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Abbreviations and Acronyms

ADMM	Alternating direction method of multiplier
ADN	Active distribution network
AS	Ancillary service
DER	Distributed Energy Resources
DG	Distributed Generator
DRES	Distributed renewable energy source
DS	Distribution System
DSO	Distribution system operator
FL	Flexible load
MILP	Mixed-integer linear programming
MINLP	Mixed-integer nonlinear programming
MIP	Mixed-integer programming
MIQCP	Mixed-integer quadratically constrained program
MPP	Maximum power point
NG ESO	National Grid Electricity System Operator
OLTC	On-Load Tap Changer
RES	Renewable energy source
STATCOM	Static compensator
SVC	Static VAR compensator
SG	Synchronous Generator
TN	Transmission network
TS	Transmission System
TSO	Transmission system operator
UC	Unit commitment
UKPN	UK Power Network

Executive Summary

The Electricity Network Transformation Roadmap estimates the Distributed Energy Resources (DERs) contribution to Australia's electricity generation capacity will reach around 45% by 2050. Alongside many potential benefits, the significant number of DERs can cause several challenges and technical problems, such as network congestion and voltage excursions. To support the integration of renewable energy sources (RESs), significant investments in new network infrastructure can be avoided by encouraging distribution system operators (DSOs) to take more proactive approaches to manage the unpredictable nature of RESs. To achieve this, it is necessary to improve the cooperation between Transmission System Operators (TSOs) and DSOs. In addition, the provision of energy and ancillary services from DERs to the transmission network without compromising the power system integrity needs to be explored.

WP 3.12 aims to assess the coordination mechanism between TSO and DSO for the ancillary services, particularly frequency and reactive supports that can be provided from the Active Distributed Networks (ADNs) to the Transmission Networks (TNs). It also aims to develop tools to estimate support services to the upstream grid from downstream and perform the network and market interaction analysis. To achieve this, the equivalent network of the distribution network connected to the transmission network must be evaluated considering several loading conditions of the network, such as demand response and DERs with present and forecast future data. There are several barriers and challenges in providing Ancillary Services (ASs) to TNs, such as adequate regulation, market design, technical and operational issues, and communication and coordination between TSO and DSO.

This report reviews the existing literature on ancillary services provided by the ADNs to TNs and provide following specific contributions:

- Conduct a comprehensive analysis of the existing AS structure, with a focus on understanding the limitations and gaps in the current system, especially in the context of DERs connected to both distribution and transmission systems. Subsequently, resources in ADNs to provide ASs are discussed.

- Examination of deterministic and non-deterministic optimization problem formulation including their objective functions and constraints in detail for AS design.

- Solution approaches, validations, test systems, simulation software, and hardware system of those specific problem formulations are discussed thoroughly which are directly related to smart grids with a high penetration of DERs.

- Identify and assess the technical, regulatory, and financial barriers that currently hinder the adoption of new ASs from DERs. Provide recommendations and strategies to overcome these barriers, enabling the successful procurement and integration of emerging ASs from DERs within distribution grids.

1 Background

The energy market has shifted towards sustainable electricity generation in recent years, with a growing emphasis on the integration of RESs into the distribution grids [1], [2]. Installation of control modules to regulate the asynchronous power of RESs in the distribution systems is quite costly. As an alternative, planning policies that revolve around the collaboration between TNs and ADNs have emerged for RESs power management [3], [4]. This approach eliminates the requirements for expensive devices and reduces operational costs for distribution systems [5], [6]. TSOs provide voltage and frequency regulation services along with congestion management for transmission systems. In contrast, DSOs focus on managing congestion and voltage within the distribution system [7]. With proper coordination between TSO and DSO, both entities can accomplish individual goals while maintaining the stability, reliability, and security of the integrated TN/ADN system.

The future distribution networks integrated with numerous active DERs will be able to operate in islanded mode and provide ASs for the upstream network in the grid-connected mode. Improving reliability and resiliency makes the entire system more dependable and better equipped to withstand failures or disruptions [8]. In recent years, the concept of ADNs providing ancillary support to a higher voltage level has gained momentum, and several proof-of-concept large-scale projects have reported promising results [9], [10], [11]. The UK Power Networks and the National Grid Electricity System Operator (NG ESO) are jointly running the world's first trial to dispatch active and reactive power services to the transmission network utilizing different types of DERs, including storage. The effective operation requires at least 90% of the response to be provided within 2s [10]. Test cases developed in the SmartNet are being used to coordinate transmission and distribution system operations [11]. The number of major AS-related projects from 2017-2022 is summarized in Table 1, highlighting the importance of ASs.

In general, regulatory factors pose significant obstacles to the development and execution of market concepts related to TSOs and DSOs [6]. Several technical challenges, such as the use of distributed optimization algorithms to solve large-scale and complex problems, frequency control, congestion management, or voltage control, are yet to be resolved [24], [25], [26]. Various network codes are introduced in the European Union (EU) to establish the foundations for creating effective coordination between TSO and DSO [26]. Further investigation is required to address data sharing, operational protocols, and market design issues. This will allow TSOs and DSOs to support each other in lowering the operation costs while efficiently integrating a large number of RESs. A detailed data flow between the aggregator and other relevant organizations is shown in Figure 1. The increasing deployment of measuring infrastructure offers new data sources, enabling the enhancement of AS performance through measurement-based analysis techniques.

Table 1. Highlights of some of the recent projects solely on ASs

Name of the Project	Duration of the Project	Type of Ancillary Services	References
CoordiNet	2019-2022	Black start, frequency response, inertial response, congestion management, and voltage regulation	[12]
EASY-RES	2018–2021	Harmonic mitigation, fault-clearing, frequency response, inertial response, reactive power support, power smoothing, and voltage regulation	[13]
OSMOSE	2018–2021	Frequency response, congestion management, and voltage regulation	[14]
MERLON	2018–2022	Frequency response, congestion management, and voltage regulation	[15]
COMPILE	2018–2022	Voltage regulation	[16]
TDX-ASSIST	2017–2020	Reactive power management, congestion management, and voltage regulation	[17]
RESOLVD	2017–2021	Self-healing, congestion management, and voltage regulation	[18]
FLEXITRANSTORE	2017–2021	Frequency response, black start, power smoothing, and congestion management	[19]
EU-SysFlex	2017–2021	Reactive power management, congestion management, voltage regulation, and frequency response	[20]
CROSSBOW	2017–2021	Frequency response, inertial response, congestion management, and voltage regulation	[21]
EnergyKeeper	2017–2019	Reactive power support and voltage regulation	[22]
UNITED-GRID	2017–2021	Self-healing, congestion management, and voltage regulation	[23]

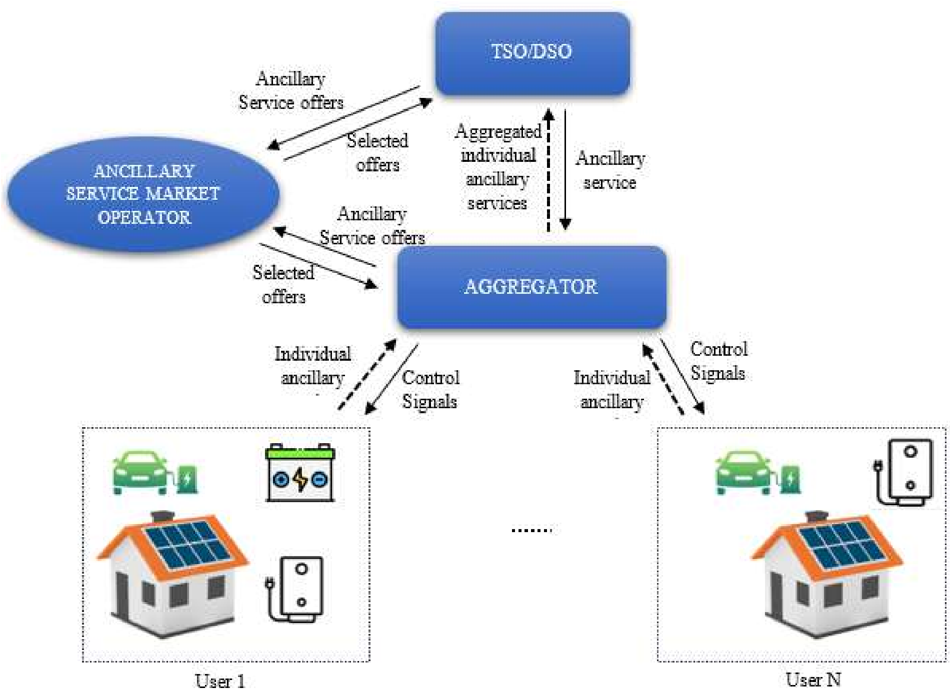

Figure 1. Data flow between aggregator and relevant organisations.

The next sections of this report are organized as follows. The energy and ASs provided by ADNs for the upstream grid are reviewed in **Section 2**. **Section 3** discusses about the various resources (i.e., conventional DERs, renewable DERs, EVs, storage, etc.) of ADNs capable to provide AS. Optimization problem formulations are presented in **Section 4**, which includes both deterministic and non-deterministic optimization problem formulations. **Section 5** discusses the specific issues and challenges based on the literature review. Finally, the work is concluded by providing final insights and recommendations in **Section 6**.

2 Ancillary Services for the Upstream Grid

Ancillary services (ASs) are essential services to ensure the secure and reliable operation of the network. Main ASs includes frequency support, voltage and reactive power management, congestion management, and system restart. DERs are small-scale generation and storage units that can potentially provide ASs in an aggregated from to the TNs. A categorization of the ASs is presented in Figure 2, where (a) represents the AS in Australia and (b) presents AS in the United States. Types of ASs vary from country to country. Thus, some of the commonly used ASs are described below.

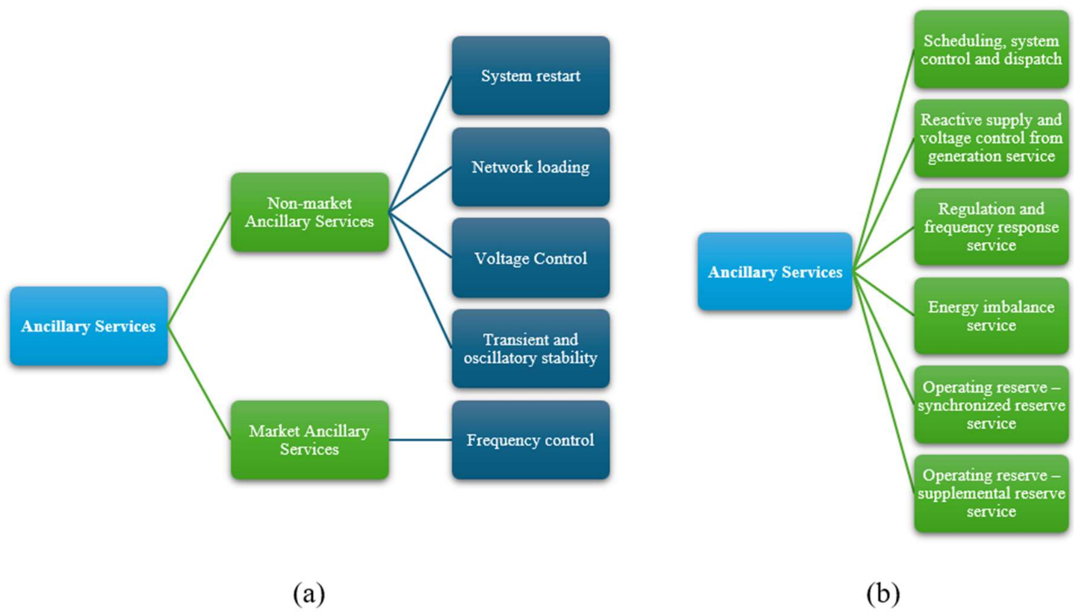

Figure 2. Categorization of the ancillary services for (a) Australia and (b) United States.

2.1 Energy Arbitrage

Traditionally, the TSO relies on fast hydro generators or thermal units to balance mismatches between supply and demand. Due to the longer time requirement to adjust fuel supply, steam pressure, turbine speed and the cooling system, the baseload generation units, such as thermal and nuclear power plants, are unable to provide fast ramping [27]. Demand response has also drawn significant attention in recent years. However, demand response requires infrastructure investment like advanced metering units, control devices, intelligent energy management systems, and smart buildings. Finally, it depends on the willingness of the customers. Furthermore, the DERs introduce more uncertainty and variability in the supply-load balance. There are different types of ESSs that can provide energy arbitrage services, such as batteries, pumped hydro, flywheels, and compressed air storage systems.

Batteries are the most widely used storage systems and highly capable of providing sharp ramps. A microgrid optimal scheduling model is proposed in [28] that is capable of providing hourly ramping, 10-min based load following and 1-min based frequency regulation. A distributed energy and reserve dispatch is presented in [29], where the flexible resources are coordinated in normal and uncertain cases for reliable and economically efficient energy arbitrage. Rapid development of coordinated TN and ADNs has the potential to provide flexibility to the TN. On the other hand, an Alternating Direction Method of Multipliers

(ADMM) based method is proposed in [30] that can be used to clear the market in a distributed manner. ADMM enables secure data preservation and limited information exchange between transmission & distribution networks.

2.2 Frequency Response

Frequency regulation helps the power system maintain the demand and supply balance, keeping the system's frequency around the nominal value (e.g., 50 Hz or 60 Hz). DERs can provide frequency regulation services to the power system by adjusting their power output or consumption according to the measured system frequency or control signals. The provision of primary frequency response (PFR) from the distribution grid to TS is discussed in [31]. It presents two methodologies for enabling PFR from ADNs to TN. The first quantifies ADNs' PFR capability range by computing aggregated P(f) droop curves, while the second optimally dispatches DERs to ensure specific frequency regulation characteristics, minimizing a DSO-defined cost function. These methodologies are developed using conventional OPF formulations, efficiently model grid constraints, and exploit ADN operational limits. Furthermore, these are easily implementable by system operators. Validation through simulations demonstrates high accuracy, low computational complexity, and potential applicability for DSOs in AS markets to achieve 100% renewable energy systems. A BESS optimization method, tailored for co-locating with renewable power plants, is introduced in the UK, targeting the latest Dynamic Containment (DC) services. It simulates BESS operations for DC responses, state of energy (SoE) management, and coordination with the power plant to estimate the project's net present value. The method suggests optimal BESS capacity, target energy footroom and/or headroom levels, and SoE ranges for interchange, addressing the techno-economic feasibility of co-location projects under evolving frequency response market reforms. The work in [8] investigates the capability of ADNs to provide frequency regulation in grid-connected mode and ensure reliable islanded operation. To participate in PFR, the DERs should operate with a headroom under their maximum power point (MPP) that ensures sufficient available generation margin at any time instance [8].

2.3 Reactive Power Support

Reactive power management controls the generation and consumption of reactive power to maintain the voltage within acceptable limits [32]. Due to increasing electricity demand, TNs must operate at higher loads and lower capacity, resulting in reactive power shortages at overloaded nodes or buses [33]. Besides, voltage problems become critical in the boundary nodes of the TN, demanding reactive power ASs to address these issues [33]. To enhance system flexibility and voltage stability, a bulk power system usually has its own reactive power support devices, such as static VAR compensators (SVCs), static synchronous compensators (STATCOMs) and capacitors at specific locations. Due to the costs and optimal placement under the changing network conditions, newer methods are sought to utilize active DERs in the distribution system to provide reactive power support to the TN [34]. It is demonstrated in [35] that existing reactive power from DERs can be used in the TS-DS interconnection to provide voltage support instead of conventional compensation devices.

Effective coordination of thousands of DERs (not centrally monitored) is challenging for voltage support [66]. For voltage support provision, DERs must be capable of (1) dynamically adapting to changes in the system voltages, (2) responding to TSO instructions within 2s, and (3) providing the first two requirements while maintaining communication efficiency [10]. The present voltage support requirements of Switzerland are identified in [67], and the potentials of ASs considering various DER operational modes are investigated. A new coordination scheme is proposed in [68] that sends periodic signals to downstream devices according to the requirements of the TN. During an emergency, DERs and flexible loads (FL) decide how to respond using local measurements. Another technology-neutral strategy is proposed in [3] that only uses suitable command actions involving all existing equipment as per their capability without investing in new devices. The grid codes of European countries have already considered the ADNs' participation in providing voltage support in TNs [66]. A recent project focuses on enabling DERs of the distribution grid to provide services in Great Britain, mainly dynamic voltage control and reactive services, to the TN in a coordinated manner [69]. The On-load Tap Changers (OLTC) can also provide additional reactive power flexibility if the voltage at ADN reaches its limit [70].

2.4 Congestion Management

Congestion management services are required to avoid the overloading of network elements and ensure optimal power flow in the system. Several models have been proposed in the literature to provide network congestion management services [36], [37], [38]. A joint chance-constrained optimization framework is presented in [38] to provide upstream voltage and congestion support at MV-LV interconnection. Another investigation has proposed an innovative control strategy that explores the full capacity of TN based on a re-dispatching strategy while keeping the conductors that are prone to weather conditions under thermal limits [37]. Applied to the IEEE 39-bus New England test system, the method effectively reduces congestion at critical lines and increases available transfer capabilities (ATCs), demonstrating its practicality and efficiency.

2.5 Power Smoothing for Grid Stability

The integration of variable RESs, such as wind and solar RESs, has resulted in significant fluctuations in net load for traditional synchronous generators (SGs). These rapid variations, occurring within short timeframes, present challenges for TSOs in ensuring power balance. For example, the California Independent System Operator (CAISO) experienced the "duck curve" in 2013, where a sudden decline in solar generation during sunset necessitated a rapid ramp-up of conventional units, potentially leading to increased energy prices [39]. Similar challenges are evident in operating reserve demand curves in US markets, causing notable price spikes and affecting the economic viability of imbalanced RES units [40].

To tackle these challenges, converter-interfaced RES has been proposed as a flexible solution capable of providing fast power ramp services. Ongoing research is directed towards developing control methods for active power ramp rates in RES power plants, aligning with the requirements of TSOs and addressing frequency events [41]. Table 2 represents the maximum ramp rate requirements comparison among different countries, including the positive and negative ramp. The introduction of "Following Reserves" as a new AS is suggested, with the aim of meeting market demands. Grid codes in various regions, including MISO and CAISO in the US, incorporate limits on RES generation to prevent extreme power ramp requirements, especially in weaker grids [42]. Certain regions, like Ireland and Puerto Rico, establish ramp-rate limits for photovoltaic (PV) systems and Wind Farms to mitigate frequency deviations [43]. Additionally, Battery Energy Storage Systems (BESSs) are being explored for output power smoothing, contingent on the technology and dynamic behaviour of the BESS [44].

Table 2. Ramp rate (maximum) requirement comparison among different countries

Country	Positive Ramp	Negative Ramp
Australia	3 MW/minute	3 MW/minute
China	3 MW/minute for <30 MW	3 MW/minute for <30 MW
	Installed capacity/10MW for 30–150 MW	Installed capacity/10MW for 30–150 MW
	15 MW/minute for >150 MW	15 MW/minute for >150 MW
Denmark	100 kW/second	100 kW/second
Germany	10%/minute	No
Ireland	30 MW/minute	No
Mexico	2 to 5%/minute	1 to 5%/minute
Puerto Rico	10%/minute	10%/minute
United Kingdom	No limit for <200 MW	No limit for <200 MW
	50 MW/minute for 200-1000 MW	50 MW/minute for 200-1000 MW
	40MW/minute for >1000MW	40MW/minute for >1000MW
United States	5 MW/minute	5 MW/minute

2.6 Inertial Response

The inherent inertia of traditional SGs, which prevents rapid frequency fluctuations following a power imbalance, is characteristic of the power systems being challenged by the gradual replacement of SGs with distributed renewable energy sources (DRESs) in efforts to reduce global carbon emissions [45]. However, this shift introduces frequency stability concerns, particularly as converter-interfaced DRESs, such as PVs, doubly-fed induction machines, and full-converter wind generators, offer minimal or no inertia to the system [46], [47]. Notably, simulations conducted by the Western Electricity Coordinating Council in the USA and an analysis of the German power system in 2013 revealed a degradation in system frequency response during high penetration of wind generation and fossil fuel generation withdrawal [48], [49], [50]. To address this, it is recommended that DRESs emulate the inertial response of SGs, known as virtual or synthetic inertia, to ensure stable grid operation in the future [51]. Some manufacturers, like WindINERTIA, ENERCON, and General Electric, already incorporate virtual inertia response features [51]. While inherently lacking inertial response, PV units could contribute through coordinated use of fast-acting ESS, such as flywheels, supercapacitors, or batteries [52].

In the realm of smart grids, the concept of Virtual Synchronous Machines (VSMs) has been proposed to provide inertia and damping behaviour, along with cascaded voltage and current controllers [53], [54]. As power grids increasingly transition to inertia-less DRESs, the demand for inertial response is anticipated to become a valuable commodity, potentially leading to significant financial compensation demands from generating plants. This shift is expected to escalate investment and operational costs, exemplified by the development of control methods for PV plants and the integration of Fast Storage Systems (FSS) based on supercapacitors. Recognized as an additional investment cost, the provision of synthetic inertia may pave the way for a future market for inertia as a service, underscoring the financial implications of this transition.

The future provision of inertial AS in the power market can be cost-effective through a market-based approach [55], offering a potential solution to the challenges posed by the transition to DRESs. Operating PV plants below their Maximum Power Point (MPP) with reserves for inertial response is another option, but this primarily constitutes Fast Frequency Response (FFR) rather than traditional inertial response [56]. In inertia trading schemes, the recommendation is to trade in terms of an inertia metric, not power or energy [57]. Some suggest a penalty factor for generators lacking inertial response, and the unit commitment framework for FFR shows that additional virtual inertia can schedule conventional units with lower costs [58]. An emerging avenue is using inertia as a "service" for power quality, employing Quality of Service (QoS) metrics, similar to cloud computing, to assess power quality based on inertial response availability [58]. Microgrid operators can offer inertial responses based on specific criteria, such as maximum allowable Rate of Change of Frequency (RoCoF) and/or frequency deviation, aligning with end-user requirements. National grid codes have established additional services, such as mitigating RoCoF, which is closely associated with inertial response, and proposed services like FFR by entities like Eirgrid and SONI [59].

3 Resources in ADN to Provide AS

In an active distribution network (AND), various DERs are connected to provide ASs. These resources typically include solar PV systems, BESSs, wind turbines, micro-turbines, EVs, small-scale hydroelectric generators, and controllable loads. Each of these resources can contribute uniquely to the provision of ASs, enhancing the stability and security of the grid [60], [61].

3.1 Conventional DERs

Today, DERs can be integrated into the distribution network to provide localized energy generation, thereby reducing strain on the centralized grid, and enhancing overall system resilience [60], [61]. DERs contribute not only to the ADN operation and performance but also provide support to the upstream grid by alleviating congestion, reducing transmission losses, and enhancing voltage stability.

DERs offer a range of services to both the ADN and the upstream grid [60], [62]. These services include peak shaving, load shifting, frequency regulation, voltage support, reactive power compensation, congestion management, and black-start capability. Through these services, DERs contribute to optimizing the operation of the entire power system, improving the system reliability, efficiency, and security. DERs are typically modelled using various techniques such as mathematical optimization, power flow analysis, and machine learning algorithms to accurately capture their nonlinear and time-variant behaviours and interaction with the grid [63].

The solution approach for integrating DERs into the ADN involves a combination of advanced control algorithms, communication technologies, and market mechanisms [63], [64]. Smart inverters, energy management systems, and advanced metering infrastructure play crucial roles in orchestrating the operation of DERs to meet grid requirements while maximizing their economic benefits for both consumers and utilities [65]. Additionally, regulatory frameworks and incentive programs are implemented to promote the deployment of DERs and facilitate their participation in grid services, fostering a more decentralized and resilient energy system [66], [67].

3.2 EVs

Connecting electric vehicles (EVs) to the ADN involves establishing charging infrastructures that allow EVs to draw power from the grid [68], [69]. This typically entails installing charging stations at various locations such as homes, workplaces, public parking areas, and commercial properties. These charging stations can be equipped with smart charging capabilities, enabling communication with the grid and facilitating coordination with DRESs and energy management systems [70], [71]. Additionally, bidirectional charging technology allows EVs to consume energy and feed excess energy back into the grid, effectively turning them into mobile energy storage units [72], [73]. By integrating EVs into the ADN, we create a dynamic ecosystem where vehicles serve as both consumers and potential sources of flexibility for grid management [68], [69].

Electric vehicles provide support not only to the ADN but also to the upstream grid [74]. At the local level, EVs can contribute to load management by allowing utilities to incentivize charging during off-peak hours or to modulate charging rates to avoid grid congestion [75], [76], [77]. Moreover, EVs can offer grid services such as demand response, frequency regulation, and voltage support through smart charging algorithms and vehicle-to-grid (V2G) technology [74], [78]. On a broader scale, aggregating the charging and discharging behaviour of EVs can enhance grid stability, improve renewable energy integration, and optimize energy usage across the entire electricity system [74], [78]. Thus, by leveraging the capabilities of electric vehicles, we can harness their potential to provide valuable services to both the ADN and the upstream grid, ultimately advancing the transition towards a more sustainable and resilient energy infrastructure.

3.3 Energy Storage

Connecting ESS to the ADN involves installing battery storage units at strategic locations within the distribution grid. These storage systems can be connected directly to the distribution network through inverters, allowing them to charge and discharge as required [79], [80]. Additionally, energy storage installations can be integrated with RESs like solar PV systems or wind turbines to store excess energy generated during periods of high production for later use during peak demand or when renewable resources are unavailable [81], [82]. Advanced control systems and communication technologies enable energy storage units to respond dynamically to grid signals, optimizing their operation and maximizing their contribution to grid stability and reliability [83].

4 Optimization Problem Formulation of ASs Provided by ANDs for TNs

In an ADN, the AS provision optimization problem formulation involves defining mathematical models to efficiently manage DERs, grid assets, and loads. These models aim to optimize various objectives, such as minimizing power losses, voltage deviations, and operational costs while maximizing renewable energy integration and grid stability and reliability. To do this, two types of modelling approaches have been considered in the literature including deterministic and non-deterministic approaches. The formulations, solution approaches, and test systems used for the validation are given next.

4.1 Deterministic Approach

4.1.1 Objective Functions and Constraints

An optimization problem can have different forms depending on the complexity and nature of the problem formulation. Nonlinear modelling can provide more accurate results for AS procurement by ADNS for a TN by considering its inherent nonlinearities. However, the process of linearising this complex problem can simplify its solution and make it possible to attain the global optimum of the linearized problem.

In addition to nonlinearities, power generation and forecast uncertainties of this problem are considered in some literature, which has been modelled, for instance, using stochastic mixed-integer linear programming (stochastic MILP) approaches [29], [38], [84], [85]. However, most of the available problem formulations for ASs' procurement by ADNs for a TN have ignored uncertainties to reduce data requirements and computational complexities in their proposed methods to facilitate their practical application. A list of different types of optimization formulations found in the selected manuscripts is presented in Table 3. The complexity and computational intensity increase with the inclusion of nonlinearity and uncertainty in the problem formulation. However, several state-of-the-art solution approaches have been developed and implemented in the literature and research works to solve this problem, considering the nonlinearities and/or uncertainties.

Table 3. Optimization problem formulations for AS provision from selected manuscripts

Problem type	Reference
Mixed Integer linear programming (MILP)	[28], [86], [87]
Mixed-integer Nonlinear Programming (MINLP)	[11], [37], [88], [89]
Mixed-integer quadratically constrained program (MIQCP)	[8], [90]
Stochastic MILP	[29], [38], [84], [85]

4.1.2 Solution Approaches

Complex optimization problems for the provision of energy and ASs can be solved using several open-source and commercial solvers. Different types of solvers are available on various platforms. GAMS has been used in most studies since specific types of solvers are available within it for different optimization problems. Besides GAMS, MATLAB solvers have been also used. Julia is an open-source platform wherein Gurobi can be used as the optimization problem solver, and JuMP can be used as the modelling language. A list of solvers along with their platforms, is presented in Table 4. GAMS has been used more than the other platforms as it includes several solvers to solve various types of optimization problem formulations mentioned in Table 3.

Table 4. Optimization problem solvers from the selected manuscripts

Platform	Solver	References
MATLAB	CPLEX	[29]
Julia	Gurobi	[90]
MATLAB	Gurobi	[8], [86]
GAMS	CONOPT	[89]
GAMS	IPOPT	[87], [88]
GAMS	CPLEX	[38], [84], [87]
GAMS	BONMIN	[87], [91]
MOSEK	MOSEK	[30], [85]

4.1.3 Validation and Test Systems

In several papers, the provision of energy and ASs to TNs from ADNs is presented as an optimization problem. The objectives used in these optimization problems are reducing network loss, increasing net profit, voltage regulation, and frequency support. Objectives used in the surveyed literature are given in Table 5.

Table 5. Categorised objectives from the selected manuscripts

Main objective	Reference
Reactive power support	[34], [87], [89], [92], [93]
Optimal sizing of ESS	[90]
Cost (Procurement/operation)	[8], [28], [30], [33], [36], [84], [86], [94], [95]
Network loss	[31], [38], [86], [88]
Social welfare	[85]

Several benchmark IEEE test systems have been used in the literature to model TNs/ADNs to study the ASs and validate proposed approaches, such as in [29], [30], [33], [34], [36], [85], [88], [89], [90], [92], [95] - [97]. Besides IEEE test systems, the European CIGRE grid and several European networks have been frequently used to study AS provisions by ADNs for TNs. A representative chart is given in Figure 4 to show how many different test systems have been used in the literature. In this figure, various models are presented in different colours, and a larger area represents a higher frequency of test system use. From Figure 4, the most frequently used models in the literature are IEEE 33-bus system, IEEE 30-bus system, IEEE 118-bus system, IEEE 123-bus distribution network, and the European CIGRE MV grid.

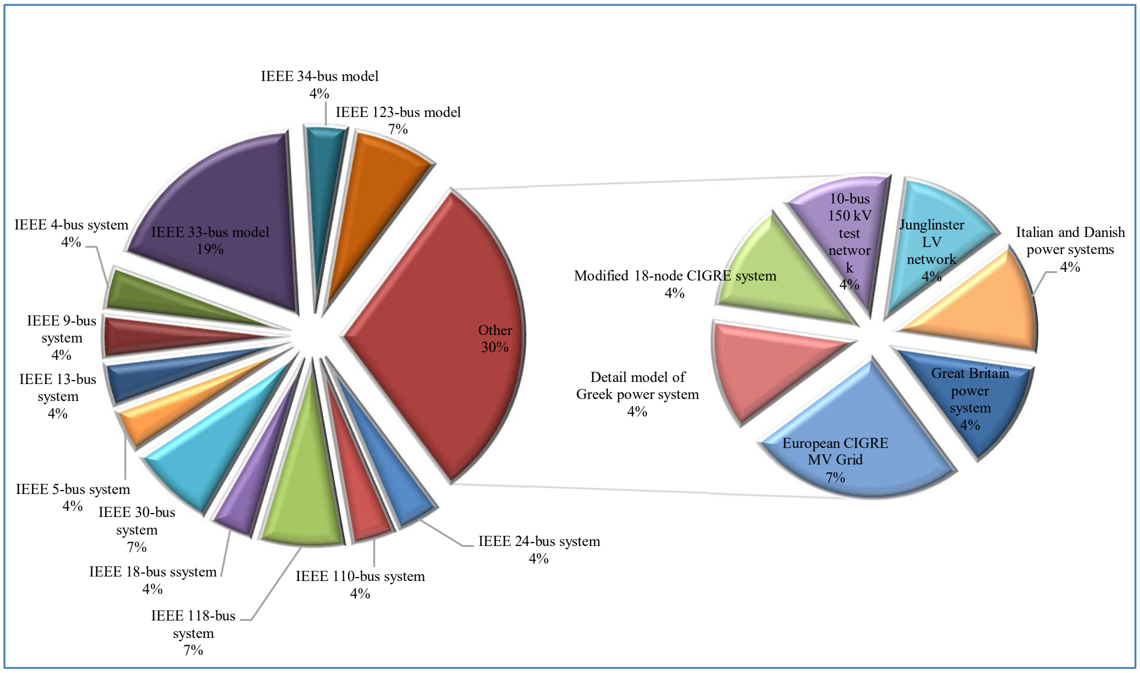

Figure 3. Frequently used test systems for providing ASs to TNs from ADNs.

4.1.4 Simulation Software and Hardware

Different software tools have been used in the literature to develop and validate physical power system models for AS procurement by active distribution systems for the transmission system. From the literature, it is prominent that MATLAB and various toolboxes associated with MATLAB, such as Matpower [34], [36], [92] YALMIP [8], [86], and CVX [85], have been used in most cases. DIgSILENT PowerFactory has been used for phasor-based dynamic stability studies [3], [98], [99], and PSCAD/EMTDC has been used for the electromagnetic transient study of a large-scale TN/ADN network in [3]. In [31], the optimal power flows are solved in Python using the Scipy library. A comparative chart of different software tools used within the reviewed literature is presented in Figure 4.

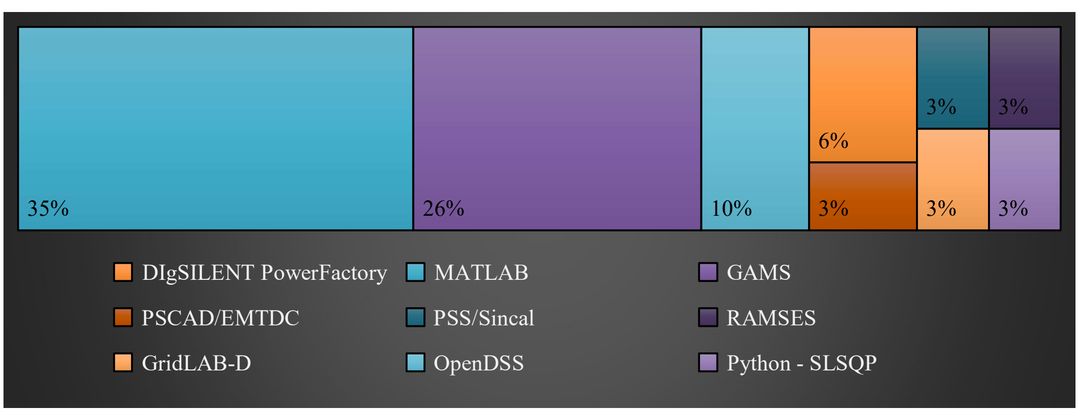

Figure 4. Power system simulation tools.

4.2 Non-deterministic Approach

In this subsection we highlight various uncertain variables, how they are modelled, and their optimization approaches. Subsequently we described about their validation and metrices.

4.2.1 Uncertain Variables

The operation of transmission and distribution systems, coupled with the integration of DERs, is subject to various uncertain variables that pose challenges to the reliable and secure operation of the entire system. One key uncertain variable is the intermittent nature of renewable energy resources, such as solar and wind power, which can lead to fluctuations in power generation and create challenges in matching supply with demand [100], [101], [102]. Additionally, the geographical dispersion of DERs introduces uncertainties related to system planning and grid management [100]. Voltage fluctuations and power quality issues are inherent uncertainties arising from the volatile and decentralized nature of DERs, requiring advanced monitoring and control mechanisms to maintain grid stability [103]. The evolving technological landscape and the integration of smart grid components also contribute to uncertainties, as the interplay between traditional and modern grid elements can introduce complexities in the system behaviour [100]. Furthermore, uncertainties related to policy and regulatory frameworks influence investment decisions and can impact the development and integration of DERs. Addressing these uncertain variables requires a comprehensive approach that incorporates advanced grid modelling, real-time monitoring, adaptive control strategies, and dynamic policy frameworks to ensure a resilient and sustainable energy transmission and distribution system [104].

4.2.2 Uncertainty Modelling Approaches

To effectively address uncertainties in the context of transmission and distribution systems, as well as DERs, various modelling approaches are employed [104]. Probability distribution or density functions serve as fundamental tools for capturing and characterizing uncertain variables. By assigning probabilities to different outcomes, these functions enable a quantitative representation of uncertainty, allowing for probabilistic assessments of the system behaviour [104], [105]. The advantage lies in the ability to quantify the likelihood of different outcomes, aiding in risk assessment and decision-making. However, challenges arise in accurately defining the probability distributions, particularly for complex and interconnected systems where correlations and dependencies between variables can be intricate [104], [106].

Constructing and sampling scenarios are another prevalent approach, involving the generation of multiple possible future states based on different sets of assumptions and/or conditions [107], [108], [109]. This method facilitates a comprehensive exploration of the system's response under various scenarios, providing insights into the range of potential outcomes and associated uncertainties [110], [111]. Bounded intervals, on the other hand, offer a more deterministic approach by defining upper and lower limits for uncertain parameters [107], [108], [109]. This method provides a conservative representation of uncertainties, often used in worst-case analysis. Integrating these approaches in a hybrid manner allows for a robust modelling framework that accounts for both stochastic and deterministic aspects of uncertainties, enabling a more comprehensive understanding of the challenges posed by uncertain variables in transmission and distribution systems with DERs [110], [111].

4.2.3 Optimization Under Uncertainty Methodologies

Optimization under uncertainty methodologies plays a critical role in ensuring the efficient operation of active distribution systems by aggregating DERs for supporting the upstream grid. Among these methodologies, Robust Optimization (RO) stands out as a popular approach. RO aims to find solutions that are robust against uncertainties in continuous parameters. By considering a range of possible scenarios, RO provides solutions that perform well across various conditions [108], [109], [112], [113], [114], [115]. However, a limitation of RO is its conservative nature, as it often leads to overly pessimistic solutions, potentially sacrificing efficiency for robustness. Another prominent methodology is Stochastic Programming (SP), which explicitly models uncertainty using probability distributions. SP offers flexibility in decision-making by accounting for probabilistic scenarios. This approach allows for more informed decision-making by considering the likelihood of different outcomes. However, SP can be computationally demanding, especially for complex systems with numerous uncertain variables, which may limit its applicability in real-time operations [116], [117], [118], [119]. Moreover, unlike RO, SP cannot provide immunization against uncertainties.

Information-gap Decision Theory (IGDT) addresses the inherent ambiguity in uncertain parameters by focusing on worst-case scenarios. IGDT is robust against severe uncertainties and provides decision-makers with insights into the performance under extreme conditions. However, IGDT may overlook less severe but more likely scenarios, potentially leading to suboptimal solutions [120], [121], [122]. Hybrid Stochastic Information Gap Decision Theory (HSIGDT) integrates features of both IGDT and SP, offering a balance between robustness and probabilistic modelling. By combining worst-case analysis with probabilistic considerations, HSIGDT provides decision-makers with a comprehensive understanding of system behaviour under uncertainty. However, the complexity of HSIGDT may pose challenges in implementation and interpretation [121], [123], [124], [125].

Adaptive Robust Optimization (ARO) is a dynamic approach that continuously updates optimization strategies based on real-time information. ARO adapts to the changing conditions, enhancing flexibility and responsiveness in decision-making. However, the effectiveness of ARO heavily depends on the accuracy and timeliness of information updates, which can be challenging to achieve in practice [126], [127], [128]. Stochastic Robust Optimization (SRO) combines robustness with probabilistic modelling, aiming to find solutions that perform well across various scenarios while considering their likelihood. SRO strikes a balance between conservatism and flexibility, offering robust solutions without overly sacrificing efficiency. However, SRO requires accurate estimation of probability distributions, which may be challenging in highly uncertain environments [114], [129]. Distributionally Robust Optimization (DRO) focuses on worst-case scenarios while incorporating uncertainty about the underlying probability distributions. DRO offers robust solutions against model misspecification, making it suitable for situations where the true distribution is unknown. However, DRO may lead to overly conservative solutions if the uncertainty set is poorly specified [108], [129], [130], [131], [132].

In summary, each optimization under uncertainty methodology has its advantages and limitations, which have been presented in the **Table A1** in the **Appendix**. While RO provides robust solutions, it tends to be overly conservative. SP offers probabilistic modelling but can be computationally demanding. IGDT focuses on worst-case scenarios but may overlook less severe uncertainties. The HSIGDT integrates aspects of both IGDT and SP but may be complex to implement. Moreover, ARO adapts to changing conditions but relies on timely information updates, while, SRO balances robustness and flexibility but requires accurate estimation of probability distributions. Moreover, it should be worth noting that DRO addresses model misspecification but may lead to overly conservative solutions. Overall, the choice of methodology depends on the specific characteristics of the problem and the trade-offs between robustness, efficiency, and computational complexity.

4.2.4 Validations and Metrics

Non-deterministic optimization problems, characterized by uncertain and variable parameters, necessitate robust validation methods and appropriate metrics to evaluate the performance of optimization algorithms. In-sample and out-of-sample analysis represent crucial validation techniques for non-deterministic optimization problems. In-sample analysis involves assessing the algorithm's performance on the trained data, ensuring that the optimization solution aligns well with the training set [133]. Out-of-sample analysis, on the other hand, evaluates the algorithm's generalization capability by examining its performance on data not included in the training set. This helps validate the algorithm's ability to handle unforeseen scenarios and provides insights into its robustness under diverse conditions [134]. Utilizing both in-sample and out-of-sample validation methods is essential for comprehensively assessing an optimization algorithm's effectiveness and reliability in real-world, non-deterministic settings [133], [134].

In terms of metrics for non-deterministic optimization problems, aggregated cost and coefficient of convergence play pivotal roles in evaluating the performance and efficiency of optimization algorithms. Aggregated cost represents the overall cost associated with the optimization process, considering both the objective function values and any associated constraints [135], [136]. This metric offers a comprehensive measure of the algorithm's ability to generate solutions that balance optimality with constraint satisfaction. The coefficient of convergence assesses the speed at which an algorithm converges to a solution, providing insights into its efficiency. A lower coefficient of convergence value indicates a faster convergence, which is crucial for practical applications where time efficiency is a critical factor [136], [137]. Together, these metrics and validation methods form a robust framework for assessing and comparing non-deterministic optimization algorithms, aiding in the selection of approaches that demonstrate both effectiveness and reliability in addressing uncertainties.

A summary of the literature review for energy and ASs provided by ADNs for TNs is presented in **Table A2** in the **Appendix**. This table summarises the objective of the study, support/ASs provided, control method, power flow modelling, optimization problem formulation approaches, test systems, optimization problem solvers, power system simulation tools, and uncertainties considered in the selected manuscripts at a glance.

5 Issues and Challenges

Based on the literature review, the following issues and challenges are identified, which can be addressed in future research.

5.1 Voltage Regulation

Several challenges in voltage regulation using reactive power are identified, including issues with the technical capability of providing the required reactive power characteristics, insufficient consideration of DG plant component impedances during planning operations, and the provision of requested reactive power at the connection terminals of DG units rather than at the Point of Common Coupling (PCC) for the entire DG [138], [139]. To address these challenges, it is essential to establish a proper definition and metric for reactive power and evaluate the reactive power capability of converter-interfaced DRESs. Additionally, the implementation of this AS adds costs to converter-interfaced DRESs, primarily due to active power losses within the converter and step-up transformers, leading to an overall reduction in efficiency [140]. These costs need to be considered and appropriately compensated during the modelling.

5.2 Primary Frequency Control

Currently, Synchronous Generation (SG) units receive compensation for their capacity offers and, in some cases, for the energy injected while providing services [170]. A significant challenge is outlined in the literature, which focuses on the involvement of DRES in PFR [171]. The study proposes a new approach to design frequency droop curves to ensure each distribution feeder delivers a reliable frequency response at the feeder head (transmission–distribution interface). However, concerns arise about individual units being unfairly penalized and not contributing adequately to the service. To address this, a solution is required to remunerate the aggregated service provided to the TSO and distribute payments to individual DRES/BESS providers based on their power output. A proper measuring system is crucial for accurate payment distribution.

5.3 Primary Frequency Control

Quantifying inertial response faces several challenges [141], [142]. Firstly, the inertial response is only detectable during significant frequency events, resulting in most cases having power deviations too small to estimate. Despite this, inertial response is consistently present and helps to stabilize the system during large frequency deviations. Secondly, when various DRES within a distribution system have different inertia constants, aggregating inertial response at the Point of Interconnection (POI) remains an open research issue. Lastly, the term "inertial response" is also used for FFR actions provided by DRES without fast ESS, making it a late inertial response that requires accurate measurement of frequency and RoCoF, posing challenges for precise quantification.

5.4 Power Smoothing

Currently, most grid operators do not officially recognize power smoothing as an AS. However, in isolated and RES-intensive power systems, grid codes may define maximum variability levels for DRES and consider power smoothing as a system support function [164], [165]. The effectiveness of power smoothing relies heavily on the deployment of Energy Storage System (ESS) technologies. Any hindrance to their use in providing additional flexibilities, particularly within distribution networks, can impede power smoothing. A study suggests that installing and controlling ESS to reduce the variability of PV units can significantly increase operating costs and the cost of power production [166]. Recovery of such costs depends on recognizing power smoothing as an AS and establishing a relevant market for it. Since TSOs primarily benefit from the service by reducing the number of units in reserve, introducing a market at the transmission system level that is parallel to the market for procuring PFR is essential.

5.5 Communication Infrastructure

There is a lack of sufficient infrastructure, communication, coordination, and control systems to provide Ass from ADN to TS. Sufficient market mechanisms and platforms are required for future service providers and prosumers. Data exchange mechanisms, data privacy, and cyber security issues for aggregating prosumers need to be addressed and new methodologies are required. There is a necessity to develop regulations for the coordination and cooperation between TSOs and DSOs to avoid conflicts and overlaps and to organize the services between TSOs and DSOs better.

5.6 Harmonic Mitigation

The concept of injecting specific harmonic currents to alleviate voltage harmonic pollution at certain nodes in the distribution system is currently not feasible due to international standards that establish limits on harmonic currents for connected facilities [143]. These standards, such as IEEE Std. 519–2014 [144] and IEC 61000-3-6 [145], either directly specify harmonic current limits or indirectly set them through voltage harmonic limits combined with system impedance considerations. Despite literature recognizing the potential of DRESs to mitigate harmonics as ASs, a revision of these standards is necessary to allow certain DRESs to function as active harmonic filters [146]. Additionally, the associated extra costs incurred by enabling the DRES to operate as an active filter have not been addressed yet.

5.7 Fault ride-through and Fault Clearing

A significant challenge in integrating DRES units into fault participation involves limitations on fault currents, especially in converter-interfaced DRESs, due to thermal constraints on switching devices [147]. This constraint makes it challenging to use conventional over-current protection techniques. Therefore, it is crucial to assess the converter's capability to provide fault currents [144]. Oversizing converters to meet this demand may result in additional costs for producers, which must be considered when offering the fault participation service [148]. Additionally, evaluating the benefits of having DRES inject specific currents during fault periods to maintain the selectivity of existing protection mechanisms, even under high DRES penetration, is essential.

6 Summary and Recommendations

In conclusion, the rapid integration of converter-based DERs into distribution grids signifies a transformative shift in the energy landscape, introducing both opportunities and challenges. The challenges, such as network congestion and voltage excursions, necessitate a proactive approach from DSOs in managing the inherent unpredictability in RESs. This report emphasizes the critical importance of enhancing cooperation between TSOs and DSOs to optimize the integration of DERs without the need for substantial investments in new network infrastructure. Moreover, exploring energy and AS provision from DERs to the transmission network is vital for maintaining power system integrity. The paper suggests that ASs are currently focused on the transmission system and mostly supplied by large-scale conventional units.

Nevertheless, the prevalence of DERs, especially those utilizing converters, is progressively replacing conventional units in the distribution system. The DRESs are recognized for their capacity to offer various new functionalities, currently classified as system-support functions in the grid-codes. Based on the presented literature review and evaluation of different research works in the TN/ADN coordination area, the following future recommendations can be made:

- The detailed system modelling for TSO/DSO studies would be challenging for practical systems due to the substantial data requirements, computational burden through co-simulation packages, and scalability issues. Therefore, a step-by-step method for an equivalent representation of the distribution system, considering grid feeding and grid forming resources, needs to be developed to study the interactions between the distribution system and the upstream grid.
- A promising research direction in this area is to develop a TSO/DSO coordination strategy incorporating DRESs by employing data mining and machine learning techniques to forecast uncertain behaviours based on historical data. This would reduce the need to obtain proprietary and commercially sensitive data, which frequently poses implementation problems in the traditional centralized and decentralized TSO/DSO coordination techniques.
- To facilitate prosumers' spontaneous participation, data exchange mechanisms, data privacy, and cyber security issues for aggregating prosumers need to be addressed.

6.1 Future Insights

Future insights from the literature review task are presented below:

+ The TSO-DSO coordination for providing frequency support and voltage support services from ADNs to TNs will be studied in this project. The provision of ancillary services from ADNs to TNs is outside the scope of this project.
+ DIgSILENT PowerFactory is a powerful software for power system modelling and performing static and dynamic analysis for different scenarios. We will use DIgSILENT for model simulation and GAMS as an optimization solver for the Ass design in ADNs.
+ Most of the reviewed literature used static nonlinear AC modelling for TSO-DSO interaction study because of the high complexity and computational burden of the quasi-dynamic and dynamic models. In addition, quasi-dynamic and dynamic modelling requires a considerable amount of data. Therefore, our study in the next phase will be limited to nonlinear Static AC modelling to assess the Ass from ADNs.

- Planned interaction between TSO and DSO, such as evaluating the services that DSO can provide to TSO, will be considered in the study. However, the unplanned interactions, such as power quality, short circuit, and fault issues are beyond the scope of the project.

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Appendix

Table A1. Comparison among different optimization under uncertainty methodologies

Optimization Under Uncertainty Approach	Advantages	Disadvantages	References
Robust Optimization	• Provides solutions that are robust against uncertainties in input parameters. • Guarantees performance across a range of scenarios, ensuring system reliability. • Low computation burden and simplicity in implementation and interpretation compared to probabilistic approaches.	• Tends to be overly conservative, potentially sacrificing efficiency for robustness. • Limited consideration of probability distributions, leading to suboptimal solutions under certain conditions. • May not capture the full range of uncertainties, especially in highly dynamic environments.	[108], [109], [112], [113], [114], [115]
Stochastic Programming	• Explicitly models uncertainty using probability distributions, offering a comprehensive representation of uncertainty. • Provides flexibility in decision-making by considering probabilistic scenarios. • Enables informed decision-making by assessing the likelihood of different outcomes.	• Computationally demanding, especially for complex systems with numerous uncertain variables. • Requires accurate estimation of probability distributions, which may be challenging in practice. • May not capture extreme scenarios adequately, leading to suboptimal decisions in worst-case situations.	[116], [117], [118], [119]
Information-gap Decision Theory	• Focuses on worst-case scenarios, providing robust solutions against severe uncertainties. • Offers insights into system behaviour under extreme conditions, enhancing decision-making in high-stakes environments. • Resilient against model inaccuracies and parameter uncertainties.	• May overlook less severe but more likely scenarios, potentially leading to suboptimal solutions. • Limited consideration of probabilistic information, which may result in overly conservative decisions. • Interpretation of results can be challenging due to the emphasis on the worst-case analysis.	[120], [121], [122]
Hybrid Stochastic Information Gap Decision Theory	• Integrates aspects of both IGDT and SP, potentially providing a balance between robustness and probabilistic modelling. • Offers comprehensive insights into system behaviour under uncertainty by combining worst-case analysis with probabilistic considerations.	• Complexity in implementation and interpretation, requiring expertise in both information-gap theory and stochastic programming. • Computational demands may be higher compared to IGDT methodology, limiting real-time applicability in some cases.	[121], [123], [124], [125]

	• Enhances decision-making by considering both extreme scenarios and probabilistic outcomes.	• The same problems of stochastic programming for the uncertain variables that will be modelled by SP	
Adaptive Robust Optimization	• Dynamically adjusts optimization strategies based on real-time information, enhancing flexibility and responsiveness. • Adapts to changing conditions, ensuring robustness in dynamic environments. • Improves decision-making by incorporating up-to-date information into the optimization process.	• Effectiveness heavily relies on the accuracy and timeliness of information updates, which may not always be achievable. • Computational complexity may increase with the frequency of information updates, potentially limiting real-time applicability. • Requires careful calibration and validation to ensure reliability and performance.	[126], [127], [128], [149]
Stochastic Robust Optimization	• Balances robustness with flexibility by considering both uncertain parameters and their probability distributions. • Provides solutions that perform well across a range of scenarios while accounting for their likelihood. • Offers a comprehensive representation of uncertainty, enabling informed decision-making.	• Requires accurate estimation of probability distributions, which may be challenging in practice. • Computational complexity may increase with the dimensionality of the problem and the number of uncertain variables. • May not capture extreme scenarios adequately, potentially leading to suboptimal decisions in worst-case situations.	[114], [129], [149]
Distributionally Robust Optimization	• Addresses model misspecification by focusing on worst-case scenarios while incorporating uncertainty about the underlying probability distributions. • Offers robust solutions against model uncertainties, making it suitable for situations where the true distribution is unknown. • Enhances decision-making by considering a wide range of potential distributional uncertainties. • Mitigates the over-conservativeness problem of robust optimization. • Capable of employing available distributional information.	• Construction of an appropriate ambiguity set can be a challenging task, while the efficiency of distributionally robust optimization depends on it. • Computational complexity may increase with the complexity of the ambiguity set and the uncertain variables. • Requires careful calibration and validation to ensure the reliability and robustness of the solutions.	[108], [129], [130], [131], [132]

Table A2. A summary of the literature review for energy and ancillary services provided by ADNs for TNs

Ref.	Target (main objective function)	Support/Ancillary Service Provided	Control Method	Power Flow Model	Optimization Problem Formulation	Test Systems			Optimization Problem Solver	Power system Simulation Tools	Uncertainty
						HV Network	MV Network	LV Network			
[88]	To minimise the network losses	Reactive power support	Distributed	AC OPF	MINLP	External Grid/Infinite bus	Detail modelling of the IEEE 33-bus network	N/A	IPOPT	GAMS, OpenDSS and MATLAB	Not considered
[92]	To minimise the real-time voltage-tracking mismatch while satisfying local physical network constraints	Voltage support	Distributed	AC OPF	Dynamic Online Optimization Framework - Online Convex Optimization (OCO)	The DN is connected to a TN. The TN can update the voltage set point that DN follows	Detail modelling of the IEEE 33-bus test feeder (12.66 kV) and the IEEE 123-bus test feeder (4.16 kV)	N/A	MATLAB/ Matpower	MATLAB/ Matpower	Not considered
[86]	To minimise the cost of DER control and the network losses. It also optimises the costs of providing voltage support to the TN	Voltage support	Centralized	Backward/ Forward Sweep (BFS) PF {BFS-OPF uses a good approximation of the nonlinear AC OPF}	MILP	Thevenin equivalent of the Swiss system	Detail modelling of European MV grid (balanced single-phase)-the Swiss case	Detail modelling of European LV grid (balanced single-phase)-the Swiss case	Gurobi	MATLAB, YALMIP	Not considered
[31]	This is not an optimization problem.	Primary frequency response	Decentralized - P(f) droop control	AC OPF	N/A	External grid	The European MV benchmark grid of CIGRE	N/A	SciPy library	Python - Sequential Least Squares Programm	Forecast error is considered

										ing (SLSQP)	
[87]	To minimise sustainability deterioration, i.e., to maximise the injected active power from renewable PV generation.	Voltage support	Centralized	AC OPF	MINLP model formulation and then linearise to MILP	N/A	Infinite bus	Detail modelling of the modified version of the 18-node CIGRE two-feeder unbalanced LV network;	IPOPT (NLP), CPLEX (MILP), BONMIN (MINLP)	GAMS	Not considered
[8]	To minimise the DN operation cost	Frequency regulation	Centralized	Chance-Constrained (CC)-OPF using BFS algorithm	Mixed-integer quadratically constrained program (MIQCP)	External Grid	MV ring model	Detail modelling of CIGRE LV network (balanced single phase)	YALMIP, Gurobi	MATLAB	PV generation and forecast errors
[93]	This is not an optimization problem.	Voltage support	Coordinated control with Decentralized and Distributed levels	AC OPF	N/A (time-series power flow simulations)	1st system: N/A 2nd system: N/A 3rd system: Thevenin equivalent	1st system: External grid (MV substation.) 2nd system: Detailed modelling of DS 3rd system: detailed modelling	1st system: Detailed modelling of a practical LV network 2nd system: Lumped modelling 3rd system: detailed modelling	MATLAB	OpenDSS; MATLAB/ Matpower	Not considered
[89]	To minimise the active power and reactive power drawn/imported from the transmission	Ancillary services	Centralized	AC OPF	MINLP	External grid	Detail modelling of modified 34-bus distribution network	N/A	CONOPT	GAMS	Not considered

	system, or equivalently to maximise the power injected/exported into the transmission system, while maximise these powers.										
[28]	To minimise the daily microgrid operation cost	1-minute frequency regulation, 10-minute load following, hourly ramping	distributed	DC OPF	MILP	N/A	A practical microgrid with four dispatchable units, two non-dispatchable units including wind and solar, one energy storage, and five adjustable loads	N/A	CPLEX	GAMS	Not considered
[96]	This is not an optimization problem.	Voltage support	decentralized	AC OPF	N/A	Detail modelling of IEEE 4-bus system; bus-1 is modelled by a Thevenin equivalent	Detail modelling of MV network	Detail modelling of LV network	N/A	RAMSES	Not considered
[84]	To maximise the profit from trading in the Day-Ahead Market (DAM) and Ancillary Services Market (ASM) while also minimising the imbalance costs that may be incurred	Frequency Containment Reserve (FCR), Frequency Restoration Reserve (FRR)	Centralized (RES aggregator)	DC OPF	Stochastic - MILP	N/A	Detailed model of the Greek power system	Aggregated model of distributed resources	CPLEX	GAMS	wind generation, day-ahead and real-time locational marginal prices, and

	due to mismatches between traded and actual RES production.										deviation penalty rates
[37]	This is not an optimization problem.	Enhance the Dynamic Thermal Rating of Transmission Lines	Centralized	Weather-based OPF/AC OPF	N/A	External grid	Detail model of the Italian sub-transmission system (10-bus 150 kV test network)	Lumped load	fmincon function	MATLAB	power injection fluctuations, conductor parameter drifting, and weather volatility
[3]	This is not an optimization problem. Dynamic and transient studies are conducted and validated through hardware-in-the-loop testing.	Voltage ancillary Services (Both static and dynamic reactive support)	Centralized	N/A	N/A	Detailed model	Detailed model	N/A	N/A	DIgSILENT PowerFactory, PSCAD/EMTDC	Not considered
[38]	To minimise the flexibility request and losses.	to provide voltage and congestion support AS	N/A	N/A	Stochastic - MILP	N/A	External grid	Detailed modelling of the real residential Junglinster LV network (data provided by CREOS, Luxembourg's TSO/DSO).	CPLEX	GAMS	End user uncertainty

[97]	This is not an optimization problem.	N/A	Coordinated control	AC OPF	N/A	Infinite bus/ External grid	the IEEE 123-bus test feeder (4.16 kV)	N/A	N/A	MATLAB	Uncertainty of transfer capability (Probabilistic model of linear discriminant analysis-LDA)
[150]	This is a report from Global PST consortium.	Frequency response, more flexibility for real-time balancing, voltage control, congestion management, power system restoration, resource adequacy	Centralized	N/A	N/A	N/A	N/A	Most DNSPs in Australia do not have validated/ complete electrical LV circuit models.	N/A	N/A	Uncertainties are due to the weather-related variability of renewable generation, the local settings (e.g., frequency response, Volt-Watt functions, etc.) and the future uptake of the technology.
[151]	This is a report from Project EDGE.	To provide network support services (such as wholesale market arbitrage,	N/A	N/A	N/A	N/A	N/A	3-phase LV network modelling from the “CSIRO LV Network Taxonomy	N/A	OpenDSS used in the “CSIRO LV Network Taxonomy Report”.	Forecast uncertainty. Especially, the power flow of non-participating

		Frequency Control Ancillary Services (FCAS), Reliability and Emergency Reserve Trader (RERT) contracts, Dynamic Network Pricing or local network support services (NSS))						Report" for city and suburban network to determine Dynamic Operating Envelope (DOE)		PowerFactory, OpenDSS, PSS/Sincal	customers is a large source of forecast uncertainty.
[91]	To estimate the hourly flexibility areas at the TSO-DSO interface that maximise the daily flexibility capacity of the distribution grid.	Active and Reactive Power flexibility	N/A	AC OPF	Nonlinear	Infinite Bus	Detailed modelling of the 20kV radial three-phase MV network	N/A	BONMIN	GAMS	Not considered
[34]	To minimise the net reactive power demand at the substation for the grid	volt/var ancillary services	Distributed	Distributed OPF (AC OPF)	Linearised	Detailed modelling of IEEE 9-bus transmission system	highly detailed unbalanced 3-phase distribution system of the IEEE 13-bus distribution feeder	N/A	MatPower for transmission solver, GridlabD for distribution solver	MATLAB	Not considered
[33]	Multi-objective function is to minimise the operating cost of the transmission	Reactive power ancillary service	Distributed market clearing	Both AC and DC OPF	linearised using the binary		Detailed modelling of the IEEE 5-bus and the IEEE	Detailed modelling of the modified	The general alternating direction method of	N/A	Not considered

	network comprising the network loss penalty term, reactive power generation cost, and the reactive power ancillary service (RPAS).		mechanis m		expansion (BE) method.		30-bus transmission network	IEEE 33-bus ADNs.	multipliers (ADMM) consistency optimization method		
[36]	To minimise the cost of reserve activation	Services related to energy balancing and congestion management.	Decentrali zed	DC OPF	Linear	Detailed modelling of IEEE 5-bus transmission system	Detailed modelling of IEEE 18-bus distribution system	N/A	MATPOWER	MATLAB	Not considered
[11]	It is not an optimization problem.	Manual frequency restoration reserve and congestion management services	N/A	TN- DC OPF DN- AC OPF	N/A	The test cases are considered from the European project SmartNet (http://smartnet-project.eu/). Detailed modelling of Italian and Danish power systems	N/A	N/A	JuMP LPs, SOCPs, MILPs, MISOCPs, are solved using Mosek; NLPs are solved using IPOPT.	Julia GAMS	Not considered
[152]	It is not an optimization problem. Simulation study is performed.	The dynamic voltage control and the provision of reactive services	N/A	N/A	N/A	Detailed dynamic modelling of transmission network in Great Britain (Southeast region)	Detailed dynamic modelling of transmission network in Great Britain (Southeast region)	N/A	N/A	N/A	Not considered

[29]	To minimise total operation cost, the system power balance cost and the power imbalance cost	Energy and reserve support	Distributed	DC OPF for TS AC OPF for DS	Stochastic-MILP	Detailed modelling of 6- bus and 118-bus transmission networks	Detailed modelling of 2-bus, 10-bus and 30 bus distribution networks	N/A	CPLEX	MATLAB	source-load power uncertainties
[95]	The objective of the DSO is to minimise the cost defined as the sum of the cost resulting from the energy and reserve provided by the resources of the DS and the cost paid to the TSO for the energy and reserve in the day-ahead clearing market.	Reserve service	Centralized and local market	DC OPF for TS Linearised AC OPF for DS	N/A	Detailed modelling of IEEE 30-bus and 343-bus transmission system	Detailed modelling of IEEE 33-bus and 110-bus distribution system	N/A	N/A	MATLAB	Not considered
[90]	To optimise ES siting and sizing decisions for the coordinated operation of the transmission and distribution systems	wholesale electricity market managed by the TSO, installed ES units can provide both the transmission and distribution system support.	N/A	DC OPF for TS AC OPF for DS	mixed-integer quadratic programming (MIQP)	Detailed modelling of the IEEE 118-bus transmission system	Detailed modelling of the IEEE 33-bus radial distribution systems	N/A	JuMP Gurobi	Julia	Not considered
[30]	To minimise flexibility procurement cost.	Flexibility support (the ramping capacity	Centralized solution	DC OPF	N/A	Detailed modelling of the IEEE 30-bus	Detailed modelling of two IEEE 33 mode ADNs	N/A	MOSEK	CVX toolbox of MATLAB	uncertainty of renewable generation

		(power) demanded by the TSO for power balancing services in real-time dispatch.)				transmission network					
[85]	To maximise the social welfare, i.e., utility of demands minus the production cost of conventional generators, renewable power units, and the load curtailment cost.	Regulation service provision	N/A	AC PF	Mixed integer linear problem	Detailed modelling of the IEEE 24-bus reliability test system	Lumped modelling of radial distribution network	N/A	MOSEK 8.0	MATLAB using CVX	the renewable power generation uncertainty is considered