage [44]. In this sense, the transmission expansion planning (TEP) is solved considering this representation and once solved, the power exchanges between TSO and DSOs are fixed as parameters within the detailed distribution network planning. In this sense, it has the potential for improving performance of integrated planning when compared to previous approaches. Nevertheless, the work does not consider ADNs as investment options within the TEP, hence it does not capture trade-offs between large- and small-scale assets. In addition, the accuracy of the surrogate model needs to be assessed carefully to truly represent the capabilities of distribution systems.

Under the same approach, a coordinated planning problem for the Italian power system that considers synthetic networks for distribution systems is analysed in [45]. However, this work focuses on how demand flexibility and/or storage can compete against conventional network reinforcements for selected congestion zones rather than a detailed analysis of the impact of ADNs in a coordinated planning process. Moreover, authors identified that a fully integrated problem with this approach is extremely heavy from a computational point of view and thus, further simplifications might be needed.

Therefore, this is a promising approach for integrated planning due to its decentralised solving methodology, and reduced data exchange between agents, opening the possibility to represent ADNs as investment options within a transmission planning context.

e. Summary

To complement this overview, Table 2-1 contains the details associated with all the papers from the literature associated to ITDEP, highlighting scope and objectives, network considerations, investment options across all levels, planning horizons, operational granularity, optimisation approaches and if there is application into a real-world problem.

Reference	Scope & Objectives	Network		Coordination Methodology	Investments		Planning Horizon	Operation Granularity	Optimisation Approach			Real World Application
		Trans.	Dist.		Trans.	Dist.			Determ.	Stochastic	Robust	
[26]	Compare coordinated and uncoordinated approaches	X	X	Centralised	Network	Network	One Year	Blocks	MINLP			-
[27]	Compare coordinated and uncoordinated approaches	X	X	Centralised	Network - BESS	Network - BESS	Multi-year	Blocks	MILP			-
[28]	Analyse the impact of DG and benefits of integrated planning	X	X	Centralised	Network - Generation	Network - DG	One Year	Hourly		MILP		-
[29]	Stochastic planning framework for network development, ensuring a reliable and secure energy supply	X	X	Centralised	Network	Network - ANM - DG	Multi-year	Blocks		MINLP		-
[30]	Multi-stage bi-level stochastic model to jointly plan transmission systems and merchant DER	X		Multi-Level	Network - DER	-	Multi-year	Blocks	MINLP	MINLP		-
[31]	Cost-based TSO-DSO coordination planning model to quantify the value of local flexibility services	X	X	Multi-Level	Network	-	One Year	Hourly	MIP			-
[32]	Leverage existing flexibility provided by ADNs into the transmission planning process	X	X	Multi-Level	Network	-	One Year	Hourly	MILP			-
[33]	Develop a planning framework that integrates the operational flexibility of ADN into TEP	X	X	Multi-Level	Network	Network	One Year	Hourly	MILP			-
[34]	Hierarchichal framework for ITDEP that leverages MPP to manage computational burden	X	X	Multi-Level	Network	Network - DG	One Year	Blocks	MPP MILP			-
[35]	Aims to achieve a more efficient and resilient power system by considering flexibility of ADNs	X	X	Iterative	Network	-	One Year	Blocks	MINLP			-
[36]	It combines robust and stochastic optimisation to improve overall system reliability and efficiency	X	X	Iterative	Network	Network	One Year	Hourly	MINLP		MILP	-
[37]	determine the planning scheme and scenario based generation schedule for ITDEP with DGs	X	X	Iterative	Network	Network	One Year	Blocks	MINLP			-
[38]	Evaluates the impact of transmission cost allocation when coplanning transmission networks and DER	X		Iterative	Network - DER	-	One Year	Hourly		MILP		-
[39]	Develops an ITDEP that efficiently allocates transmission cost	X	X	Iterative	Network	Network	One Year	Hourly	MINLP			-
[40]	Aims to create a comprehensive ITDEP strategy that optimises both infrastructure and market interactions	X	X	Iterative	Network - Generation	Network - DG	Multi-year	Blocks		MILP		-
[41]	Hybrid robust and stochastic ITDEP to determine a robust portfolio in a coordinated manner	X	X	Iterative	Network - Generation	Network - DG	Multi-year	Blocks		MILP	MILP	-
[42]	Multiple energy vectors are included in ADNs, comparing a decision-making problem with and without DSR	X	X	Iterative	Network	Network - DG - Heating - Cooling	Multi-year	Blocks	MILP			-
[43]	Present an open source software that is able to co-optimise grid and storage in a top-down approach	X	X	Decoupled	Network - BESS	Network - BESS	One Year	Blocks	NLP			German PS
[44]	Introduces a Julia/JuMP-based open- source tool for holistic planning of transmission and distribution grids	X	X	Decoupled	Network - BESS	Network - BESS - Demand Flexibility	One Year	Hourly		MILP		-
[45]	Presents the optimization results for Italian case study of the FlexPlan project	x	x	Decoupled	Network - BESS	Network - BESS - Demand Flexibility	One Year	Hourly		MILP		Italian PS

Table 2-1: Summary of literature review associated to ITDEP

3. Methodological Proposal
3. Methodological Proposal

Integrated planning frameworks could bring potential benefits regarding investment and operational costs, as well as improved resource allocation if compared to independent planning approaches. For these reasons, system planners and regulatory entities around the world have identified the need for new methodologies and improve the coordination to better address the challenges of future power systems.

Nevertheless, in the literature it is often assumed there is full knowledge over transmission and distribution networks and thus, the size of optimisation formulations is increased (e.g., more variables and constraints). This assumption does not allow for a tractable problem and an efficient coordination between system operators that typically have independent planning roles. Consequently, the implementation of ITDEP in real-world scenarios would be difficult to achieve. Therefore, to fill this gap and truly unlock the benefits that ITDEP could bring, developing a methodology that efficiently coordinates system operators will be key.

In this context, this work will develop a distributed methodology to represent the planning of ADNs, and consider them as options to invest on within a TEP as presented in Figure 3-1. Thus, the aim is to establish clear methodological steps on how to build a ***parametric representation*** of the investments needed within ADNs that unlock the adoption and orchestration of CER. In turn, this information could be provided to power system planners, such as AEMO, improving the coordination of the decision-making process.

In this context, this methodology would allow deciding on the optimal participation from the demand side, and the corresponding distribution network enhancement alternatives, from a whole-system planning perspective and in turn, improving the consideraitons of trade-offs between large- and small-scale developments.

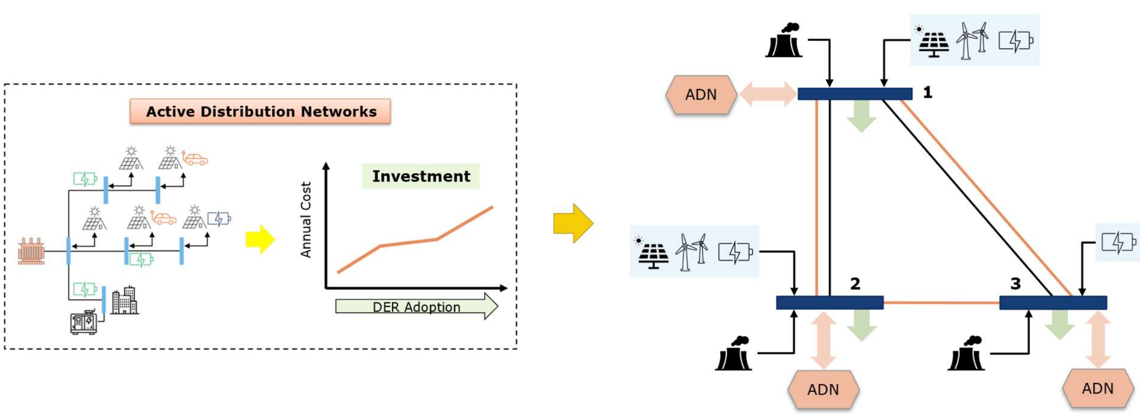

Figure 3-1: Distributed framework to represent ADNs investments

More in depth, as depicted in Figure 3-2, this approach is based on an investment problem that minimises the investment and operational costs, subject to constraints that depend on the DSO's perspective, to support CER adoption over a planning horizon. Then, in an iterative fashion, by increasing the adoption of CER in the network, the optimal portfolio of investments (e.g., distributed storage, network reinforcement, active network management) and its costs will be found and thus, a **parametric cost function** that represents the investments needed to unlock these resources can be built. It is worth mentioning that, any DSO can produce this information by employing their own tools and projections.

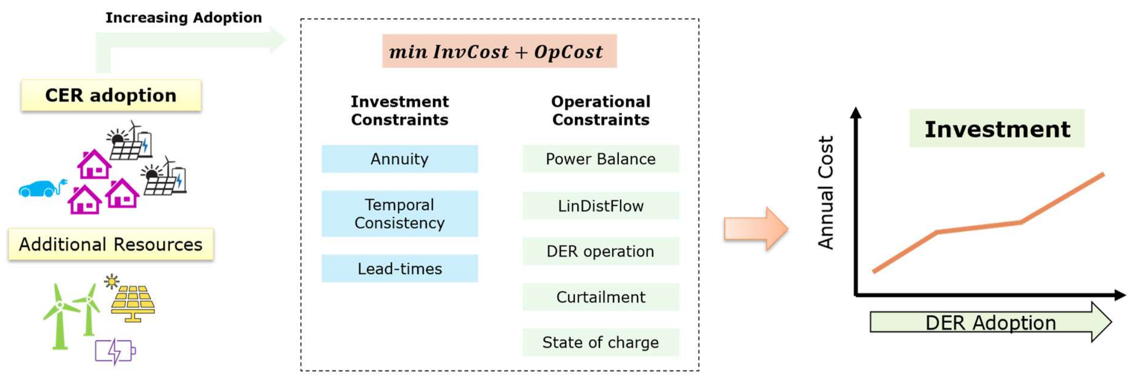

Figure 3-2: Investment cost functions for ADNs

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