Broadband PLC over Low Voltage Deployment: Planning Tool Development

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Abstract – **This Project has focused on the integration of advanced telecommunication solutions into the power distribution grid. More concretely, the deployment of broadband power line communications (BPL) over the low voltage (LV) grid to face the current challenge that encounters narrowband PLC (NB-PLC) – that is the telecommunication solution that is currently used in the LV grid to collect the information from the smart meters (SMs) – because this technology cannot provide the real-time monitoring that is required nowadays not only by the consumers but also by the emerging technologies whose presence is changing the paradigm of the power distribution grid structure, operation, and supervision. This article will review the fundamentals of the thesis highlighting its contributions and implications for the power distribution landscape.**

Keywords – Power distribution grid, Power line communications (PLC), Broadband PLC (BPL), Smart meters (SM), Street Fuse Box (SFB), Smart Grids, Low voltage network.

I. INTRODUCTION

The energy sector is undergoing a transformative evolution, and the need for power distribution grids to incorporate innovative telecommunication solutions is evident. Iberdrola as a power distribution company had already been part of this transformation carrying out pioneer initiatives such as the STAR Project that meant a revolution for the power consumption measures that finally allowed improved metering precision, optimized grid management, and consumer empowerment by providing consumption patterns information that may influence in their demand. Thanks to this project, not only has Iberdrola modernized its distribution network but also has gained advantage versus other competitors that are not able to collect the accurate data that Iberdrola can now manage to anticipate faults and provide better quality of service for its consumers. Therefore, this Project may have the same relevance as the STAR Project had at the time of its deployment from 2010 to 2018. In line with this path that Iberdrola has set to continue investing in technology that optimizes and digitalizes the grid. In this case, by deploying a network of BPL over the LV grid that will mean a decrease of the latency with data transmission rate of above 400 Mbps in contrast with the under 1 Mbps data rate that is characteristic of the current grid.

This thesis encourages the power distribution companies and sector to embrace evolution and take the example of Iberdrola whose goal is to acquire a level of knowledge of the new technologies and their deployment that allows the company to carry out these deployments in the most efficient way to adapt as fast as possible to the dynamic requirements of the new paradigm of distribution grid, the smart grid.

II. PROJECT DEFINITION

A. *Objectives of the Project.*

This Project involves different tasks and subprojects. However, it can be summarized as the designing of the future topology for the LV distribution grid. This design requires previous phases to analyse the variables that have potential influence on the deployment of BPL and that need to be considered. So, first to the strategy decision on the deployment, it will be necessary to select the most relevant variables that have the most influence and that will be significant in later Project's development.

This Project suggest a change that pursues two main goals: first one is to bring the BPL network closer to the SMs. Before, the BPL network was designed for the MV grid and only reached the secondary substations (SS). However, this new approach wants BPL-LV to reach the end-users: until the street fuse box (SFB) or the SM centralizations. The second principal goal is to reduce the number of nodes that belong to each NB-PLC (PRIME) network. The objective is to transform the current huge PRIME v1.3.6 networks that include hundreds of SMs to smaller and more efficient PRIME v1.4 networks that include dozens of SM.

B. *Proposed LV grid topology.*

To understand this change in detail, *Figure 1* shows how the traditional LV grid looks like and later *Figure 2* will do the same with the proposed grid within this Project. Now, the LV grid consists of a large PRIME v1.3.6 network that required the installation of a base node (NB) in the SS. This PRIME network gathers and communicates all the smart meters that belong to the SFB that are connected to the substation. The data collection from the SM is done following a sequence to be later communicated to the substation and it is accomplished via DLMS, that is a telecommunications protocol published in IEC 62056-5-3. This protocol uses a "client-server" framework, where the "client" – which is the base node installed in the SS in this case – requests data to the "server" or service nodes – which are the SM supplied by ZIV in this representation – that react accordingly. Its adaptable data modelling, authentication procedures, and compatibility with various communication technologies make DLMS essential for advanced metering. Another unique characteristic of this topology that will be different in the new one is that all the low voltage lines are communicated through NB-PLC.

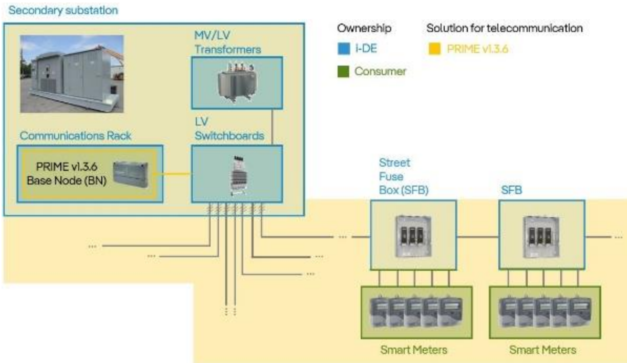

Figure 1: LV grid topology (traditional).

In the new paradigm of low voltage grid, there is a combination of PRIME v1.4 – that is an evolution of the previous version – and BPL. The BPL backbone starts in the secondary substation and continues through the LV lines until it reaches the target SFB. Then, the target SFB contents a BPL repeater that acts as a new BPL node that gets connected the following SFB of the line. Besides that, there will be a PRIME v1.4 base node to communicate – using DLMS through PRIME as explained before – to the smart meters. As mentioned, this NB-PLC will require new base nodes that are currently provided by ZIV and NEURON, which has been the one selected for the representation of the new topology in *Figure 2*. The main difference between these two PRIME v1.4 base nodes is that the supplied by ZIV is triphasic while the other is monophasic.

As overviewed from the comparation of the two LV topologies, there is a main difference: before, there was a larger PRIME v1.3.6 network connecting all the smart meters together with the substation. However, now these PRIME v1.4 are smaller since each SFB has its NB-PLC network. This difference is one way in which this new solution offers more efficiency in terms of lower latency. As explained before, the reading of the SMs is done sequentially, what means that smaller SMs networks will mean not only faster but also simultaneous readings. Besides that, the existence of a BPL network that communicates the SFBs to their correspondent SS will also provide a reduction of latency that is the ultimate aim of this deployment.

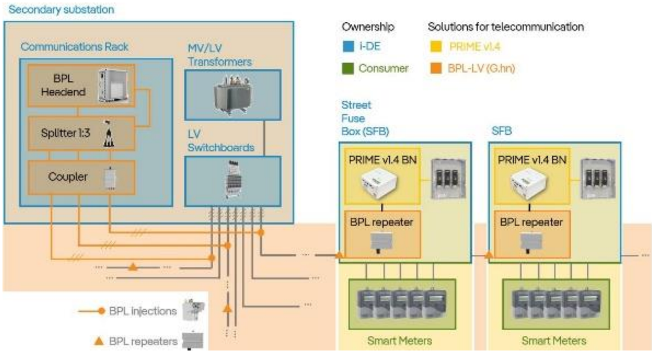

Figure 2: LV grid topology (after BPL-LV deployment).

This change has already started in some selected grids. More concretely, there is a plan definition for deploying this new topology in 349 SS by 2024 that will involve the modification of 4.723 SFB. Besides, it has been already done it in 25 SS corresponding to 66 SFB. The evolution of the number of SS involved in each of the phases of this deployment plan is summarized in *Table 1*.

Table 1: Phases of the BPL-LV deployment. [4]

		Number of SS							Total SS / city
City	**Region**	**Phase 0**	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5**	**Phase 6**	
San Agustín De Guadalix	Centre	3							3
Alcalá De Henares	Centre		7		3	4			14
Getafe	Centre			8	4				12
Madrid	Centre			12	14	13	11	14	64
Móstoles	Centre		5			6	5	3	19
Toledo	Centre						4	2	6
Torrejón De Ardoz	Centre		2	3	3		5	9	22
Rafelbunyol	Northern East	3							3
Castellón De La Plana	Northern East		5	8	6	6	6	7	38
Valencia	Northern East		26	14	13	12	10	17	92
Alicante	Southern East			5	6	1			12
Benidorm	Southern East					5			5
Murcia	Southern East						7		7
Zalla	North	19							19
Bilbao	North		6	2					8
San Sebastián	North				5				5
Logroño	North					5			5
Pamplona	North						5		5
Burgos	West		1	2	1	2	1	2	9
Valladolid	West		1						1
Total SS / phase		**25**	**53**	**54**	**55**	**54**	**54**	**54**	**349**

The criteria to select the secondary substations that will take part of this deployment plan and that has led to the final selection of *Table 1*, was developed in [1]. The first step consisted of the selection of the set of SS that may be eligible for the field trials. To do so, the sequence of decisions shown in *Figure 3* has been made. As seen, from the 103.387 total secondary substations of i-DE, 6.260 are eligible for BPL-LV deployment. This means a 6% of the total number of SS that it supplies electricity to around a 17% of the total consumers of i-DE.

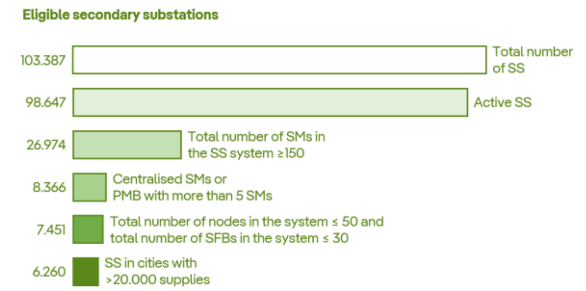

Figure 3: Criteria to select the eligible SS for field trials. [Own preparation]

After selecting the eligible SS, there is a process of classification of these SS based on some relevant parameters. The objective is to rank them, so it is possible to choose those 324 SS that meet the requirements more accurately. These parameters that have ended with the selection of 324 out of the 6.260 eligible SS are: the **higher number of SMs,** the **higher percentage of SFBs that are target** per each SS, the **lower number of PMB**, the **lower number of LVL**, and the **shorter distance from each SFB to its SS**.

Finally, after having ranked the SS with these constraints, the last criteria to reach those 324 SS is to choose **SS without BPL over their MV grid** to avoid interferences, **SS with more than 50 non-securable SM** to take advantage of the requirement to deploy new SM that are compatible with PRIME v1.4 in order to modernize those SM that are less updated, and other **geographical criteria** such as the election of enough large locations that makes possible to deploy simultaneously at various points, and locations that have target SS that are not too far one from each other.

C. Challenges for this Project.

After defining the changes that this Project suggest, it can be understand what are the challenges that it involves. In the case of the BPL-LV network, it will be necessary to define which of the low voltage lines (LVL) will be injected with BPL, and also which SFB will need to include a BPL repeater. On the other hand, in the case of NB-PLC network, the new features introduced by PRIME v1.4 also brings challenges. Not only will be necessary to install base nodes of this telecommunication solution in each one of the selected SFB but also, as this technology provides a wider frequency band to transmit data rather than the previous PRIME version, PRIME v1.4 uses 8 different channels to communicate and therefore, it is necessary to define an approach to allocate the communications for these different channels that did not exist before.

III. STATE OF THE ART

Power Line Communications (PLC) consists of using the physical channel that is already used to transport and distribute energy – medium and low voltage power lines – as the medium to transmit information signals. This is done by superimposing the carrier signal (above 1 kHz) that transmits the data to the power signal (50 Hz in Spain and the UK) that transmits the energy [11]. This technology is significantly advantageous since it does not require the installation of a new independent grid for telecommunications, but it uses the electric grid that is already deployed, reducing expenses, and increasing the cost-efficiency ratio. Moreover, since no further installation is needed, the modernization of the telecommunication networks can be done more quickly and can reach all the places that electricity already can. This means that the coverage area of this solution can be considered widespread, and this ubiquity makes this technology interesting over others such as xDSL and perfectly suitable for Smart Grids.

The origins of PLC started in 1918 [12] when this technology was used to transmit voice messages. This application was almost the unique one until the 1930s and the common frequencies that were used by that time were around 130 kHz achieving a data rate of 10 kbps. After that, around 1990, the PLC evolved using a wider bandwidth and reaching higher data transmission rates up to 10 Mbps using frequencies from 2 to 30 MHz.

Depending on the bandwidth, PLC can be Ultra Narrowband (UNB), Narrowband (NB-PLC) or Broadband (BPL). NB was the first implemented PLC technology, and it achieves under a 1 Mbps bit rate using frequencies between 3 kHz and 500 kHz. Below, from 30 Hz to 3 kHz corresponds to UNB. On the other hand, BPL enables signals being sent and received with high transmission speeds of hundreds of Mbps using frequencies from 1.8 MHz to 250 MHz.

A. Narrowband PLC (NB-PLC).

The evolution of NB-PLC standardization began in 1990s when the International Electrotechnical Commission proposed the regulation IEC 61334 for low-speed reliable PLCs operating between 20 kHz and 100 kHz and with a separation of 10 kHz. This standard corresponds to low data rate power line communications. After that, in 2009, **G3-PLC** – standard ITU-T G.hn 9903 by the International Telecommunications Union – was published for NB-PLC to operate from 36 kHz to 90.6 kHz. The Orthogonal Frequency Division Multiplexing that is proposed provided improvements in terms of resiliency against interferences. This standard was promoted by Électricité de France (EDF) in France, and it is currently used by distribution companies such as Enel that operates as Endesa in the Spanish territory. Meanwhile, in Spain some companies were promoting its own standard ITU-T G.hn 9904 also known as **PRIME** [13]. The version 1.3.6 of PRIME proposed 96 OFDM subcarriers with frequencies from 42 kHz to 89 kHz (i.e., within CENELEC A-band) reaching 61.4 kbps. Lastly, the Institute of Electrical and Electronics Engineers proposed in IEEE 1901 NB-PLC up to nearly 500 kHz via AC and DC power lines reaching 46 or 234 kbps depending on the configuration of the network.

Meanwhile, the new update of NB-PLC (**PRIME v1.4**) offers advanced features as its wider available frequency band and multi-channels. PRIME v1.4 uses frequencies from 42 to 472 kHz. Besides that, it includes a repetition encoder that provides robustness to the system by the repetition of bits to improve the reliability of the data transmission in channels polluted with noise. This new version will enable data rates up to 1 Mbps and a bandwidth division into eight channels that provides flexibility to the communication since they can be combined in different ways establishing independent "bands". The planification of this combination makes possible to avoid interferences between adjacent PRIME networks by avoiding them to transmit using adjacent channels. This planification will be developed in the section *Definition of the NB-PLC Network*.

Furthermore, the comparison of the mentioned standards has been summarized in *Table 2*.

Table 2: Comparison of NB-PLC standards' features. [12]

	IEEE 1901	G3-PLC (G.hn 9903)	PRIME v1.3.6 (G.hn 9904)	PRIME v1.4 (G.hn 9904)
Frequency range	30 – 490 kHz	36 – 90.6 kHz	42 – 89 kHz	42 – 472 kHz
Modulation (Physical layer)	OFDM	OFDM	OFDM	OFDM
Data rate (Data link layer)	46 kbps / 234 kbps	50 kbps	61.4 kbps	1 Mbps

B. Broadband PLC (BPL).

As it was already mentioned, the main advantage of BPL over NB-PLC is the higher speed rates that this alternative can offer thank you to a wider use of the frequency band. This does not only have impact on the lower latency but also on the capacity of sending larger volumes of data, which is essential for supporting advanced applications that require significant data exchange, such as real-time monitoring and control of grid devices.

b.1. Broadband PLC over Medium Voltage (BPL-MV).

BPL integration over MV grid is currently extended for applications such as grid automation (i.e., activation and management of switches and breakers), and monitoring (i.e., real-time data transmission about the network's status to detect potential faults or frauds and analyse the power quality). Besides that, the development of this technology was specifically useful for telecontrol purposes in MV and as smart grids backbone – in telecommunications, it is referred to the principal data routes – in the secondary substations.

There are three main blocks that make possible the telecommunications through BPL in MV: injector, receptor, and repeater [14]. **Injection** needs of two components: the head-end (HE) and a coupler. The coupler injects the signal to the grid while the HE assigns resources to all the nodes of the BPL cell. Then, Time Division **Repeaters** (TDR) allows the signal to be increased – and thus to increase the coverage – to avoid the loss of Signal to Noise Ratio (SNR) caused by the attenuation or by the noise and impedance along the trajectory of the signal. Finally, signal reaches to the **receptor**, the Customer Premise Equipment (CPE) in customer's household that is used to receive and send back **information** of the demand point.

In the case of Iberdrola, the company currently uses UPA (Universal Powerline Alliance) technology and owns 25.900 devices supplied by two manufacturers: *Corinex* and *Ormazabal* [11]. This equipment follows the standard **IEEE P1901.2** that establishes that the communication is made at high frequencies (1.8 to 100 MHz) achieving speed rates of 500 Mbps. It uses OFDM modulation and allows multiple devices to communicate simultaneously over the same MV power line, which is crucial for maintaining efficient data transmission in a shared communication environment.

b.2. Broadband PLC over Low Voltage (BPL-LV).

The deployment of BPL-LV would significantly decrease the latency in the telecommunications and will lead them to the new paradigm of real-time data collection, supervision, and control, which is the desired scenario that coming innovative applications require to optimize their use [15].

Utilities have been using BPL-LV since the 1990s for two main purposes: internet access parallelly to wireline technologies such as xDSL and *smart grids services*, mainly smart metering. The use of BPL in LV has specific features compared to BPL-MV:

- LV grids are less controlled by utilities since it is difficult to plan its performance.
- LV grid topologies are more complex due to several branches and sub-branches extending radially. This implies signal reflections at high frequencies and therefore needs the installation of BPL repeaters.
- The budget of utilities for LV grid is lower than for MV and so is its maintenance. This could cause the degradation of LV cables that may negatively affect the BPL.

The first specification for BPL in LV was promoted by the Open PLC European Research Alliance (**OPERA**) [1] starting in 2004 with the aim to *"offer low-cost broadband access service to all European citizens using the most ubiquitous infrastructure, power lines"* [2]. It operates within a frequency range of approximately 2 to 28 MHz using OFDM modulation with adaptive coding and multiple-input-multiple-output (MIMO) techniques and it provides a data rate up to 205 Mbps.

The recommendations of BPL use for in-home technology were developed by ITU in 2006 and supported by the HomeGrid Forum (see **G.hn 9960**, G.hn 9961, G.hn 9962, G.hn 9963, and G.hn 9964 from years 2009 and 2010). The specific characteristics of this PLC are: OFDM with a frequency separation between subcarriers of 24.4 kHz, a network divided in 16 domains which can be designated as master of up to 250 nodes, and synchronized access to the media where transmissions are coordinated by the domain master. This standard is the one implemented by the suppliers that are collaborating with Iberdrola for the BPL over LV deployment.

At the same time, IEEE published the standard **IEEE-1901** in 2010 defining the characteristics of BPL [16]: bandwidth of 1.8 MHz to 50 MHz, data rates up to 420 Mbps, possibility to use both – but not at the same time – conventional OFDM or wavelet OFDM (that uses wavelet functions instead of sinewaves offering improved time-frequency localization and robustness against non-stationary channels).

In 2011, Panasonic Corporation promoted the standard **High Definition-PLC** (HD-PLC) that has four versions [1]: the first one uses a frequency band of 4 to 28 MHz and provides data rates of 190 Mbps while the second one operates within 2 to 28 MHz for 210 Mbps. Besides that, the third version introduces two new specifications: HD-PLC3 Complete based on IEEE 1901 with wavelet OFDM, and HD-PLC3 Multi-hop which integrates standards IEEE 1901 and ITU-T G.hn 9905. The last one version is aligned with the IEEE 1901-2020 standard featuring the flexible channel wavelet for the physical layer. This version introduces the option of broader bandwidth – up to 62.5 MHz – and incorporates advanced error correction techniques that improves overall performance and adaptability.

The standard **ISO/IEC 12139-1** was developed by the Korean Agency for Technology and Standards. After that, ISO and IEC implemented it and defined its physical layer. In this case, the communication also uses OFDM modulation within a frequency range of 2.15 to 23.15 MHz. It is adaptive to other modulations as FSK and provides data rates up to 100 kbps.

The HomePlug Alliance has published various specifications in the past years starting in 2001. Ones of the last ones was defined as **HomePlug Green PHY** and **HomePlug AV2** in 2010 and 2012 respectively. The first one used the frequency band from 2 to 28 MHz reaching a bit rate of 200 Mbps and the second one, uses frequencies from 1.8 to 87 MHz for a communication of a speed of 1.5 Gbps. Green PHY was developed for automotive applications regarding the integration of electric vehicles whereas AV2 is more commonly used in residential and commercial environments for in-home networking and entertainment applications (i.e., smart TVs, gaming consoles, computers, etc.)

Since 2018, the **PRIME** Alliance has been conducting surveys together with the *International Data Corporation* (IDC) and in 2021 they have concluded that smart grid communication is actually shifting from narrowband to broadband PLC. This is the reason why the PRIME Alliance is supporting the research and development of solutions that provides BPL solutions for the electric network. Finally, during Enlit Europe 2022 in Frankfurt, the Alliance standardized BPL for deployment based on ITU's G.hn protocol and enhanced its main features: high-speed communication, edge computing, security, extensive network coverage, and cost-effectiveness.

Once the principal standards regarding to BPL-MV and BPL-LV has been described, *Table 3* serves as a summary to understand the differences among these two types of standards to avoid mix up MV and LV standards and to understand which are the rules that each of the telecommunication solutions suggested for the new LV grid will be required to follow.

Table 3: Solutions for telecommunications: before vs. then.

	Traditional (*Figure 1*)		Suggested (*Figure 2*)	
	Standard	**Organization**	**Standard**	**Organization**
NB-PLC	G.hn 9904 (PRIME v1.3.6)	ITU	G.hn 9904 (PRIME v1.4)	ITU
BPL-LV	-	-	G.hn 9960	ITU
BPL-MV	IEEE P1901.2	UPA	IEEE P1901.2	UPA

IV. BENCHMARK OF SIMILAR PROJECTS

A. *Use Cases of BPL Deployment.*

The selected supplier for the BPL-LV equipment is *Corinex* and it is actively working with Tier 1 utilities that have validated its BPL solution. These companies are: *E.ON, Iberdrola, Stromnetz Hamburg, Stromnetz Berlin,* and *westnetz.* As seen, the countries that are currently more involved with this transition from NB-PLC to BPL is Germany together with Spain that will adapt the solution to other countries. *Corinex* is specialized in developing, manufacturing, and implementing complex solutions for smart metering and smart grid infrastructure projects, with a focus on BPL.

The use cases that have been carried out to validate this solution are mainly four [5]:

1. **BPL Smart Meters with BPL concentrator:** this is the case of *ČEZ Distribuce* in the Czech Republic with major relevance in Central and Eastern Europe. This company chose a solution where a BPL smart meter was the end point of the network, and the concentrator was the controller. This trial achieved the decrease of the peaks of energy.
2. **Coexistence of BPL and NB-PLC:** this is the case of Iberdrola that has combined the existence of a solution similar to the previous one with the already installed PRIME (NB-PLC) base nodes for smart metering.
3. **BPL Smart Meter Gateway:** this is the case of *E.ON* that will be described later in this section. This solution is also the origin for new solutions that are not standardized yet by the PRIME Alliance but offers similar benefits to the standardized solution; one example is the *BPL EnergyGrid* by Corinex.
4. **BPL over MV lines:** this is the alternative used by Iberdrola as a substitute for optic fibre or other wireless networks in 25.000 BPL MV devices. This option enables reliable real-time connectivity for all the expected IoT devices in the electric network.

B. *The experience of E.ON.*

The most relevant test of this solution within a large-scale distribution grid has been carried out for E.ON, whose headquarters are in Düsseldorf, Germany and has already started the deployment of BPL-LV along its low voltage grid. E.ON [6] is an energy company focused on energy networks, customer solutions, and renewable energies. It has 32 million customers to whom the company provides gas and electricity in multiple countries generating sales of around $42 billion and having already invested over $11 billion in nearly 5.4 GW of renewable capacity. E.ON started the deployment of the BPL Smart Meter Gateway in late 2019. It was done over 100.000 network elements with high availability element management software, being the first complete implementation of a BPL network at that scale [5]. The company plans to keep expanding their BPL infrastructure in the near future based on the standard ITU-T G.hn.

b.1. New features achieved by E.ON.

The approach of Corinex for power line communications gathers the three solutions that are currently fragmented in three different chips – **security** for the incorporation of several new applications that share data, **communication** in real-time among different devices, and **edge computing** that allows the computation closer to the data source and user devices instead of the traditional centralized computing [8]. These solutions are now gathered in only one chip that provides all the features cost-effectively (at 30% of the cost of the three chips) thanks to research that has developed this technology oriented to digitalize smart grids applications. Besides that, BPL solution of Corinex provides proven features such as superior and cost-effective connection over competing technologies such as 5G, LTE (4G), or G3-PLC. These features are summarized in *Table 4*.

Table 4: Comparison of telecommunication solutions. [7]

		Speed (Mbps)	Cost per MB	Coverage	Persistent link	Voltage sensing	Security	Real-time data	Scalability	Latency
BPL		250	$0,71	Y	Y	Y	Y	Y	High	< 100 ms
Wireless	5G	100	-	N	N	N	Y	Y	Limited	< 50 ms
	LTE	20	$4,65	N	N	N	Y	Y	Low	< 100 ms
NB-PLC	G3	0,3	$68	Y	N	N	N	N	Low	> 3 s
	PRIME	0,3	$68	Y	N	N	N	N	Low	> 3 s

b.2. BPL equipment for E.ON's deployment.

In Germany, this solution is based on the elements [9] that are represented in *Figure 4*:

Figure 4: Smart Grid Solution of Corinex. [Own preparation]

- **BPL endpoint:** this modem is designed to work seamlessly with the German deployed smart meters, enabling the monitoring of residential loads and production, and facilitating secure real-time communications over existing electric infrastructure.
- **BPL repeater:** it gathers data from multiple modems and forwards it to a headend, which then transmits it to a centralized energy management system. This is done securing a reliable real-time communication over existing electric infrastructure.
- **BPL headend:** it secures real-time communication over utilities' electric infrastructure by gathering data from multiple modems or repeaters and forwarding the collected data to a centralized energy management system (EMS).
- ***GridValue* EMS:** it is an advanced software that aggregates data and analyses it in order to boost the efficiency of the low voltage grid. It acts like a top-level solution for managing the network allowing utilities to offer new generation smart-grid applications. This software can manage 5.000.000 nodes, 2 million messages per minute, and 10.000 configuration requests in parallel [10].

V. PROJECT DEVELOPMENT

Following the needs mentioned in the previous section, the thesis will focus on the specifications needed for the deployment of the two communication networks for the LV distribution grid. To structure the development of the Project, it will be divided in two essential phases related to each one of the telecommunication networks:

A. *Definition of BPL-LV Network.*

The initial phase required a detailed analysis of the variables involved in the deployment to study the relevance of them in this process. The conclusions from already conducted field trials and the suggestions from the BPL-LV equipment suppliers have been the most influential parameters for the following developments.

After the comprehensive study of these conclusions, it was necessary to understand the LV network and the equipment that is already part of the grid and therefore may be transformed because of this deployment. For this phase, it was necessary to use the Geographic Information System (GIS) that is a computer-based tool for gathering, managing, analysing, and visualizing spatial data. In the case of Iberdrola, it gathers its electrical and telecommunication inventory data and represents it on map, making easy for grid planners to design the most optimal deployment plans or maintenance initiatives as they have an accurate digital copy of what is it in the field.

The specific GIS that it is used within the company is *MapInfo Professional 12.0*. By working with this tool, it was possible to understand the structure of the grid and the challenges that may be faced because of the transformations that are suggested. The graphical representation is based on large alphanumeric databases that have been analysed to extract meaningful insights. The parameters that have been the most significant to achieve the characterisation of the LV grid are summarized in *Table 5*. As represented, there are some parameters obtained from the original alphanumeric database while there are others that have been computed directly using the graphic information of the GIS and therefore needs to be queried directly from *MapInfo*.

Table 5: Parameters for the LV network characterisation. *[Own preparation]*

Original Database				MapInfo
Per SS	**Per LVL**	**Per segment**	**Per duct**	**Per SFB**
ID code	ID code	ID code	ID code	ID code
City	SS father	LVL father	LVL father	SS father
Type	# Clients	Total length	Total length	LVL father
# Transformers	Overhead length			# Clients
# LV switchboards	Underground length			Distance to the SS
# Clients (mono- and tri- phasic	SFBs (codes)			Distance to the previous SFB
# SFBs	Distance from each SFB to the SS			

After having collected all this information from various data and process it when necessary to get useful conclusions, it was possible to design the detailed specifications that will eventually allow the development of the actual tool that helps to automatize the deployment. These aimed results focused on the definition of the BPL-LV network focus on three primary outcomes: the selection of the lines that will need to be injected with BPL, the determination of the injection solution that better fits each of the lines, and the precise allocation of resources described in terms of the phases in which this Project is divided to better understand the magnitude of the deployment and the equipment that will be required for each one of the phases, helping the planification of the working team involved in the Project.

B. Verification of the deployment performance.

After the deployment of the BPL-LV, it is necessary to check if the process has been successful. As it is an empiric method, there is a need to set key performances indexes (KPIs) to verify the accuracy of the communication between devices in the deployed network. This supervision is not yet automatized but it requires the measurement of certain parameters that can be checked in different sources: *GridValue* and *Grafana*, to check if the performance after the BPL deployment is precise enough for the quality of service that needs to be provided to the end-customer.

As mentioned, *GridValue* is the software provided by the BPL-LV equipment supplier that serves as the digital manager of this specific equipment. It is in fact an Energy Management System (EMS) that enables the collection of data from the power distribution system, providing provisioning, management, and real-time visibility across the electric grid. This is feasible because *GridValue* is compatible not only with BPL-LV (G.hn 9960, ITU) but also BPL-MV (IEEE P1901.2, UPA), the two standards of BPL used by i-DE. The tool is still in process of development and allows the visualization of the main parameters that can be measured from the grid through dashboards that make easier for the audience to interpret the energy data that is collected. This feature is possible because of the integration of *GridValue* with the GIS, resulting in maps that helps the visualization of out-of-box analytics, previously undetected patterns, and unnoticed behaviours. The three main parameters that are measured and are determinant to determine if the BPL-LV deployment is functioning correctly are the availability, the physical rate, and the profile analysis.

- **Availability:** it is the measure of how much a system is operational (available) compared to the total time during which it is expected to be available. Therefore, this parameter tracks downtime, outages, and disruptions in the telecommunications systems and consequently the reliability of the power distribution system.
- **Physical rate:** it measures the transfer speeds for the data download and upload in the telecommunications systems. These speeds are measured in bits per second (bps) and usually reaches the magnitude of Mbps. These parameters help to identify bottlenecks were data transfer needs to be improved to increase the speed rates.
- **Profile analysis:** it analyses the voltage profile to check that the voltage levels across the power distribution system are as expected to track deviation from the ideal voltages. Detecting these voltage imbalances is useful to prevent potential damage in the equipment and therefore ensure stability in the power distribution system.

On the other hand, *Grafana* is a software that serves to visualize data that is collected from the deployed equipment. The software has the capability to transform raw measured data from field into meaningful charts, and graphs. Besides that, it is possible to set alerts and notifications to detect some potential failures in the performance of the BPL-LV deployment.

For this Project, *Grafana* has been customized to show the results of a **ping analysis** for the different SS that are part of the phase 0 of the Project. A ping analysis like this involves the assessment of the network connectivity and latency between two devices in the recently deployed BPL-LV network. This verification uses the Internet Control Message Protocol (ICMP) *echo request* and *echo reply* messages. The ICMP Echo Request message is sent to the target device to ask if it is reachable. Moreover, the ICMP Echo Reply message is the answer to that first request: if the target device is active, this message is sent.

By carrying out a ping analysis, it is possible to determine the latency, reliability, and stability of the communication network as explained below. The parameters that indicate these features of the established connection are the following:

- **Round-Trip Time (RTT):** time that the ICMP Echo Request message takes to reach the target device and receive its answer back. RTT is also known as **latency**, its measuring unit is usually milliseconds (ms), and the target of this Project is to minimize it.
- **Jitter:** it analyses the variation between latencies from consecutive ping tests. The lower jitter, the higher **stability** of the communication network.
- **Packet loss:** it is the phenomenon when the ICMP Echo Reply is never sent, meaning that the communication between the two analysed devices is not proper working. The computation of the percentage of lost packets represents the **reliability** of the connection.

Once the parameters that are relevant in a telecommunication system have been described, now it is possible to define a set of KPIs that the working team needs to check in the following weeks after the deployment. These KPIs have been gathered in *Table 6*.

Table 6: KPIs to check after the BPL-LV deployment.

	Feature	Criterion
GridValue CORINEX	Availability	≥ 98%
	Physical rate	≥ 10 Mbps
	Profile analysis	≤ 10% *
Grafana	Availability	≥ 98%
	Round-Trip Time	≤ 50 ms
	Packet loss	≤ 5 %
	Jitter	≤ 20 ms

* Note that all the indexes have been selected through empiric analysis and they are values that are considered to ensure a reliable connection and communication among devices. They are usual parameters for wired systems of telecommunications. This is not the case with the KPI for the profile analysis where the criterion has been obtained from the Spanish *Royal Decree 842/2002* that states that the supply of electrical energy at low voltage must be kept within the limits of ±10% of the nominal voltage.

C. *Definition of NB-PLC Network: PRIME v1.4.*

As mentioned, PRIME v1.4 uses a wider frequency band than PRIME v.1.3.6 (42 to 472 kHZ in the newest version versus 42 to 89 kHz before). This characteristic makes possible to avoid certain interferences that commonly appears in lower frequencies. This is done by expanding the frequency band and allowing the communication to be done through higher frequencies with less noise. Besides that, another feature related to this one is that PRIME v1.4 can use 8 different channels to communicate. Regarding these 8 channels of the new version, only 6 of them are available for PRIME v1.4. This phenomenon is represented in *Figure 5* where channel 1 is used for PRIME v1.3.6 communications and channel 2 is avoided so there is no overlapping of data transmission from the equipment of these two different standards that will coexist but cannot communicate with each other. *Figure 5* shows the huge difference between the frequency band that is used for NB-PLC in countries such as the United States (FCC spectrum), and Japan and China (ARIB spectrum) with respect to the use given in Europe (CELENEC A spectrum). The expansion of the bandwidth for telecommunication systems in the power distribution network is a trend now and one of the reasons for the developing of the newer version of the PRIME standard.

Figure 5: Frequencies band for NB-PLC. [Own preparation]

This feature introduces new challenges as this new possibility is directly related with the necessity to design an approach that helps to associate each PRIME network to a different channel. This allocation is significant since an allocation that ensures that two adjacent PRIME networks does not share the same or adjacent channels will avoid interferences that may affect the communication.

c.1. Approach to allocate PRIME v1.4 channels.

The proposed approach for this challenge is based on the Four-Colour Theorem that establishes that 4 different colours are enough to ensure that two adjacent areas do not share the same colour. The similarities of this theorem with the channel allocation problem are represented in *Figure 6* and it can be summarized as: 4 different channels are enough to ensure that two adjacent PRIME networks do not share the same channel.

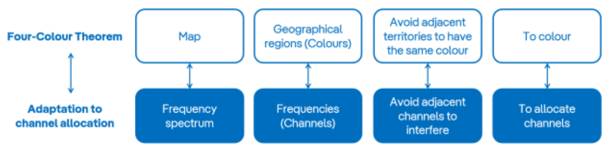

Figure 6: Application of Four-Colour Theorem to Channel Allocation. [Own preparation]

The algorithm to allocate the channels to the PRIME networks would **iterate** through the communication channels and assigns frequencies (channels) in a way that adjacent channels receive different colours. This approach guarantees minimal interference and can be extended to account for constraints such as frequency availability and transmission power. However, this approach does not provide a solution to determine the order in which various contiguous networks would be better allocated. To solve this problem, this work suggests getting inspired from the Welsh-Powell algorithm that suggests a process to be followed to establish an automatization for this channel allocation. This algorithm considers the networks to be vertices and the frequencies to be edges as they were forming a graph. Furthermore, the similarities from the *graph theory* concepts with the ones that would be used when allocating channels need to be taken from *Figure 6*. The steps of Welsh-Powell algorithm are the following:

1. Calculate the number of edges that end in each vertex (i.e., degree) of the graph.
2. List the vertices in order of descending degree. The criterion to break ties is not relevant.
3. Colour the first vertex in the list with colour 1.
4. Go down the list and colour every vertex assigning the selected colour to all the vertices that is not connected with an already coloured vertex.
5. Repeat the steps on the uncoloured vertices with a new colour.
6. Do it as many times as required to eventually get all the vertices coloured (i.e., all the channels allocated).

c.2. Further considerations for channel allocation.

Apart from iterative, the algorithm needs to be **dynamic** as it is necessary to lively allocate frequencies while avoiding congested bands and allocating available frequency bands. Moreover, the algorithm should prioritize unused frequencies to expand the possibility for two adjacent areas not to share the same channel.
Besides that, efficient channel allocation should not be limited to frequency assignment but also involves optimizing transmission power levels to minimize interference effects. Because of that, the algorithm may also suggest reducing power of adjacent channels and increasing it when they are not to minimize the interference signals while keeping the signal quality. To sum these criteria up, the algorithm should consider greedy colouring, frequency availability to choose free frequency bands, and power management.
As well as in the case of the BPL injection, the performance of the deployed networks needs to be tested after implemented. To do so, KPIs as the suggested in *Table 6* are required to be met to ensure an accurate and valuable telecommunication and connection of the equipment compromised in the PRIME v1.4 network. Besides that, incorporating machine learning and artificial intelligence techniques for predictive management of interferences can help to optimize NB-PLC systems. These KPIs are parameters that can measure interference levels, data throughput, and network stability as a way of identifying the efficiency of the channel allocation process and mitigating potential interferences.
According to this theorem, only four different frequencies would be needed to achieve this, assuming that interferences only occur between adjacent channels. However, there is still another two channels that can be used. This gives the planification an extra advantage for those cases in which the geographical area covered by the PRIME network may be more complex and requires an additional channel not to coincide with the other channels already used for the networks in the SS. Because of the magnitude and complexity of the power distribution grid, some further challenges such as frequency availability, transmission power, environmental characteristics, and other technical constraints may be required to be taken into account.

VI. RESULTS

The principal results that have been obtained from the research carried out in this Project are the following: a specification to standardize the BPL injection process, a specification to establish the criteria to choose the injection solution that will be used for each selected low voltage line, and a list of the involved electrical components in the development of this Project as well as a list of equipment that need to be procured for the deployment. Furthermore, these lists will also involve another table of data that helps to overview the configuration of the LV network by defining the percentages of SFB that are found in different scenarios of constraints. These lists have been defined per phase of the Project, that is divided into 6 different ones, so the overview of the concerned devices is accurate and will help to plan the strategy for the deployment and purchase processes. In the following sections, the most relevant conclusions extracted from this research will be summarized.

A. BPL-LV deployment criteria

The first relevant criterion to define is to choose which SFB are the ones considered to be part of the BPL-LV network. These are called target SFB (SFB_T) and are all of them that have at least 5 SM. So that:

$$SFB_T = SFB \,/ \sum SM \geq 5$$

This restriction will be the most significant to make decisions regarding the injection. Therefore, target LVL (LVL_T) will be referred to all the LVL to which a SFB_T is connected.

After these important definitions, the first verification that will be done before a BPL-LV deployment is if the LVL share the same direction for at least 30 m. In these cases, the group of LVL will be treated as a “cable bundle”. This differentiation is important due to the existing restriction of avoiding the injection in more than 4 LVL per SS. When there are cable bundles, the criterion is to inject that LVL whose SFB_T is the furthest but within a distance of 150 m. This length constraint is another very important condition to consider in the deployment: in the cases where the distance between a SS and a SFB_T is lower than 50 m, no injection is needed. However, when overpassing the limit of 150 m, this is called to be "problematic" due to related problems of attenuation when the distances get longer. In the event of a SFB_T distanced more than 150 m from its SS and when there is no other SFB_T that shares the same line and that is located closer, it is necessary to make use of a common – non target – SFB to install in it an additional BPL repeater that could ensure the communication system.

The results of this analysis have been represented as a flow diagram that will be essential for the future development of the tool that automatizes the deployment process. The reason for choosing this method of results' representation is to adapt to Iberdrola's usual procedure to design specification for third parties to eventually develop the solutions that are defined by these diagrams. Because of the large extension of the flow diagram that represents the automatization of the BPL deployment process, it has been attached as an annex to this document.

B. BPL-LV injection criteria.

The main parameter to consider when deciding the injection solution for the selected low voltage lines is the type of SS that these lines belong to. The injections can be done through two methods: using the AMI sensor that is commonly used for supervision or with a *Niled*. The second option is used if the first option is not possible and when the SS is not floodable. The first option is the preferrable, and it is suitable always then the SS is standardized. When this option is used, the supervision of the injected LVL is disabled and substituted by a "*dummy* card" while the rest of lines continue to be supervised. This is done to take advantage of the intermediate phases used by the advanced supervision card to connect the BPL injection through them.
Although today the AMI sensor is the preference, the favoured BPL injection solution before was to use Niled or to screw it rather. This change of strategy was driven by empiric tests that proved that the Niled solution has disadvantages due to its condition of "biting" the cable to inject it. This action provokes the perforation of the cable – insulation and conductor get perforated – and therefore some risks associated with the use of Niled such as short-circuit and "hot points" risks. As the insulation is perforated, in the case where the SS gets filled with water that gets in contact with the cable, it may occur a short-circuit because of the contact of this water and the conductor that is bare because of the perforation. Because of this reason, it will be relevant to identify the type of SS and also to identify those SS that are part of the planned deployment and that are floodable. On the other hand, "hot points" are created when there is high resistance in an electrical connection due to poor contact or bad connection. In this case, created by the screw used in the injection that perforates the cable. This increase of resistance heats the cable up as the current encounters this risen resistance and this reaction can cause damage in surrounding materials such as other cables, insulators, or electronic components. In the last stage, it could also lead to a fire in the SS if it is not controlled.
These criteria have been represented as a decision tree in *Figure 7.* As seen, in the cases where it is not possible to inject by using the LV-AMI sensor and the SS is at risk of flooding, the only solution is to note that case and SS and wait for it to be substituted for a new one that has standardized LV switchboard and therefore is compatible with the AMI sensor solution.

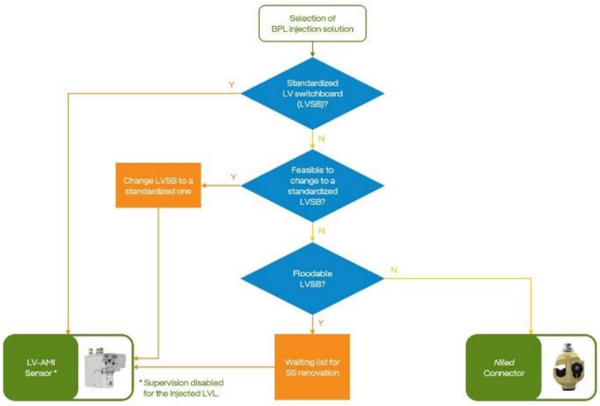

Figure 7: Decision tree - BPL injection solution.

D. BPL-LV equipment requirements.

c.1. LV grid characterisation.

The preparation of the definitive list of required equipment needs a previous analysis of what are the electrical components involved in the Project. This information is relevant as it will determine the telecommunication devices that are needed. Because of this reason, *Table 7* gathers all the elements that are planned to be modified during the deployment process.

Table 7: Count of electrical elements per phase. [Own preparation]

	Total	Phase 0	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6
SS	349	25	53	54	55	54	54	54
SFB_T	4.723	66	454	550	814	948	1.070	821
SFB no target but necessary	429	6	41	50	74	86	97	75
SS / LVL_T <= 2	4	1	1	1	0	0	0	1
SS / LVL_T = 3	15	4	3	3	1	3	0	1
SS / LVL_T >= 4	330	20	50	49	55	50	54	52
Floodable SS	136	6	16	25	24	17	24	24
Non-floodable SS	213	19	38	28	32	36	30	30

To finish with the analysis of the data from the 349 SS selected for the field trials, some information about the distances from the target SFB and other SFB to these SS has been obtained. For instance, that the average distance from the SFB to the SS is 106,45 m for all the cases and 105,91 m specifically in the case of target SFB. Besides that, *Table 8* gathers more relevant data about the allocation of these SFB downstream the SS. One of the most valuable insight that will be relevant for the planning of the equipment needed is the number percentage of situations in which the target SFB is further than 150 m from the SS, there is no target SFB closer in the same line but it is a SFB that is not target but it can be used to host an additional BPL repeater that can ensure a reliable communication from the SS to the target SFB by going through this additional repeater. This is the case of the 9,08% of the total target SFB that equals the 42,11% of these target SFB that are further than 150 m. In the other cases, there are another target SFB before the furthest one whose installed BPL repeater can help to that communication (it is the case of the 52,63% of the target SFB that are further than 150 m). Finally, it exists the case in which the target remote SFB has neither a target SFB previous to it nor a common SFB. This is the case of 1,14% of the total target SFB whose injection and BPL deployment is at risk due to the potential attenuation that the communication may face and that can lead this number of SFB without reliable BPL connection.

Table 8: Analysis of allocation of target SFB. [Own preparation]

	Target SFB	SS with target SFB > 150 m	SS with target SFB > 150 m + previous target SFB ≤ 150 m	SS with target SFB > 150 m + previous SFB ≤ 150 m	SS with target SFB > 150 m + no previous SFB
% of total SFB	44,3%	17,42%	9,17%	7,34 %	0,92%
% of target SFB	-	21,57%	11,35%	**9,08%**	1,14%
% of target SFB >150 m	-	-	52,63%	42,11%	5,26%

c.2. List of equipment.

Based on these values, now it is possible to design the list of equipment per phase that may be later significant to plan the budget for the different phases. To design this list that is summarized in *Table 9* it is necessary to know the relation between the electrical components and these devices. This relation can be verified in *Figure 2.*

There is one BPL headend per selected SS to take part of the deployment plan. Then, a BPL repeater will repeat the sent signal by being installed in each one of the target SFB. Additionally, there will be some BPL repeaters located in SFB that are not actually target but that are necessary to be used to ensure a reliable communication. Furthermore, these target SFB will also include a PRIME v1.4 base node that will establish the PRIME network for the smart meters belonging to those target SFB.

Following with the equipment required in the SS for the BPL injection, there will be splitters that are connected to the BPL headend and that will allow the injection in various LVLs.

There will be one (1) splitter 1:2 in those SS with 2 target LVLs, and two (2) in those SS with 4 target LVLs. Also, there will be one (1) splitter 1:3 if there would be 3 target LVLs. The injection will also require couplers to be connected to the injected LVLs. Following the same reasoning, there will be one coupler per each selected LVL to be injected: two (2) if there were 2 LVL, three (3) if there were 3 LBT, and four (4) if there were 4 selected LVL.

Lastly, as specified below, the injection will be done through an AMI sensor or a Niled depending on the type of SS. According to the data of floodable and non-floodable SS from *Table 7*, it was possible to define the number of *dummy* cards and Nileds required.

Table 9: List of required equipment. [Own prepartaion]

	Total	Phase 0	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6
BPL Headend	349	25	53	54	55	54	54	54
BPL Repeater	5.152	74	491	598	888	1.034	1.167	896
PRIME v1.4 Base Node	4.723	66	454	550	814	948	1.070	821
Splitter 1:2	664	81	101	99	10	100	108	105
Splitter 1:3	15	4	3	3	1	3	0	1
Coupler	1.373	94	211	207	223	209	216	213
***Dummy* card**	213	6	16	25	24	17	24	24
Niled	136	19	38	28	32	36	30	30

VII. SUGGESTIONS FOR FUTURE WORKS

This Project is active and dynamic, and these are the reasons why many changes and improvements may be introduced to the present work. At the same time as the different phases progress, more and more insights and knowledge will be acquired, and it will be possible to increase the efficiency of the described process to much higher levels. However, as said, these upgrades need the evolution of the field trials and therefore cannot be guessed in advance. On the other hand, there are some future works that can be defined more objectively. These are: the suggestion of benchmarking potential suppliers of BPL-LV equipment, and the necessity to be aware of the Spanish regulation regarding the deployment of BPL over the LV grid and over the already installed elements.

A. Benchmark of Potential Suppliers.

Iberdrola is relying on Corinex as its supplier for the required BPL-LV equipment, who is probably the world leader in BPL as it has developed remarkable partnerships not only with *E.ON* but also with other tier 1 utilities in Europe such as *Stromnetz* Hamburg, *Stromnetz* Berlin, or *westnetz,*

Regarding the suppliers' policy of i-DE there are procurement protocols that state that there must be more than one supplier for each of the required equipment in the network. This case is therefore special as when it comes to BPL-LV devices, an IPU – *Informe de Proveedor Único* – has been signed with the aim to allow the procedures to run counting on only one unique supplier. This has been done this way as currently the BPL-LV technology is not so widely developed and consequently there are not many suppliers that today can offer the same services and quality as Corinex does.

This is the reason why a significant suggestion for future works would be to benchmark different suppliers in the market on a regular basis. When more suppliers will be available and eager to develop their technology for such a relevant utility as Iberdrola, this benchmark would allow to analyse Corinex's competitors frequently to increase the resilience of the procurement process by counting on the most qualified suppliers in the industry.

B. Changes in the Regulation.

Power distribution companies in Spain are regulated and therefore its activity needs to be within a regulatory framework. More concretely, two of the main rules that i-DE needs to follow is the *"Manual Técnico de Distribución"*, which are a set of specifications that are particular for the company and its installations. This manual – specifically the document MT 3.51.20. Ed. 3. May 2019 – outlines the requirements for implementing remote management and automation systems for LV supplies. The document covers technical aspects, such as the installation of communication cabinets, sensors, and remote-control devices for monitoring MV and LV lines. Besides that, it defines criteria for installation, materials, and connections for the system's functionality. Additionally, the installation of mobile operator antennas and PLC communication equipment is addressed. This manual needs to be followed to meet the dictated constraints. However, there is in Spain a manual that is public and that needs to be complied: the *Reglamento Electrotécnico de Baja Tensión* (REBT) already mentioned in this document.

The REBT is periodically reviewed and so it is the case in the last years when a modification of this standard is in progress with the main objective to adapt the safety regulation for LV installations for the new paradigm of widespread self-consumption. Specifically, a new instruction (ITC) related to direct current installations has been approved.

This modification is relevant for this Project as modifies rule such as the ITC BT-13 by adding restrictions for adding elements and devices in the SFB and may be a problem for the deployment of BPL-LV as the current plan is to install new equipment in the SFB: both the BPL repeaters and the PRIME v1.4 base nodes. These revisions are published so the utilities and other companies can participate and submit their pleadings. As the aim of Iberdrola is to install these telecommunication devices in the SFB, the company has presented the justifications for doing it that way and is waiting for the definitive version to get published to confirm that this modification of the SFB is possible. It is important to check the regulation and this update concretely to adapt the deployment process to the rules that determine the operation of the LV power distribution grid.

VIII. CONCLUSIONS

This thesis has suggested approaches to develop a planning tool to deploy BPL over the LV grid. The knowledge acquired from the analysis of the databases and the field trials insights has allowed the obtention of the following results: a flow diagram of the BPL deployment that evidences the criteria to consider in this process and presented as a sequence of verifications that need to be done to complete the deployment, therefore serving as an applicable automatization process. Additionally, a flow diagram of the BPL injection solution that best suits each injection case. To complete these diagrams that serves to standardize the deployment process, also a table of expected KPIs after the deployment has been provided after analysing the measurement from the field trials. These specifications will serve to design the BPL-LV deployment. On the other hand, regarding the deployment of NB-PLC, an approach to allocate PRIME v1.4 channels has been defined so the installed PRIME base nodes in the selected SFB avoid interferences between adjacent PRIME networks. Finally, a list of required equipment for the deployment has been designed to help the procurement process during the different phases of the deployment.

The presented specifications and results for an automated tool reflect the thesis' practical impact, facilitating efficient deployment, while considering logistical and procurement considerations. By leveraging insights from field trials and extensive databases, this Master's Thesis has contribute to the advancement of an agile and adaptive power distribution landscape.

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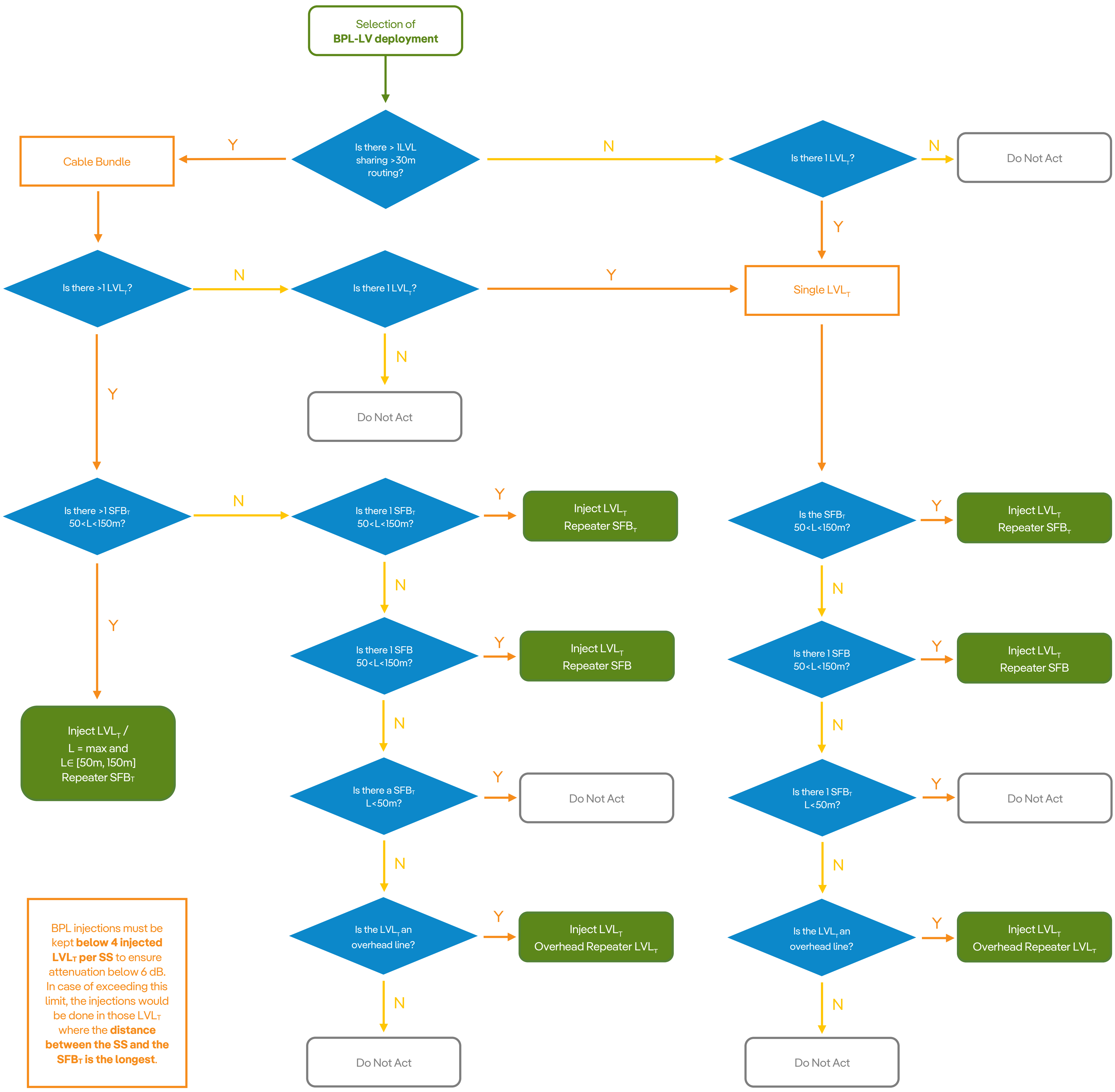
Selection of
BPL-LV deployment
Is there > 1LVL sharing >30m routing?
Y
Cable Bundle
N
Is there 1 LVL$_T$?
N
Do Not Act
Y
Single LVL$_T$
Is there >1 LVL$_T$?
N
Is there 1 LVL$_T$?
Y
N
Do Not Act
Y
Is there >1 SFB$_T$ 50<L<150m?
N
Is there 1 SFB$_T$ 50<L<150m?
Y
Inject LVL$_T$ Repeater SFB$_T$
N
Is there 1 SFB 50<L<150m?
Y
Inject LVL$_T$ Repeater SFB
N
Is there a SFB$_T$ L<50m?
Y
Do Not Act
N
Is the LVL$_T$ an overhead line?
Y
Inject LVL$_T$ Overhead Repeater LVL$_T$
N
Do Not Act
Y
Inject LVL$_T$ / L = max and L∈ [50m, 150m] Repeater SFB$_T$
Is the SFB$_T$ 50<L<150m?
Y
Inject LVL$_T$ Repeater SFB$_T$
N
Is there 1 SFB 50<L<150m?
Y
Inject LVL$_T$ Repeater SFB
N
Is there 1 SFB$_T$ L<50m?
Y
Do Not Act
N
Is the LVL$_T$ an overhead line?
Y
Inject LVL$_T$ Overhead Repeater LVL$_T$
N
Do Not Act
BPL injections must be kept **below 4 injected LVL$_T$ per SS** to ensure attenuation below 6 dB. In case of exceeding this limit, the injections would be done in those LVL$_T$ where the **distance between the SS and the SFB$_T$ is the longest**.