Borenius, Seppo; Kekolahti, Pekka; Hämmäinen, Heikki; Lehtonen, Matti; Mähönen, Petri

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RESEARCH ARTICLE

Novel Industry Architectures for Connectivity Solutions in the Smart Distribution Grids

SEPPO BORENIUS, (Member, IEEE), PEKKA KEKOLAHTI, HEIKKI HÄMMÄINEN, MATTI LEHTONEN, AND PETRI MÄHÖNEN
School of Electrical Engineering, Aalto University, 02150 Espoo, Finland
Corresponding author: Seppo Borenius (seppo.borenius@aalto.fi)

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ABSTRACT The electric energy system is undergoing a major change due to the increasing requirements of dynamic performance. In distribution grids, this evolution will necessitate expanded automation, which in turn will require enhanced connectivity solutions. Strongly evolving communications technologies and architectures, particularly mobile communications as well as cloud and edge computing, will provide new opportunities and alternatives for connectivity solutions. This paper contributes by identifying potential technical and industry architectures for the connectivity solutions required to manage distribution grids in the early 2030s. The study utilizes a senior expert panel and a Delphi survey. Industry architectures are modelled as value networks. The paper uses the Finnish distribution grids as a case example. Regarding technical architectures, the results reveal skepticism concerning those emerging 5G mobile network features that target industrial applications and about the need for extensive distributed computing in the proximity of consumers and prosumers. The most probable industry architectures are found to be those that enable the Distribution System Operators (DSOs) to maintain direct control of critical technical components, or that enable Communications Service Providers (CSPs) to handle the operations of both communications solutions and distributed computing. CSPs are seen as well positioned for this task due to their existing networking and computing infrastructure. However, this may also involve business risks for both DSOs and CSPs.

INDEX TERMS Cloud computing, communications, distributed computing, edge computing, industry architectures, mobile communications, overlay networks, power grids, smart grids, value networks.

I. INTRODUCTION

Power grids are evolving into dynamic meshed smart grids consisting of distributed intermittent renewable generation, electricity storageand active consumers (Fig. 1). Such smart grids will suffer from lower system inertia due to a decreasing number of large synchronous generators. While the evolution is vital in order to create a sustainable energy system, it poses a challenge to grid management. Controlling the power balance and maintaining an adequate continuous energy supply will require seamless co-operation between transmission and distribution grids. In distribution grids, intermittent inverter-based generation is likely to cause problems with voltage levels and other power quality aspects, as well as with protection solutions. These issues, together with the requirement of enhanced co-operation with the transmission grid, will necessitate more extensive automation in distribution grids, which in turn will require enhanced connectivity. The latest communications technologies and architectures, particularly fast evolving mobile (cellular) networks as well as cloud and edge computing, will provide interesting opportunities and alternatives to implement connectivity in geographically large distribution grids. This paper contributes by identifying and analyzing the potential technical and industry architectures necessary in providing connectivity solutions for the distribution grids of the early 2030s.

This study assumes that similar to today, we can expect that in the early 2030s, one organizational entity, a Distribution System Operator (DSO), will continue to be responsible for

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the management and operation of a distribution grid. Another alternative - not included in this study - could be a pure peer-to-peer model consisting only of directly inter-connected micro grids operated by energy communities without utilizing any distribution grid. The tasks of a DSO include the maintenance and operation of power lines and cables, maintenance and operation of electric power equipment such as transformers and switching gear, maintenance of physical buildings and facilities such as primary substation sites and substation sites, managing voltage levels and other aspects of power quality, as well as managing the security of the grid. In this study, we discuss the role of active users and electricity markets only to the extent needed to analyze the information and communications technology (ICT) solutions necessary for managing and operating the evolving distribution grid. As a case example, we use 76 Finnish distribution grids [1]. These 76 DSOs and their grids vary greatly in size, with the fifteen largest DSOs covering 70% of the total Finnish distribution network in terms of grid size, number of customers and sales in a country with a population of only 5.5 million inhabitants covering a fairly large area of 304,000 square kilometers [2].

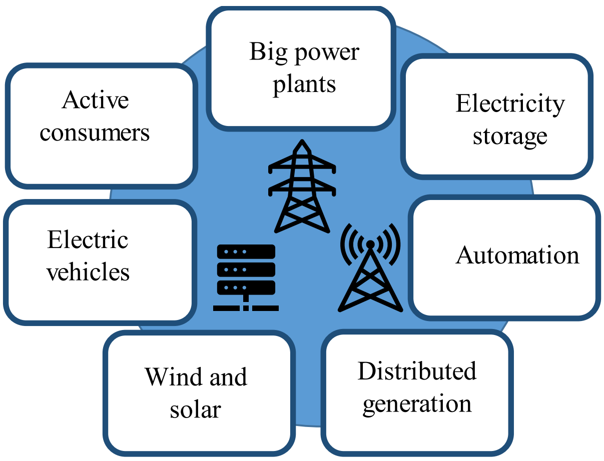

FIGURE 1. Dynamic meshed smart grids.

The study seeks answers to three research questions (RQ):

RQ1: What is the potential of a connectivity architecture supporting overlay networking and edge computing functionalities for distribution grid management?

RQ2: What are the potential business actors and industry architectures (modelled as value networks) needed to operate such a connectivity architecture? What are the most probable value networks in the early 2030s?

RQ3: What are the reasons that certain value networks will be more probable than others in the early 2030s?

The rest of the paper is organized as follows. Section II describes the applied Value Network Configuration (VNC) and Delphi methods. Sections III and IV provide background, with Section III summarizing the current status of networking technologies and their evolution, while Section IV provides an overview of state-of-the art research on the role of communications in power grids, as well as on power grid business actors and industry architectures. The results are presented in the following two sections: Section V provides the value network analysis, while Section VI elaborates these value networks through the Delphi process. Finally, Section VII provides a summary and concluding remarks.

II. METHODS

This study first outlines new technical connectivity architectures to address the distribution grid connectivity challenge described in Section I, followed by candidate industry architectures, according to the Value Network Configuration (VNC) method. The likelihood, advantages and disadvantages of these technical and industry architectures is then estimated using a senior expert panel and a Delphi survey.

A. VNC METHOD

In a value network, the actors interact with each other to create value, i.e., benefit for the entire group. As the name indicates, value networks are suitable for networked business environments, while other methods, such as value chains [3] consisting of a chronological process spanning from suppliers through production to customers, might be more applicable to businesses such as manufacturing. Compared to traditional value networks or value chains, which typically focus on a single company, the VNC method is an industry-level value analysis framework that visualizes the relationships from the whole systems perspective both on technical and business levels [4], [5], [6]. VNC method makes it possible to describe the interplay between technological components, roles, and actors more systematically than the other methods. Once industry architectures have been created and analyzed using the higher level VNC method, individual business models of each stakeholder could be further studied by utilizing for example Business Model Canvas [7].

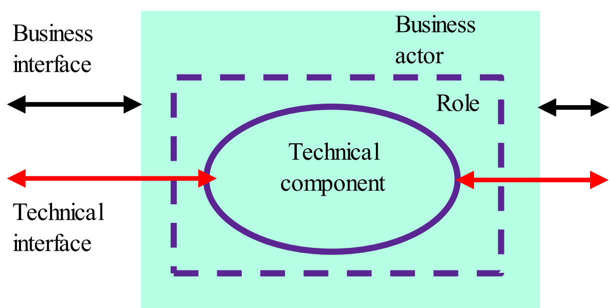

FIGURE 2. Components in Value Network Configuration (VNC) method.

The VNC method has two layers: a static technical architecture and a dynamic industry architecture on top of the technical architecture (Fig. 2). The technical architecture consists of technical components interconnected by technical interfaces such as a wireless local area network (Wi-Fi) router and the Ethernet cable connecting that Wi-Fi router to the central switches and routers of the enterprise, respectively. As shown in Fig. 2, the role links the technical and industry

TABLE 1. The parameters employed in this study compared to established guidelines.

Survey	Number of experts	Expertise areas	Number of rounds	Consensus measure	Survey process	Controlling judgement bias
Proposed in [11], [12],[13], [14]	8-18	Expertise in at least four areas, such as 5 years expertise in the business domain, a managerial role, a writer of a research paper, invited presenter at a conference, or a faculty member of an institute.	2-6	Standard deviation or absolute deviation	The interview process was the same for all; questions in randomized order; questions received in advance; feedback as the mean response; the answers are justified with reasons (arguments)	Anonymity among the panelists; randomized order of questions between the panelists; panelists with only recent experience were excluded; conduct multiple rounds; reasons were required in the feedback
This survey	A total number of 27 panelists, 10-18 per expertise domain	Each of the panelists on professional level in one or more of the seven defined expertise domains	2	Standard deviation	Same as above	Same as above

architectures. A role is an activity performed on a technical component, such as managing (role name ''Manage'') or operating (role name ''Operate'') the Wi-Fi router. The industry architecture is formed through the creation of different value networks by allowing business actors (stakeholders) to adopt different roles on top of the technical architecture. Thus, the technical architecture does not vary between the value network configurations. Business interfaces, e.g., contracts, are established between different actors, depending on the roles taken by the actors. Hereinafter, we use the acronym VNC to refer to a value networks in a generic sense (i.e., not only as the name of a specific method to create value networks).

B. DELPHI METHOD

Multiple methodologies exist for eliciting expert opinions and achieving consensus, including brainstorming [8], the Nominal Group Technique (NGT) [9], the RAND/UCLA Appropriateness Method (RAM) [10] and the Delphi method. The Delphi method [11], [12], [13], [14] is a widely used survey technique where, compared to other methods, face-to-face contacts among panelists are not allowed [11] to reach a common consensus without group bias. The inclusion of this feature was imperative for the participation of numerous experts in the panel, primarily driven by confidentiality considerations. Limitations of the Delphi method include the absence of open expert discussion, susceptibility regarding expert identification, and the potential for bias in participant selection. Nevertheless, these limitations can be mitigated through the precise definition of expertise and careful selection of panel members, as described later in this section.

The Delphi method contains multiple parameters to be considered for a successful nonbiased survey, including the selection of panelists and their number for the survey as well as the number of review rounds used. Although a large number of participants is possible, the number for a personal interview is kept low due to practical reasons, varying between 8 and 18, as can be seen from Table 1. Based on the data presented in Table 1, the parameters employed in this study adhere well to the established guidelines provided in the literature.

The panelists were selected based on their recognized expertise in the following seven expertise domains: information and communications technology integration (ICT), technology and business consulting (Consulting), communications network equipment provider business (NE), power grid management (Power grid), R&D in academia (Academia), mobile network operator business (MNO), and cloud computing technology and business management (Cloud). The panel consisted of 27 senior experts, each of whom conducted a self-assessment to classify their degree of competence in the above-mentioned expertise domains into the following categories: *no expertise*, *basic*, *professional*, and *world-class* expertise. The amount of either professional or world-class expertise of a panelist varied between 1 and 7 expertise domains, with an average of 3.8 per person. Table 2 shows the number of *professional* and *world-class* experts in each of the expertise domains. As can be seen from the table, the expertise distribution is slightly skewed towards the ICT and Consulting domains. However, the number of experts per each expertise domain remains within the range of 8 to 18. In our perspective, a skewed distribution can be considered acceptable due to two main reasons: achieving a perfectly even distribution among panelists is in practice challenging and the communication technologies examined in this study fall under the domain of Information and Communication Technology (ICT). The panelists were interviewed individually in two rounds. The task of each panelist was to estimate the probability that a certain presented VNC will be in commercial use at least within one DSO in Finland by 2030. This survey question was presented in the following form:

What is the probability that at least one distribution grid will operate according to the presented technical and industry architecture?

TABLE 2. The number of professional and world-class experts in each expertise domain.

Information and communications technologies integration (ICT)	18
Technology and business consulting (Consulting)	17
Network equipment provider business (NE)	16
Power grid	14
R&D in academia (Academia)	14
Mobile network operator business (MNO)	14
Cloud computing technology and business management (Cloud)	10

To help the panelists in estimating the probability for each VNC shown, a typical dependency between a verbal expression of likelihood and probability value range was used, as expressed in [15]: *almost no chance* (1-5%), *very unlikely* (6 - 20%), *unlikely* (21- 45%), *roughly even chance* (46 - 55%), *likely* (56 - 80%), *very likely* (81 - 95%), or *almost certain* (95 - 99%). In addition, the panelists were asked to present three arguments (reasons) to justify the given probability value. As the argumentation was not constrained in any way, it could be related to themes such as revenue, costs, risks, technical aspects, actors' competence, politics, security, environmental aspects, regulation, or legislation. This approach was repeated in the second round, though this time each panelist was first informed how his or her probability compared to the average of the first round. Furthermore, the panelists were given a summary of their own arguments during the first round, as well as information about the most common arguments given by other panelists. After having received this new information, the panelists were then allowed to adjust the probability value they had given during the first round.

III. FUTURE COMMUNICATIONS NETWORKS

This section summarizes the status of communications networks and the technology trends, taking the context and potential needs of the evolving electric distribution grids into account. The wireless and fixed connectivity technologies covered consist of mobile (cellular), optical, wireless local area networks (Wi-Fi), ultra/very high frequency (UHF/VHF) private radio, satellite communications, as well as cloud and edge computing. Particular focus is placed on the mobile technologies due to their strong evolution and fairly recent attention in industrial applications.

Since its launch in 2017-2019, the 3rd Generation Partnership Project's (3GPP) 5th generation (5G) networks have targeted the industrial and business sectors (referred to as verticals in 3GPP terminology), in addition to the traditional consumer segment [16]. Currently, 5G forms the mainstream of 3GPP's specification work, though 4G launched originally in 2008 has also been further developed in parallel with 5G. Furthermore, initial research aimed at 6G is currently ongoing, with the first 6G networks being expected to emerge in the early 2030s [17]. At that point in time, 5G probably will form the mainstream technology, even though there could still also be 4G deployments co-existing with 5G networks. 5G can be considered revolutionary due to its industrial focus and its new virtualized Service-Based Architecture (SBA) for controlling both the core network and the radio access network (RAN). Conversely, 5G can be considered evolutionary due to the similarity of the 4G and 5G air interfaces, as well as backporting of successful 5G features into 4G and end devices seamlessly supporting both the 4G and 5G networks. The 5G features of particular interest for electric power grids are listed in Table 3. As of early 2023, many of these features have not yet been implemented nor deployed in commercial products. In fact, the only 5G feature widely deployed is enhanced Mobile Broadband (eMBB), which is essentially a faster 4G targeting the traditional consumer segment. At the time of writing (early 2023), the main 3GPP work is currently focusing on both Release 18 specifications, which has been branded as the first 5G Advanced release, and on early Release 19 activities [19], [20]. Earlier 3GPP 5G releases have studied the specific needs of many industrial segments (verticals). Now, in Release 18, the electric energy system will also receive specific attention, including discussion on frequency control, voltage control, distribution automation, load control, as well as distributed generation and energy storage control [21].

Optical fiber as a communications channel offers inherently high bandwidths and a good basis for security, because of its high frequencies and insensitivity to electromagnetic interference. Advances in optical pluggable transceiver technologies enable integration of routing and traditional optical layers [22], [23], [24]. Currently, commercially deployed 400G ZR transceivers, which can be directly mounted on a router Ethernet port, are capable of transferring a 400 Gigabit Ethernet on a single wavelength over a 100 km long optical cable. Mobile networks are also primarily optical networks – only the last hop between the base station and the end device is wireless. However, this last hop introduces a physical air channel which is essentially harder to control than the optical one. Wi-Fi 6 is the latest commercially deployed Wi-Fi Alliance wireless network protocol generation based on the IEEE 802.11 family of standards [25]. It was introduced to the market in 2019 and supports the traditional unlicensed 2.4 GHz and 5GHz bands. The Wi-Fi 6 technology, termed Wi-Fi 6E, was extended to the new 6 GHz band in 2021. The 6 GHz band allows essentially higher bandwidths, up to 1.2 GHz depending on the jurisdiction, enabling multi-gigabit speeds and latencies below 1 ms. IEEE has already begun work on the next generations, with Wi-Fi 7 being possibly available already in 2024 and Wi-Fi8 in 2028. Wi-Fi focuses on local networks and unlicensed bands. Nevertheless, IEEE standards currently exist to enable longer distances for limited throughput IoT-type communications (802.11ah Wi-Fi HaLow) and some licensed bands (802.11y) [26], [27]. So far, these have received little attention and remained niche technologies. In local industrial applications, such as factories, 5G Non-Public Networks might challenge Wi-Fi, as well as optical technologies in particular if licensed spectrum is available. However, the advantages of Wi-Fi and optical

TABLE 3. 5G features of particular interest for electric power grids.

5G Feature	Description
Ultra-Reliable Low Latency Communications (URLLC)	99,999% reliability and 1 ms latency in the radio interface
Massive Internet-of-Things (MIoT) and High-Performance Machine-Type-Communications (HMTC)	For large-scale sensoring
Slices	A logical overlay network on top of the physical network for specific communications requirements, such as those related to throughput and reliability
Timing as a service	Accurate (comparable to GPS) time information to the end devices
Non-Public Networks	Local mobile network deployments, for example at factory sites
Support for higher frequencies (above 24 GHz, i.e. mmWave)	Very high throughputs at short distances
Mobile Edge Computing (MEC)	Support for local processing close to the end devices
5G LAN-type service	Ethernet communications over a mobile network (instead of the traditional IP) [16], [18]

networking include easy deployment and inherently reliable physical channel, respectively.

In Finland, UHF private radio operates on the 135-175 MHz band, while the VHF frequency range covers 400-470 MHz. In industrial monitoring and control applications for large geographical areas such as distribution grids, data rates are typically around 20kbps over a narrow private spectrum band of 12 or 25kHz at maximum ranges of 30-50 kilometers [28].

Satellite communications have been evolving at an accelerating pace and become more affordable over the past five years, driven by reduced space craft launch costs and innovative entrepreneurs [29]. Elon Musk's SpaceX and Starlink with its Low Earth Orbit (LEO) satellites are already offering commercial broadband services, with Jeff Bezos' project Kuiper and the British OneWeb targeting the same services [30], [31].

Cloud computing has been a strong trend in the IT industry for more than a decade [32]. Businesses are switching from hosted on-premises applications to cloud-based software solutions, thus enabling companies to pay flexibly on an as-needed basis and offering virtually infinite resources without the need to invest in and maintain their own computing platforms and solutions [33]. The term cloud computing refers to both the applications and services delivered from a remote location over the Internet, as well as to a pool of computing resources such as servers and storage in data centers on which those applications and services are run [34], [35]. The typical delivery (service) models of cloud computing include Software as a Service (SaaS), Platform as a Services (PaaS) and Infrastructure as a Service (IaaS). These models refer to running applications and services in the cloud, development and deployment of applications and services utilizing a cloud-provider specific toolset, as well as to allowing fine-grained access to computing, storage and networking resources [36], [37]. Edge computing [38], [39] refers to placing computing resources, applications and services as well as related server, networking and storage capabilities at the edge of the network close to the users and end devices such as IoT sensors. Edge computing is a form of distributed computing that aims at lower latencies between end devices and the computing platform as well as reducing the data volumes on wide area communications networks [40].

IV. STATE-OF-THE-ART RESEARCH

This section provides an overview of the state-of-the-art research on the role of communications in power grids, as well as on the new business actors and industry architectures involved in distribution grid management.

A. COMMUNICATIONS NETWORKS IN POWER GRIDS

Many recent reviews and surveys have focused on communications technologies in distribution grids [41], [42], [43], [44], [45], [46], [47]. They all describe as background how traditional power grids are gradually transitioning into smart grids enabling integration of distributed intermittent generation and active prosumers, as well as how this evolution necessitates more extensive use of ICT in the power grids to ensure stable operations.

In [41], the authors study communication technologies, architectures and applications related to IoT-assisted smart grids. The term IoT-assisted smart grid refers to the need to deploy a large number of monitoring and controlling devices into the grid in order to enable large-scale integration of various distributed energy sources (RES) and self-healing for ensuring reliability. The paper divides the topology of an IoT assisted smart grid communications network into three domains: (1) Wide Area Networks (WAN) covering power generation and transmission, (2) Neighborhood Area Networks (NAN) covering distribution, and (3) Home Area Networks (HAN) covering prosumers and consumers, including management of their Electric Vehicles (EVs) and distributed generation. With a particular focus on consumers and prosumers, the authors introduce a cloud-based model and a web-based model to manage HANs as well as introduce flexibilities and savings. The paper provides an overview of both IoT-specific communications technologies, such as NB-IoT, and generic communications technologies, such as cellular and optical communications, as well as summarizes their main application domains (WAN, NAN, HAN). According to the authors, cybersecurity is a particular area of concern, partially driven by the limited resources in IoT devices.

In [42], the authors study active distribution network communication technologies, applications and communication standards. The term Active Distribution Network (ADN) refers to distribution networks that have the necessary automation and ICT systems in place to enable large-scale integration of distributed energy resources and that can address related issues such as bi-directional power flows and varying voltage level [42], [48]. The paper identifies six active distribution grid applications: (1) Advanced Metering Infrastructure (AMI), (2) Demand Response (DR), (3) Wide-Area Situational Awareness (WASA), (4) Distributed Energy Resources (DERs) and Energy Storage (ES), (5) EVs, and (6) Distribution Management Systems (DMS). The communications requirements for each of these applications are defined in terms of latency, data rate, security and reliability requirements. Similar to [41], this paper divides the smart grid communications and information system architecture into three domains: (1) WANs covering power generation and transmission, (2) NANs and Field Area Networks (FANs) covering distribution, and (3) HANs, Building Area Networks (BANs), and Industrial Area Networks (IANs) covering consumers and prosumers. The authors' extensive review of communications technologies includes both wired and wireless technologies, describing their applications areas in the preceding three domains, as well as listing their advantages and disadvantages. The challenges facing ADNs are related to interoperability, security, privacy concerns, and the demand for a more extensive set of applications and services. Research trends for ADNs include Energy Internet (EI), big data analytics, machine learning, edge computing, and blockchain applications.

In their survey article [43], Goudarzi et al. review the architecture and infrastructure of IoT-enabled smart grids and discuss their challenges. The four enablers for IoT-enabled smart grids comprise (1) cloud computing, (2) communications networks, (3) edge computing, and (4) physical entities for control and monitoring of the grid. The paper extensively studies the increased vulnerability to cyber and physical attack introduced by more pervasive use of ICT, highlighting game-theoretic models and deep learning methods as potential solutions. The former method could particularly address energy market related risks, while the latter could help to understand normal versus abnormal system behavior.

In [44], Suhaimy et al. discuss the convergence of Operational Technology (OT) and Information Technology (IT) in their overview of different networking technologies and physical communications media. In [45], the authors review smart grid evolution trends followed by a proposal for a next generation smart grid architecture driven by Artificial Intelligence (AI), IoT and 5G. They also make multiple proposals, such as exploring more extensive usage of unlicensed spectrum, to promote smart grid evolution. Abrahamsen et al. [46] divide the smart grid communications architecture into three domains in the same manner as [41] and [42]: WAN, NAN and premise network, covering conventional power generation and transmission, power distribution and end-users, respectively. The authors then provide an overview of different communications technologies, both wired and wireless, in these domains, including application areas, advantages and disadvantages.

De Almeida et al. [47] discuss a means to increase resilience in power grids in their overview of different communications technologies. The authors identify three important techniques to increase resilience: (1) teleprotection (i.e., utilizing protection solutions where protection relays communicate with each other over a communications channel), (2) power grid self-healing, and (3) extensive communication with control centers and reclosers. Uzir et al. [49] present a proof-of-concept how Multi-Protocol Label Switching – Transport Profile (MPLS-TP) based fixed wide area networking can be used for teleprotection. Hovila et al. [50] have explored and tested the usage of mobile networks as a communications channel in line differential and inter-trip protection applications. Their results indicate that 4G networks are very close to fulfilling the practical latency requirements but struggle with providing high reliability. Both emerging 5G URLLC and slicing techniques aim at addressing the reliability issue and further decreasing latencies. Adrah et al. [51] provide a theoretical analysis of utilizing 5G in a line differential protection application, in addition to discussing two other 5G use cases in distribution grids: intelligent distributed feeder automation and fault location detection with synchronized Phasor Measurement Units (PMUs). The authors state that latencies can be further reduced by utilizing Mobile Edge Computing (MEC) to shorten the communication path.

In [52], edge computing supported fault indication has been tested using 5G networks. The results indicate the total data rate in urban areas to be the limiting factor due to uplink capacity constraints. By contrast, in rural areas, achievable latencies are more critical due to the longer distances. In [53], Minh et al. provide a summary of edge computing applications so far identified in the state-of-the-art research, including distributed generation control, Volt/VAR control, as well as a transforming the traditional centralized Supervisory Control And Data Acquisition (SCADA) management system into a distributed Edge Cloud and IoT enabled SCADA system. Similarly, Pau et al. [54] propose decentralization of a Distribution Management System (DMS) by utilizing cloud technologies such as microservices and containers. Proper behavior and control of DERs is becoming increasingly vital for the stability of power grids. In [55] and [56], the authors explore a new protection concept based on virtualization of all protection functionalities and 5G communications. The proposed solution enhances the operation of DER Loss of Mains (LoM) protection by aiming to prevent unintentional islanding during wide area disturbances. Simulation and laboratory testing demonstrate that the proposed solution can fulfill the protection requirements.

B. NEW BUSINESS ACTORS AND INDUSTRY ARCHITECTURES

In a traditional DSO domain, management of the distribution network is handled by DSO itself, which uses Communications Service Providers (CSPs) on on-need basis to enable the communication needs for distribution grid management. In addition, DSOs might use System Integrators (SIs) as dedicated service providers for fault location, repair of their power grid or for data center services. DSOs are facing challenges due to the increasing requirements of dynamic performance, changing market frameworks and technological innovations in computing and communication domains [57]. Therefore, it is no surprise that recent research has focused on smart power grid business models and new business actors that allow, for example, consumers to act as also producers and energy to flow omnidirectionally [58], [59], [60], [58], [61], [62], [63], and [64]. New actors can include Distributed Energy Resource (DER) providers for those consumers acting as producers, DER aggregators that aggregate multiple DERs, and Virtual Power Plans (VPPs) that not only carry out aggregation tasks, but also sell and trade the aggregated energy. Multiple other actors emerge, such as service providers that help consumers with their investments in and use of renewable energy, smart utility-in-a-box service providers that help DSOs to enter the smart energy business, EV charging system providers, as well as multiple ICT-related product and service providers that offer innovative technologies and platforms for use in the energy sector, especially in the distribution domain. Chasin et al. [60], [63] discuss the use of innovative platforms as data driven approaches, where cloud-based solutions play a central role. Examples of these include Smart Energy Platform-as-a-Service (SEPaaS) and Smart Energy Management-as-a-Service (SEMaaS) targeted to consumers for managing and optimizing their smart energy usage [65], [66]. Similarly, Smart Energy Data-as-a-Service (DaaS) and Smart Energy Data Analytics-as-a-Service (DAaaS) aim at helping DSOs enter the smart energy management business. DaaS and DAaaS manage centrally the data analytics for DSO needs, including fault analytics, predictive maintenance, weather analytics and energy consumption predictions [63], [67]. Kivekäs et al. [64] utilize the VNC approach for performing a techno-economic analysis of CSP's potential business when acting either as a smart home service provider, a back-end provider, or a billing system provider.

3GPP's planned 5G slicing and edge computing architecture [16] has motivated researchers to investigate the potential use cases and actor roles that they enable in different industry verticals, including power distribution networks and smart energy management, see e.g. [67], [68], [69], and [70]. For this purpose, 3GPP proposes a slice provider as an actor to ensure secure communication services [67]. This actor can be either the mobile network operator itself or an independent slice provider that buys slices from mobile network operators and then re-sells and implements them according to the needs of the DSO.

Based on the conducted literature review, there exists research on the applicability of various communications technologies in different power grid domains such as HAN, WAN and NAN, as well as research on new business opportunities such as providing computing as a service to increase visibility to the grid and to integrate consumers and DERs to the smart grid. Our paper contributes by identifying and analyzing the potential connectivity architectures and industry (business) architectures necessary in providing connectivity solutions for the distribution grid management required in early 2030s.

V. VALUE NETWORK ANALYSIS

This section consists of three parts. Section VA describes a typical traditional technical architecture for connectivity in distribution grids. Section VB identifies key drivers motivating the need for new technical components and then presents two variations for a new technical architecture. Finally, Section VC analyses the needed business actors and related VNCs, resulting in the construction of eight potential VNCs based on the two variations of a new technical architecture presented in the Section VB.

A. TRADITIONAL DISTRIBUTION GRID TECHNICAL ARCHITECTURE

As presented in Fig. 3, the computing environment in a distribution grid operated by one DSO has traditionally been fairly centralized. The grid control and monitoring systems of a DSO, such as SCADA and DMS have typically been run in a dedicated computer system either in the DSO's own premises or in a computer system hosted and managed in a data center. Due to the large geographical area covered by distribution grids, WANs are needed to interconnect the distribution grid to the central computing platform. While connectivity between the SCADA and the primary substations is an established practice, connectivity to the secondary substations is a newer constantly expanding phenomenon, typically based on mobile communications. In addition to mobile communications, UHF/VHF private radio can serve in rural areas as an alternative that is used along long feeders for disconnector control and fault location.

B. INTRODUCING OVERLAY NETWORKS AND EDGE TO THE TECHNICAL ARCHITECTURE

As described in Section I, the evolution of power grids will require more extensive distributed data processing capability and connectivity at distinct service levels. The former need is addressed in this study by establishing overlay networks and the latter by the use of edge computing. Overlay networks are logical networks on top of physical communications networks. Examples of overlay networks include IP/MPLS

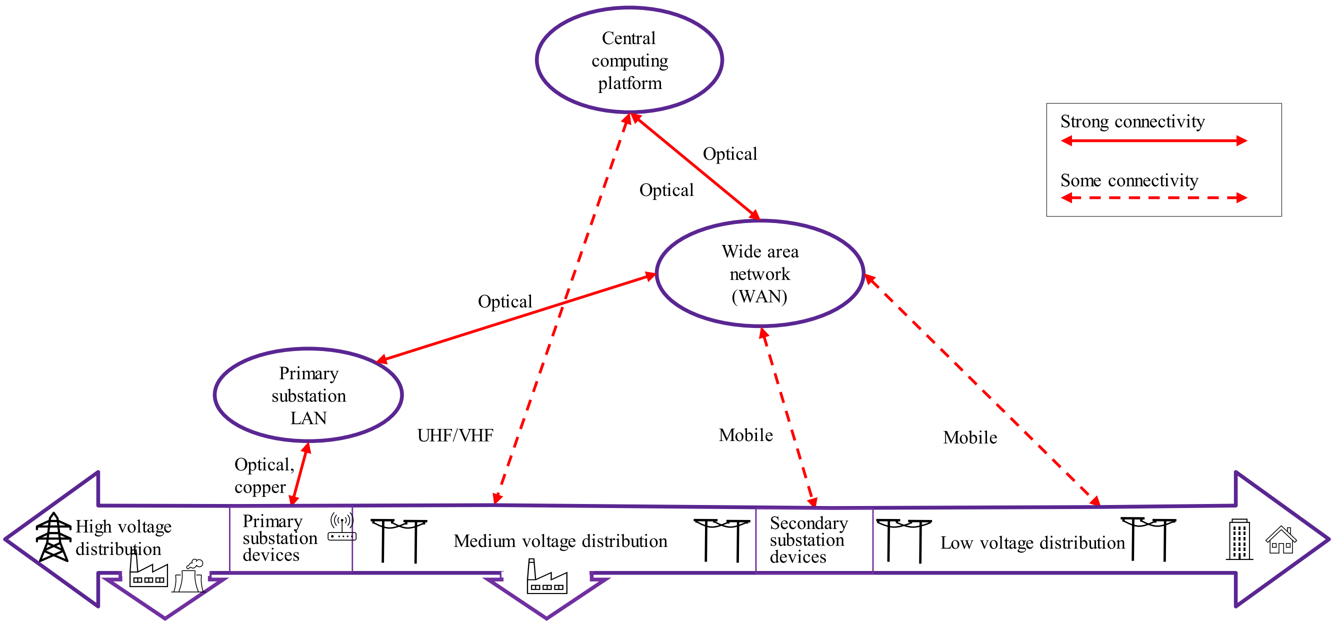

FIGURE 3. The traditional connectivity architecture in a distribution grid.

(Internet Protocol / Protocol Multi-Protocol Label Switching) tunnels, prioritized IP VPNs (Virtual Private Networks), wavelengths on optical fiber, and 5G mobile network slices. The concept of edge covers computing anywhere between the end-device in the distribution grid and cloud-based or dedicated-server-based central computing. In the distribution grid context, edge computing can be divided into two hierarchical levels based on the location in the distribution grid: (1) aggregation-edge (far-edge) in the proximity of the primary substations or inside the primary substations and (2) near-edge in the proximity of secondary substations or inside the secondary substations. The edge can be implemented by distributing either traditional computing infrastructure and applications or virtualized cloud-based computing infrastructure and applications (cloud edge) closer to the distribution grid and its primary and secondary substations.

Adding the concepts of overlay networks and edge computing to the traditional connectivity architecture results in two new connectivity architecture variations, denoted hereinafter as Architecture A and Architecture B in Fig. 4 and Fig. 5, respectively. Architecture A uses one wide area Communications Service Provider (CSP), and Architecture B uses multiple wide area CSPs in a balanced way. Furthermore, Architecture B tightly integrates the overlay networks with the physical communications network, while the coupling in Architecture A is looser, allowing different actors to operate the overlay and physical networks. Architecture B requires routing between different CSP overlay networks, as shown in Fig. 5 as a separate technical component. For Architecture B, Fig. 5 outlines the usage of four CSPs as an example.

Fig. 4 and Fig. 5 introduce four overlay networks for applications with distinct service level requirements: (1) a critical real-time communications network, e.g., communication between line differential relays or accurate GPS-level timing in Wide Area Monitoring Systems (WAMS), (2) a network for other control activities, e.g., disconnector control and alarms, (3) a network for vital data collection, e.g., voltage and current measurements for state estimation, and (4) a network for upwards streaming of bulk data, e.g., high-definition video surveillance data or voltage and current data with very high sampling data for specific fault location purposes, which are denoted by dark red, light red, yellow, and green colors, respectively. The amounts of data in the first three overlay networks are fairly modest, kilobits per second for occasional control, such as disconnector opening and closing or fault indication, or a few megabits per second for sampling current and voltage levels or regular communication between line protection relays. The fourth overlay network is responsible for upwards streaming of bulk data, where the data amounts can approach hundreds of megabits per second, The reliability requirements of the first three overlay networks can be as high as 99.999% for line differential communication [50], while the fourth network is not very critical, thus making it suitable for best effort type of communication.

Two deployment alternatives can be utilized for edge computing: either aggregation-edge alone or expanded aggregation-edge complemented by deploying near-edge computing. The choice is determined by application needs, particularly latency and reliability requirements as well as amounts of required data transmission. The choice is subject to constraints such as limitations on operational complexity

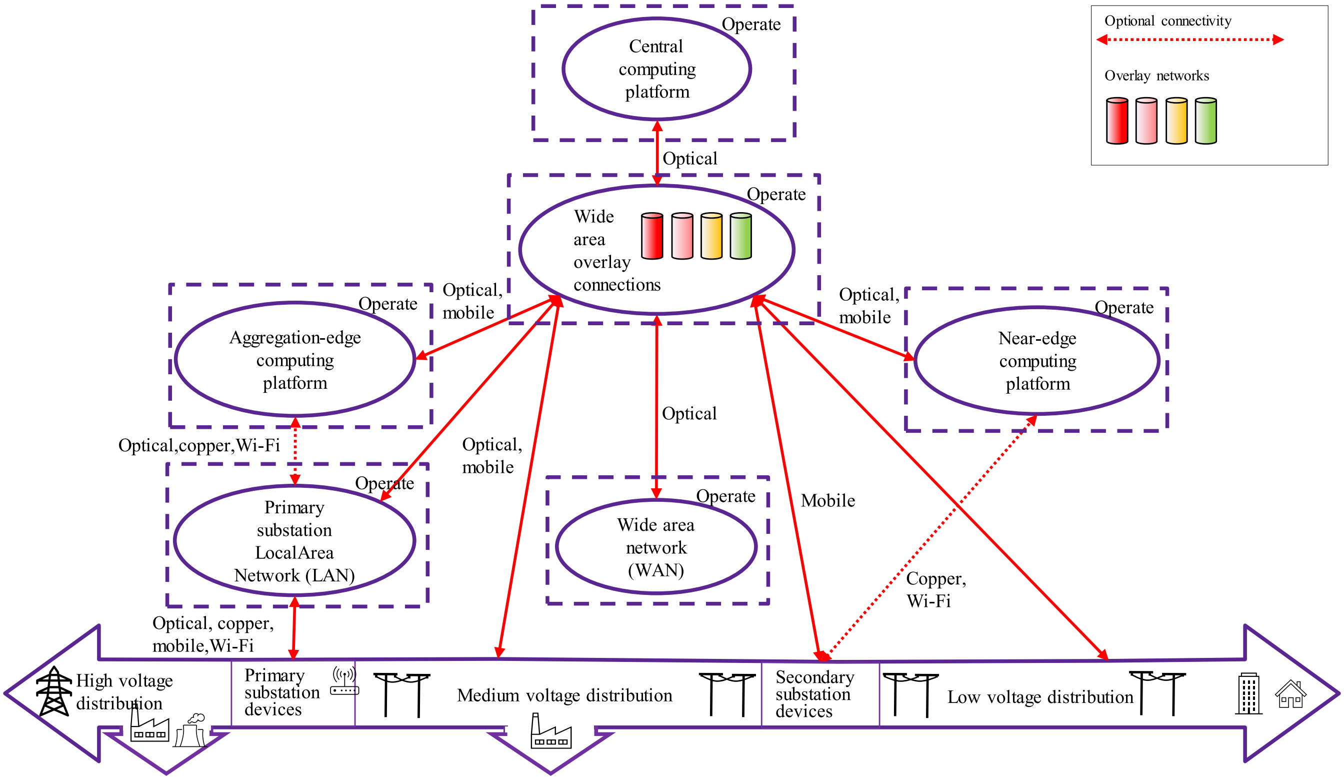

FIGURE 4. Architecture A and roles.

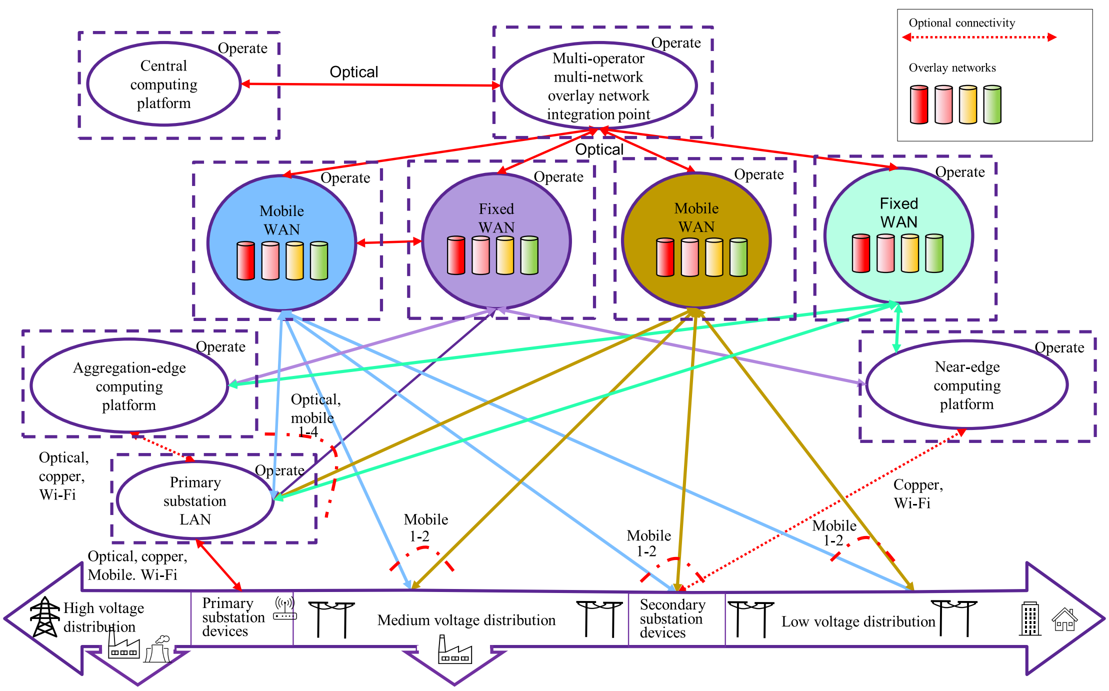

FIGURE 5. Architecture B and roles. Connectivity from the four communications networks to the grid depicted as blue, purple, brown and turquoise arrows (instead of red) for readability.

and cost, as introducing the near-edge very close to the distribution grid essentially increases the complexity and costs compared to utilizing aggregation-edge alone. Driven by the challenges discussed in Section I concerning intermittency and adequate energy supply, applications for edge computing include distributed generation control, voltage level control,

TABLE 4. Communications and computing technologies (explained in Section III) in Architectures A and B.

Communications and computing technologies	Potential applications in Architectures A and B
4G	Wide range of applications excluding the most critical ones such as protection. Overall wide area connectivity.
5G MBB	Wide range of applications excluding the most critical ones such as protection. Overall wide area connectivity.
5G Ultra-Reliable Low Latency Communications (URLLC)	The most critical applications having tight reliability and latency requirements, such as protection. To fulfil the tight reliability and latency requirements, capacity reservations in the communications network are needed, though this can introduce substantial costs.
5G Massive Internet-of-Things (MIoT) and High-Performance Machine-Type Communications (HMTC)	Large-scale sensoring in the grid such as sampling and monitoring of current and voltage values and fault indication.
5G Slices	Increasing the reliability of important control applications such as disconnector control
5G Timing as a service	Providing an alternative to GPS, for example, in Wide Area Monitoring Systems (WAMS) to time stamp the phasor values provided by the Phasor Measurement Units (PMUs)
5G Non-Public Networks	Communication within a primary substation
5G support for higher frequencies (above 24 GHz, i.e., mmWave)	Communication within a primary substation
5G Mobile Edge Computing (MEC)	Applications benefitting from having computing extremely close to the monitored or controlled entity, such as distributed generation control, voltage level control, power quality control, and possibly also relay protection applications, as well as analysis of video surveillance data.
5G LAN-type service	Communications between primary substation LANs
Optical communications	Wide range of applications including the most critical ones, such as protection. Overall wide area connectivity.
Wireless local area networks (Wi-Fi)	Communication within a primary substation. Communication within parts of a low voltage network.
Ultra/very high frequency (UHF/VHF) private radio	Communications along long rural feeders for functions such as disconnector control and fault indication.
Cloud computing - the applications and services delivered from a remote location over the Internet	Wide range of power grid applications possibly excluding the most critical ones, such as SCADA and DMS.
Cloud computing - the pool of computing resources such as servers and storage in the data centers	Wide range of power grid applications including the most critical ones, such as SCADA and DMS
Cloud computing – software development techniques such as microservices and containers.	Wide range of power grid applications including the most critical ones, such as SCADA and DMS
Edge computing	Applications benefitting from having computing extremely close to the monitored or controlled entity, such as distributed generation control, voltage level control, power quality control, and possibly also relay protection applications, as well as analysis of video surveillance data.

power quality control, and possibly also relay protection, as well as analysis of video surveillance data. Some of these applications have quite stringent latency requirements. For example, in case of a fault, the protection application can be required to be capable of de-energizing the faulty grid section in less than 100 ms [50], while immediate power balance issues have to be handled within a second [71]. Table 4 provides a summary of how the communications and computing technologies explained in Section III could be utilized in Architectures A and B.

As explained in Section IIA, roles are used to link the technical architecture and the industry architecture. The role "Operate" is applied in this study to all technical components in Architectures A and B. The role "Operate" refers in general to the deployment, configuring, monitoring, troubleshooting and updating of the technical component. For the central computing platform, the aggregation-edge computing platform and near-edge computing platform, the role "Operate" refers more specifically to three tasks. These tasks include managing the computing platform, its operating system, as well as ensuring that the application (e.g., SCADA or DMS) is updated and available to end users. It should be noted that usage of the applications to manage the distribution grid is excluded from the role "Operate". It is assumed that the DSO utilizes the applications to manage the grid or outsources it to a third party, i.e., DSOs and any third party are the end users of the applications.

C. VALUE NETWORKS (VNCs)

Having established the technical architectures, the analysis continues by identifying the business actors. These consist of the DSO itself, or more specifically its information and operational technology department (IT&OT), a CSP, an SI such as Cap Gemini or IBM, and a virtual CSP. Hereinafter, virtual CSP will be termed either an Overlay Network Provider (ONP) or an Overlay Network Integrator (ONI), depending on the technical architecture. The first three business actors, DSO, CSP, and SI, are those stakeholders currently active in providing distribution grid ICT solutions, as described in Section IVA. The two latter business actors, ONP and ONI, are potential new actors inspired by virtual CSPs in the consumer mobile communications business and by 3GPP, as indicated in Section IVB, when discussing slice providers.

Having identified the actors, we now construct the VNCs by letting one of the actors take the driving (leading) role. In this study, the driving role refers to an actor that builds and operates the edge and/or overlay network functionality for use in distribution grid management. Based on this approach, eight VNCs have been constructed: four VNCs depicted in Fig. 6-9 based on Architecture A (described in Fig. 4) and four VNCs depicted in Fig. 10-13 based on Architecture B (described in Fig. 5). Fig. 6 presents VNC1A, in which the DSO (indicated by light red color) is the driving actor and operates the whole computing platform, starting from the near-edge through aggregation-edge to the central computing platform. In addition, the DSO operates the primary substation LAN. In this VNC, a single CSP delivers the majority of mobile and fixed network connectivity in the geographical area of the distribution grid.

Fig. 7 presents VNC2A, in which a single CSP (indicated by light blue color) not only delivers the majority of mobile and fixed network wide area connectivity in the geographical area of the distribution grid, but also provides the platform for aggregation-edge and near-edge computing, as well as manages connectivity within primary substations. The connectivity within primary substations can be provided either through a local private mobile network or directed public mobile millimeter radio, or by operating the existing fixed LAN network as a service. The management of primary substation power grid equipment, including protection relays and instrumentation transformers, is assumed to be performed by the DSO or by a third party to whom the DSO has outsourced this activity.

Fig. 8 presents VNC3A, in which a SI (indicated by light yellow color) not only provides and operates the whole computing platform, including near-edge, aggregation-edge and the central platform, but also contracts with the CSP to provide the overlay network on top of the bulk physical communications capacity supplied by the CSP. The SI can manage the overlay network through interfaces provided by the CSP. In this VNC, the DSO operates the primary substation LAN, which is closely integrated with primary substation power grid equipment, such as protection relays and instrumentation transformers.

Fig. 9 presents VNC4A, in which the ONP (indicated by light grey color) creates and operates the overlay networks on top of the bulk communications capacity provided by the CSP. As shown in the figure, the ONP has commercial relationships with the CSP and also interfaces with the CSP's physical network to manage the overlay networks. The DSO itself operates the whole computing platform, including

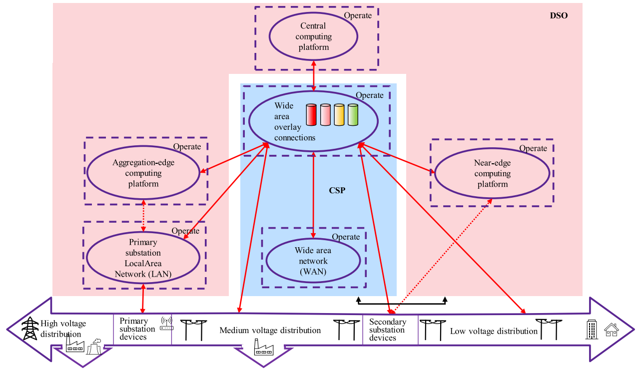

FIGURE 6. Distribution System Operator (DSO) driven VNC1A.

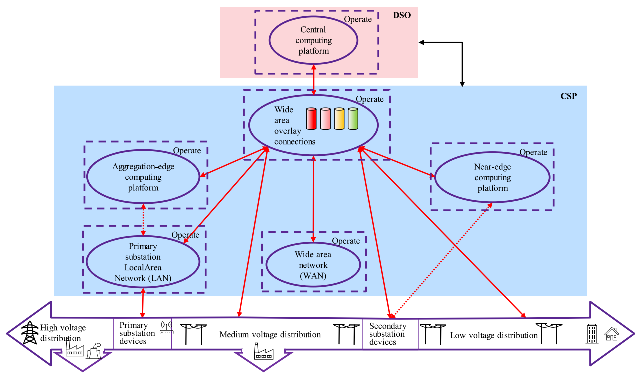

FIGURE 7. Communications Service Provider (CSP) driven VNC2A.

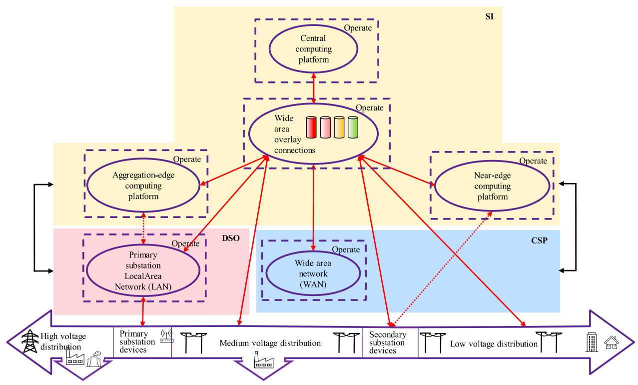

FIGURE 8. System Integrator (SI) driven VNC3A.

near-edge, aggregation-edge, the central computing platform, as well as operating the primary substation LAN.

Fig. 10-13 present the remaining four VNCs, which use multiple wide area CSPs in a balanced way, i.e., they are based on Architecture B (Fig. 5). In the DSO-driven VNC1B shown in Fig. 10, the DSO (indicated by light red color) not only integrates various multi-technology based wide area network connections into a resilient logical overlay network, but also operates the whole computing platform, including near-edge, aggregation-edge and the central computing platform, as well as operates the primary substation LAN.

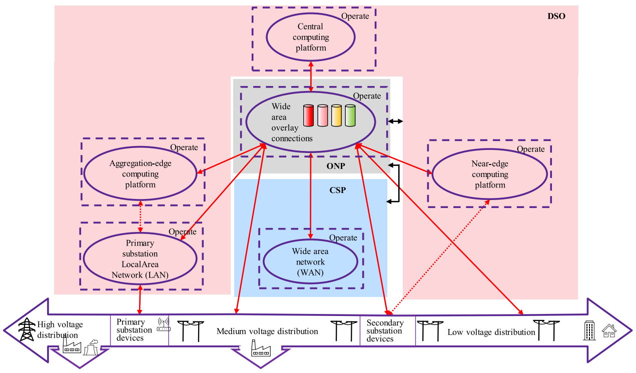

FIGURE 9. Overlay Network Provider (ONP) driven VNC4A.

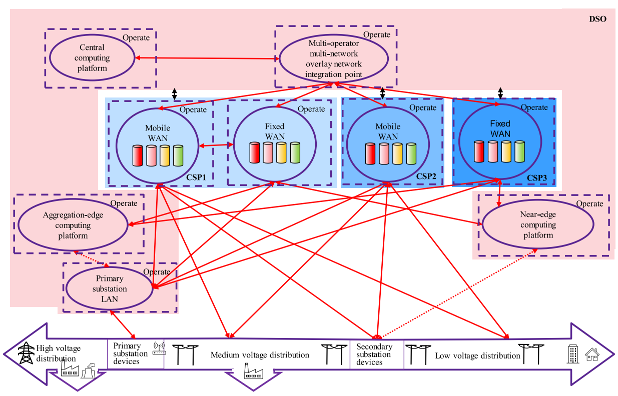

FIGURE 10. Distribution System Operator (DSO) driven VNC1B.

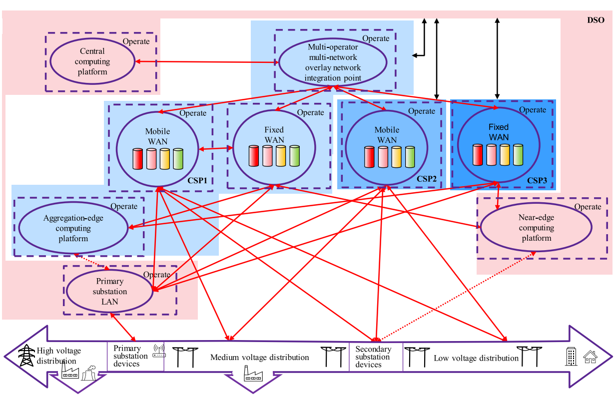

FIGURE 11. Communications Service Provider (CSP) driven VNC2B.

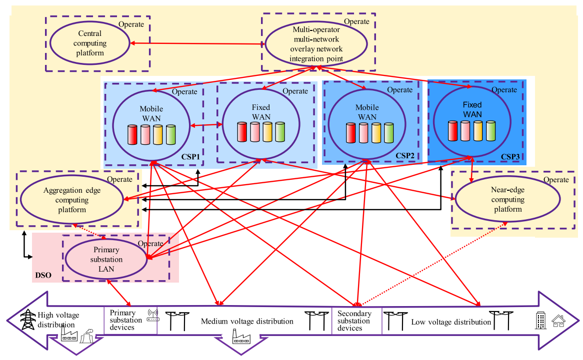

FIGURE 12. System Integrator (SI) driven VNC3B.

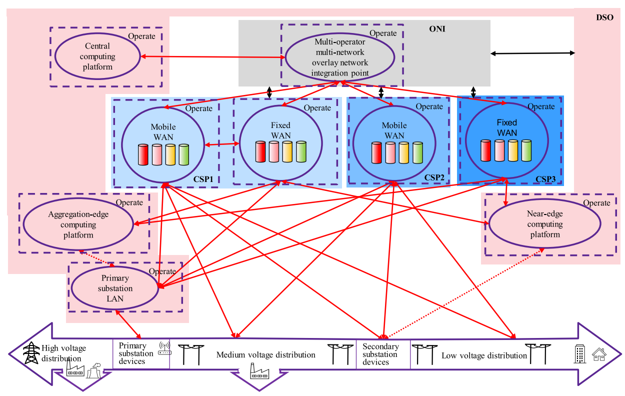

FIGURE 13. Overlay Network Integrator (ONI) driven VNC4B.

Fig. 11 presents VNC2B, in which one of the CSPs, having both a mobile and fixed network, takes the leading role. This leading CSP (indicated by the lightest blue color) not only integrates its own multi-technology overlay network and the overlay networks from the other mobile and fixed network operators (CSPs) into a holistic overlay network, but also operates the aggregation-edge computing platform. The DSO operates the central computing platforms and the primary substation LAN, as well as the near-edge computing platform if it is used to complement the aggregation-edge.

Fig. 12 presents VNC3B, in which a SI (indicated by light yellow color) not only integrates multi-technology overlay networks from the mobile and fixed network operators (CSPs) into a holistic logical overlay network, but also operates the whole computing platform, including the near-edge, aggregation-edge and central computing platforms. The DSO operates the primary substation LAN, which is closely integrated with primary substation power grid equipment, such as protection relays and instrumentation transformers.

Fig. 13 presents VNC4B, in which the ONI (indicated by light grey color) provides a holistic communications solution and operates the overlay networks provided by the CSPs. The DSO not only operates the whole computing platform, including near-edge, aggregation-edge and the central computing platform, but also operates the primary substation LAN.

VI. DELPHI ANALYSIS

This section describes the results from the expert Delphi survey concerning the eight VNCs introduced in the previous section. As described in Section II, two individual interview rounds of the panelists were carried out. Fig. 14 summarizes the average probabilities and the standard deviation obtained for each VNC in the first (r1) and second (r2) rounds for the question: *What is the probability that a certain presented VNC will be commercially in use at least within one DSO in Finland by 2030*? In addition, the panelists expressed in

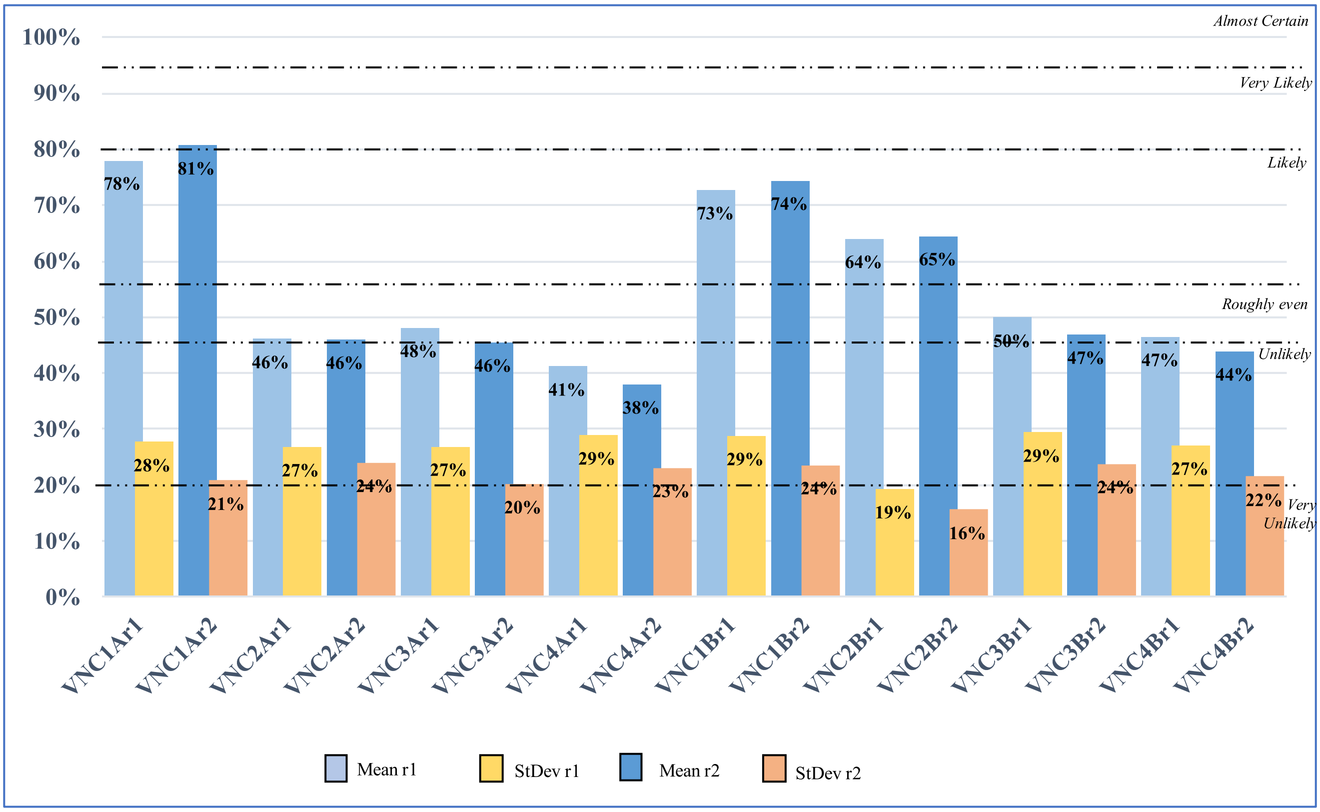

FIGURE 14. **The mean and standard deviation of the probability of the VNCs. Delphi rounds 1 and 2 are represented as r1 and r2, respectively.**

their own words at least three reasons (arguments) for the probability value given for each VNC. These are summarized in Tables 5 and 6. The total number of reasons varied between 80 and 100 per each VNC. To analyze the panelists' justification for their choice of probability, the reasons given were initially classified into two groups. The first group consisted of all reasons that clearly tend to increase the given probability value, and the second group comprised those that tend to decrease the given probability value. Next, the reasons were classified based on their similarity into different categories, the number of which varied between four and eight categories. The number of individual reasons given in each category varied between 1 and 28 reasons. Tables 5 and 6 divide the most frequently given reasoning categories into those which either increased or decreased the probability, as well as indicate in parentheses the number of panelists giving that particular reason.

As can be seen in Fig. 14, the panelists regard DSO-driven VNC1A (Architecture A) as *very likely*, DSO-driven VNC1B (Architecture B) and CSP-driven VNC2B (Architecture B) as *likely*, the ONP-driven VNC4A and the ONI-driven VNC4B as *unlikely* and the rest, i.e. CSP-driven VNC2A, SI-driven VNC3A and SI-driven VNC3B, as *roughly even*. The standard deviation values indicate that CSP-driven VNC2B, SI-driven VNC3A and DSO-driven VNC1A showed the three highest consensuses (the lowest standard deviations), and VNC2A, VNC1B and VNC3B showed the lowest consensus. It can be seen from the figure that based on the new information received by the panelists in the second round, the average probability value either increases or decreases depending on the VNC, though the consensus increases slightly in all cases, i.e., the standard deviation decreases. This result is in line with previous findings, e.g., in [13] and [14].

As indicated in Tables 5 and 6, the high probabilities given for DSO-driven VNC1A (based on Architecture A) and DSO-driven VNC1B (based on Architecture B) can most likely be explained by the similarity of these VNCs to the current, prevailing mode of operations. However, many panelists pointed out that these setups are expensive due to the large number of complex technical components under DSO's direct control. The CSP-driven VNC2B (based on Architecture B), which also has a high probability, was considered to provide a flexible one-stop-shop solution for DSOs, although it would include business risks for DSOs due to the CSP's large role in critical operations. The CSP-driven VNC2A, SI-driven VNC3A and SI-driven VNC3B, having the score *roughly even*, were considered to include risks due to extensive outsourcing of critical operations. However, they would also provide benefits to both the driving actors and the DSOs, as the VNCs would allow DSOs to focus on their core business. The new ONI and ONP actors of the *unlikely* VNC4A and VNC4B were assessed to have a narrow business

TABLE 5. Architecture A VNCs: Reasoning categories.

VNC	Increases probability	Decreases probability
1A	Prevailing business model today, simple and clear responsibilities (22)	Very costly for the DSO to deploy edge and the cloud in general. This drives consolidations among DSOs as well as other VNCs (14)
	DSOs prefer to take care of the critical parts themselves and have low willingness to give up the status quo (16)	Lack of talent and resources at DSO to implement complex computing platforms (8)
	The speed of change in the power industry is slow and the planning period long (12)	The communications and edge will be very complex for DSOs and should thus be outsourced (8)
	Consolidation of DSOs might make this model more probable (11)	Risky for DSOs due to reliance on one CSP (8)
	The edge is an extension of the central computing platform managed by the DSO (6)	Lack of trust towards CSPs among DSOs (4)
2A	Due to their existing network and computing infrastructure and competence, CSPs are well positioned for this model (14)	High security, technical and business risk for both DSOs and CSPs. Lack of trust towards CSPs and their power grid competencies among DSOs (24)
	Cost pressure among DSOs concerning both operating expenses and capital expenditure. Lack of competence concerning computing platforms and communications among DSOs (12)	DSOs prefer not to outsource central, critical operations (12)
	Some CSPs have shown interest in this model to broaden their portfolio. To be successful, they should increase their understanding of the power systems business in co-operation with DSOs (10)	Technical and business challenges in building and managing a mission critical core distribution grid based on a mobile network (8)
	This is a good example of a generic industry trend towards different types of "Something as a Service", which is especially suitable for the secondary substation and consumer-related solutions (6)	CSPs do not have the needed competences to manage OT platforms and the primary station network (7)
3A	Potential new business for local or dedicated SIs (17)	DSOs are against this, as it gives too much responsibility to SIs, which may create security problems. DSOs prefer not to outsource central, critical operations. (20)
	A current, natural business model for SIs (hosting as a service) (14)	SIs not familiar with power grid and overlay network management (11)
	This VNC is driven by cost pressure (both Opex and Capex) especially on small DSOs. Enables the DSOs to focus on their core business. (5)	Complex responsibilities, liability problems, risk of unclear service level agreements (SLAs). Lack of trust towards SIs among DSOs. (7)
	A clear, straightforward approach from the DSO point of view. The overlay network and edge complexities are hidden from the DSOs (5)	SIs might consider the distribution grid management business to be too small (4)
	Existing business (e.g., IT system hosting) between SI and the DSO might boost this model for certain DSOs (3)	Doubts about cost savings. Big SIs are expensive and have poor local coverage. (3)
4A	Opportunities for a technically very skilled niche actor as a neutral player between DSOs and the CSPs (22)	Long learning curve required to implement a credible industrial overlay business. Unclear business potential (20)
	From the DSO point of view, it does not matter whether the overlay network is provided by an ONP or a CSP (7)	CSPs are more credible than virtual CSPs. No examples exist of virtual CSPs focusing on the industrial segment. The ONP offers limited added value. The value chain is too long. Complex SLAs. (15)
	Allows CPSs to focus on the more straightforward wholesale business in the industry segment. An ONP serving multiple DSOs might offer cost benefits. (6)	Risks related to the technical maturity of 5G slicing and to how it can handle high reliability requirements by the early 2030s (13)
		ONPs are likely to be smaller companies, thus making them risky to DSOs (10)

potential and to provide little added value, although they might also reduce complexity from DSO's point of view.

According to Tables 5 and 6, considering all VNCs, the most likely explanation for the given probabilities is the distribution grid industry's resistance to changes, its willingness to take care of the critical parts itself, and a lack of competence and resources within DSOs to implement complex new connectivity solutions based on distributed edge computing and overlay networking.

Moreover, there seemed to be widespread skepticism about the emerging 5G features targeting industrial applications. This skepticism was particularly directed toward the future maturity of 5G. The panelists questioned not only whether 5G would be able to provide the necessary industrial features by the early 2030s but also whether it would be likely to fulfil the stringent latency and reliability requirements for distribution grid management. Concerning 5G slicing, many panelists stated that it does not bring any more capacity to the network nor does it remove the fact that the physical air channel is unreliable. These panelists were also often of the opinion that extensive slicing would essentially make network management more complex. This operational complexity, together with potential capacity (resource) reservations, particularly in base stations, in order to guarantee performance and Service Level Agreements (SLAs), might increase the cost of wide area slice deployments to levels that would no longer

TABLE 6. Architecture B VNCs: Reasoning categories.

VNC	Increases probability	Decreases probability
1B	Resembles the current model, will be relevant also in the early 2030s due to slow changes in the DSO industry. (16)	An expensive solution (7)
	Coverage reasons (12)	A technically complex solution (6)
	Resilience and reliability/backup reasons (11)	DSOs are not interested in integrating overlay networks which are essential to industrial services (4)
	Competition between CSPs lowers prices (9)	Only the biggest DSOs have the required additional competencies and capabilities in computing and networking to support this model (3)
	DSOs keep control of critical parts of the grid (7)	
	Technical evolution of SCADA supports this model. Since SCADA already covers some routing needs and may evolve towards distributed computing as well, VNC1B can be assumed to be a future proof (4)	
2B	A flexible one-stop-shop model for DSOs with clear SLAs. CSPs are already familiar with the model and have the needed communication, aggregation, slicing and edge computing possibilities, and competence which DSOs lack (28)	Liability and business risks for DSOs (16)
	The value chain is in balance: both DSOs and CSP can focus on their core business (12)	The business might be risky and too complicated for CSPs (13)
	CSPs are forced to develop new business (11)	DSOs might face challenges and risks in finding a trusted and competent main CSP for co-operation in developing an overall solution. Only large DSOs might be capable of doing this (3)
	Coverage, resilience and reliability/backup (8)	A new model, slow pace of change in the DSO industry (3)
3B	Enables DSOs to focus on their core business (15)	Unclear and risky DSO business case (16)
	SIs are credible business partners (13)	The Finnish market has no reasonable business potential for big SIs (12)
	Coverage, resilience and reliability/backup (6)	Lack of trust towards SIs among DSOs (8)
	Might offer new business innovations where local small DSOs will together build this model, or a big DSO offers services to smaller DSOs (4)	Inadequate maturity of 5G slicing technologies by the early 2030s (7)
		The competence of SIs in overlay networks is poor (4)
		Regulation might not support this model, e.g. due to use of cloud computing by big cloud players in critical areas (3)
4B	DSOs might prefer this actor, as it reduces the complexity. CSPs might prefer this as well, as it makes their life “easier” by allowing them to focus on more straightforward wholesale business in the industrial segment (16)	The business potential and value in the value network for the actor is thin. (15)
	A potential exists for a special niche player with a clear focus between two main players. In fact, the power grid industry needs such start-ups to stimulate evolution of the industry (9)	Lack of credibility concerning such a new actor (9)
	This could also support other business models such as SI-driven VNC3B and totally new models in the power grid industry, such as joint ventures between multiple DSOs or the emergence of a new communications player offering communications services to the DSO industry (7)	The actor’s business role between two main actors is unclear (8)
	Coverage, resilience and reliability/backup (5)	Long value chain: multiple margins on top of each other (7)
	The ONI can select the best (both technically and commercially) communications network partners and solutions (4)	Complex, demanding and risky technically, especially due to multiple evolving technologies (6)
		CSPs and SIs are capable of taking on this role (5)

be economically feasible for widespread use in power grid management. Economical feasibility of 5G URLLC was of concern as well due similar reasons – achieving low latencies and high reliability in wide area deployments might be very costly.

Due to their existing networking and computing infrastructure, CSPs are seen to be well positioned to tackle the distributed computing needs of DSOs, and some of them, in fact, seem to have already created solutions for DSOs. However, CSPs having a leading role in distribution grid computing platform management was also regarded as a business and technical risk for both DSOs and CSPs, since critical distribution grid operations might be too complex for CSPs to operate and might offer them only limited business opportunities in Finland.

Furthermore, many panelists challenged the need for extensive distributed computing in the proximity of consumers and prosumers: aggregation-edge was regarded as sufficient for power grid application requirements such as those related to latency, and near-edge would mostly introduce excessive complexity. Even though increasing service level differentiation and guarantees in the form of overlay

TABLE 7. VNC mean probabilities of professional and world class experts (pr, %) and the Causal Effects.

	VNC1A		VNC2A		VNC3A		VNC4A		VNC1B		VNC2B		VNC3B		VNC4B	
Expertise	**CE**	**pr**	**CE**	**pr**	**CE**	**pr**	**CE**	**pr**	**CE**	**pr**	**CE**	**pr**	**CE**	**pr**	**CE**	**pr**
ICT	-0,05	82	0,39	51	0,35	47	-0,22	34	-0,05	76	0,85	69	-0,10	49	-0,50	39
Consulting	-0,07	83	-0,34	47	-0,37	44	0,08	36	0,04	77	-0,11	67	-0,31	47	0,09	41
NE	0,03	81	0,58	51	0,24	45	0,10	35	-0,09	75	-0,16	66	0,09	50	0,29	40
Power grid	0,20	83	-0,43	38	0,16	47	0,02	43	0,34	77	-0,20	62	-0,07	45	0,02	49
Academia	0,00	79	0,09	45	0,20	47	-0,52	31	-0,08	71	-0,11	63	0,16	49	-0,10	43
MNO	0,34	83	-0,17	49	0,14	45	-0,16	35	0,19	78	-0,33	64	0,33	50	-0,01	39
Cloud	-0,13	77	-0,27	42	-0,06	44	0,29	39	-0,16	67	0,02	64	-0,12	48	-0,08	41

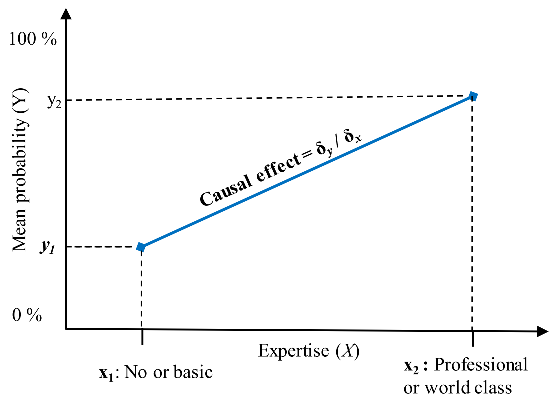

FIGURE 15. Causal Effect (CE) of expertise as slope of mean probability as a function of expertise.

networks were considered important and included as concepts in the current mode of operations, the ONP-driven VNC4A and ONI-driven VNC4B were both deemed *not likely*. This is primarily attributable to the close relationship between overlay networks and physical networks. However, many of the experts view ONP and ONI as welcome neutral actors between the DSOs and CSPs, as they would enable DSOs to focus on their core business, while allowing CSPs to focus on a more straightforward consumer and wholesale business instead of directly serving a diversified industrial segment. Some panelists had observed that CSPs are reluctant to implement operationally complex industrial services, such as overlay networks in the form of 5G slices.

To understand how the domain expertise of a panelist reflects in the given probabilities, Causal Effect (CE) analysis was performed (column "CE" in Table 7) and means of probabilities calculated for the probability values given by those experts who have judged themselves as professional or world class in each expertise domain (column "pr" in Table 7). Referring to Fig. 15, the CE values vary between −1 and 1. A positive CE value (blue color in Table 7) indicates that the professional and world class experts of a certain expertise domain ($x_2$on Fig. 15) give that particular VNC higher probabilities (y2 on Fig. 15) than those panelists who only had basic or no experience in that expertise domain (x_1 on Fig. 15). Thus, in case of a positive CE value, it can be said that the professional and world class experts prefer or favor that VNC compared to those panelists who only have basic or no experience in that expertise field, and in case of negative CE value the professional and world class experts do not favor that VNC.

More specifically, eight Augmented Naïve Bayes Networks, one for each VNC, were learned by using BayesiaLab 10 [72] to perform the CE analysis. The target variable in the CE analysis is the one which contains the probability values given by the panelists for a certain VNC, and the explanatory variables are binary variables, where true (x2 on Fig. 15) indicates that the panelists have classified themselves as a professional or world class expert, while false (x_1 on Fig. 15) indicates no or only basic expertise. The Augmented Naïve Bayes learning algorithm was selected for this task, since it relaxes the assumption of independence between explanatory variables given the target variable, and thus the potential inter-dependencies between the explanatory variables can be eliminated [73]. To estimate CE of the expertise (explanatory variables) on the probability values given by experts (target variable), Jouffe's Likelihood Matching (JLM) algorithm analysis has been implemented from the learned Augmented Naïve Bayes networks, as the JLM requires no causal network to estimate the strength of the causality [74]. The JLM measures the relationship of a conditional mean of each state of variable X on the mean of variable Y utilizing the Kullback's minimum cross-entropy method, MinxEnt [74].

Concerning the expertise angle, it can be observed from the Table 7 that power grid experts prefer DSO-driven VNCs more than experts of other expertise domains (VNC1 CE 0,2, pr 83% and VNC1B CE 0,34, pr 77%). Mobile Network Operator (MNO) experts similarly prefer DSO-driven VNCSs and do not favor CSP-driven VNCs (VNC2A CE -0,17, pr 49% and VNC2B CE -0,33, pr 64%). ICT experts clearly preferred CSP-driven VNCs most (VNC2A CE 0,39, pr 51%, VNC2B CE 0,85, pr 69%). Consulting experts did not favor CSP driven VNC2A (CE -0,34, pr 47%) nor SI driven VNC3A (CE -0,37, pr 44%) but otherwise no big differences between consulting experts and other experts was visible. Concerning the VNC (column) angle on Table 7, compared to other experts, power grid experts did not favor the CSP-driven VNCs. This is visible in both strong negative CE value and low pr-value.

VII. CONCLUSION

The smart grid evolution will necessitate expanded automation, which in turn will require enhanced connectivity solutions. The novelty and contribution of this paper is to identify and analyze the potential technical connectivity architectures and industry architectures necessary in providing connectivity solutions for the smart distribution grids of the early 2030s. The authors outline two technical connectivity architectures and eight industry architectures by utilizing the Value Network Configuration (VNC) method (Section V) and evaluate their feasibility by utilizing a senior expert panel and a Delphi survey (Section VI). The paper uses as case examples the Finnish distribution grids, which are technically strong and operated by multiple Distribution System Operators (DSOs). Typical limitations of the applied Delphi and VNC methods are described in Section II. These issues must be considered when attempting to generalize the results to other contexts.

Drawing upon the findings outlined in Sections V and VI, the conclusions regarding the three research questions posed in Section I can be summarized as presented in Table 8. Overlay networking and aggregation-edge are seen as essential components of the connectivity architecture in the early 2030s. However, the need for near-edge computing (close to the secondary substations) is questionable since it could be costly due to its technical and operational complexity. Because of its practically unlimited capacity and high reliability, optical networking is well positioned to provide the communications solutions needed for the most critical applications. Although mobile communications suffers from the ultimately unreliable physical air channel, they provide - due to their flexibility and straightforward deployment process - a feasible and compelling option to address the automation needs of new distribution grids for all except the most critical applications. Many of the emerging industrial 5G mobile communication technologies are seen as relevant for distribution grid management. However, there are also concerns about the feature maturity, realization, and economic feasibility of these features. Concerns about economic feasibility are related to the costs introduced by capacity (resource) reservations as well as technical and operational complexity.

Although industry architectures that enable DSOs to maintain direct control over critical components of the grid are deemed to be most likely in the early 2030s, the complexity of increased connectivity solutions might require DSOs to utilize partnerships and outsourcing more extensively (Table 8). However, at least currently, there seems to be lack of trust towards potential partners such as CSPs and System Integrators (SIs) among DSOs. Virtual CSPs were considered to have limited business potential and the resulting small size of these potential new actors would undermine their credibility.

TABLE 8. Summary of answers to the research questions.

Research question	Summary
RQ1: connectivity architectures	• Overlay networking and edge computing form essential parts of the technical architecture to enable connectivity at distinct service levels and extensive distributed data processing capability. • The need for near-edge is questionable since application needs could potentially be fulfilled using only the aggregation-edge. This would also essentially reduce the technical complexity and costs. • There exists disbelief in 5G slicing as overlay technology, due to both technical and financial reasons.
RQ2: probable industry architectures	• Industry architectures that enable DSO to maintain direct control over critical technical components (VNC1A, VNC1B), an observation supported by the Causal Effect (CE) analysis as well. This view is challenged by the complexity of connectivity solutions. • Business actors such as Communications Service Provide (CSPs), System Integrators (SIs) and virtual CSPs might offer holistic services, thus hiding the complexity. CSPs are particularly well positioned due to their existing networking and computing infrastructure (VNC2B).
RQ3: reasons for probabilities	• The distribution grid industry's slow speed of change, its willingness to manage the critical parts itself. • Limited competence and resources within DSOs necessary for implementing complex new connectivity solutions based on distributed edge computing and overlay networking. • The business potential in distribution grid managements is rather small for major SIs and CSPs. This might provide an opportunity for industry specific SIs offering holistic services including not only the management of the connectivity solutions but also grid operations, construction and maintenance. • DSOs do not seem to trust CSPs´ capacity and interest for handling industry applications.

Future work should focus on studying the above issues. Concerning the technical architectures, reliability, end-to-end latencies, architecture variations and economic feasibility would warrant further study. For industry architectures, areas of future research include additional actors and going beyond the VNC method (e,g., by applying Business Model Canvas [7]) to explore business models for the additional actors and the most transformative virtual-CSP-driven VNCs.

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SEPPO BORENIUS (Member, IEEE) received the M.Sc. (Tech.) degree in computer science from the Helsinki University of Technology (nowadays Aalto University), Espoo, Finland, in 1986, where he is currently pursuing the Ph.D. degree. Prior to joining Aalto University, he had a 35-year industrial career in the information and communications industries and consultancy. During his industrial career, he served in technology companies, such as Nokia, Cap Gemini, and Tellabs/Coriant in various management roles. His research interest includes the management of smart grids.

PEKKA KEKOLAHTI received the D.Tech. degree from Aalto University. He is currently a Visiting Researcher with the Department of Information and Communications Engineering, Aalto University. His nearly 40-year career has focused on the software development, telecommunications, and ICT consulting domains. Recently, his activities has included data analysis, machine learning research, and data architecture modeling for various domains, including telecommunications, marketing, education, health care, and talent management. His current research interest includes the management of smart grids.

HEIKKI HÄMMÄINEN received the M.Sc. and Ph.D. degrees in computer science from the Helsinki University of Technology (nowadays Aalto University), Finland, in 1984 and 1991, respectively. He is currently a Professor Emeritus of network economics with the Department of Information and Communications Engineering, Aalto University. His earlier industrial career includes several management positions at Nokia. His research interests include techno-economics and the regulation of mobile services and networks. Recently, his research has focused on smart cities, smart grids, the measurement and analysis of mobile usage, the value networks of flexible internet access, and 5G small cells.

MATTI LEHTONEN received the master's and Licentiate degrees in electrical engineering from the Helsinki University of Technology (nowadays Aalto University), in 1984 and 1989, respectively, and the Ph.D. degree in technology from the Tampere University of Technology, in 1992. He was with VTT Energy, Espoo, Finland, from 1987 to 2003. Since 1999, he has been a Professor with Aalto University, where he is currently the Head of power systems and high voltage engineering. His research interests include power system planning and asset management, power system protection, including earth fault problems, harmonic related issues, and the applications of information technology in distribution systems.

PETRI MÄHÖNEN is currently a Professor of networked systems with the Department of Information and Communications Engineering, Aalto University, Finland. He is also the Vice Dean of the School of Electrical Engineering, Aalto University. Before joining Aalto University, he was the Chair and a Professor of networked systems with RWTH Aachen University, Germany. His current research interests include cognitive programmable network architectures, spectrum regulation, telecom AI and cross-layer optimization, and the techno-economical analysis of communication systems. He was a recipient of the Telenor Research Prize and the IEEE Jack Neubauer Memorial Award.