COMILLAS
UNIVERSIDAD PONTIFICIA
ICAI

MÁSTER EN INGENIERÍA INDUSTRIAL

TRABAJO FIN DE MÁSTER

BROADBAND PLC OVER LOW VOLTAGE DEPLOYMENT: PLANNING TOOL DEVELOPMENT

Autor: Leire Ayala Bernaola
Director: J. Sebastián Gómez Guajardo
Co-Director: Javier Matanza Domingo

Madrid
Agosto de 2023

I, Leire Ayala Bernaola, hereby declare that this Master's Thesis submitted titled as

BROADBAND PLC OVER LOW VOLTAGE DEPLOYMENT:

PLANNING TOOL DEVELOPMENT

at ETSI - ICAI (Universidad Pontificia Comillas)

within the academic year 2022/23

is of my authorship, original and unpublished

and has not been previously submitted for other purposes.

This Thesis is not plagiarism of any other, either in whole or in part

and the information from other documents is duly referenced.

Signed: Leire Ayala Bernaola Date: August 24th, 2023

Authorizing the Thesis submission:

INDUSTRIAL SUPERVISOR OF THE PROJECT

Signed: Juan Sebastián Gómez Guajardo Date: August 24th, 2023

ACADEMIC SUPERVISOR OF THE PROJECT

Signed: Dr. Javier Matanza Domingo Date: August 24th, 2023

MÁSTER EN INGENIERÍA INDUSTRIAL

TRABAJO FIN DE MÁSTER

BROADBAND PLC OVER LOW VOLTAGE DEPLOYMENT: PLANNING TOOL DEVELOPMENT

Autor: Leire Ayala Bernaola

Director: J. Sebastián Gómez Guajardo

Co-Director: Javier Matanza Domingo

Madrid

Agosto de 2023

Acknowledgments

To ICAI, that has been part of my life during the last 7 years, and it feels like a home today.

To Félix, who prevented me from quitting ICAI 7 years ago. You were right after all; it has been worth it.

To Scotland, that is brave and beautiful.

To my two families, that are my support.

To my friends, that I will meet again after having submitted this work.

To Álvaro, because he is the best partner to share the life with. You bring so much joy.

"Paz y ciencia… y si con eso no lo solucionas, tira de electrónica que para eso has estudiado". – My mum.

BROADBAND PLC OVER LOW VOLTAGE DEPLOYMENT: PLANNING TOOL DEVELOPMENT

Author: Ayala Bernaola, Leire.

Industrial Supervisor: Gómez Guajardo, Juan Sebastián.

Academic Supervisor: Dr. Matanza Domingo, Javier.

Collaborating Entity: IBERDROLA, S.A.

ABSTRACT

This executive summary provides an overview of this Master's Thesis focusing 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 faces 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 summary reviews 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.

1. 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.

2. Definition 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 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. This change of topology is represented in *Figure 1*. 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 and it has been already done it in 25 of them.

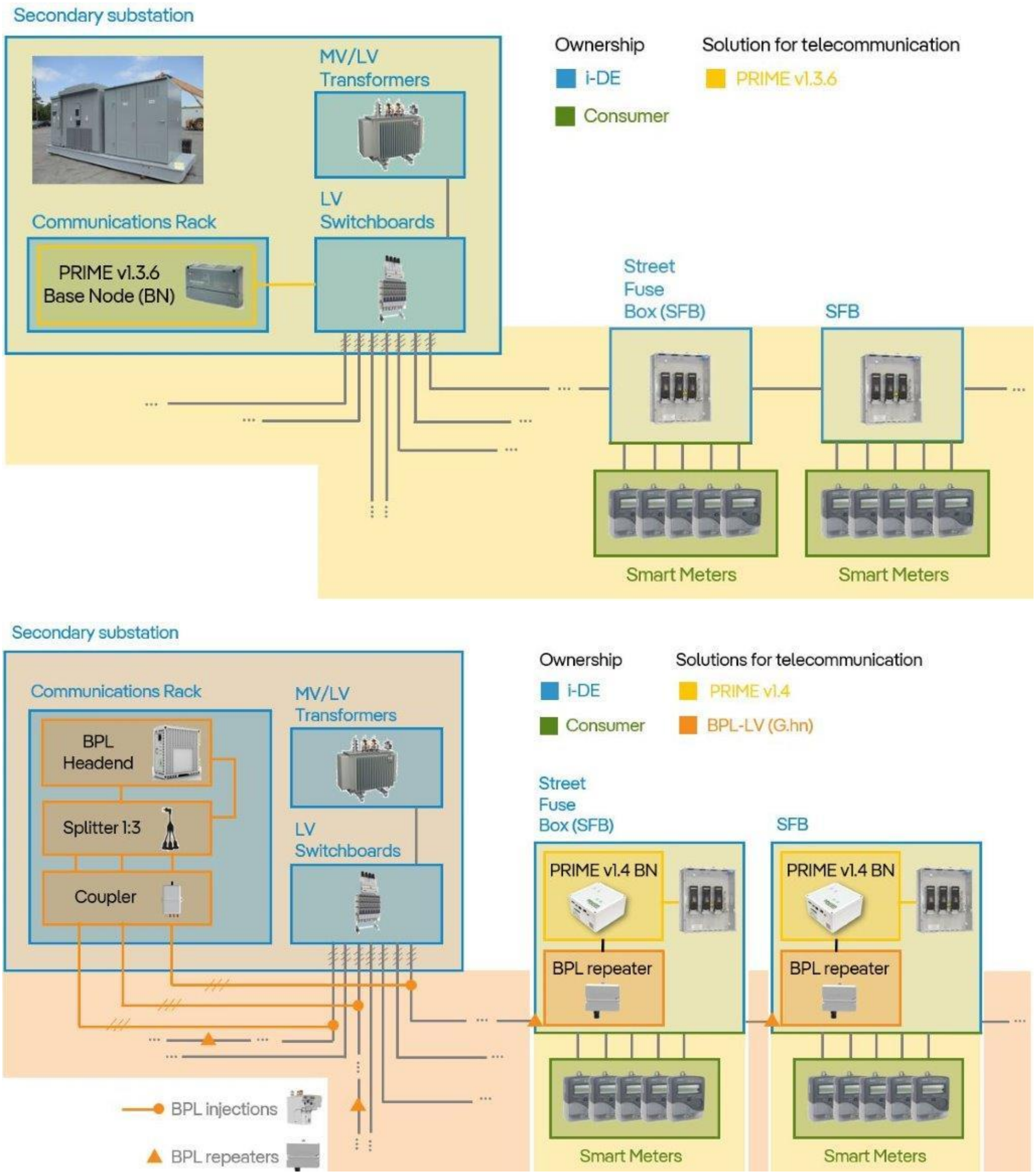


Figure 1: Deployment of the new LV grid.

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.

3. Development of the project.

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:

3.1. **Definition of BPL-LV Network.**

The initial phase required a detailed analysis of the variables involved in the deployment and to study the relevance of them in this process. There were various sources of information that helped in this phase. First of all, it is important to point out that the most relevant insights were acquired from the already conducted field trials. The conclusions from these trials and the suggestions from the BPL-LV 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 gathers Iberdrola's electrical and telecommunication inventory data. 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. These large databases have been analysed to extract the principal insights and conclusions that will help to the design of a specification for the deployment that fits the actual configuration of the grid.

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.

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

As mentioned, one of the new features that is introduce with the use of PRIME v1.4 over its previous version is that now the NB-PLC network can use 8 different channels to communicate. This 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.

The proposed approach for this challenge is based on the Welsh-Powell algorithm that not only is based on the Four-Colour Theorem that establishes that 4 different colours (4 different channels in this case) are enough to ensure that two adjacent areas (networks) do not share the same colour (channel) but also suggests an order or process to be followed to establish an automatization for this channel allocation.

4. Results.

The principal results that have been obtained from the research carried out in this Project are the following: an specification to standardize the BPL injection process, an 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. 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 actually helps 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.

4.1. **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.

4.2. **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 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. The three cables coming out of the coupler are connected with *Nileds* or with the AMI sensor to the three phases and of the low voltage lines (LVLs).
Because of these criteria, 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.

4.3. **BPL-LV equipment requirements.**

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 1* gathers all the elements that are planned to be modified during the deployment process.

Table 1: 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

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 2*, it is necessary to know the relation between the electrical components and these devices. This relation can be verified in *Figure 1*.

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 1*, it was possible to define the number of *dummy* cards and Nileds required.

Table 2: List of equipment per phase. *[Own preparation]*

	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

5. 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.

6. References.

[1] J. Berzal, *"Broadband PLC Deployment in the Low Voltage Grid"*. Escuela Técnica Superior de Ingeniería ICAI, Universidad Pontificia de Comillas. August 2022.

[2] A. Sendín, J. Matanza and R. Ferrús, *"Smart Grid Telecommunications: Fundamentals and Technologies in the 5G Era"*. IEEE Press and Wiley. 2021.

[3] J. Matanza, *"Improvements in the PLC Systems for Smart Grids Environments"*. Escuela Técnica Superior de Ingeniería ICAI,Universidad Pontificia de Comillas. October 2013.

[4] R. Ayala Arranz, *"Novedades de Telecomunicaciones. Sesión a CSDs"*. (Internal Use of i-DE). Red Acceso Digital. June 2023

ESPECIFICACIÓN DE UNA HERRAMIENTA DE PLANIFICACIÓN PARA EL DESPLIEGUE DE PLC DE BANDA ANCHA EN LA RED DE BAJA TENSIÓN

Autora: Ayala Bernaola, Leire.

Director industrial: Gómez Guajardo, Juan Sebastián.

Director académico: Dr. Matanza Domingo, Javier.

Empresa colaboradora: IBERDROLA, S.A.

RESUMEN

Este resumen ejecutivo proporciona una visión global de este trabajo de fin de máster que se ha enfocado en la integración de soluciones avanzadas de telecomunicaciones en la red de distribución. En concreto, en este Proyecto, se trata el despliegue de *power line communications* (PLC) de banda ancha (BPL) en la red de distribución de baja tensión (BT). El despliegue de BPL permitirá solucionar los desafíos que la red actual – PLC de banda estrecha, que se encarga de la comunicación de los dispositivos de medida inteligente o *Smart meters* (SM) – no puede asumir. El principal problema al que se enfrenta actualmente la red de telecomunicaciones de baja tensión que se encarga de la obtención de datos de los contadores inteligentes es que no puede proporcionar información y control del consumo en tiempo real al usuario. Este fenómeno presenta contradicciones en un momento en el que la red de distribución avanza hacia la *Smart Grid* y en la que las tecnologías emergentes requieren esta supervisión en tiempo real. Este resumen subrayará los puntos más relevantes del trabajo desarrollado y remarcará las principales aportaciones del mismo al desarrollo de la nueva red de distribución.

Palabras clave: Red de distribución, *Power Line Communications* (PLC), PLC de banda ancha (BPL), Caja General de Pro

tección (CGP), Centro de Transformación (CT), *Smart Grids*, Especificación.

1. Introducción.

El sector energético se encuentra en un momento de transformación que inevitablemente requiere la combinación de las novedades introducidas en el ámbito de las telecomunicaciones a la red de distribución. Estos avances son necesarios para hacer que la red de distribución se adapte a la integración de las tecnologías emergentes que los usuarios finales requieren (por ejemplo, vehículos eléctricos, autoconsumo, etc.).

Iberdrola como empresa distribuidora de energía ha formado parte de esa evolución y ha llevado a cabo iniciativas revolucionarios como el proyecto STAR (2010 – 2018) que supuso un cambio significativo en la medida de los consumos y que finalmente permitió medidas precisas y más frecuentes que consiguieron mejorar la operación y gestión de la red así como brindar poder a los usuarios para aprender de sus hábitos de consumo para adaptarlos hacia otros que supusieron un ahorro y una mayor estabilidad para la red. Gracias a este Proyecto, Iberdrola no sólo consiguió modernizar su red de distribución, sino que le permitió ganar ventaja con respecto a sus competidores ya que era capaz de tomar medidas sobre información que otros no tenían y que a esta compañía le sirvió para anticiparse a fallos y proporcionar una calidad de servicio a sus clientes tres veces mejor que anteriormente.

Siguiendo el hilo y logros obtenidos gracias a este proyecto de innovación, el presente proyecto persigue tener la misma relevancia en términos de mejora de eficiencia de la red. Para ello, en este Proyecto se continua con la filosofía de la inversión en innovación: en este caso, para desplegar una red de PLC de banda ancha en la red de baja tensión que conseguirá reducir la latencia en la toma de medidas de los SM con velocidades de transmisión por encima de los 400 Mbps en contraste con los debajo de 1 Mbps que se consiguen con la red actual de PLC de banda estrecha.

Por tanto, este trabajo quiere animar a las compañías de distribución de energía a que asuman el camino de la evolución e innovación y tomen el ejemplo de Iberdrola, cuyo objetivo principal es el de estar al día de las novedades tecnológicas que puedan aportar eficiencia a la red y cuyos despliegues en la red propia se realicen mediante procesos dinámicos en los que exista un aprendizaje continuo que permita adaptarse lo más rápidamente posible a las nuevas funcionalidades que se espera de la red de distribución, la *Smart Grid.*

2. Definición del Proyecto.

Este Proyecto incluye diferentes tareas y subproyectos; sin embargo, se pueden resumir en que el objetivo principal es diseñar la nueva topología de la red de distribución de BT. El cambio propuesto busca dos objetivos: primero, expandir la red de BPL más cerca de los SMs. Anteriormente, las redes BPL servían para comunicar en la red de media tensión y sólo alcanzaba hasta los centros de transformación (CT); sin embargo, este nuevo enfoque busca que la red BPL-BT llegue hasta los clientes finales: que comunique los CT con las cajas generales de protección (CGP) o las centralizaciones de contadores. El segundo objetivo principal es reducir el número de nodos que agrupan las redes de PLC de banda estrecha o red de PRIME, que es el estándar usado para la comunicación actual de los SM con los CT. Actualmente, las redes de PRIME v1.3.6 abarcan cientos de SM mientras que se busca minimizar estas redes hacia unas PRIME v1.4 que incluyan sólo unas decenas de SM. Como la lectura de estos contadores se hace de forma secuencial dentro de una misma red, una red más pequeña dará lugar a medidas más rápidas y eficientes: las redes más pequeñas podrán leerse de forma paralela y en menor tiempo. Este cambio de topología se ha representado en la *Fig. 1*. Este cambio ya se ha llevado a cabo en la red aguas debajo de 25 CT y se planea realizarlo en un total de 349 CT para finales de 2024.

Para la consecución de este nuevo esquema de la red BT, se presentan diferentes desafíos. En el caso de la red de BPL-BT, será necesario definir qué líneas de baja tensión (LBT) serán las inyectadas con BPL así como la decisión de qué CGPs necesitarán incluir un repetidor de BPL. Por otro lado, en el caso de PLC de banda estrecha, las nuevas características que introduce la versión PRIME v1.4 también traen desafíos ya que no sólo se necesita especificar qué CGPs incluirán un nodo base de esta solución de telecomunicaciones, sino que la característica de una banda de frecuencias más ancha que en el caso de la versión anterior PRIME v1.3.6 hace que esta nueva alternativa ofrezca 8 canales de transmisión diferentes que necesitan de un criterio que defina cuál de estos canales debe usar cada red de PRIME para comunicarse y que no existan interferencias entre ellos.

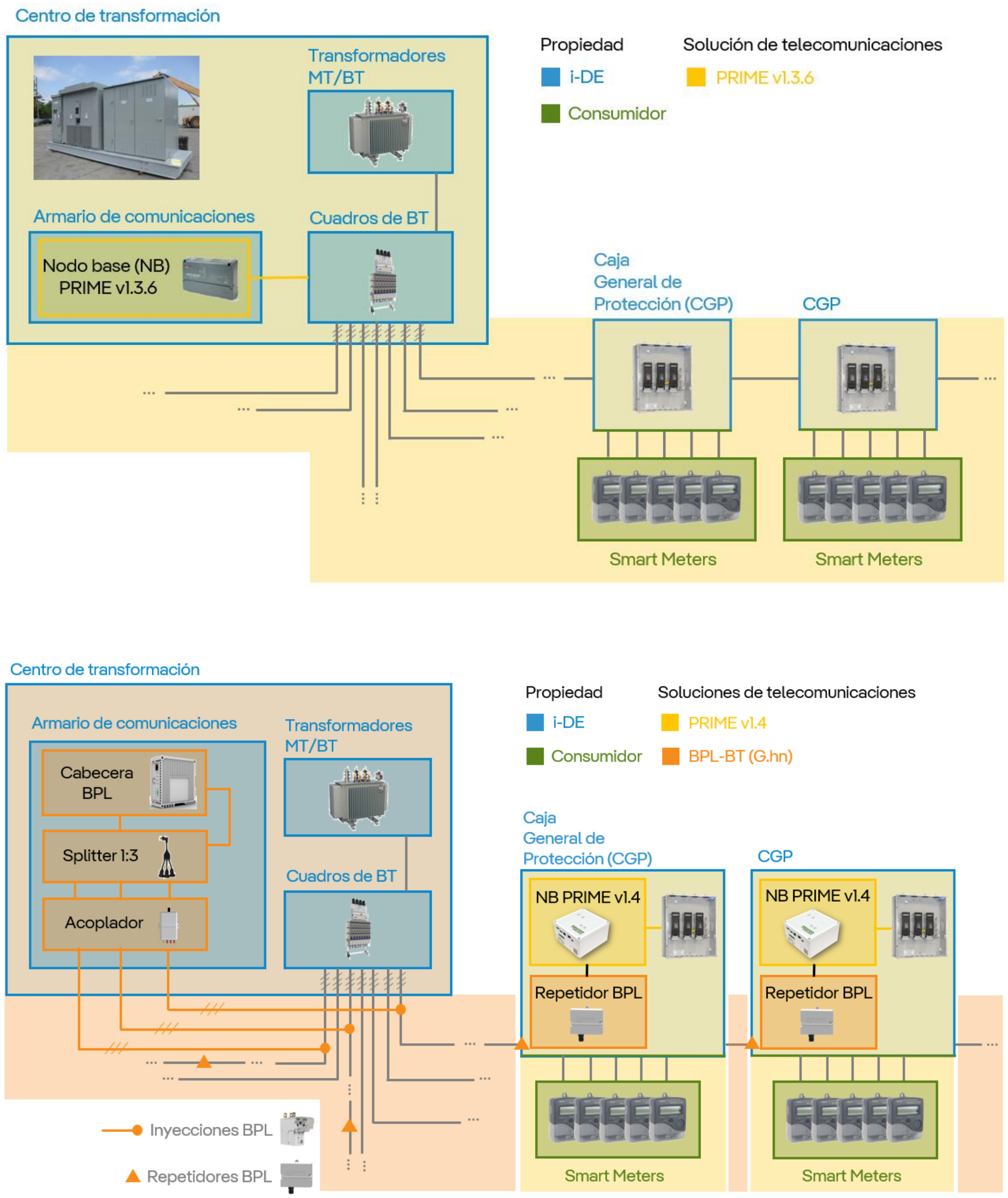


Fig. 1: Actualización de la topología de la red BT.

3. Desarrollo del Proyecto.

Basándose en las necesidades recién descritas, este trabajo se enfocará en diseñar las especificaciones que sirvan para el despliegue de las dos redes de telecomunicaciones para la red de distribución en BT. Para estructurar y describir el desarrollo del Proyecto, este se ha dividido en dos fases principalmente que se relacionan con cada una de estas dos redes:

3.1. **Definición de la red de BPL-BT.**

La primera fase ha requerido un análisis detallado de las variables que están involucradas en el despliegue para determinar la influencia de cada una de ellas en este proceso. Para ello, se ha acudido a diferentes fuentes de información: en primer lugar, es importante recalcar que las conclusiones más relevantes han sido obtenidas tras el estudio de las conclusiones recogidas en diferentes momentos de los despliegues ya realizados como pruebas piloto. Estas conclusiones junto con las recomendaciones ofrecidas por los propios proveedores de BPL-BT han sido determinantes para la obtención de los resultados de este Proyecto. Tras este estudio de las conclusiones, ha sido necesaria la comprensión de la configuración de la red BT para poder hacer las especificaciones más precisas posibles y que se ajusten a las instalaciones, tanto eléctricas como de telecomunicaciones, que ya hay desplegadas en campo antes de este nuevo despliegue y que podrían ser modificadas para conseguir la nueva topología que se busque. Durante este proceso, ha sido especialmente importante el uso del Sistema de Información Geográfica (GIS) desarrollado por Iberdrola y que reúne todo el inventario y la información de los equipos desplegados en campo. La utilización de esta herramienta ha hecho posible la comprensión de la estructura de la red y la detección de potenciales desafíos que habría que enfrentar en este proceso de transformación de la red. Las conclusiones y aprendizajes obtenidos del análisis de esta base de datos tan extensa, que reúne datos alfanuméricos y gráficos, han sido esenciales para el posterior diseño de las especificaciones técnicas que se adecúen a una descripción de despliegue que se adecúe a la configuración real de la red.

Como se ha comentado, el análisis de estaos datos y el estudio del proceso y de sus requerimientos ha hecho posible desarrollar especificaciones que serán utilizadas finalmente para desarrollar una herramienta que ayude a optimizar el proceso de despliegue. Estos resultados se han enfocado en la definición de la red BPL-BT y se destacan tres principalmente: el criterio de selección de las líneas que deben ser inyectadas con BPL, el razonamiento de selección de la solución de inyección que mejor se adecúa a cada caso y cada línea y la asignación de los recursos que serán necesarios a lo largo de las distintas fases definidas para el Proyecto (en este caso, 6 hasta finales de 2024) y que se han descrito de esta forma para facilitar el trabajo de aprovisionamiento al equipo encargado.

3.2. **Definición de la red de PLC de banda estrecha: PRIME v1.4.**

Como se ha explicado, una de las nuevas características que introduce el uso PRIME v1.4 con respecto a la anterior versión es que, ahora, la red de PLC de banda estrecha puede usar 8 canales de transmisión diferentes; por tanto, esto hace necesaria una nueva tarea que no se había definido antes y que se trata de la asignación de los canales (bandas de frecuencia) a cada red de PRIME. Esta asignación es relevante ya que tiene el potencial de evitar interferencias entre canales adyacentes si se evita que redes contiguas compartan canales contiguos. El enfoque que se ha propuesto en este trabajo para resolver este problema se basa en el algoritmo “Welsh-Powell” que se inspira en el Teorema de los Cuatro Colores que asegura que 4 colores diferentes (en este caso, 4 canales diferentes) son necesarios para asegurar que dos áreas (redes de PRIME) adyacentes no usen el mismo color (canal). Además, este algoritmo propone un orden que seguir en esta asignación de canales, permitiendo así la automatización de este proceso que definirá la red de PLC de banda estrecha.

4. Resultados.

Los resultados principales que se han obtenido son: una especificación para estandarizar el proceso de inyección de BPL, una especificación para establecer los criterios para la elección de la solución de inyección que mejor se adecúe a cada línea de baja tensión y una lista del equipo que se verá involucrado en este proyecto: de los elementos eléctricos que se verán modificados y de los elementos de telecomunicaciones que se necesitan para el despliegue propiamente dicho. A continuación, se describen más en detalle estos resultados.

a. Criterios para el despliegue de BPL-BT.

El primer criterio y que resulta esencial para el despliegue de BPL-BT es el de la definición de las CGPs que se consideran objetivo y que, por tanto, deberán transformarse para adecuarse a la nueva topología definida en la *Fig. 1*. En este caso, se ha determinado que las CGP objetivo (CGP_O) son aquellas que cuentan con al menos 5 SM; es decir:

$$CGP_O = CGP \,/ \sum SM \geq 5$$

Esta restricción será imprescindible para seleccionar las CGPs que serán parte de la red de BPL-BT y por tanto para la toma de decisiones respecto a las inyecciones. De la misma forma, se considerarán líneas objetivo (LBT_O) todas aquellas que tengan conectada al menos una CGP_O.

Tras esta definición, la primera verificación que se deberá hacer será si las LBT comparten al menos 30 m de canalización. En los casos en los que la respuesta sea afirmativa, este grupo de LBT será tratado en conjunto como un manojo. Esta diferenciación es importante sobre todo debido a la restricción que existe para evitar más de 4 LBT inyectadas por CT. Cuando existen manojos de cables, el criterio de inyección es hacerlo en la línea que contenga la CGP_O más lejana que no supere los 150 m de distancia con respecto al CT. Esta restricción de longitud es otro de los criterios fundamentales a considerar en el despliegue: en los casos en los que la distancia del CT a la CGP_O sea menor a 50 m, la inyección en esa línea no es necesaria ya que se considera que la señal llega directamente desde el CT. Por otro lado, cuando se supera dicho límite de los 150 m, se considera la CGP_O como problemática ya que esta distancia está relacionada con problemas de atenuación de la señal. En el caso en el que exista una CGP_O a más de 150 m y no exista un CGP_O más cercana en la misma línea, el criterio es hacer uso de una CGP común – no objetivo – para instalar en ella un repetidor BPL adicional que pueda asegurar que la comunicación llegue al objetivo.

b. Criterios para la selección del tipo de inyección de BPL-BT.

Con respecto al criterio que tener en cuenta para elegir la mejor solución para inyectar las LBT seleccionadas, el parámetro más relevante es el tipo de CT que contenga dichas LBT. Las inyecciones pueden usarse a través del sensor de supervisión avanzada de las líneas usando uno de los canales del aparato para introducir la inyección de BPL o mediante un *Niled* que directamente "muerde" la LBT_O para inyectarle BPL. De estas dos alternativas, siempre es preferible la primera – para la que la tarjeta supervisión avanzada debe ser retirada y sustituida por una tarjeta *dummy* – y puede llevarse a cabo siempre que se trate de un CT estandarizado; sin embargo, para los casos en los que el CT no lo esté y siempre y cuando no sea un CT inundable, se usará la opción del *Niled.* Como se ha representado en la *Fig. 1*, los tres cables que salen del acoplador se conectan mediante *Niled* o el sensor de supervisión a las tres fases de las LBT_O.

Debido a estos criterios, será importante definir e identificar el tipo de CT: si son estandarizados y si tienen riesgo de inundación.

c. Lista de equipo BPL-BT necesario para el despliegue.

El diseño de la lista de equipos requeridos para el despliegue necesita un análisis previo para obtener el número de elementos eléctricos que se verán involucrados en dicho despliegue. Esta información es significativa ya será la que determine el número de los aparatos y sistemas de telecomunicaciones que se necesitarán. El resultado de este estudio se ha recogido en la *Tabla 1*.

Tabla 1: Recuento de elementos eléctricos involucrados por fase. [Elaboración propia]

	Total	Fase 0	Fase 1	Fase 2	Fase 3	Fase 4	Fase 5	Fase 6
CT	349	25	53	54	55	54	54	54
CGP_O	4.723	66	454	550	814	948	1.070	821
CGP no objetivo pero necesarias	429	6	41	50	74	86	97	75
CT / LBT_O <= 2	4	1	1	1	0	0	0	1
CT / LBT_O = 3	15	4	3	3	1	3	0	1
CT / LBT_O >= 4	330	20	50	49	55	50	54	52
CT inundable	136	6	16	25	24	17	24	24
CT no inundable	213	19	38	28	32	36	30	30

A partir de estos valores, ya es posible diseñar la lista de equipos necesarios en cada fase que después se podrá utilizar para planear un presupuesto asignado a cada una de estas fases. Para realizar esta lista que se ha resumido en la *Tabla 2*, es necesario conocer la relación entre los elementos eléctricos y estos aparatos de comunicaciones. Esta relación se explica a continuación y puede verificarse en la *Fig. 1*.

Hay una cabecera BPL en cada CT seleccionado para el plan de despliegue. Después, habrá un repetidor BPL en cada CGP_O además de un repetidor BPL adicional en cada una de esas CGP que no son objetivo pero que son necesarias para asegurar una conexión estable. Además, en cada CGP_O se instalará un nodo base de PRIME v1.4 para establecer la red de PRIME para los SM que pertenecen a esas CGP_O.

Siguiendo con los aparatos necesarios en los CT seleccionados: habrá splitters que se conectarán a la cabecera BPL y que permitirá la inyección en las LBT seleccionadas. Habrá un (1) splitter 1:2 en los CT que tengan 2 LBT seleccionadas y dos (2) en los CT con 4 LBT seleccionadas. Por otro lado, se necesitará un (1) splitter 1:3 en aquellos CT con 3 LBT seleccionadas. Siguiendo la misma lógica, habrá un acoplador por cada LBT seleccionada: dos (2) cuando haya 2 LBT, tres (3) cuando haya 3 LBT y cuatro (4) cuando haya 4 LBT seleccionadas.

Por último, como se ha comentado, la inyección se hará mediante el sensor de supervisión avanzada o mediante *Niled* dependiendo del tipo de CT. Según la información de los CT calificada en la *Tabla 1* como "inundable" o "no inundable" se podrá saber el número de tarjetas *dummy* y *Nileds* que se necesitarán.

Tabla 2: Lista de equipos necesarios por fase. [Elaboración propia]

	Total	Fase 0	Fase 1	Fase 2	Fase 3	Fase 4	Fase 5	Fase 6
Cabecera BPL	349	25	53	54	55	54	54	54
Repetidor BPL	5.152	74	491	598	888	1.034	1.167	896
Nodo base PRIME v1.4	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
Acoplador	1.373	94	211	207	223	209	216	213
Tarjeta *dummy*	213	6	16	25	24	17	24	24
Niled	136	19	38	28	32	36	30	30

5. Conclusiones.

Este trabajo ha propuesto enfoques determinados para desarrollar una herramienta que sea capaz de gestionar y automatizar el proceso de despliegue de la red de BPL en la red de BT. A partir del conocimiento adquirido del análisis de las bases de datos de la red y los equipos eléctricos y de telecomunicaciones ya desplegados, junto con el estudio de las conclusiones obtenidas a partir de las pruebas piloto ya desarrolladas, ha sido posible proporcionar los siguientes resultados prácticos a este proyecto de despliegue: un **diagrama de flujo del despliegue BPL-BT** que especifica los criterios que se deben seguir en este proceso presentándose como una especificación de la secuencia de verificaciones que hay que llevar a cabo para completar el despliegue. De esta forma, se ha propuesto un proceso automatizado que servirá para estandarizar el despliegue y para definir los pasos que la herramienta que se desarrollará debe seguir. Además, se ha aportado un **diagrama de flujo de la solución de inyección BPL** que especifica qué alternativa de inyección se adapta mejor en cada uno de los casos. Por último para complementar estos diagramas, se ha proporcionado una **tabla de KPIs esperables tras el despliegue** que servirá para hacer comprobaciones del funcionamiento del despliegue y que se han obtenido tras el análisis de los parámetros habitualmente medidos en las pruebas piloto realizadas.

Por otro lado, respecto al despliegue del PLC de banda estrecha, se ha proporcionado un **método para la selección de canales de PRIME v1.4** que van a permitir que los nodos bases de los CGPs seleccionados se configuren para comunicar en unas bandas de frecuencias que eviten interferencia con las redes de PRIME contiguas.

Por último, se ha diseñado una **lista de equipos necesarios para el despliegue** que contribuirá en el proceso de aprovisionamiento ya que se ha realizado una estimación de los equipos que serán necesarios en cada una de las fases del proyecto de despliegue basándose en los objetivos de cada una de ellas.

Estas especificaciones diseñadas y el resto de los resultados descritos que sirven para dar una perspectiva de proceso automatizado al despliegue de la red de BPL en BT refleja el impacto práctico que este trabajo tendrá para facilitar el proceso de despliegue. A través de un análisis en detalle de los datos obtenidos de las bases de datos (alfanuméricas y gráficas) y de los resultados de las pruebas piloto, este trabajo contribuye a la consecución de una red de distribución dinámica y adaptativa.

6. Referencias

[1] J. Berzal, *"Broadband PLC Deployment in the Low Voltage Grid"*. Escuela Técnica Superior de Ingeniería ICAI, Universidad Pontificia de Comillas. August 2022.

[2] A. Sendín, J. Matanza and R. Ferrús, *"Smart Grid Telecommunications: Fundamentals and Technologies in the 5G Era"*. IEEE Press and Wiley. 2021.

[3] J. Matanza, *"Improvements in the PLC Systems for Smart Grids Environments"*. Escuela Técnica Superior de Ingeniería ICAI,Universidad Pontificia de Comillas. October 2013.

[4] R. Ayala Arranz, *"Novedades de Telecomunicaciones. Sesión a CSDs"*. (Internal Use of i-DE). Red Acceso Digital. June 2023

Table of Content

Table of Figures

Table of Tables

Chapter 1. INTRODUCTION

This chapter will serve as a starting point for this Master's Thesis and it will begin with a brief introduction to understand the context in which the Thesis will be carried out. After realizing the circumstances, the importance to develop this Project will be explained and related with that context. Once the motivation of the project is understood, the objectives to be achieved and the scope of the project will be defined. This will be useful in the time of the real implementation of the given solution, so it can be confirmed a list of goals that have been met. Finally, the structure of this document will be described in order to have a big picture of the Thesis before going deeper into it.

1.1. CONTEXT OF THE PROJECT

The energy sector is undergoing an intense transformation due to two main reasons. Firstly, the Energy Transition that aims to reduce the negative impacts of the climate change that is essential to ensure the sustainability of the life on Earth. Secondly, this revolution is aligned with the digital transformation of the industry to which the energy sector cannot be detached [4]. The focus on the electrification – that is required to contribute to the decarbonization – and digitalization of the energy sector is not something from the future anymore but a contemporary challenge that needs to be assumed. Not only because of the electrification but also because of the requirement of further monitoring and control, modernization of the electrical grid to remotely operate and control it is crucial.

To make these advances feasible, entities in the energy sector have been investing large amount of both human and economical capital on projects aiming this progress. One of them is Iberdrola[1] – and particularly i-DE, the electrical distribution company within the holding company. i-DE was pioneer in innovation in the Spanish electrical system with the STAR

[1] Because of the engagement of Iberdrola in this Project, this document will refer to the technologies developed and used by this company.

Project that finished in 2018 after investing a total of 2.000 M€ to allow the deployment of 11 million smart meters and the upgrade of 99.000 distribution substations [5]. This Project was developed on the initiative of the PRIME Alliance that was born in 2009 pointing standardized solutions for smart grids functionalities.

Now, some of the mid-term objectives of i-DE related to the digitalization of the distribution grid are to encourage the use of electrical vehicles that reduces the use of fossil fuels and the increase of the observability and control of the grid to provide a high-quality service to their customers offering real-time data supervision and control. Moreover, the next aim of the distribution company is to become a Distribution System Operator (DSO). This will consider **bi-directional** flow of electricity, high penetration of distributed generation (DG) and electric vehicles (EV), proactive management of resources, flexibility, existence, and management of prosumers (electricity consumer that also produces it [6]), demand participation, etc. In other words, the future of the electric grid lies on making its functioning observable, and its operation automated.

These upgrades in the electrical grid need to be achieved through the synergy of various disciplines [7] and specifically two of them: electrical and telecommunications engineering, making the future of the energy sector and the shift of paradigm – smart grids – possible. Based on this collaboration, this Project aims to design a planning tool for the deployment of a telecommunications technology – Broadband Power Line Communication (BPL) – in the low voltage (LV) electrical grid. BPL will make possible for distribution substations and smart meters to communicate several times faster, enabling real-time features that are required by the customers and are necessary to reach the objective of Iberdrola becoming a DSO. The main advantages of this integration of technology to success in the development of Smart Grids can be summarize in these three standpoints:

- **Improved network efficiency and quality of service:** the remote management and supervision of the grids allow efficient monitoring and control of supply points. This enables the early detection of potential faults, reducing these faults and their duration. Besides that, an automated and digitized network can detect fraud and minimize losses, what enhances the quality of service that can be offered to the customers.

- **Increase of the consumers connectivity:** digitalization of the grid allows the consumers to have real-time data and knowledge about their consumption patterns and peak power demand. This information gives them greater decision-making capacity.
- **Key player in the energy transition:** Smart Grids play a crucial role in the decarbonization and electrification of the economy as they facilitate the integration of renewable energy generation, promote sustainable mobility, smart cities, and decentralized consumption and self-consumption.

1.2. MOTIVATION OF THE PROJECT

The activity of an electricity distribution business – likewise the transmission activity – is significantly regulated. Because of this feature, all the research and development (R&D) investments required for innovation in companies such as i-DE needs to be accurately justified to the corresponding Government Office so the investment – that is public – is validated. This fact makes necessary to argue the motivation of the Project as an essential first step before the beginning of the Project itself.

The motivation – and therefore justification – for this research to be developed is because **the current NB-PLC technology cannot provide the real-time monitoring that is required nowadays not only by the customers but also by the new technologies** that are about to being integrated in the distribution grid and that needs of the improved features of BPL. Nowadays it is possible to collect data from the smart meters (SMs) every 15 minutes. However, it is not yet possible to receive this data in real time but in a report that can be done once a day, week, or month and specifically to certain type of big consumers.

As it was explained in previous sections, the eventual goal of DNOs as i-DE is to become a DSO, whose characteristics have been briefly described in *1.1. Context of the Project,* and whose graphical explanation is represented in *Figure 2*. Both DNO and DSO notions include the concept of "operator" because they both are owners and responsible for the maintenance of the elements such as power lines, transformers, substations, and other equipment. Their major role is to ensure a reliable power supply. However, the main difference between these two is that DSO has additional features such as the integration of renewable energy production, other DG, EV, … and naturally the pursued goal of this

Project: **real-time data collection and supervision**. This is why the transition from DNO to DSO is directly linked with the digitalization since it is necessary to provide accurate remote measurements and real-time information.

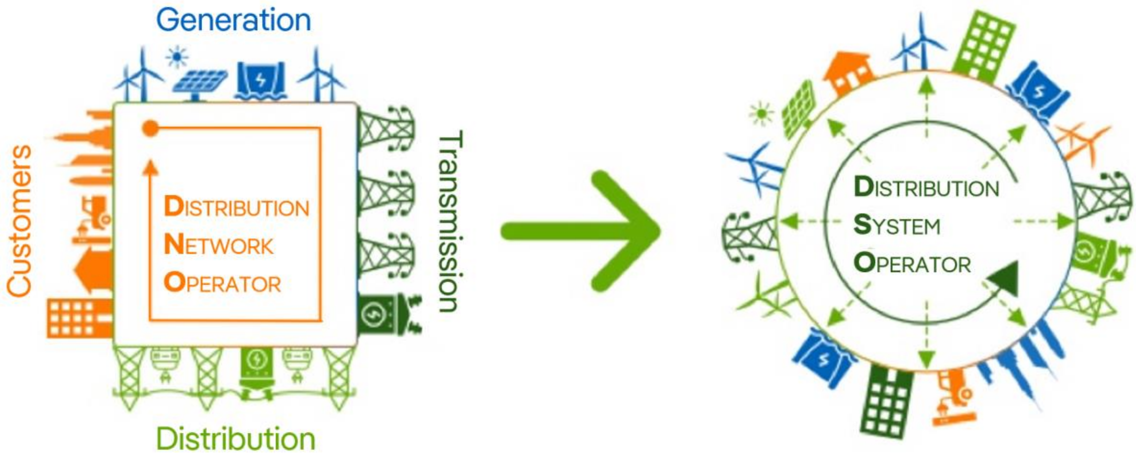


Figure 2: Transition from DNO to DSO.

To achieve this target, BPL over LV (BPL-LV) needs to be further analyzed and tested because it seems to meet the condition to become a potential solution for a new generation of SM, real-time data management, and the access of an increasing number of customers. This requirement of live supervision is not yet mandatory for Distribution Network Operators (DNOs), but it will surely be soon. To proactively respond to this coming requirement, i-DE aims to incorporate an improvement strategy that counts on BPL-LV and a new version of PRIME (v1.4) to achieve:

- Broadband telecommunications closer to the smart meters: BPL over low voltage, not only until the secondary substation (SS) but reaching up to the customers (until the street fuse boxes (SFB) or the smart meters concentrators (SMC).
- Reduction of the PRIME networks from hundreds of SM to dozens of SM depending on the same PRIME base node.

1.3. OBJECTIVES OF THE PROJECT.

The eventual objective of this Project is to develop a tool that helps to the deployment of broadband PLB (BPL) technology in the low voltage grid. This tool will be used at the time of the deployment of this technology to provide something alike a *standardized method* to proceed during that deployment. To sum up the main objectives of this Project that are expected to be completed at its end are:

1. Analysis of the variables that have potential influence on the deployment of BPL that need to be considered: selection of all of them and analysis of their impact.
2. Selection of the most relevant variables that have the most influence and that will be significant in further development of the Project.
    a. Definition of general parameters based on the previous analysis.
3. Design of future telecommunication network in low voltage for each CT:
    a. Which low voltage sections needs to be injected with BPL considering the previous mentioned variables (parallel lines, number of clients depending on the CT, distance between lines with BLP, etc.).
    b. Route of the lines with BPL.
    c. Optimum quantity of BPL equipment's.
    d. Which smart meters will be connected through PRIME v1.4.
    e. Selection of PRIME v1.4 channels for each group of smart meters.

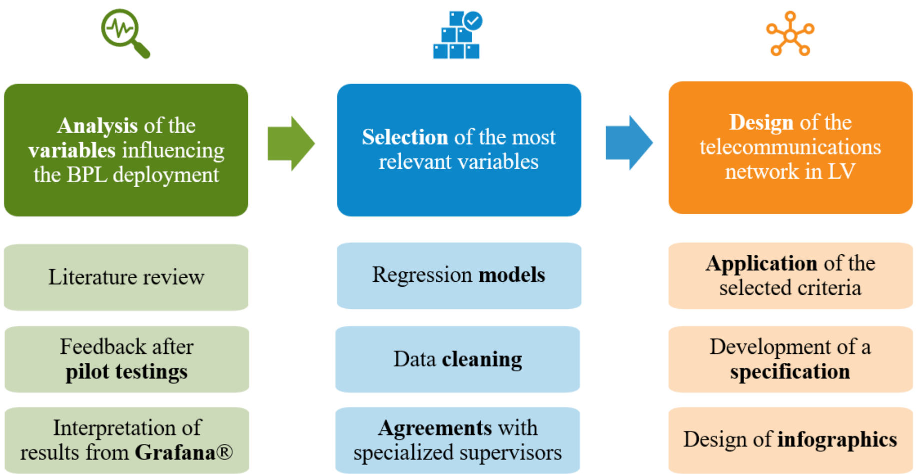


Figure 3: Block diagram of the sequential objectives within this Project.

1.4. METHODOLOGY AND RESOURCES

For each of the goals described in previous section, *1.3. Objectives of the Project*, different procedures to achieve them will be needed. The first phase of this Project involves research to understand the actual necessity to develop the BPL technology in BT – that has been already explained in *1.2. 1.2. Motivation of the* Project – so the methodology for this period is the **bibliographic research.** After the motivation is already understood, to fulfil one of the most relevant objectives of this Project – selection of the variables that will be considered at the time of BPL deployment in BT –, it is necessary to previously analyse the data base of the CTs, CGPs, etc. that is available. This phase needs **data analysis**: data downloading, classification, cleaning, analysis, and selection. Afterwards, the selection of the exact injections of BPL will be done after the data analysis by **maximization** of the results and performance of the network. Parallelly, the selection of the PRIME channels will be done by adapting the "**Four colours theorem**" for this case where CTs are preferable not to use adjacent PRIME channels. Finally, the desired goal to graphically represent the obtained results will be done by **specify it in high level**. This specification will be possible once the selection of the telecommunication networks in BT has been done based on the analysed variables. These results will be classified so patterns are found, and their characteristics can be described and specified for later implementation in the correspondent GIS.

The development of these solutions will be supported by different software depending on the phase. Bibliographic research phase will need access to **academic papers** from IEEE, ResearchGate, repository of *Comillas*,… In the development of solution, the analysis of data will be done with **Microsoft Access**. Lastly, the specification of graphic representation is planned to be designed in high level, so no software will be needed for this phase. When this specification is developed, it needs to be done in a software that is supported by the GIS used at Iberdrola: **Mapinfo**.

On the other hand, as the analysis of the compatibility of the deployment of BPL had already started before this Project was started, some **Field Trials** are in process. Therefore, the results obtained from these tests will be also used as very valuable data for this Project. To analyse them, **Grafana** and **GridValue** will be needed.

1.5. STRUCTURE OF THE THESIS.

As described in section *1.3. Motivation of the Project*, the principal importance of this work is to design the specification for the BPL over LV, so the deployment of this telecommunication is automatized and therefore the efficiency of the process is increased. To reach the final goal that is the design of this specification, first it is essential not only to understand the BPL technology itself but also all the innovation that is flourishing in the energy sector and that will talk about the future of the electrical grid. Therefore, to reach to that point of the specification and understand the inside and the magnitude of this Project, this thesis has been structured so each chapter contributes to acquire different and complementary knowledge that leads to a holistic understanding of the project's context, involved technology, challenges, approaches, similar projects, etc.

In Chapter 2, "Context of the Solution," the evolution of smart grids is explored, underlining the Project's significance in the larger context of energy distribution. This chapter highlights Iberdrola's role, innovative projects, and the emerging solutions for telecommunications within the company.

The following chapter, "State of the Art," dives into telecommunications protocols, power line communications (PLC), and the components of power distribution systems. This first sections of the chapter are meant to be the perfect synergy between the required telecommunications and electrical engineering knowledge to understand the technical part that has involved the development of this Project. After understanding the insights of both worlds, this chapter justifies the role of geographical information systems (GIS) for this Project as a tool to gather all the telecommunications and electrical information about the devices that are already deployed in the power distribution system. Furthermore, to finish the understanding of this Project significance, the chapter ends with a benchmarking of similar projects that are currently in progress and that may serve to Iberdrola to acquire an outlook of what can be done within the company to boost the efficiency of the Project.

Chapter 4, "Description of the Model," delves into the heart of the project, illustrating the proposed changes in the low voltage grid topology. Field trials and insights assembled from these trials provide essential information for the development of technical specifications. Not only the key criteria for these specifications have been gathered from the previous experience in the field trials but also other relevant information such as the key performance indexes that may be expected from the following field trials have been defined in this chapter.

Chapter 5, "Results of the Research," showcases the culmination of efforts by presenting technical specifications for BPL deployment. Besides that, a very substantial result that has been obtained from the analysis of the databases regarding this Project is the list of required equipment that will be necessary in the deployment. This outcome is relevant since it may help the working team to plan their budget and overview the quantity of equipment that it will be required in each specific phase of the work.

Finally, Chapter 6, "Conclusions and Future Works," concludes the project by summarizing the findings, suggesting future directions for exploration, and addressing potential areas of expansion and refinement.

The Bibliography in Chapter 7 and Annexes in Chapter 8 provide supporting materials, from references to annexes covering technical details, algorithms, and supplementary information that contribute to the comprehensive understanding of the research.

Throughout this thesis, the reader is guided through a logical progression, from understanding the project's foundation to exploring the research's depths and culminating in insightful conclusions. This structured presentation aims to facilitate an immersive learning experience, ensuring that readers engage effectively with the intricate world of Broadband Powe Line Communications deployment over the Low Voltage Power Distribution Grid.

Chapter 2. CONTEXT OF THE SOLUTION

This chapter will cover the evolution in terms of telecommunication systems and solutions that have changed the way in which the electric grid – and especially the power distribution grid – performs. Firstly, there will be an overview about some of these elements that take part in the creation of the so called "smart grids": they will be described and also their evolution through time and adaption to the changing grid requirements. After that, there will be a section that will focus on the innovation projects that are carried out within i-DE to improve their processes. It will be shown how this progress relates to the telecommunications and how new applications have impact on i-DE's operation and development of the solutions that best adapt to their workflows. This section will serve to illustrate the position and leadership of Iberdrola compared to other energy distribution companies, and to evidence its huge efforts that aim to evolve at the same time as the demand requires it.

2.1. EVOLUTION OF SMART GRIDS

In order to understand the context in which the solution is being described in this thesis, the first concept that needs to be described is the one known as "Smart Grids". This concept has been used lately to define all the new applications that are increasingly taking part on the electric distribution network. These applications not only provide new functionalities and advantages for the final consumer but are also designed and developed aiming to modernize and optimize the traditional power distribution systems. Smart Grid applications are essential as traditional power distribution systems are not able to manage bi-directional electricity flows, handle distributed energy resources (DERs), or respond to dynamic demand fluctuations.

The main element that is required for these Smart Grids to be really effective is the telecommunications that are being combined with the electrical engineering. Due to the reasons exposed above, telecommunications are crucial for real-time data communication and automation that ensures efficient Smart Grid features. Although the concept has increased its popularity in the last years, the reality is that the synergy of telecommunications and power systems started several years ago and there were some applications yet in the mid-20th century.

2.1.1. SCADA SYSTEMS.

One of these advances was the development and implementation of Supervisory Control and Data Acquisition (SCADA) systems back in the 1950s and 1960s. This technology allowed the utilities to remotely manage – monitor and control – some of the devices that were deployed in their grids. Their evolution has made possible to enable real-time monitoring and control of grid devices and facilitate fault detection, isolation, and restoration (FDIR), enhancing grid resilience. Although SCADA systems are firstly deployed for generation, they progressively spread to transmission (EMS) and eventually to distribution (DMS). Elements that are found in the distribution grid and in particular in the substations that need to be managed are: transformers, circuit breakers, switches, and voltage and current transformers [9]. Firstly, these communications were done by using copper-based (wired) communication channels, so it was necessary to establish a physical connection between the equipment that was monitored and the control station. After that, in the 1970s, the insertion of wireless SCADA technologies took place supported by the introduction of digital technologies and protocols. This shift in technologies allowed to manage more data, so the control and exchange of data between substations and control stations severally increased its efficiency and the possibility to reach remote locations that were isolated before. Also, there was an increase of flexibility and decrease of installation cost because of the end of using physical channels whose installation may be challenging and costly. This progress of the SCADA technology was possible again supported on the evolution of telecommunications that occurred in different stages. This evolution of the SCADA systems is mainly standardized in the series of the International Electrotechnical Commission (IEC) 61850 and will be briefly explained below:

1. **Radio Frequency** (RF) Communication: it started in the 1970s and 1980s by making use of the radio frequency spectrum to transmit data. It allowed for the first time that transmission to be done over short and long distances without a physical connection.

2. **Spread Spectrum Technologies**: it included two main features – Frequency Hopping Spread Spectrum (FHHS) and Direct Sequence Spread Spectrum (DSSS) – that introduced more security for the transmitted data, noise immunity, and increased reliability in challenging radio environments.

   Frequency Hopping Spread Spectrum allowed the transmitter and receiver of the RF signals to instantly switch between different frequencies within a specific frequency band, so it provides robustness against interferences and immunity against noise, and security as it makes more difficult to intercept the transmission. Direct Sequence Spread Spectrum allowed the transmitted data to be spread over a wider bandwidth by modulating it with a pseudo-random noise sequence. The receiver uses the same noise sequence so it can de-spread the signal to obtain the original message. The main advantage of DSSS is that enables multiple devices to share the same frequency band, increasing the capacity of the communication system.
3. **Cellular Communication**: it enabled real-time data transmission from remote locations to central control centres. Cellular communication is a wireless technology that use SIM cards to connect devices and stations through a network of cell towers (also called base stations). Each tower covers a specific geographic area that is known as "cell” and allows the communication with all the SIM cards of the devices that are found in this area. In the case where devices that try to communicate belong to different cell towers, it is necessary a process of “handover” that consists of the communication of different cell towers that eventually communicate the geographic area in which the transmitter is to the area in which the receiver is. Also, in areas were there is poor coverage or high user density, repeaters are used to provide the required additional coverage or capacity by amplifying the transmitted signal.
4. **Satellite Communication**: it allowed the communication with grid elements that have limited access such as remote or offshore locations.

Once it is understood how the SCADA systems have evolved, the major components of these systems can be defined to explain each one’s main function. A representation of a SCADA network architecture is shown in *Figure 4*.

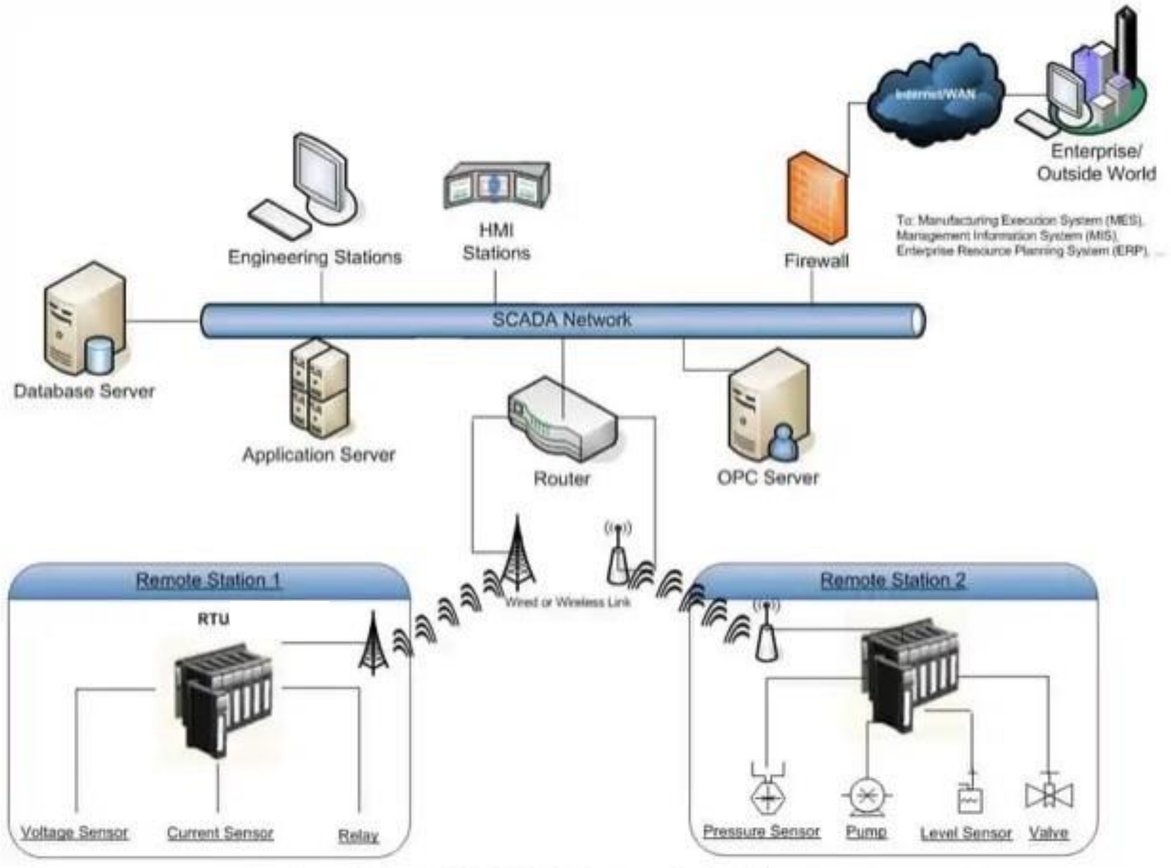


Figure 4: SCADA network architectures. [10]

Some of the principal components of a SCADA systems include:

- **Remote Terminal Units** (RTUs): they are also known as “Programmable Logic Controllers” and their main function is to collect data from the different sensors in the substation (i.e. voltage sensor, current sensor, pressure sensor, level sensor, pump, valve…) in order to transmit this data to the central SCADA router. There is a bi-directional exchange of information between the RTUs and the central SCADA system which is done based on communication protocols like IEC 60970-5. This way, the RTUs send information about the substation status to the central station and also receive signals from this master unit that helps to control the operation of actuators, switchboxes, etc.
- **Master Terminal Unit** (MTU): it is also called SCADA centre and its function is to communicate with the RTUs. They read the sent information that is collected by a sequential scanner, and it can control its functioning and detect alarms in their network.

- **Communications systems**: the medium through which the data is transmitted depends on the type of the SCADA system. As it has been explained above, it can be cellular, satellite, cable, etc.
- **HMI stations**: these stations provide the human-machine interface (HMI) that is required to monitor and control the parameters in the field.
- **Engineering stations**: they are responsible for the design, configuration, and maintenance of the SCADA system as a whole. It is the "brain" that defines the communication protocols, the data acquisition points, the alarm, etc. Their functions also include the analysis of the historical data of the systems to predict events and identify patterns to optimize its functioning.

2.1.2. METERING.

One of the most relevant progresses in terms of telecommunications used in the distribution grid to enable the smart grids is the Advanced Metering Infrastructure (AMI) – also defined as "smart metering" – that will be explained in more detail within the next section.

As an introduction for this section, it is important to mention that the deployment of smart meters has enabled the two-ways communication between the end-consumers and the utilities as it allows the exchange of real-time data that provides the data acquisition that is needed to make decisions regarding the grid behaviour [11]. AMI is a direct evolution of the Automatic Meter Reading (AMR) systems that were firstly used by utilities from the 1970s that allowed to remotely access to the meter readings. Before that, the traditional devices that were used for measuring the energy consumption were called **Manual Meter Reading** (MMR), they were firstly used from the end of the 1800s and they looked as the one represented in *Figure 5*. They required that a worker from the utility visited that concrete meter on-site and recorded the measure of the device. That measure was not precise enough to detect the consumption of reactive power or residual corrects. Besides that, this reading of the consumption was typically done monthly instead of each 15 minutes as today, so it was not possible to adapt the consumers' demand in real-time, detect short interruptions of supply or design flexible tariffs that depends on the consumption patterns.

Figure 5: Manual monophasic energy meter. [13]

The next progress regarding the meters was introduced by the **Electronic Meter Reading** (EMR) that used radio-frequency transmitters to allow those workers that needed to enter the installation to read the consumptions to do it just by walking-by. This alternative started to work during the 1980s and 1990s and it was specially applied to industries more than to particular consumers. This progress introduced increased efficiency to the meter reading process, and it was the basis for the following developments.

As it has been previously mentioned, the next advance of this technology was defined as **Automated Meter Reading** (AMR), and it was the time were finally the measures could be done remotely. To do so, utilities make use of telecommunications solutions such as radiofrequency, mobile, or power line communications (PLC) to gather all the measurements of the energy consumption done by the smart meters at the consumers end-points and transmit them to the utility operation centre that serves as the centre to manage the whole system by monitoring its performance and detect potential anomalies. This gathering of information is done in the data concentrator units.

Obviously, these devices had no real-time or two-way communication features as the next generation of meters, the **Advanced Metering Infrastructure** (AMI) has. Besides that, these new metering devices measure a wide range of parameters that include instantaneous voltage, current, active and reactive power, etc. It also enables the remote connection and disconnection of supply points in case of a need of addition of a point of supply or disconnection of a fraudulent one. Other functionality is that these systems can generate and communicating special events and alarms that helps detect abnormal behaviour of the consumption. The architecture of a neighbourhood that uses smart metering has been represented in *Figure 6*. Here, it can be seen how the different consumption points are linked by both the power distribution network and other communication network – that is wireless in this example.

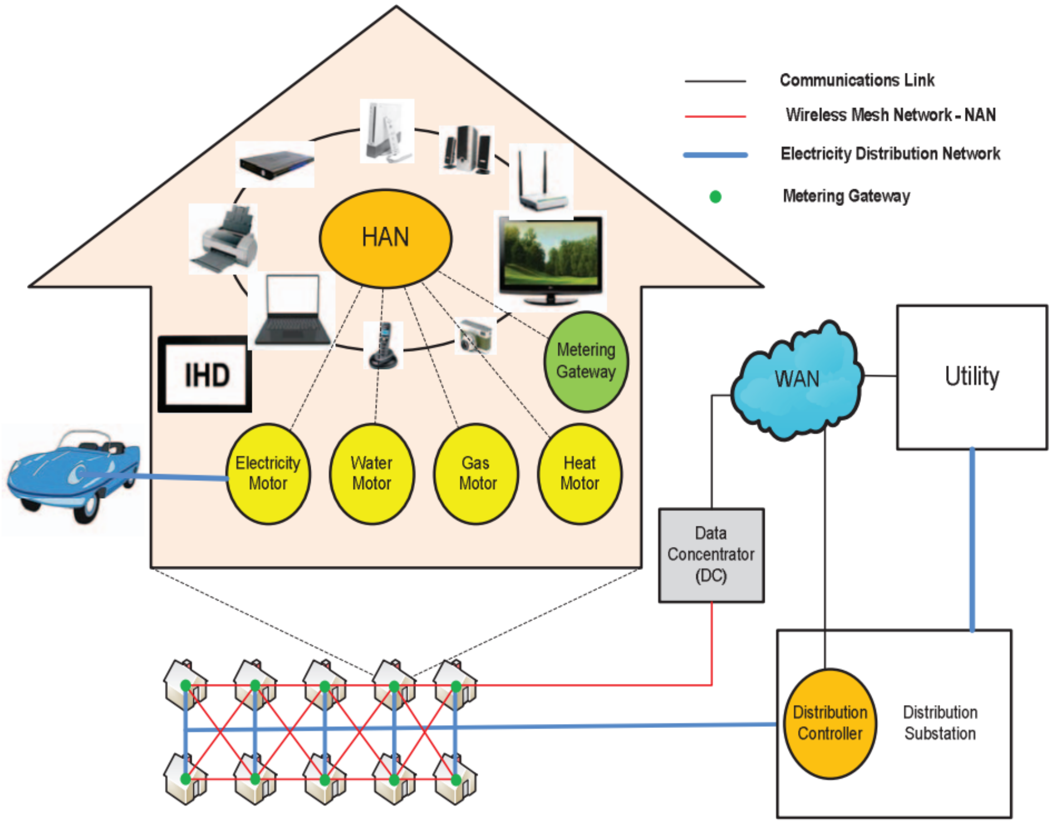


Figure 6: Smart metering system architecture. [11]

On the side of the consumers, they get benefits from the AMI systems since they are allowed to become active users that can make decisions based on their knowledge about their demand and electricity prices so its consumption is optimized for both the grid – because the demand curve is flattened avoiding high peaks that endangers the grid stability – and their own benefit as they can consume at times of minimum cost, their billing process is made more accurately to their actual consumption, and the energy efficiency is promoted to enable the integration of new electric devices in the grid that can be supported by this optimization of the distribution network. To get all these features, it is necessary to install smart meters that are compatible with AMI not only to record all the required parameters but also to be controlled by the utility. One of these compatible devices is the represented in *Figure 7*, which is supplied by ZIV and is one of the used by Iberdrola. Every smart meter is designed to be used following some protocols. The different options of communications protocols to ensure smart metering will be latterly explained.

Figure 7: Smart meter compatible with AMI supplied. [14]

Before getting to the protocols, *Table 3* gathers all the information collected regarding the evolution of the meters from the most traditional ones to the current smart ones. The described differences have been summarized here.

Table 3: Evolution of the energy consumption metering - Main features.

	MMR	EMR	AMR	AMI
Predominance	1900s	Late 20th to early 21st	Early 21st	From 2010
Reading method	Manual	Electronic (Walk-by)	Automated (Remote)	Automated (Remote in real-time)
Reading frequency	Monthly	Monthly or periodically	Frequent (i.e., daily)	Frequent (i.e., every 15 mins)
Communication	-	Radiofrequency (RF)	RF, PLC	RF, PLC, Cellular, others
Data storage	-	Meter memory	Meter and data collector	Meter and central database
Data accessibility	Limited	Limited	More accessible	Accessible for consumers and utilities
Remote control	-	-	Limited	Remote control capabilities
Security	-	Basic measures	Improved	Enhanced
Consumer participation	Low	Limited	Improved	High awareness and energy mgmt.

The remote communication from the smart meters that were introduced to bring developments to the metering process of the utilities relies on different protocols and technologies. Some of them are described below:

- **Device Language Message Specification** (DLMS): it is a protocol defined in the IEC 62056 that allows the communication between the smart meters and the utility management centres. It provides versatility as it supports different types of meters, bi-directional transmission of data and it is compatible with other technologies because it does not define the physical and transmission layer but only applications and interfaces with transmission protocols. DLMS is combined with Companion Specification for Energy Metering (COSEM) that helps to standardize the measured data by describing the attributes that define the energy consumption, billing information, etc.
- **ZigBee**: it is a wireless communication protocol mostly used in home area networks as is designed to support low-power transmissions. Zigbee is usually present in the communications between domestic appliances and the smart meters so they can send their consumption information to the meters or so the smart meters can serve as control centres for these appliances.
- **Wireless Fidelity** (Wi-Fi): this well-known protocol standardized as IEEE 802.11 allows that the smart meters in their coverage area can be part of the wireless network so they can use it as the medium to exchange data. It uses a data collector to gather all the information from the smart meters and sends it over a local Wi-Fi network. This solution supports real-time monitoring and remote configuration so the configuration, parameters, and new functionalities of the smart meters can be remotely and lively defined. In the cases where there is an existing Wi-Fi network, using it for meter data exchange is very cost-effective as it does not require the installation of any further infrastructure aimed for exclusively metering purposes. One of the examples where this remote control shows to be decisive is the one that will be explained in the next section *2.1.3. Active Demand Response*, where this Wi-Fi network allowed to significantly reduce the consumption by remotely controlling the AC.
- **Cellular** (3G or 4G or 5G): this type of communication is not only used for the supervision function – as explained before in the SCADA systems section – but is also

capable of supporting the metering function. This communication is considerably appropriate in the cases where there are challenging end-points to reach or when there is no other communication option that may be feasible. Through the cellular network, smart meters and the rest of the equipment communicate directly.

- **Power-Line Communications** (PLC): it is based on the use of the power distribution infrastructure – low voltage lines in the case of smart metering – as the medium to transmit data between the sensors or the smart meters to the concentrators or utility systems. As *Chapter 3. State of the Art* will deeply explained what is behind this technology, here there is only a brief introduction.
- **Modbus:** this protocol is often used for industrial environments to automate and control their applications. This protocol was developed in 1979 by *Modicon* (currently known as *Schneider Electric*) and uses a communication architecture that requires the presence of a master and a slave. In this case, the master is the Modbus reader as the represented in *Figure 8* that are connected to the target devices which energy consumption needs to be read: the slaves. The gathered information is transmitted to a higher level that depends on the industry's size and purpose: it can be a local SCADA, or a remote SCADA, a HMI, an automation system, or a cloud platform.

Figure 8: Modbus reader. [15]

- **Meter-bus** (M-bus): this protocol is widely used in Europe as it was specifically developed for the purpose of remote reading in utility applications as defined in standard EN 13757. It is not only used for energy consumption reading, but also to measure the consumption of other utilities as gas, water, or heat. The elements that are needed include data concentrators that act as master devices that force the read of the data measured by the meters.

- **BACnet**: this protocol is more used in cases of building automation. A clear of example of this is the integration of various systems within the same building such as the HVAV (heating, ventilation, and air conditioning) system with others like the lightning, security, fire alarms, elevators, etc. Also, the smart meters that can be installed in the building. This protocol allows the monitor of all these systems so all of them are coordinated seamlessly and so patterns of behaviour can be defined and monitored.

This comparation of different protocols has been synthesized in *Table 4* to easier compare their characteristics and main features.

Table 4: Characteristics of smart-metering protocols.

	Launch year	Communication medium	Main features
DLMS	Early 1990s	Wired and wireless	Bi-directional, standardized data formats, robust
ZigBee	Late 1990s to early 2000s	Wireless (Low power)	Support for small devices
Wi-Fi	Late 1990s to early 2000s	Wireless	High-speed, ubiquitous over the coverage area
Cellular	3G: early 2000s 4G: late 2000s to early 2010s. 5G: late 2010s.	Wireless	Wide coverage, mobile connectivity
PLC	Late 20^{th}	Wired	Use of existing infrastructure
Modbus	1979	Wired (Serial)	Easy to implement in industry
Meter-bus	Late 1990s	Wired (Serial)	Low-power communication
BACnet	Late 1980s to 1990s	Wired and wireless	Suitable for building systems, interoperable and standardized data

2.1.3. ACTIVE DEMAND RESPONSE.

The active management of the grid from the consumers is commonly defined as "demand response" and it is one of the features that telecommunications in smart grids enable. It was actively promoted by the Electric Power Research Institute (EPRI) since the 1980s [9]. The main objective of this organization was to encourage the customers to change their demand profile to balance the grid electricity generation and consumption. When is the utility that controls these profiles, it is called Demand-Side Management (DSM) and it is done by encouraging initiatives to improve the efficiency of the consumption. For instance, they may include incentives for the adoption of energy-efficient or less-pollutant appliances or the consumption in valley-hours that does not endanger the stability of the grid as the consumption during peak-hours. The main goals therefore are linked to the long-term energy savings, the reduction of greenhouse gas emissions, and the enhancement of the system's efficiency. On the other hand, the implication of the consumer it is also essential to achieve short-term plans that require the adjust of the electricity consumption in real-time. This is what is called Demand Response (DR) itself.

By sending signals to smart appliances and devices, utilities can shift energy consumption during peak hours, reducing strain on the grid and promoting energy conservation with the aid of the consumers. Also, when these consumers are not only active in their demand by managing their consumption profile but also by participating in the generation of energy by introducing for instance solar panels on their rooftops, are called "prosumers". The integration of these new actors requires the characteristic robustness and efficiency that telecommunications can provide to the grid as well as the possibility to have bi-directional flow of electricity as these prosumers will be not only consuming electricity from the grid but also supplying with it. Finally, telecommunications are essential in these cases also to fairly bill these actors by taking accurate measures of their consumption and generation.

One of the clear examples where the integration of telecommunications makes a difference and make possible for utilities to act in their consumers behaviour depending on the boundary conditions is the remote control made possible through the Wi-Fi technology. This wireless solution can be used to control smart meters that are also actuators as explained in previous section. In this case, the Wi-Fi network allowed to manage the smart thermostats to control a working central air conditioning (central AC) system during a heat wave in *Southern California Edison* (SCE) territory back in July 2018 [16]. As it has been represented in *Figure 9*, the reduction supposed a decrease of 365 MW. This achievement was possible as SCE offered their customers a "Summer Discount Plan" that established the conditions that can be read on *Figure 10*. As it is shown, consumers can contract one of these options of the plan and adjust their use of their AC system in the utility company's favour. The client may contract one of these options to get the offered discounts (that are estimated for a 4.5-ton AC unit) and select the alternative that is more or less strict in the control that the utility company has over their AC system to get less or more earning, following an inverse proportion as it is shown in *Figure 10* obtained from SCE webpage.

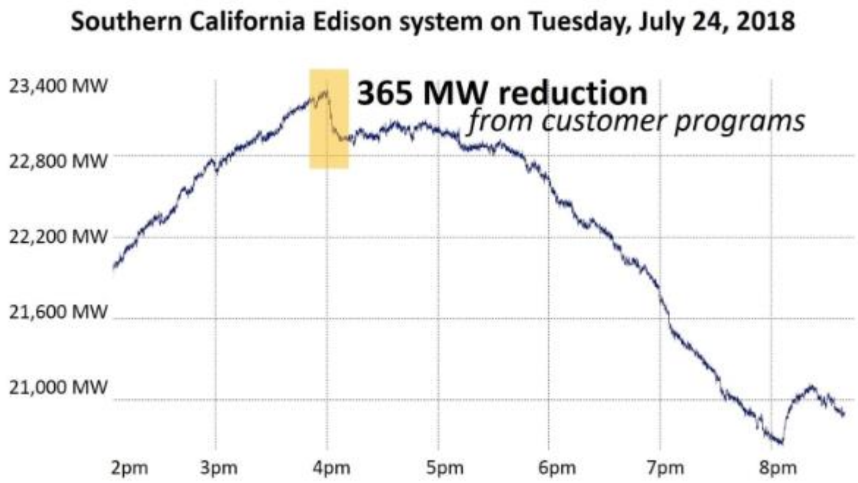


Figure 9: Energy consumption reduction by the use of Wi-Fi. [16]

Option	Earn up to*	A/C Shutoff	Push-Button Override**
Maximum Savings	$180	Continuously, up to 6 hours per event.	
Comfort	$90	15 minutes of each half-hour, up to 6 hours per event.	
Savings with Override Control	$90	Continuously, up to 6 hours per event.	✔
Maximum Comfort with Override Control	$45	15 minutes of each half-hour, up to 6 hours per event.	✔

Figure 10: "Summer Discount Plan": Southertn California Edison. [17]

The SCE case is a brilliant example that shows how demand response and management can contribute to the system's efficiency by optimizing the consumption, reducing the operation costs, and improving the grid's stability.

Other examples on how DR can be beneficial for both companies and the end-users are:

- **Time-Of-Use Pricing** (TOU): division of the daytime into blocks of hours so the price for each period is predetermined and constant for the customers. This way, the demand curve tends to grow in the valley period when the tariff is cheaper for the consumers, and it flattens the peaks of demand as the price of energy for these hours is more expensive. This saving method that serves for the consumer positively affects the stability of the grid as it avoids those peaks that may not be supported by the generation planned for this period. Furthermore, the demand management is much more efficient to reduce the peaks as it has been graphically explained in *Figure 11* where it can be seen how the traditional method requires the reduction of the overall consumption. However, by according curtails with the consumers and managing their demand, the overall consumption does not need to decrease but just adjust to the most optimal time of the day. Some of the actions that may be taken to reduce the peak demand [18] are turning down non-essential lightning, temporarily lowering air conditioning capacity, pausing the use of pumps and non-essential equipment, and installing smart thermostats and load switches.

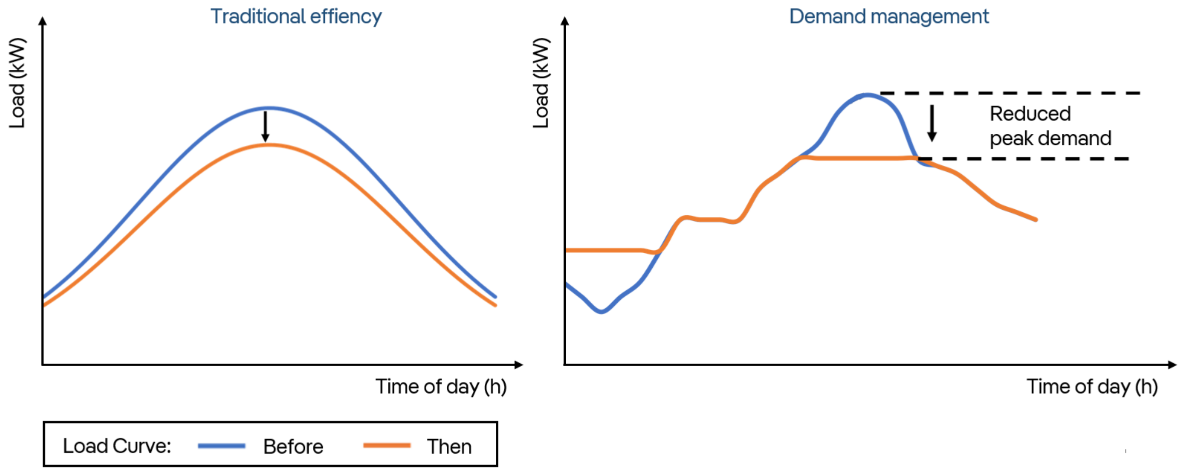


Figure 11: Traditional efficiency vs. Demand management. [Own preparation]

This type of actions can make a difference in the consumer's bill considering that looking into the electricity cost components for the Spanish consumers, 15-20% corresponds to capacity costs, 20-25% corresponds to ancillary costs, and 45-55% to energy costs as *Figure 12* shows [19]. Because of this reason, optimizing the demand profile and consequently optimizing the bill, the consumer can make impact in these costs related to their contracted capacity and consumed energy, meaning that they have impact on 65-80% of the costs that build their final bill.

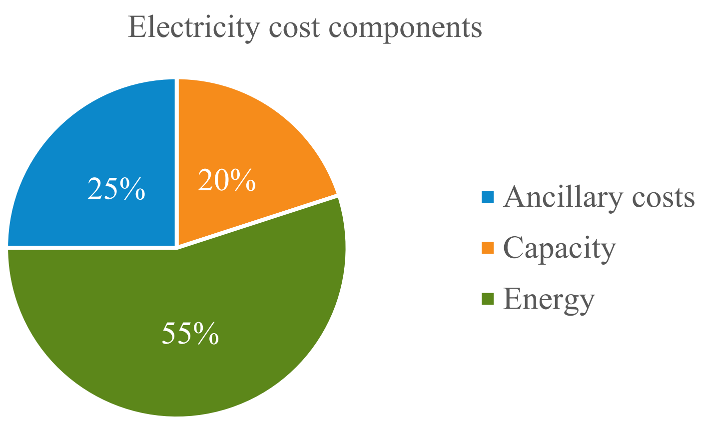


Figure 12: Electricity cost components.

- **Demand Flexibility for Industrial Customers**: the same mechanism through which the consumers adapt their demand depending on the overall demand curve to model it and make it flatter can be done with a greater dimension in the cases of industries that offer their flexibility to produce (meaning an electricity consumption) so they reduce their production during peak hours.

2.1.4. DISTRIBUTED GENERATION.

The integration of distributed generation (DG) or Distributed Energy Resources (DERs) into the distribution grid means that a large number of small, decentralized power production plants are dispersed along the grid. An appropriate example of DG is the renewable energies (solar PVs, wind turbines, biomass, etc.) because it easily shows how their integration – by 2021, the renewable energies meant the 34% of the total installed capacity in Europe [20] with around 491 GW of installed renewable capacity – affects to the grid stability. This is caused mainly by the characteristic variability of generation capacity along the day of these energies that are highly dependent on the weather and boundary conditions. This fact makes essential to improve the telecommunication that provide real-time forecast of this generation to enables real-time power generation and consumption to ensure grid stability that can be at risk without this accurate control. The introduction and promotion of this type of energy is obviously essential to reach all the aimed reduction of greenhouse gas emission and to achieve a sustainable energy production system for all the countries in which this is a potential energy resource.

However, something that is also a principal advantage of the integration of DG is related to the demand management that has been mentioned before. Regarding that, DR can contribute to flatten the demand curve as it moves the peak periods to the valley ones. Now, DG can contribute to this flattening by producing during these peak periods [21]. This is done certainly because of the nature of renewable energies: for instance, solar photovoltaic panels produce during the daytime because of their need of sun, and it is during this "sun hours" while the peak periods occur. Furthermore, this production of renewable energies during the peak hours also has an impact on the mix generation of the traditional power plants. This is because the production of this significant amount of energy during peak demand periods relaxes the need of conventional power plants of ramping up rapidly to meet that peak demand. This is called "offsetting peak load" and it reduces the strain on traditional power plants that avoid the requirement of capacity to meet that ramp up. On the other hand, one of the consequences of this type of "daytime" production leads to a phenomenon that is called "the duck curve" that represents the difference between the energy demand through the day and the solar and wind energy production. This effect is represented in *Figure 13*.

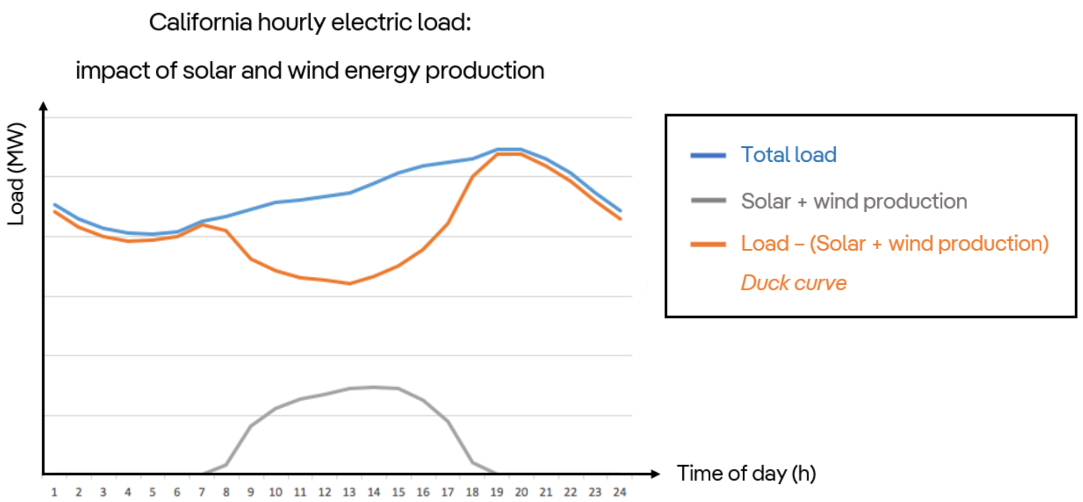


Figure 13: Effect of solar and wind production - Duck curve. [22]

As shown in *Figure 13*, if there was no renewable production (blue curve), conventional power plants needed to plan their ramp ups and downs to supply the demand. This process was usually very predictable, so the planning was easier. However, the integration of these new renewables, make the demand curve look like a "duck curve". This has implications on the traditional power plants because they need to face a very quick ramp up to meet the demand requirements once the renewables stop generating. Besides that, when there is an excess of solar or wind production, utilities may curtail this production and therefore waste the renewable power generation. This is the reason why utilities try to "flatten the *duck* curve" for this ramp up to become less abrupt for the traditional power plants. This defined effect through which renewable energies (and other distributed generators) produce energy during the peak periods is related with a phenomenon that is: "flattening the *duck* demand curve" and some initiatives that can contribute to it while avoiding a shortcut on the demand or a waste of energy production are the following [23]:

- Add flexibility by including diverse energy sources that can better handle the ramp up.
- Develop better prediction to plan the generation mix more accurately of technologies.
- Incentivize evening energy use, as explained before, to reduce the peak demand around noon and homogenise the distribution of the demand through the day.
- Store solar power to be used at night, as shown in *Figure 14*.

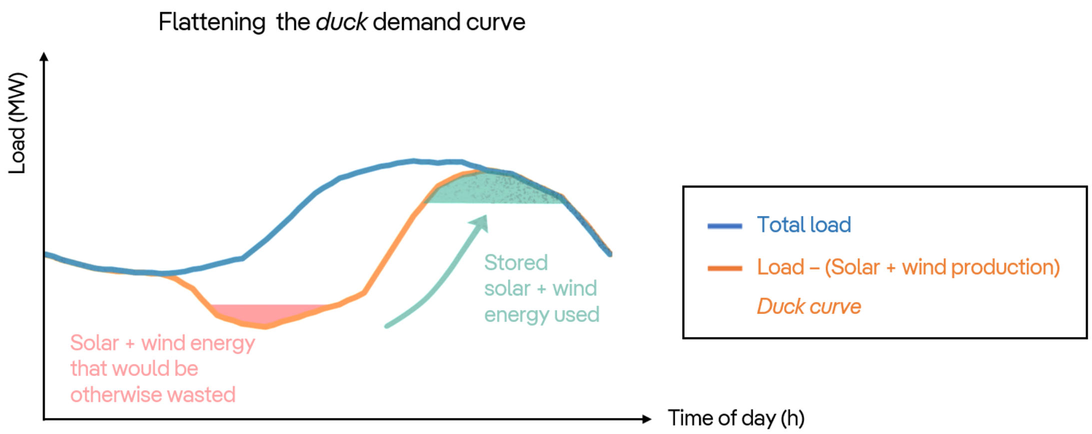


Figure 14: Flattening the duck demand energy by using energy storage.

These initiatives together with the demand response from the consumers involves a huge challenge for utilities that need to progress and develop their telecommunications and electric grid robustness so they can assure the distribution grid stability.

2.1.5. ELECTRIC VEHICLES INTEGRATION.

The other principal actor in the development of the smart grids are the electric vehicles (EV). Their integration has been significantly promoted lately since the transportation sector is second placed in carbon emission [24] and because of this reason this sector needs to be electrified. The penetration of EVs could radically reduce the greenhouse emissions. Furthermore, in relation with the already explained demand management and response, utilities are incentivizing the owners of this type of vehicle to offer the energy that their EV storage in their batteries to be used by the power distribution grid in high-demanding periods, in which is called a Vehicle-to-Grid (V2G) connection. V2G could be also helpful in the events of blackouts or other emergency situations. These characteristics are potential benefits from the integration of EV into the grid. However, there are also lots of challenges related to it in terms of telecommunications and grid stability and robustness [24]. *Figure 15* gathers the positive and negative impacts that the integration of EV may introduce to the distribution grid.

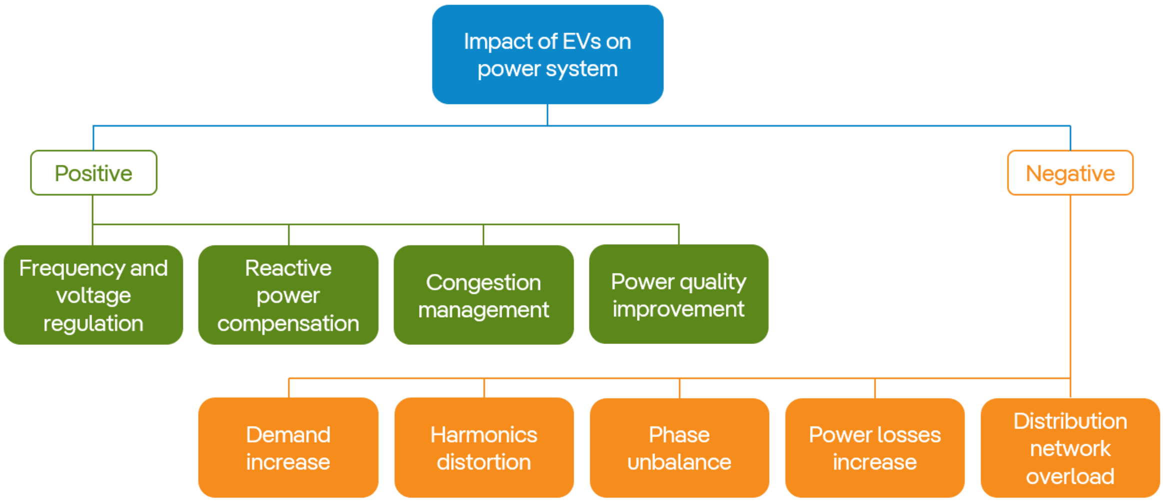


Figure 15: Impact of EVs on power system. [25]

Added to these negative impacts, there is also some economic and social problems – the high price of EV and the lack of charging stations – and technical problems – limited autonomy, long charging period, or safety concerns – that makes the society be reluctant to accept its integration. However, this is progressively changing and the penetration of EVs is increasing exponentially year by year as shown in *Figure 16*. This progress is leading to a scenario where it is supposed that 1 in 5 new cars sold will be electric by 2025 and 2 in 5 by 2030 [26].

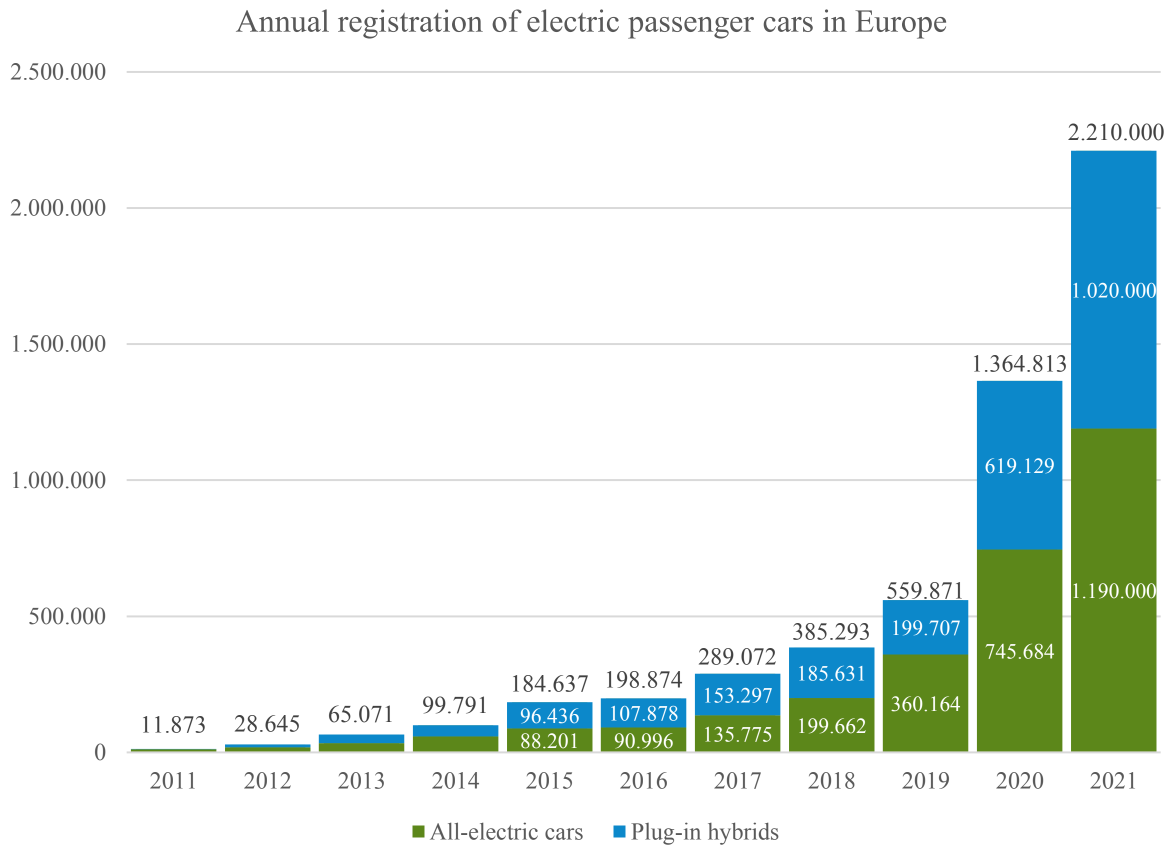


Figure 16: Evolution of EVs acquisition in Europe (2011-2021). [27]

This unstoppable increase is due to the development of new technologies that are helping to the reduction of EVs cost. According to research conducted by Bloomberg New Energy Finance [28], the events that will cause that reduction of prices will be the following:

- **Falling of the battery costs**: Nowadays, the battery cost represents around the 40% of the total vehicle price; however, it is planned to be reduced to the 20% by 2025, making possible for EV suppliers to make their products less expensive.
- **Dedicated production lines**: the increasing interest on EV makes feasible for manufacturers to be able to dedicate specific production lines for EVs and therefore apply economies of scale that will decrease the prices.

- **New vehicle architectures**: innovation in vehicle design may lead to more efficient manufacturing processes, streamlined production, and better integration of electric powertrains.

Apart from these initiatives that are related to technology progresses that positively affect to the economic viability of a product, there are also other initiatives related to the regulation that will be helpful in this process, for instance: **such tighter CO_2 targets** for petrol vehicle manufacturers, **stronger support for charging**, or increased **incentives for consumers** to make EVs more appealing. According to the stated research, these actions may make possible for EVs to reach a 100% of new sales across the European Union by 2035. On the other hand, if these initiatives are not applied, this figure will decrease to the 83%, failing to success the European's decarbonization goal by 2050.

By the appliance of these initiatives, according to Bloomberg, petrol and electric cars will meet their crossover point by 2026 when the prices of both car alternatives will be similar as *Figure 17*. In other words, by that year, progresses and initiatives regarding the promotion of electric vehicles will make possible that the current EV prices decrease until they meet the current prices of petrol cars that will gradually increase due to the taxes related to their contaminant impact on the environment.

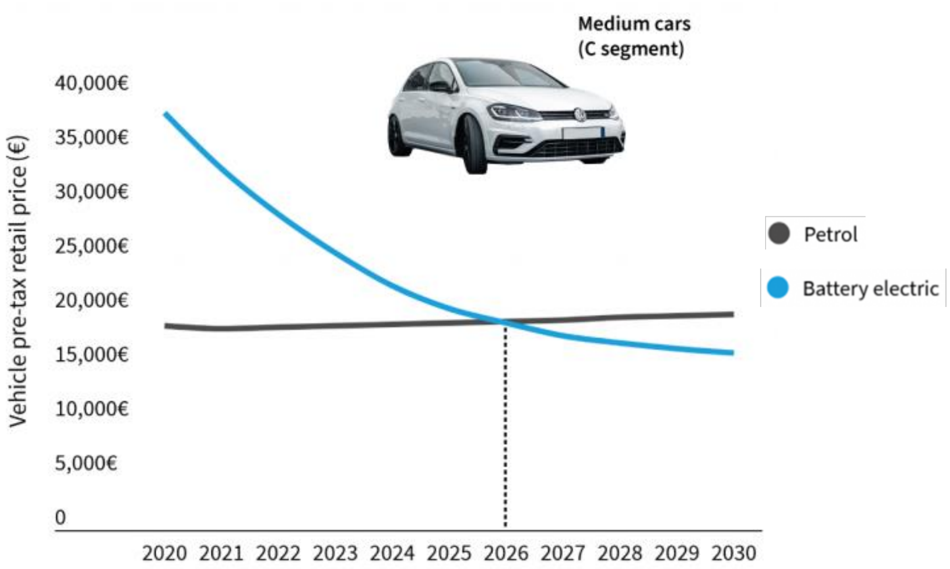


Figure 17: Crossover point: petrol vs. battery electric vehicles. [28]

2.2. THE ROLE OF IBERDROLA.

The energy systems are mainly divided into four different activities: generation, transmission, distribution, and commercialization. In the case of the Spanish energy systems, the energy production and commercialization are liberalized activities in which unlimited actors can take part and there is competence among them. To be specific, in Spain there are 762 trading companies [29] participating in the commercialization business. In the case of Spanish consumers, depending on their size, they can choose among all the trading companies (small and medium consumers) or buy the energy directly from the generator (wholesale purchase for big consumers). The sale between generation and the energy bidders is done inside the electricity market that is responsibility of *Operador de Mercado Ibérico de Electricidad* (OMIE) in the case of Spain. OMIE oversees the process of matching the supply and the demand. On the other hand, the distribution and transmission networks are regulated monopolies. The transmission network is owned by one company, *Red Eléctrica Española* (REE), that not only owns the grid but also is the Transmission System Operator (TSO) in charge of the transmission network operation, maintenance, and expansion. Regarding the distribution network operators (DNOs), in Spain there are 5 of them, as represented in *Figure 18*.The regulator in Spain is *Comisión Nacional de los Mercados y la Competencia* (CNMC) that sets prices to pay operation costs, the investment, and to make a reasonable profit as well as ensures an open and non-discriminatory access to the networks.

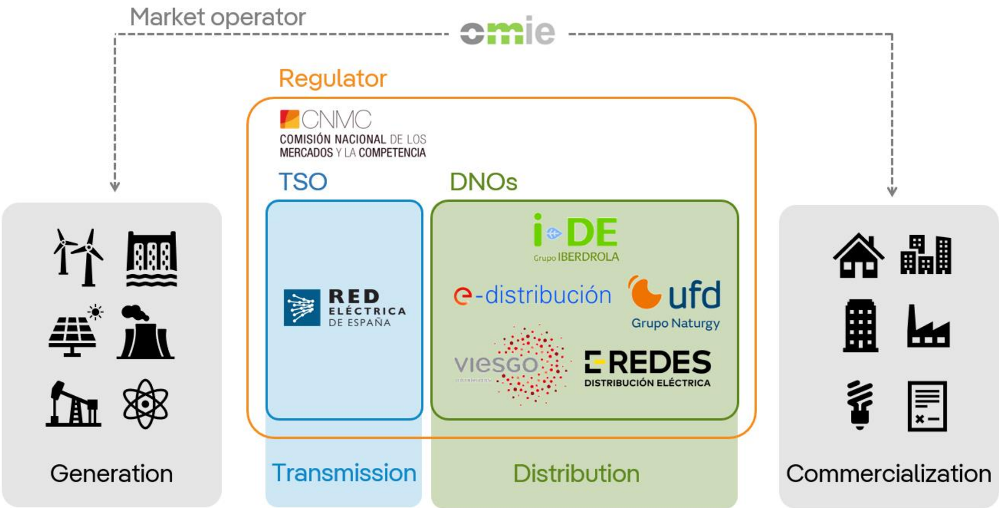


Figure 18: Energy systems in Spain: main actors in the regulated activities. [Own preparation]

As shown, Iberdrola has its participation in the energy systems as a DNO. However, it is also part of the generation with an installed capacity of 29.816 MW in Spain [30] and also a trading company managing over 11 million of demand points [30]. Besides that, as Iberdrola is a multinational company, it is also investing in other countries and has reached an amount of 10.544.00 € of investment in the last 12 months distributed in different countries as represented in *Figure 19*. Due to that investment, Iberdrola counts with a total installed capacity of 41.250 MW and another 7.000 MW in construction [31].

Figure 19: Gross investment per country (€). [31]

Since this Project is carried out within i-DE – that is the Spanish DNO owned by Iberdrola – and it is directly linked to the development and improvement of the power distribution grid, this section will be focused on this company, and it will show some of the figures that illustrate the presence of i-DE as a DNO in Spain.

2.2.1. IBERDROLA AS A DISTRIBUTION NETWORK OPERATOR.

Similar to what happens with the transmission network, DNOs are the owners of the distribution networks and therefore they are responsible of their operation, maintenance, and upgrade. Besides that, they need to ensure quality of service for the customers – that is usually measured in the frequency and duration of the electricity supply interruption – as well as facilitate the process of connecting new customers to the distribution grid, pursue fraud, or collect the data from the smart meters for the commercialization companies to create accurate bills.

The performance of the DNOs in Spain is geographically determined as represented in *Figure 20*, where it can be seen that i-DE operates in 23 different provinces that are internally divided into regions following the map of *Figure 21*.

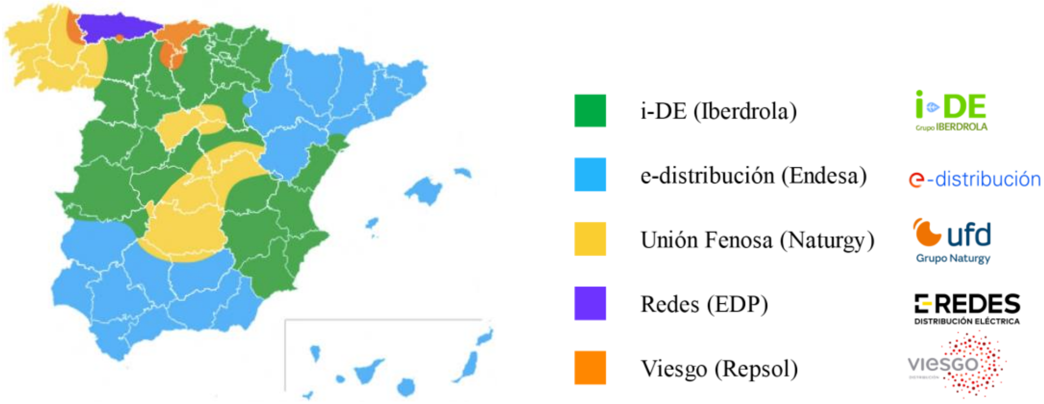


Figure 20: Map of DNOs' operation area in Spain.

Figure 21: Structure of i-DE - Division by regions. [32]

Along these areas, i-DE is distributing 90.963.347 GWh a year to a total of 11.218.365 clients. These and other figures illustrating the presence of i-DE and the importance of each one of their regions have been gathered in *Table 5*. This information shows that the region with greater concentration of assets, clients, etc. is the east region. This phenomenon is due to different causes: for instance, although the west region is larger than the east one, this area is affected by the depopulation while the east region is crowded because of the impact of big cities such as Valencia. Same thing happens in the centre region that includes Madrid, making it the second greater of the areas in which i-DE operates.

Table 5: Presence of i-DE in Spain. [32]

	Centre	North	West	East	TOTAL
Number of clients	2.934.849	1.973.103	1.891.075	4.419.338	**11.218.365**
Primary substations	258	291	360	249	**1.158**
Secondary substations	24.621	18.364	19.768	34.875	**97.628**
Lines length (km)	59.747	38.644	63.967	101.195	**263.553**
DG: number of installations	19.325	13.959	9.534	25.804	**68.622**
DG: production (MW)	6.072	3.340	9.009	4.279	**22.700**

i-DE has a huge impact on Iberdrola's results, and it also represents a great cost of investment. In the case of the 10.544 M€ invested in the last 12 months mentioned in the introduction to this section, 48% was destinated to distribution networks (over 5.000 M €). After this investment, the total assets that i-DE owns raises to 40.000.000€, which is a 10% greater than the total of network's assets 12 months before.

2.2.2. INNOVATION PROJECTS WITHIN IBERDROLA.

The total budget allocated to distribution networks and the firm belief of Iberdrola that the innovation and improvement of their grids are the key to its optimization makes the company the most innovative utility in Spain and even it has been consolidated as the private utility with the highest funds earmarked for innovation around the world [33]. From all of this investment in innovation, networks and systems mean a total of 57% where the absolute figures will reach a total of 2.000 M€ in innovation projects by 2025 and 4.000 M€ by 2030.

Among the main objectives of the company in terms of strategy regarding R&D&I, there is a determination to improve the smart grids and the electrification of the demand with the aim of reaching the cycle that has been represented in *Figure 22*.

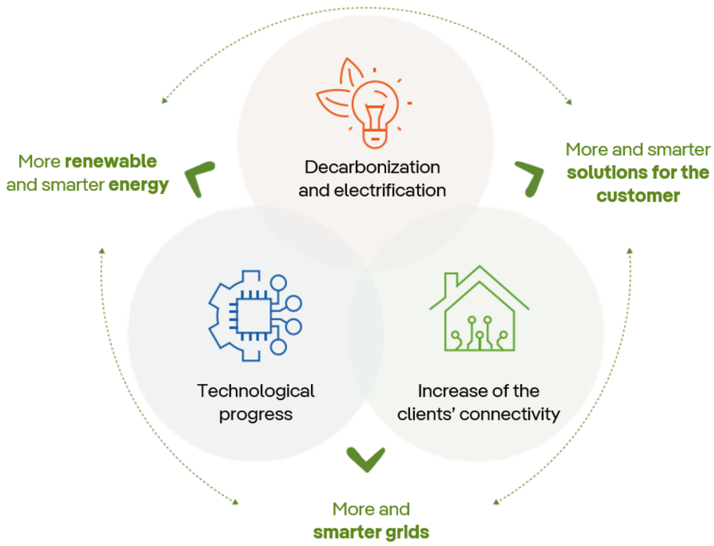


Figure 22: Innovation within Iberdrola: main objectives. [33]

Some of the innovation activities that Iberdrola has developed in the last years and that have particularly had impact on the power distribution system that is the concern of this Project will be briefly explained in the following sections [34] being the STAR Project for the deployment of smart meters the most relevant one in relation with this Project, so it will be explained in more detail than the others.

a. Projects in Europe

- ***UPGRID*:** This project focused on improving LV and MV networks by integrating active demand management and distributed generation. There were Field Trials being carried out in European cities such as Bilbao (ESP), Lisbon (PRT), Åmål (SWE), and Gdynia (POL). The objectives of this projects were mainly two: the development and validation of technological solutions that will allow the creation of a smart integrated system, and the increase of observability and control of LV and MV grids.
- ***GRID4EU*:** It began in 2016 aiming to demonstrate advanced smart grid solutions to overcome obstacles in achieving European 2020 objectives. It demonstrated the power of distribution grids in managing supply and demand dynamically and integrating

renewable energy sources. The project also seeks to optimize energy flows and improve the reliability, flexibility, and resilience of the grids that were starting to integrate small and medium distributed generators.

- ***DISCERN*** (Distributed Intelligence for Cost-Effective and Reliable Distribution Network): it evaluated the optimal level of intelligence in distribution networks to identify replicable technological options for cost-effective and reliable operation. This estimation was done by the use and validation of demonstration projects, simulation and testing of the solutions, and the creation of use cases for improved network management.
- ***iGREENGrid*****:** within this Project, there were six Field Trials in different countries evaluating the effectiveness of integrating distributed renewable energy sources into the power distribution networks. Some of the objectives were identifying solutions for effective integration, optimizing energy flows, and providing more accurate data.

b. Projects in Spain

- ***TABÓN*****:** it aims to analyse the correlation between voltage values and ground resistance and develop an intelligent platform for modelling, designing measurement systems, and defining sampling points for ground resistance calculation. These systems will be helpful for the integration of DG as it allows the management of the lines that in the case of the grounding systems was usually characterized by high dynamism that made difficult the analysis and diagnosis of these lines.
- ***MATUSALEN*****:** its main objective is to develop an interoperable technological solution for estimating the degradation level of underground medium voltage cables. It is focused on the analysis of cable aging patterns and instrumentation to better understand them and to develop new monitoring and diagnostic systems for measuring cable life that is compatible with the current requirements for the Smart Grids architectures.
- ***SILECTRIC*****:** it aims to improve the quality and efficiency of high-voltage lines and electrical equipment that is operating in extreme conditions giving place to premature aging processes. This Project is focused on diagnosing the aging mechanisms, obtaining new insulating materials with improved properties, and developing new validation tests. The main objective is to obtain improved network elements that will have positive impact on the quality of services in the long term.

- **INTENSYS4EU:** This Projects is part of the European DSO Association for Smart Grids (EDSO4SG) and it gathers various initiatives that have the aim to find new R&D&I approaches in the field of Smart Grids to address the challenges of energy storage and integration of DG. Some of these initiatives carried out in Spain are the following:
  - LAYCA: it is developing a smart system that allocates faults in medium voltage lines and characterizes them.
  - mGRIDSTORAGE: it is involved in the design of a microgrid model that includes storage for the power distribution networks.
  - CARTODILAR: it is using photometry technology mounted on helicopters to improve the inventory of lines and obtain a more accurate map of vegetation around power lines, that is a usually a reason that causes faults in power lines.

c. STAR Project: PRIME and Smart Meters Deployment

The STAR Project was promoted by i-DE with the aim to substitute the traditional electromechanical meters with a new generation of meters which provide real-time data and enable two-way communication between the utility and consumers. This communication was based on the creation of an international standard that is public and open to modifications. This standard is defined as PoweRline Intelligent Metering Evolution (PRIME) and it was started in 2009 promoted by the European Commission, which provided the Electricity Directive 2009/72/EC (see *Annex I.2*). Spain applied this normative into the Order IET/290/2012 that required distribution companies to change the Type 5 meters from analogic to digital before the end of year 2018. To understand how the meters are classified depending on their appliances and characteristics, *Table 6* gathers the principal information.

Table 6: Types of meters. [36]

	Type 1	Type 2	Type 3	Type 4	Type 5
Clients' contracted power	≥ 10 MW	≥ 450 kW	Rest	> 15 kW ≤ 50 kW	≤ 15 kW
Generation apparent power	≥ 12 MVA	≥ 450 kVA		-	≤ 15 kVA
Energy exchanged	≥ 25 GWh	≥ 750 MWh		-	-

The STAR Project has decided to be supported by the PRIME Alliance as i-DE is one of the principal members of the alliance [38]. The same thing happens to other Spanish DNOs that have also adopted this standard: UFD (Naturgy), Viesgo (Respol), and E-Redes (EDP). They are now using the version 1.3.6 of the PRIME solution, that it was the one used to deploy the STAR Project. On the other hand, e-distribución (Endesa) – that is property of Enel – uses a different standard: G3-PLC in Spain and G.hn in Italy. The differences between these standards will be mentioned in *Chapter 3. State of the Art.*

i-DE showed proactivity in relation with this initiative and the company started the substitution in 2010 before the Spanish Order was launched and finish with the required deployment before the deadline stablished by that Order. Furthermore, what the legal obligation required was to enable the remote management. However, Iberdrola went beyond and added other features [39]: directional fault detector, LV monitoring, alarms, and automation of these features. Thanks to the initiative, at the end of the deployment, Iberdrola achieved to triple the quality of service since 2001 [40]. Some of other achievements related to that Project are the following:

- Improved metering and data collection: as detailly explained in previous section, smart meters enabled real-time monitoring of electricity consumption, reducing the need for manual meter readings, and providing accurate data for billing purposes.
- Enhanced grid management: the deployment of PRIME technology allowed Iberdrola to monitor the low-voltage grid more efficiently, detect faults or outages, and respond proactively to potential issues decreasing the average resolution time.
- Consumer empowerment: as mentioned, among the advantages of the development of the smart grids, the access to real-time consumption data allow to make informed decisions about their energy consumption habits.

Some of the figures that the STAR project achieved regarding annual operations were [39]: 45 million invoices based on remote meter readings, 55 million remote meters reading, 300.000 remote operations (disconnection, reconnection, etc.), 6,6 million changes of tariff orders (power limitation orders), and 210.000 on-demand readings.

This deployment required the installation of smart meters that enabled those required features, and that are compatible with the PRIME standard. As it was shown in section *2.1.2. Metering*, one of the most common smart meters used in Iberdrola is the one supplied by ZIV. However, the benchmark of potential meters was done considering all in *Figure 23.*

Figure 23: PRIME smart meters. [41]

Apart from that, the successful deployment of the STAR project and the adoption of PRIME technology has positioned Iberdrola as a leader in the adoption of smart grid solutions in Spain. Not only Iberdrola has modernized its distribution network but also has gained advantage versus other competitors because the adoption of this new smart meters allows the company to collect data that the competitors are not capable of measuring from their own grids. This fact has direct relation with the capability of Iberdrola to anticipate and manage faults with an efficiency and provide better quality of service for their customers, that are relevant keys for its success and put the company on the top of innovation and efficiency among its competitors.

Furthermore, the success of the STAR Project has set a path for Iberdrola to continue investing in technology that modernizes and digitalizes the grid. This fact has provoked that other stakeholders (i.e., regulators, policy makers, and environmental groups) support initiatives like this, what pushes all the energy companies to follow the path that Iberdrola has already started time ago. This is the reason why the STAR Project is considered to have a big impact on the company's strategy as it has positively influenced the electricity industry.

2.2.3. NEW SOLUTIONS FOR TELECOMMUNICATIONS.

Iberdrola's projects related to innovation within its telecommunication department is called "Network for Digital Access" (*Red Acceso Digital*). This department has an increasing importance within the company as it is responsible for the deployment of new solutions for telecommunications that are needed to make possible the integration of the new smart applications that have been already described.

These projects will change the paradigm of telecommunications not only for the company but also for other energy distribution companies that will need to look up to i-DE optimization of its network that is aiming to optimize its functioning. Some of them will be described in this section. Those technologies that involve the Communications over Power Lines will be later described in depth as this Project relies on this specific technology. However, it is important to also mention them in this section to illustrate the importance of its deployment in terms of improvement of the telecommunications.

a. ADSL to FTTH.

ADSL stands for Asymmetric Digital Subscriber Line, and it is the telecommunications technology that was predominant from the late 1990s and early 2000s until the early 2010s. This solution used the telephone cable to transmit data. The additional feature that ADSL offered over the traditional phone connection was the possibility to transmit data at high speed. Furthermore, ADSL is known to be asymmetric because the speed at which data could be downloaded or uploaded is different. Usually, download speed used to be faster than upload speed, which is a characteristic that matches the behaviour of an average user that commonly used internet to download content.

However, new technologies that offer higher speeds, lower latency, and more symmetrical upload and download speeds appear to be clear substitutes for ADSL as it provides a more reliable and faster internet connection.

One of these technologies is the optic fibre that is called FTTX (Fibre to the X) depending on the end-customer. Among the possible types, the fibre can be deployed to Node (N), Curb or Cabinet (C), Business (B), or Home (H). The difference among these deployments have been represented in *Figure 24*. The elements to the right of the *Figure 24* represents the Point of Presence (POP) where the Internet Service Provider (ISP) is connected to the fibre network; the frontier between the optical fibre – coloured in purple – and the metallic cables – coloured in yellow – represents the Optical Network Termination Point.

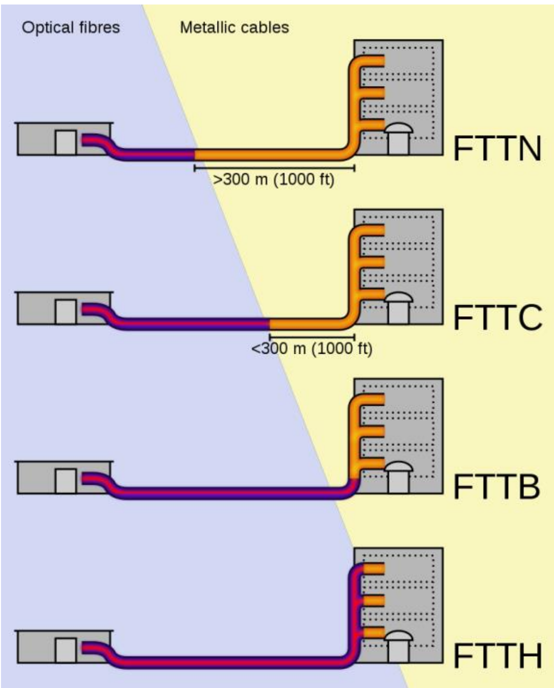


Figure 24: Fibre To The X visual description. [42]

Besides the fact that in the case of private consumers, FTTH can provide improved features over ADSL, the reality is that telecommunications operators in Spain such as *Telefónica* have already started the dismantling of their ADSL network which is supposed to be completed by April 2024. i-DE [43] has currently over 1.000 secondary substations using ADSL solution that need to be migrated to another solution such as FTTH.

The switch to this new solution will require that operators like *Telefónica* provide its optic fibre. Also, in a short future, other operators like *Orange* will also be included as potential suppliers of FTTH. These operators will provide the fibre that reaches the Termination Point that will be placed in the SS façade. After that, Iberdrola needs to deploy a short fibre cable that reaches the Optical Network Terminal (ONT), which is a device inside the home. There, the optic fibre is switched to an ethernet cable that finally reaches the *Teldat* router. To make this change of telecommunications even more effective, Iberdrola is developing a solution to avoid the cabling. This alternative requires the use of a SFP-ONT (Small Form-factor Plugable) that is supplied by *Nokia* and it allows the fibre to be directly connected to the 4G *Teldat* router as represented in *Figure 25*. As it is showed, the optic fibre reaches the GPON node of the SFP-ONT and then its Ethernet node is inserted into the router.

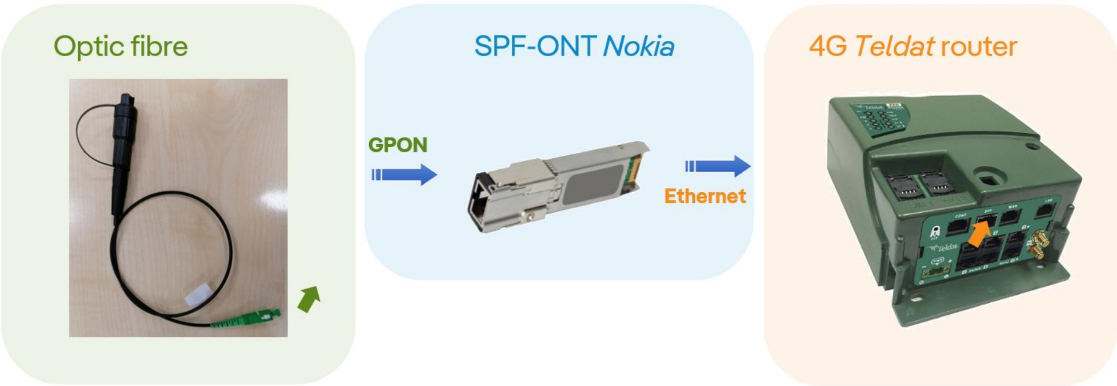


Figure 25: New SPF-ONT+ 4G Router solution for FTTH. [Own preparation]

b. 2G – 3G to BPL-MV.

As it was mentioned before, more details about the Broadband Power Line Communications (BPL) will be given in next sections. BPL allows the transmission of data by using the power lines, what allows the telecommunications to be present in all the places where the power lines are. The main reason for Iberdrola to want to shift their telecommunications networks that use 2G and 3G is because they are supplied by operators that develop technologies much faster than the amortization periods of the distribution company's assets. An example of this is that *Vodafone* is already dismantling its 3G network and plans to complete it by the end of 2023. Also, *Movistar* and *Orange* are planning the same by the end of 2025. Because of this, Iberdrola is aiming to achieve a higher degree of independency from these operators that also cannot provide the level of electric autonomy that elements like the secondary substation require. Reducing the dependency to telecommunications operators can be done by making use of the power line communications. i-DE has already carried out a study that reveals that this solution can be applied to 12.000 SS that currently use operator's solutions.

The plan is to shift the technology of 2.500 SS per year so the complete project will be completed in the next 5 or 6 years. To do so, i-DE is incorporating new equipment of BPL-MV (*General Electric "Powercom"* and *UVAX*) that is compatible with the previous one (*Current/Ormazabal* and *Corinex*). Furthermore, i-DE has outsourced the development of an online tool called "SGRWIN" that allows the management of the equipment from different manufacturers. This will make possible to combine diverse equipment in the same BPL cell. This tool is being designed by *CIC Consulting Informático*, a Spanish engineering and informatic projects developer.

c. BPL-MV to Fibre.

In those cases where the already existing cabling among SS is suitable to deploy optic fibre, this solution is being used for the communication of these SS. The fibre connection, as already explained, will allow higher speed, lower latency for the communications. Furthermore, a switch to this technology will also reduce the interferences in the BPL band (2 - 30 MHz) as the communications among SS will not be done through BPL anymore. This free BPL band could therefore be used for other applications as the BPL over low voltage which is the subject of this document.

A field trial of this migration of technologies has already been done in Pamplona, Spain involving 52 SS that belonged to 7 different BPL-MV cells. The testing was successful as it was proved that the downtime of the equipment was minimized.

d. Private 4G (LTEP)

i-DE is starting to deploy its own 4G that needs to be operated and maintained by the own company. This private LTE (LTEP) network is a mobile telecommunications technology that uses the frequency of 2300 MHz to transmit data. This solution will require the creation of Iberdrola's SIM cards. In terms of technology, this solution is similar to Wi-Fi access points, and it is based on the creation of a small-scale public cellular network that covers a certain area. When the LTEP network is completely deployed, the order in which i-DE will choose the operator for their communications will prioritize private networks over public ones.

The principal upside of using LTE versus directly using Wi-Fi is that 4G networks provide more reliable and faster transmission of data, allows the control of the network's devices, and limits the entrance of undesired ones. Besides that, by using private LTE instead of public LTE, Iberdrola is providing their telecommunication with an increase of privacy, security, flexibility, mobility, and quality of service as well as a decrease on their latency. The representation of the required elements for both types of LTE can be seen in *Figure 26.*

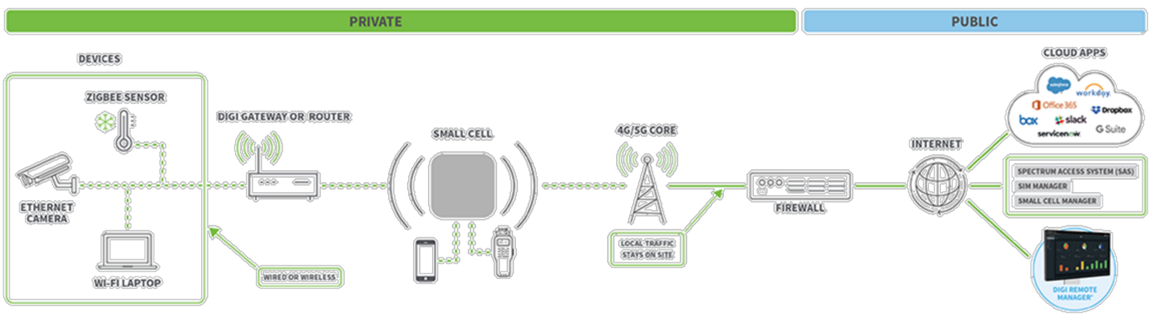


Figure 26: Private - Public LTE configuration. [44]

As of today, the equipment that will be able to connect to this private network are the Teldat and General Electric (GE) 4G routers. This selection leaves out ZIV routers because they are not compatible with the frequency band of 2300 MHz that this LTEP is using. Another technical constraint that needs to be considered is that GE routers can only be fed to 48 VDC, so they are not compatible with secondary substations (SS) that are exclusively fed to 230 VAC that are the SS used for remote management. *Table 7* summarizes the benchmark of 4G routers' suppliers that will be needed for the deployment of private LTE.

Table 7: Suppliers of 4G routers compatible with private LTE.

Supplier	**Model**	**Power supply**	**LTEP (IBD SIM)**	**SS for remote management**
ZIV	3EMRT6E28Q2D4102 3EMRT6E28Q2D4112	AC DC	Unsuitable	Unsuitable if IBD SIM
Teldat	Regest-Smart-PRO	AC DC	**Suitable**	**Suitable**
General Electric	MXCXE4SNNNNN1S3EDSCND MXCX4GZNNNNNN1S3EGSCND	DC	**Suitable**	Unsuitable

e. PRIME v1.4.

The newest update of the PRIME standard that will be used to communicate the smart meters is known as PRIME v1.4. This version uses more frequencies, and it has eight channels, as it will be furtherly explained in section *3.1. Power Line Communications.* It was released by the PRIME Alliance on May 27th, 2014 and includes new features comparing with its previous version [45]. Among them is remarkable its robust mode operation and extends the frequency band. Furthermore, the introduction of PRIME v1.4 helps to address American and Asian markets since it allows the opening to the full spectrum of the Federal Communications Commission (FCC) in the United States and Association of Radio Industries and Businesses (ARIB) in China and Japan.

This version aims to making possible for new devices to interoperate with the previous devices using PRIME v1.3.6. to secure that the already made investment is still usable. However, although PRIME base nodes are currently compatible with both versions, the reality is that these versions cannot be used simultaneously. The strategy to guarantee their coexistence of them is to keep PRIME v1.3.6 base nodes at the same time as the newest version of base nodes is being deployed. There are also some gateways that are being developed to guarantee interoperation in every possible scenario.

Some of the suppliers that i-DE is currently relying on are: *Neuron*, *ZIV*, and *Teldat*. Their PRIME v1.4 base nodes are being tested in field trials, and their main characteristics are gathered in *Table 8.* As shown, there is no information regarding the *Teldat* base node. This is because i-DE is now just being supplied but the other two.

Table 8: PRIME v1.4 Base Nodes supplied to i-DE.

Supplier	Model	Type	Field Trials	Channels tested
Neuron	nbox-sg-1.0	Monophasic	> 130 SS	5 and 7
ZIV	4GWCL110200B020	Triphasic	3 SS	5
Teldat	Regesta-Smart-PLC	Monophasic	-	-

2.3. CONCLUSIONS OF CHAPTER 2

This chapter has started with the evolution of Smart Grids and the crucial role the technology involved in them plays in modernizing power distribution systems. One of the main conclusions from this chapter is to become aware of the significant importance of the integration of telecommunications in the power distribution systems. Several examples have been given through this section: smart metering, integration of prosumers and distributed generation, enablement of bi-directional electricity flows… Each one of these applications require telecommunications that allows real-time data acquisition and control, and dynamic grid management.

Additionally, this chapter has focus on the significant role that Iberdrola plays not only in the Spanish but in the European and global energy landscape thanks to its relevant investments that aim for the modernization of their networks worldwide. Within Iberdrola, the STAR project emerged as a notable innovation initiative. The deployment of PRIME 1.3.6 technology and smart meters across the LV grid demonstrated Iberdrola's commitment to improve grid efficiency, quality of service, and consumer connectivity. The STAR project's achievements exemplify Iberdrola's leadership in adopting smart grid solutions. This proved tendency of Iberdrola to explore new solutions has led to other progresses such as FTTH, BPL-MV, optic fibre, private 4G, and PRIME v1.4.

The adoption of innovative solutions as the mentioned along this chapter has shown the possibility for the DNOs to be closer to become a DSO and to act in some fundamental aspects of the grid management such as in the demand response and in the process of flattering the demand curve that provides stability and reliability to the distribution grid.

The next chapter will delve deeper into the state of the art of power line communications, with a specific focus on the role of Broadband Power Line (BPL) technology. It will explore its features, benefits, and applications. After that, there will be a detailed explanation of the elements that are the most relevant in the power distribution system. The combination of these two sections will serve to understand how this Project is necessarily gathering the knowledge about telecommunications and electric engineering to be aware of all the aspects to take into account at the time of the deployment of the technology.

Chapter 3. STATE OF THE ART

The purpose of this chapter is to describe the level of knowledge that already exists regarding the Power Line Communications (PLC) for the power distribution system and specifically about the broadband PLC (BPL).

The previous chapter has already served as a state of the art of the telecommunications regarding the energy distribution companies and of the level of progress in terms of innovation for distribution network operators as Iberdrola. Now, this chapter will focus on the technology behind the telecommunication solution that is being used in this Project to improve the power distribution network.

Before focusing on the technology, a brief section will explain how the telecommunications protocols are defined to clarify the concept of layers and it will serve as an introduction for the chapter. After that, the chapter will explain what are power line communications and the different features that the narrowband and the broadband PLC can provide. After that, the chapter will cover the electrical engineering background that is behind this Project and will give an overview of the electrical equipment that will be involved in this deployment. Then, the chapter will explore the state of the art of the resources that are being used for this Project (Mapinfo and databases).

The last sections will delve deeper into the progress of projects that are similar to this one and that are developed in other countries and within other companies. Here, there will be a benchmark of the types of deployment of BPL over LV as well as the description of concrete field trials that are carried out in Germany and that serve as an example to i-DE's currently plan of BPL-LV deployment.

Eventually, this chapter will serve to understand what the technical context of this project is, and the level of development and acceptation of BPL as the telecommunication solution for the distribution grid in low voltage.

3.1. INTRODUCTION TO TELECOMMUNICATIONS PROTOCOLS.

A protocol allows entities (i.e., programs or applications) that belong to different stations or nodes to communicate. To achieve that, protocols define conventions for communicating information. This means to define syntax (the way the bits are organized), semantics (the meaning of every set of bits), and timing [46]. The protocols that are the reference to set telecommunication models are mainly two: the OSI model and the TCP/IP model. OSI (Open System Interconnection) was developed in 1984 and edited in 1995 to give solution to the disorganized development of telecommunication solutions and it provides an efficient and scalable solution for all the possible interconnections. However, the architecture based on seven layers can be complex. On the other hand, TCP/IP protocol is a variant used for Internet applications that offer a solution that is easier to implement and deploy. However, it is less efficient than the other alternative [47]. The representation of each model's layers and comparison between them has been represented in *Figure 27.*

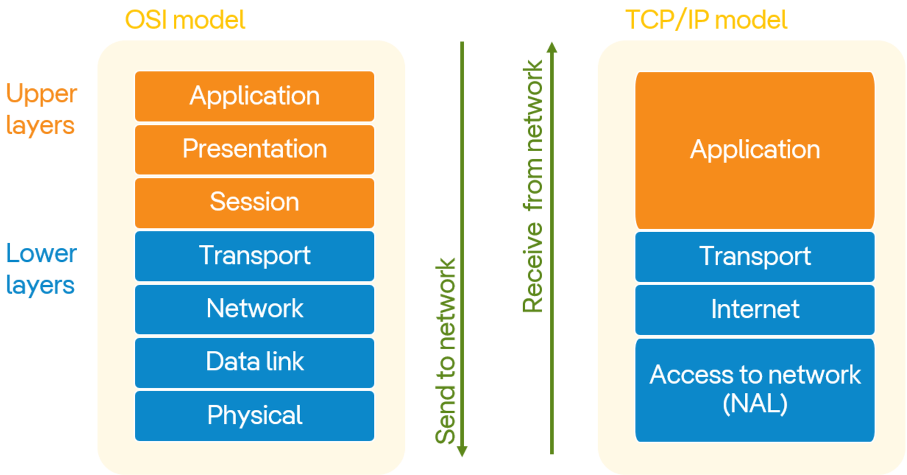


Figure 27: OSI stack. [Own preparation]

As shown, there is a difference between the upper and lower layers. This is because it is said that upper layers use the services of the lower layers. Other difference is that upper layers manage data while the units of data exchange in the subsequent layers are – from the top to the bottom – segments, packets, frame, and bits. The process of transformation from data to bits is called *encapsulation* while the inverse process is called *de-encapsulation.*

Each of these layers is responsible of performing a specific set of tasks. This introduction will briefly define the seven layers of the OSI stack [48] since the next sections will be related to power line communications that use this model for their communication protocols.

- **Physical layer:** it defines the electric and/or the mechanic specifications of the interfaces and it does so by sending *bits*. It is directly related to how data is transmitted through the transmission medium (i.e., cables, electromagnetic waves, optical fibre…). It establishes technical details on how data is encoded, modulated, etc. and also the frequency, bandwidth, and other electrical characteristics that are required for a reliable communication.
- **Data link layer:** it is responsible for the reliable transfer of data between connected nodes in a network by handling data error detection and correction. It defines how data needs to be structured and the way that the *frames* are physically addressed.
- **Network layer:** it provides data routing and switching to ensure efficient delivery of data. To do so, it requires accurate addressing to route data *packets* across different networks by defining a hierarchical addressing.
- **Transport layer:** it defines *segments* that are analysed to detect and correct errors in the transmission to ensure data integrity and it establishes a flow control to ensure reliable and ordered delivery of data.
- **Session layer:** it establishes, manages, and terminates communication sessions between application on different devices. It also provides recovery in case of interruptions and communicates with the other upper layers to give them alternatives to report their problems and other available resources for the communication.
- **Presentation layer:** it ensures that the information transmitted by one node's application layer is clearly understood by other one. To do so, the information sometimes needs to be transformed into a common standard (ASCII – EBCDIC) or it negotiates the syntaxis for the communication between application layers.
- **Application layer:** it is the interface of the interlocutors of the communication. It defines how network services are accessed and synchronizes the applications to establish agreements about the procedures to control the data integrity.

3.2. POWER LINE COMMUNICATIONS (PLC).

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 [49]. 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 [50] when this technology was used to transmit voice messages. This application was almost the unique application 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 reaching 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. The standards that establish the communication protocols and guidelines for PLC depending on the width of the band that are gathered in *Figure 28*. In the case of this Project, the more relevant standards are the related to the high data rate narrowband: PRIME (G.hn 9904), G3-PLC (G.hn 9903), and IEE 1901.2. Besides that, some of the broadband PLC standards will be also explained in the following sections.

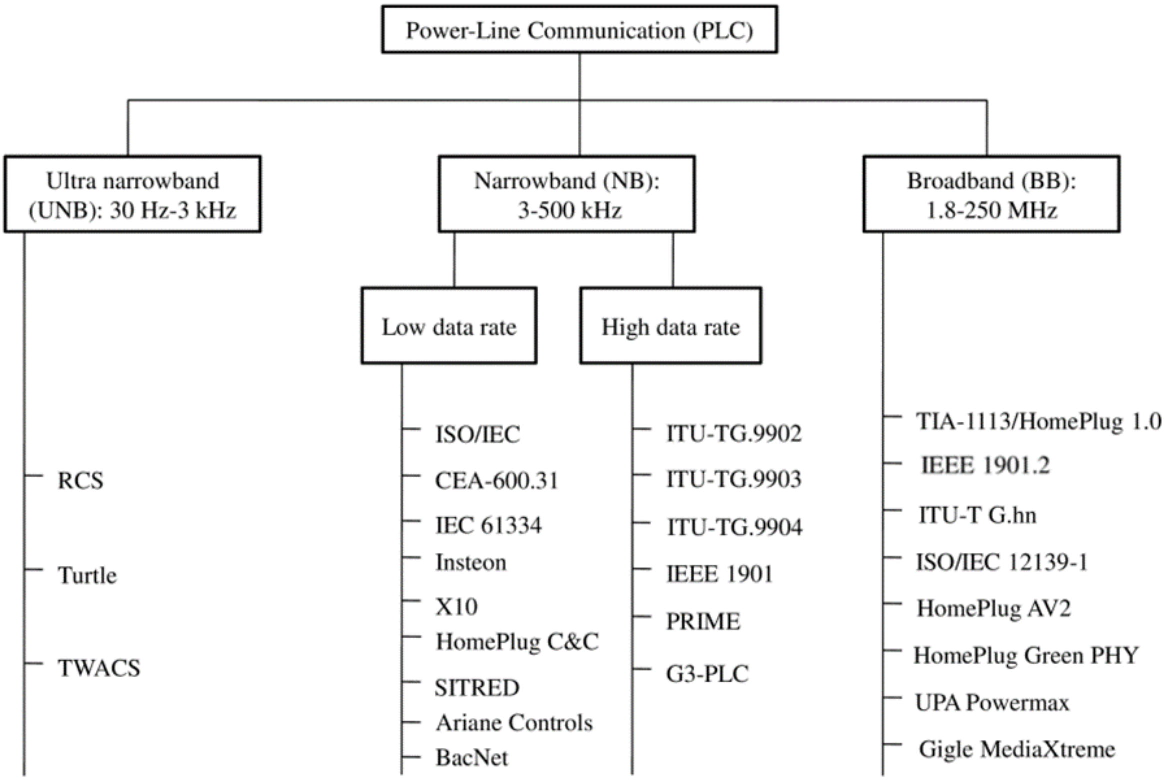


Figure 28: PLC standards. [50]

3.2.1. 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. Also, Orthogonal Frequency Division Multiplexing (see *Annex II – OFDM* [52]) 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** [53]. It proposed 96 OFDM subcarriers with frequencies from 42 kHz to 89 kHz (i.e., within CENELEC A-band as in

Annex III – CENELEC Frequency Band [57]). Lastly, the Institute of Electrical and Electronics Engineers proposed in **IEEE 1901** NB-PLC up to 500 kHz via AC and DC power lines. These three last standards define technologies considered to be of high data rate and are the most relevant for this Project. Therefore, the information regarding these protocols has been gathered for better understanding in *Table 9.*

Table 9: Comparison of NB-PLC standards' features. [50]

	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

Narrowband PLC can be single- or multi-channel. Specifically talking about Iberdrola's technologies, PRIME v1.3.6 is single channel with frequencies between 40 kHz and 89 kHz.

On the other hand, as mentioned in section *2.2.3. New Solutions for Telecommunications,* the new update of NB-PLC (**PRIME v1.4**) offers advanced features as its wider available frequency band and multi-channels. PRIME v1.3.6 (42 – 89 kHz) operates within the CENELEC A (3-95 kHz) frequency band while PRIME v1.4 explores higher frequencies in order to find bands with less noise and interferences. This expansion of the frequency band makes PRIME v1.4 compatible with FCC (10 – 490 kHz in the United States) and ARIB (10 – 450 kHz in Japan and 3 – 500 kHz in China) spectrums as it is suggested for PRIME v1.4 to use the frequencies from 42 to 472 kHz. Besides that, PRIME v1.4 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 possibility to use different channels makes essential to design the configuration of the bands to be used by the different low voltage lines (LVL).

3.2.2. 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.

Each utility will require BPL in order to meet the increasing demands on the grid driven by distributed generation, electric vehicles, and storage. Applications that require high wide bandwidth and intelligence for the needed grid digitalization. These required features together with the regulation rules that mandate detailed, real-time information not only for the distribution companies but for the consumers that are becoming prosumers.

This section will explain some of the differences between BPL used over medium and low voltage although it will be more focused on the low voltage aspect. In the case of LV grid, BPL is typically employed for in-home networking, home automation, and smart metering. The infrastructure in this case is simpler, with operations in the frequency range up to several MHz. On the other hand, BPL-MV uses lower frequencies up to few hundred kHz and it serves larger areas and neighbourhoods. Regarding the attenuation, MV lines faces longer signal propagation paths, leading to potential signal integrity problems and the possibility to introduce signal noise and interference sources. Finally, to sum this information up, the main challenges for BPL over the different voltage levels are: signal quality within homes and potential interference from household devices in the case of BPL-LV and signal attenuation, noise from high-voltage equipment, and reliability in the communication over long distances in the case of BPL-MV.

a. 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 [59]. **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 technology (Universal Powerline Alliance), and owns 25.900 devices supplied by two manufacturers: *Corinex* and *Ormazabal* [49]. This equipment follows the standard **IEEE P1901.2** that establishes that the communication is made at high frequencies (1.8 to 100 MHz) achieving data rates up to 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. Broadband PLC over Low Voltage (BPL-LV).

As it has been already mentioned in section *1.2. Motivation of the Project*, new applications that need a high intensity use of the network cannot be supported with the current distribution grid that uses narrowband PLC. To solve this, low voltage grid can follow the example of medium voltage grid and start using broadband PLC too. This change in the distribution grid may make all these applications accessible. 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 these applications require to optimize their use [56].

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 is similar to its use in MV, but it has some specific features:

- 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 that need to be compensated with the installation of 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**) [51] 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. As explained, G.hn standard developed by the ITU is different from the BPL over MV standard used in Iberdrola that is the IEEE P1901.2 developed by the UPA.

At the same time, IEEE published the standard **IEEE-1901** in 2010 defining the characteristics of BPL [60]: 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 [51]: 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, the 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 also adaptive to other modulations such as frequency shift keying (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, and streaming devices).

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. The description of this solution approved by the Alliance, and the use cases carried out to get conclusions will be detailed in section *3.4. Benchmark of Similar Projects*.

3.3. POWER DISTRIBUTION SYSTEM.

The distribution network is the most challenging part of the energy systems because its vast extension: as mentioned in section *2.2.1. Iberdrola as a Distribution Network Operator*, only Iberdrola owns 1.158 primary substations in Spain. However, this figure reaches to 97.628 secondary substations, illustrating the difference of magnitude between the transmission and the distribution network. This is one of the reasons why the distribution grid is also much more biased to present faults than transmission networks. In fact, more than 90% of end-consumer outages are caused by faults in the distribution networks.

The operation of distribution systems is made in three different voltage levels: high (45, 66, or 132 kV), medium (15 or 20 kV), and low (below 1kV, usually 380V or 400V). Within this voltage levels, the medium voltage distribution grid presents three main topologies as represented in *Figure 29*: radial, ring, and networked. As it has been represented, radial topology is used to connect primary and secondary substations. One single PS can reach several SSs. A variant of the radial topology is the ring topology that allows SSs to be connected to different PSs. This improvement provides reliability to the network as it creates redundancy. In the case of a failure in a PS or the disconnection of a medium voltage line, the grid can be reconfigured, and the SS will be able to find a different power supply. The third of the topologies is the networked that improves that reliability since there are not one buy multiple options available to reroute electricity.

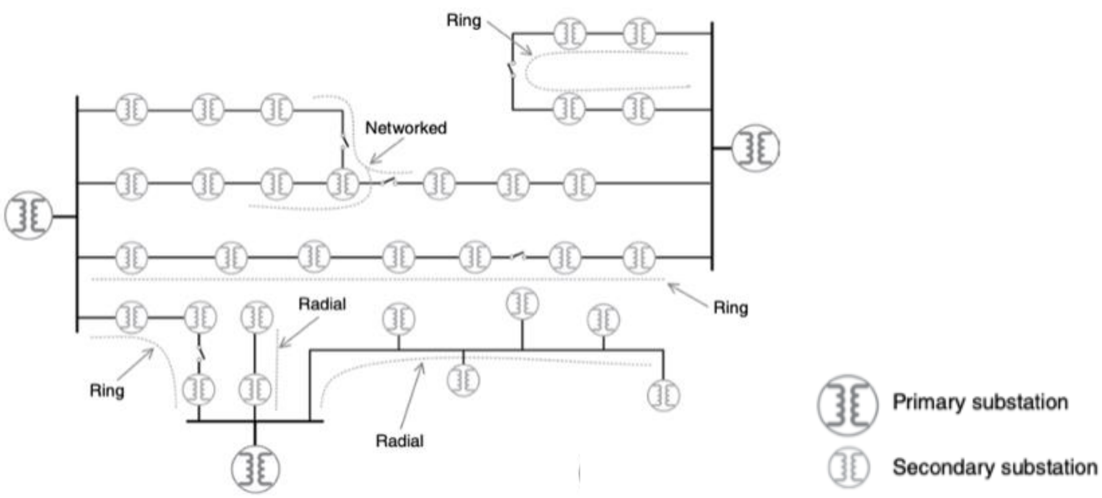


Figure 29: Topologies in the MV distribution grid. [64]

On the other hand, LV networks are much more complicated because of their mentioned magnitude. In the case of Spain, there are roughly 300.000 secondary substations, and each SS may have 6-12 outgoing LV lines (LVL) [65]. LV topology is usually radial where one SS is the starting point of different LVL that may have evolved in a less coordinated manner because of the diverse areas and operational procedures that the utilities that have installed them have followed.

3.3.1. SECONDARY SUBSTATION.

Secondary Substations (SSs) are the premises at the end of MV networks where electricity is transformed to LV. From the SSs, LVLs are deployed to reach the customers, so they are usually located close to the end-users. In Europe, SSs normally supply to an area of some hundred meters. The electrical scheme of a secondary substation has been represented in Figure 30, where the MV feeders coming from the primary substation face the switchgears and sensors before the transformer that converts the voltage into a low level that is suitable for residential, commercial, and small and medium industrial customers.

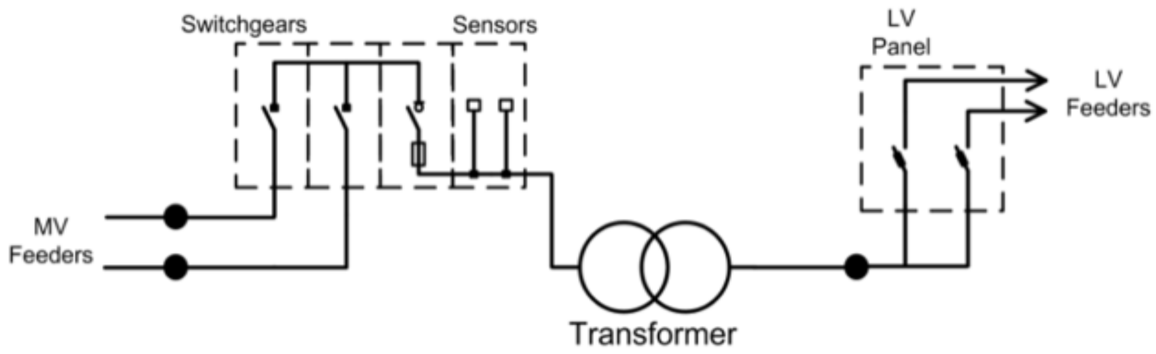


Figure 30: Secondary Substation Electrical Scheme. [66]

The main parts of a SS are the following:

- **MV lines/feeders (MVLs):** outgoing from the primary substation.
- **MV switchboard / panel:** interface between MVLs and the transformer. They serve on two main purposes: protection (connection, disconnection of the transformer) and line interconnection to guarantee continuity and allow for operation of MV feeders. Modern switchgears are insulated using SF6, a gaseous dielectric medium.

- **Transformer:** reduces the voltage level from medium to low.
- **LV switchboard / panel:** it is connected after the transformer and divides the total power that goes out the transformer in a number of LV lines. LV panels have switches, overcurrent, and other protective devices.
- **LV feeders:** power lines that deliver electric energy to customers.

Secondary substations can be located indoors or outdoors. Indoor SSs provide enclosure for the transformer and there are different types of them. The most common indoor locations may be standalone shelters – that can be either overhead or underground depending on the precedence of the MV lines -, compact (also called padmount transformers), underground, and integrated – this last type is the most usual for commercial or residential buildings. Meanwhile, outdoor SSs are more commonly located on a structure or on a pole.

Figure 31: Standalone shelters, padmount transfomer, underground, and integrated SS.

3.3.2. LOW VOLTAGE LINES (LVL).

In Spain, the installation of overhead or underground low voltage lines needs to follow the national regulation that states all the standards that the low voltage cables are required. This information is outlined in the *Reglamento Electrotécnico de Baja Tensión* (REBT).

Concretely, in the ITC BT-06 for the overhead and ITC BT-07 for the underground LV installations. In this section, some of the characteristics of these cables will be outlined. However, for further details or in case of needed calculations, REBT needs to be consulted.

a. Overhead Low Voltage Lines.

As mentioned, the LVLs can be overhead or underground. In the case of overhead lines, they lay on poles that can be made of wood or concrete as the example of *Figure 32*.

Figure 32: Overhead LVLs laid on a pole. [66]

Overhead lines are usually classified according to the conductor although the latest tendency is to use aluminium. However, there are still several copper overhead lines in service. The principal types of cables have been gathered in *Table 10*. These cables that only use aluminium are called homogenous, but there are also cables that combine aluminium with steel as it increases the mechanical properties of the cable: these cables are called heterogenous. Besides that, the cables can be insulated or not. The most common materials for the insulation are polyethylene (PE), cross-linked polyethylene (XLPE), polyvinyl chloride (PVC), and ethylene propylene rubber (EPR). Insulated lines are more robust against damage from vegetation or wildlife, exhibiting improved reliability.

Table 10: Typical components of overhead lines. [68]

	Type of conductor	Insulation
AAC (All Aluminium Conductor)	Homogenous	PE or XLPE
AAAC (All Aluminium Alloy Conductor)	Homogenous	PE or XLPE
ACSR (Aluminium Conductor Steel Reinforced)	Heterogenous	PE or XLPE
ACAR (Aluminium Conductor Alloy Reinforced)	Heterogenous	Bare wired
ACSS (Aluminium Conductor Steel Supported)	Heterogenous	Bare wired
AACSR (Aluminium Alloy Conductor Steel Reinforced)	Heterogenous	Bare wired

b. Underground Low Voltage Lines.

On the other hand, underground lines are safer and report less faults because they are more protected. Statistically, they are more reliable and with lower maintenance cost. As a disadvantage, their installation is more challenging because of the equipment that requires to make the trench, etc. This complex process has been represented in *Figure 33.* Besides that, the cables being underground requires more protection than the overhead lines do. That is the reason why underground cables have as many layers as *Figure 34* shows.

Figure 33: Installation of underground LVLs.

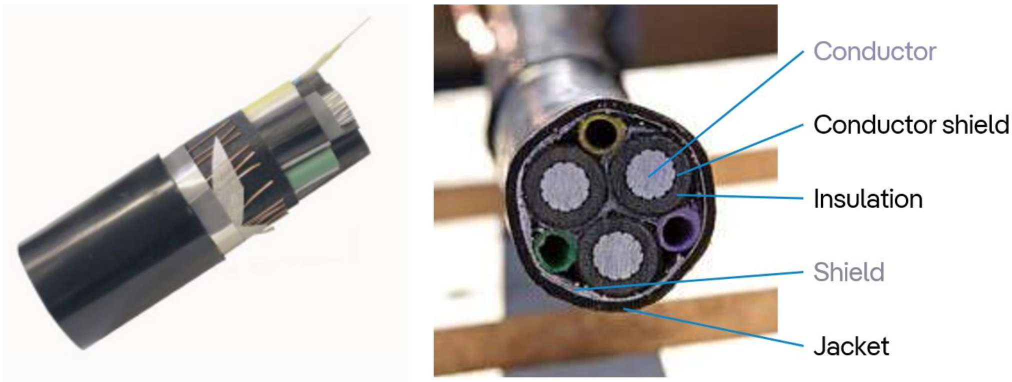


Figure 34: Three core underground cable.

As seen, the main components are the following:

- Conductor: it is actually the element that carries the electricity, and it is usually made of aluminium or copper. They can be solid or stranded: solid conductors have better conductivity and are less expensive while stranded cable as the one in *Figure 34* present improved mechanical flexibility and durability.

- Conductor shield: it surrounds the conductor, and its main function is to create a radial electric field within the insulation. Without this shield, the electric field gradient would concentrate at the interface between the conductor and the insulation, and this increased localised stress could negatively affect the insulation.
- Insulation: it is a non-conductive material that ensures that the electricity that is being carried through the conductor stays confined within the conductors and does not pose a risk to people or surrounding objects. According to the insulation, the underground LV cables can be Paper Insulated, Lead Covered (PILC), or as in the case of overhead lines: PE, XLPE, PVC, or EPR.
- Insulation shield: it surrounds the insulation, and it balances the electric field at the interface between the insulation and the shield, similar to what the conductor shield does.
- Shield: it is the metallic barrier that surrounds the insulation shield. It forms an external structure for the cable and provides it a path for return and fault currents. The shield protects the cable from lightning strikes and from current from other fault sources.
- Jacket: it is the outer cover of the cable and protects all inner elements from mechanical damage, chemicals, moisture, and exposure to harmful environment conditions.

One of the characteristics that influence the type of SS, LVL, and other features of the low voltage configuration is if the distribution network is placed in a high- or a low-density residential area. The differences in these two cases have been summarized in *Table 11.* As an outline: low density areas require less equipment in terms of transformers and LVLs and the area covered by the SS is wider but includes less customers.

Table 11: Main features of European LV networks. [66]

	High density residential area	**Low density residential area**
Type of SS	Underground or integrated	Standalone shelter or pole
Transformers per SS	1 – 4	1
LV customers per SS	150 – 300	5 – 100
LV feeders per SS	4 – 20	1 – 6
Length of LVL (m)	100	300
Type of LVL	Underground	Overhead

c. Splicing and branching.

Due to the mentioned length of the LVLs, there is sometimes the need to make splices to make the cables longer or branch them so one LVL can be the start point for other lines that can reach further locations. This fact is a reason why the LV grid is a radial network, what makes it more difficult to manage and maintain it as well as inventorying its elements.

These elements (splices and branches) have a significant impact on the behaviour of the lines, and it can affect the security of the power distribution system [69]. Some of these effects are the following:

- **Energy loss**: splices and branching introduce additional resistances in the circuit. Splices are usually made through mechanical connectors that use screws and clamps. These elements not only increase the resistance of the line but also if done inadequately they can cause additional resistances and generate heat leading to cable damage and premature failures.
- **Reliability**: splices and branches are used to ensure electric continuity from the LVLs outgoing the secondary substations until they reach to the end-consumers. However, these solutions present a higher risk of lack of reliability because if done poorly they can cause interruptions in the power supply.
- **Safety:** following the previous point, if splices and branches are not done correctly, the conductor may become poorly insulated, and this can be source of electrical accidents caused by short circuits or fires.
- **Maintenance:** these potential risks require splices and branches to have special supervision that may be more complex or costly than the standard supervision of continue LVL.

3.3.3. STREET FUSE BOX (SFB).

Street Fuse Boxes (SFBs) are the enclosure that keeps the protection elements of the supply lines coming from the secondary substation to the consumption point [70]. It is therefore the frontier between the installation that is owned by the distribution company and the customer's own property. The basic structure of a SFB consists of a fuse corresponding to each one of the existing phases – one if monophasic and three if triphasic – and a removable copper connector for the neutral phase that needs to be placed always at the left side of the box. The final decision on which is the scheme of the SFB for each consume is responsibility of the distribution company. To show how a real SFB looks like, *Figure 35* serves as an example of a SFB with a triphasic supply (see the three fuse holders) and the removable copper connection for the neutral.

Figure 35: Triphasic Street Fuse Box.

SFBs need to follow the regulation stated in the Spanish standard UNE-EN 60439-1. Besides that, their degree of flammability needs to comply with standard UNE-EN 60439-3. In Spain, the regulation that prescribes the guidelines that need to be followed regarding the low voltage systems is the *Reglamento Electrotécnico de Baja tension* (REBT) – or "Low Voltage Electrotechnical Regulation" –. The rule that focusses on the definition of the SFB and its characteristics is the ITC BT-13 of the REBT. Also, this rule describes the types of SFBs that are standardized and therefore can be used within the distribution network. These types have been represented in *Annex IV – SFB Standardized Schemes*.

Besides that, Iberdrola has its own internal regulation – *Norma Iberdrola* (NI) 76.50.01 – that states the schemes of SFBs among the listed in the REBT that are the ones that the company uses. These ones used by the company have been gathered in *Figure 36*. As explained in *Annex IV – SFB Standardized Schemes*, among the options that the NI gives for the SFBs of the company: scheme 1 is suitable to monophasic supply and although schemes 7, 9, 10 and 11 correspond to triphasic supply, the most common among them are 7 and 9. Furthermore, scheme 1 can be used outdoors and so can scheme 7. As seen, depending on the final location of the SFB, one or another scheme can be more appropriate.

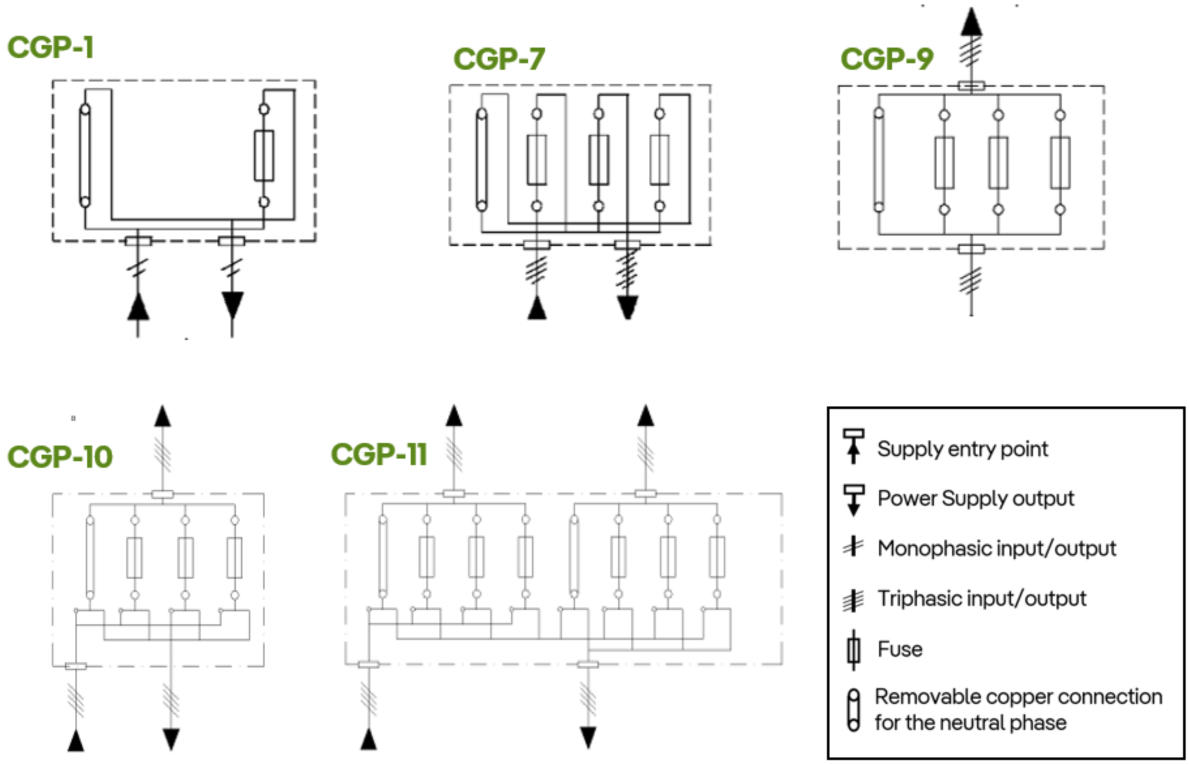


Figure 36: Standardised SFB used by i-DE. [Own preparation]

3.3.4. PROTECTION AND METERING BOX (PMB).

In the cases of private houses where there is one or two end users, the protection (corresponding to the SFB) and the metering are simplified and only one element is used: the protection and metering box. PMB follow their own standards that in the case of the Spanish regulation can be checked in the ITC BT-13 of the REBT. Some of the differences between SFB and PMB is that PMB are required to be installed at a height of 0.7 to 1.8 m. As well as in the case of the SFB, PBMs need to follow the regulation stated in the Spanish standard UNE-EN 60439-1, and their degree of flammability needs to comply with standard UNE-EN 60439-3. Besides that, the enclosure is required to provide the necessary internal ventilation that ensures that there is no condensation inside. Lastly, the enclosure needs to include a transparent window to allows the reading of meter as shown in *Figure 37.*

Figure 37: PMB showing the protection of three phases and the meter.

3.3.5. BONDING INSTALLATIONS.

Bonding installations are those that connect the SFB and the installation of the end-customer. The principal schemes of bonding installations that are standardized in the ITC BT-12 of the REBT have been summarized and gathered in *Figure 38.*

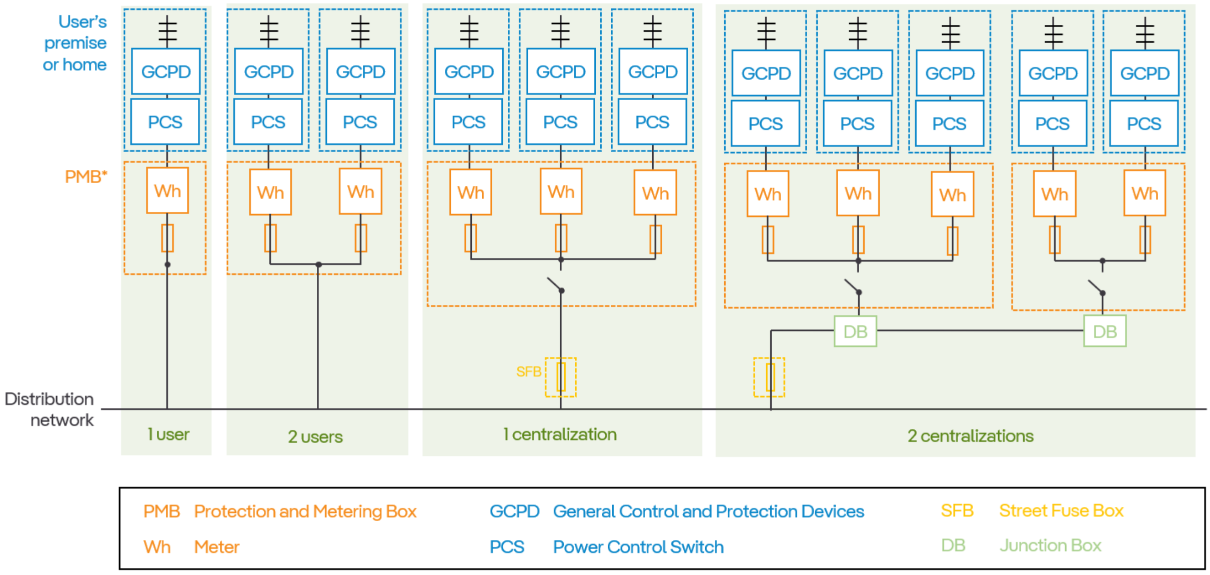


Figure 38: Summary of the types of bonding installations. [Own preparation]

Note that in *Figure 38*, the element "Protection and Metering Box (PMB)" has a sign (*). This is because when there is not a centralization, but each user is directly connected to the distribution network, the SFB and the metering box are allocated together and so is called PMB. When there is a centralization, SFB and metering box are separated.

Some of the elements that are represented but that have been not yet mentioned in this document are defined below and represented in *Figure 39* for better understanding:

- **Power Control Switch** (PCS) is a device that controls that the customer does not demand more power that the contracted. It supports a maximum current of 63 A.
- **General Control and Protection Devices** (GCPD) include the **main circuit breaker** that protects the home/premise from overloads or short circuits by automatically cutting off the current when there is a large increase of circulating intensity; the **residual current circuit breaker** that protects the users against accidental contact with live metallic equipment that may be due to a current leakage in the installation; and the **miniature circuit breakers** that are magneto-thermal CB that protect each of the individual circuits of the premise/home against overloads and/or short circuits.

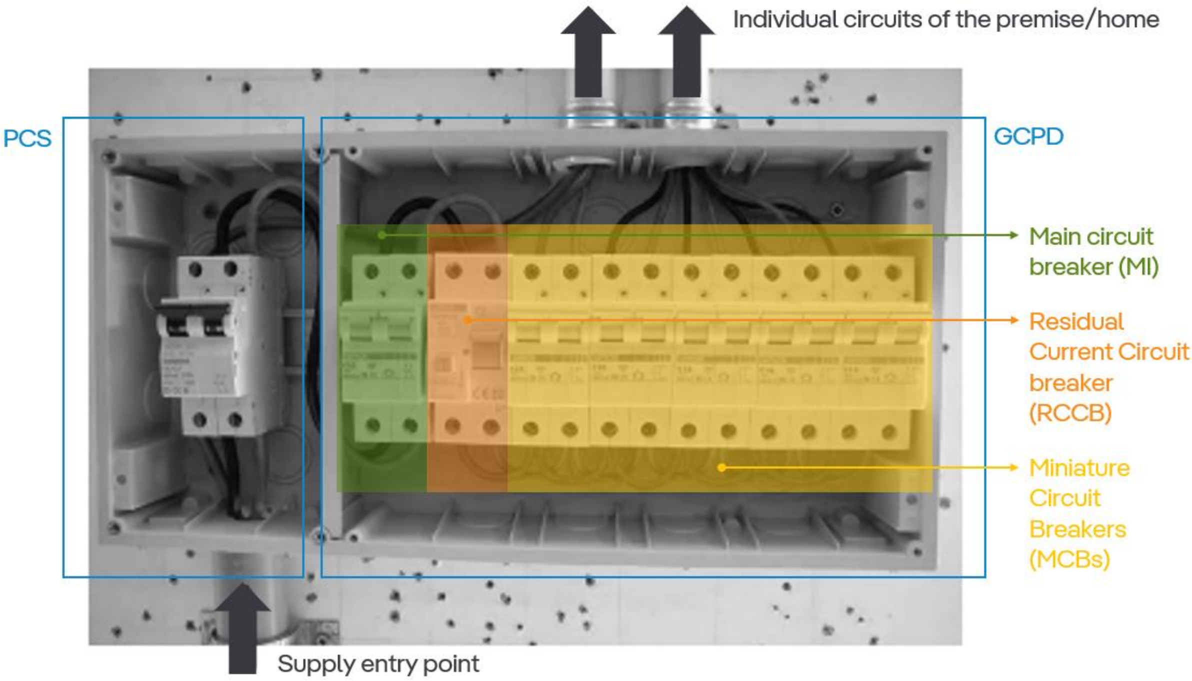


Figure 39: PCS and GCPD elements. [Own preparation]

3.4. GEOGRAPHICAL INFORMATION SYSTEMS (GIS).

The EU Directive 2019/944 (June 2019) set the framework and objectives to modernize the distribution grid in the European Union. It required grid updates to allow the integration of decentralized generation and the implementation of smart metering, demand response systems, and integration of DG. After that, the *EU Action Plan on Digitalizing the Energy System* (October 2022) aimed to facilitate the integration of renewable resources into the distribution grid. This process involved the creation of a "digital twin" of the electric grid, and this required the digitalization of that grid. This "digital twin" can be produced through a Geographical Information System and indeed it is used for that purpose in Iberdrola.

A Geographical Information System [71] is a computer-based tool for gathering, managing, analysing, and visualizing spatial data. Software based on GIS can be used for several applications [72] such as urban planning (analysing land use, transportation networks, and infrastructure), environmental management (management of natural resources), agriculture (soils analysis and planning of agricultural activities), culturaDel heritage (mapping of archaeological sites and managing of historical records), etc.

However, this tool is also relevant for this Project since GIS is widely used by energy distribution companies and has been proved to increase the efficiency of the company. By developing a model of their assets in the field and the possibility to query detailed information about them, the company is allowed to cost-effectively find insights about their investments and risks, reduce the time to obtain accurate information about the assets, and make 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.

In the case of Iberdrola, the specific GIS that it is used within the company is *MapInfo Professional 12.0* in which a tool defined as SICOID – *Sistema de Información de Comunicaciones de Iberdrola* or "Telecommunications Information System of Iberdrola" – has been developed to collect and graphically represent all the telecommunications assets that the company has in field. This software shows the Spanish geographical area that is owned by Iberdrola as a distribution company and permits the selection of the type of telecommunications that needs to be overviewed. As illustrated in *Figure 40*, some of the telecommunication's solutions – *Equipos de Transmisión* – that can be checked are: SDH, DWDM, MPLDS, etc. as well as optic fibre – *Fibra Óptica* – and radio. Besides that, SICOID is combined with SIGRID, so the map not only allows to overview telecommunications networks but also electrical networks. Especially relevant for this Project is the overview of the LV grid in terms of electrical and telecommunication networks.

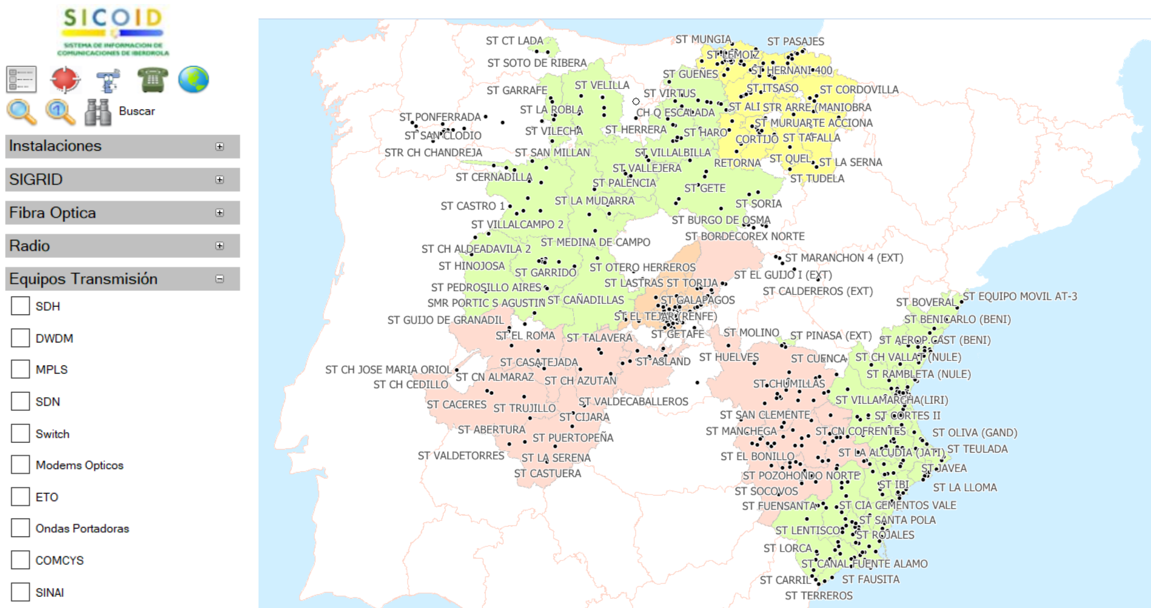


Figure 40: Sample of the welcome site of SICOID.

The capability of GIS to make these representations of infrastructures require the previous creation of a database that gathers all the data that needs to be represented. In the case of a distribution network, it is essential that each element of the grid is registered in a digital inventory that not only gathers the data about the equipment itself but also about their connections, composition, elements, etc. The information that is collected by the distribution company is almost infinite and the main function of a GIS is transform that huge amount of data and alphanumeric information into graphical information.

In the case of Iberdrola, the master database was firstly created for GENESIS (Geographical Network SYStem) which was a first GIS for the company that collected and represented the information about the electrical grid without the telecommunications. This original database is the same for SICOID and it can be queried to obtain all the knowledge regarding Iberdrola's inventory in the field. Apart from this data, a working group has succeeded at obtaining some additional information that is not yet registered in the alphanumeric but that has allowed to get even more data than before. Gathering the information from both sources (the original database and the additional data obtained in SICOID through graphical computing done by a specific working group) the overall knowledge that nowadays is available [2] for the deployment required in this Project is summarized in *Table 12*.

Table 12: 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			

Additionally, the guidelines that explain how this information can be queried in order to characterise the low voltage grid for this telecommunication deployment has been officially developed for this Project so anyone can replicate the database that has been used. These guidelines have been attached in *Annex V – LV Network Characterisation*. As mentioned before, the low voltage grid is more complex because of its dimension. Besides that, its digitalization and graphic representation is also more problematic due to the defined spliced and the overlapping of the LVL. These facts make difficult to achieve the same level of graphic accuracy as the accomplished for medium voltage grid.

[2] Since the information gathered in the databases of Iberdrola is confidential, this document will not show graphic examples that clarifies the usefulness of the GIS for the company. Instead of this, Table 12: Parameters for the LV network characterisation.*Table 12* gives an overview of the information with which the company can characterise the LV grid and shows the data that may be valuable for this Project. This knowledge together with the graphical information makes the company able to make informed and convenient decisions.

3.5. BENCHMARK OF SIMILAR PROJECTS.

As mentioned in section *3.1.2. Broadband PLC (BPL)*, the PRIME Alliance standardized a BPL protocol that allows the interoperation of the existing NB-PLC and other telecommunication solutions (i.e., Internet IP v.6). In order to set performance requirements, some Field Trials have been carried out. This section will briefly explain four use cases with different scenarios where BPL is used together with other telecommunication solutions. After that, this section will focus on one of the Field Trials that is the most relevant for Iberdrola and serves an example for the Spanish company. The results from this example will serve to set KPIs for the deployment of this Project.

3.5.1. USE CASES OF BPL DEPLOYMENT.

The selected supplier 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* [73]. As seen, the countries that are currently more involved with this transition from NB-PLC to BPL is Germany together with Spain that will later be able to 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 [74]:

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 (narrowband PLC) base nodes for smart metering. More details about this use case will be given in *Chapter 4. Description of the Model*.
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:** as seen in section *2.2.3. New Solutions for Telecommunications*, this is an alternative already used by Iberdrola as an alternative 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.

3.5.2. 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 [75] 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 [74]. The company plans to keep expanding their BPL infrastructure in the near future based on the standard ITU-T G.hn.

a. New features achieved by E.ON.

The BPL solution of Corinex gives improved features as in *Table 13*, where it is proved that this solution provides superior and cost-effective connection over competing technologies.

Table 13: Comparison of telecommunication solutions. [76]

		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

One advantage of BPL is the level of integration of PLC technologies like NB-PLC as *Figure 41* shows. This is a benefit because this means that the utilities have already standardized their telecommunications based on PLC so this BPL solution that is compatible with those, will make able to replace the previous technology with the new BPL devices.

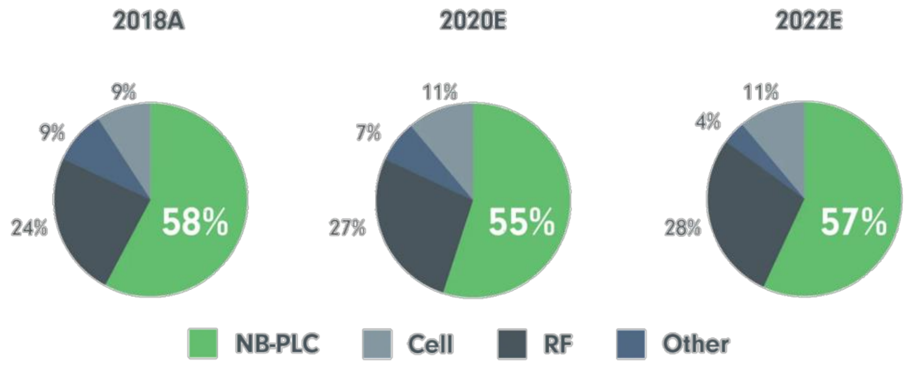


Figure 41: NB-PLC as the preferred technology for global markets.

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

The new approach of Corinex for power line communications intends to gather 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 – into one [73]. These solutions are currently 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 specifically oriented for digitalized smart grids applications.

In Germany, this solution is based on the elements [77] that are represented in *Figure 42*:

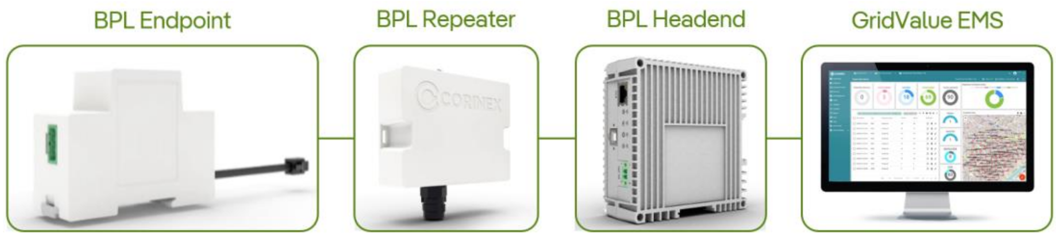


Figure 42: Smart Grid solution of Corinex. [Own preparation]

- **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 [78].

3.5.3. BENCHMARK OF SOFTWARE FOR THE DEPLOYMENT.

One of the objectives of this Project is to make able for working teams that are in charge of the deployment of BPL over LV grid that they can check how to carry out this deployment through the GIS (*MapInfo* in this case). The idea is that once the selection of the low voltage lines that are going to be injected with BPL – following the criteria that will be described in *Chapter 4. Description of the Model* – the working teams can select each SS in the GIS and overview the particular BPL deployment for the LV lines of that SS. According to some requirements that will be developed within this Project, the *software* will enable the possibility to consult the deployment plan for each SS, and it will give all the information from that SS and their LV lines, the SFB that will be within the BPL network, etc. Comparing this desired feature with the ones that the companies that already have started the deployment of this solution, the reality is that none of them have such characteristics integrated in their GIS. Following the example of E.ON, which is the company that Iberdrola looks up, and the one that is sharing their evolution regarding the deployment of BPL over LV: they do not use any tool but follow some design rules to plan where they can cover with BPL networks and where they cannot.

Currently, the planning of the BPL over LV deployment is done remotely, and it is an experimental process: once the working team has decided what are the SS and concrete LVL that they are injecting with BPL, they just carry out a field trial and check if the deployment is actually successful as they expected or not. In other words, this is totally an empiric method. Once it appears to be that the connection and communications are really working, the working team follows up the situation during a week checking if those communications are still working through the time. If not, they try to understand the reasons for it to fail and make the accurate changes so they can make it function. Some of these changes that may enable the telecommunication solution to finally work is changing the LVL to inject, inject more LVLs than the expected, deploy more repeaters, etc. Therefore, this means that this process is hardly scalable but needs a detailed study of each of the cases. However, of course there are common rules that can be followed and that are likely to offer a good communication network.

In terms of deployment of telecommunications over the electric grid, the only applicable example of tool that is already developed and commonly used are the planification software for radio network deployment. As this is the unique benchmark that can be carried out in terms of tools designed for a telecommunication network deployment, the gathered information has been summarized in *Table 14.*

Table 14: Tools for radio networks deployment. [80]

Features	Examples of software	Description
Network Planning Software	Atoll, iBwave, Ranplan, Mentum Planet	Simulation of network coverage and performance based the topography, antenna location, and user density.
GIS	ArcGIS, QGIS, Google Earth	Information about base station and antenna locations.
Signal Propagation Tools	SPLAT!, Radio Mobile	Computation of propagation considering parameters for coverage that estimates the signal levels in different areas, aiding base station placement.
Interference Modeling	Interference Advisor, Cognosos	Prediction and mitigation of potential interferences between cells and nearby devices.
Traffic and Capacity Analysis	ns-3, OPNET	Simulation of network traffic and assess capacity to handle user demands across different areas.

On the other hand, as stated, a direct benchmark about tools for BPL over LV cannot be drawn due to the lack of similar developed project. The reason why there are developed tools for radio lays on the nature of the transmission medium of radio networks in which the communication uses electromagnetic waves. This fact offers advantages such **as propagation predictability**, (due to the relatively uniform signal propagation in air, it is easier to develop models and coverage simulations), **minimal interference sources** (radio communication avoids several PLC noises, harmonics, and reflections as well as coupling and coupling loss in LV networks), **centralized infrastructure** (radio communication rely on dedicated base stations and the planning of these base stations locations facilitate the rest of the communication planning), and **clearer signal metrics** (for coverage analysis of radio networks, simple indicators as received signal strength indicator – RSSI – or signal-to-noise ratio – SNR – are sufficient while BPL needs more sophisticated metrics).

This mentioned predictability and knowledge of how the radio communication is propagated makes possible for radio networks deployment tools to offer attenuation maps that simulates the communication as the shown in *Figure 43*. This technology and the possibility to simulate the behaviour of the network before actually deploying it has positive impact on the quality of the communication and provides improvement in the performance and reliability of the radio network.

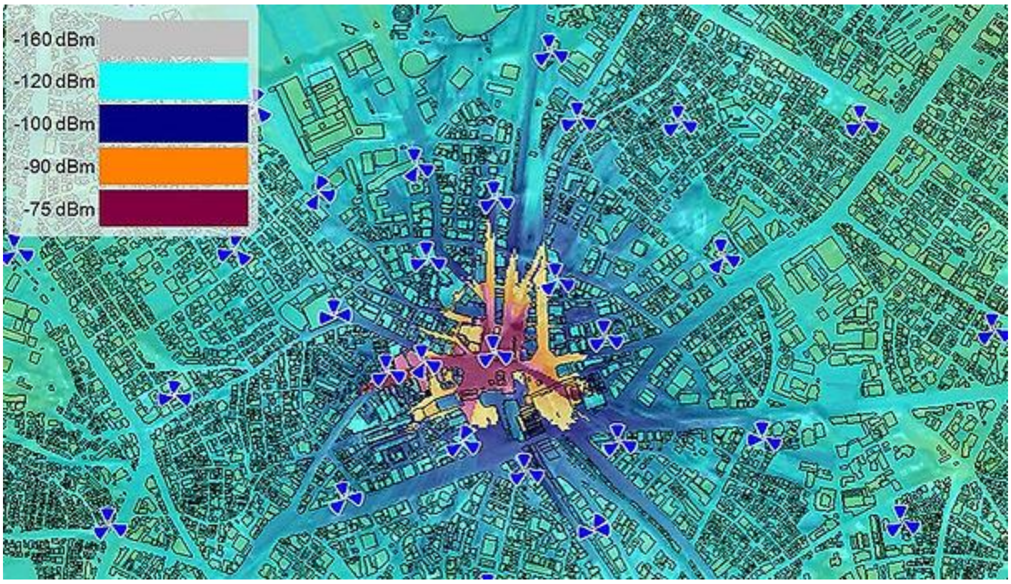


Figure 43: Example of signal attenuation for radio networks. [81]

Despite this, it is possible to learn from the approaches of the existing tools for radio networks to inspire the development of a solution that is suitable for the automated planning and deployment of BPL-LV. Some of the features that the radio deployment tools have and that can be adapted to develop the BPL-LV deployment tool are gathered in *Table 15*.

Table 15: Radio network deployment features applied for BPL-LV deployment. [82]

	Radio deployment tool	BPL-LV deployment tool
Site placement	Identify optimal **base station locations** based on geographic data.	Identify suitable **locations for LV distribution nodes**/equipment considering accessibility and signal loss.
Coverage analysis	Simulate signal propagation **to assess coverage areas** and dead zones.	**Simulate PLC coverage and signal quality** for LV distribution to ensure effective communication coverage.
Capacity planning	**Model network capacity** based on user density, data demands, and bandwidth.	**Estimate data demand** and communication needs of connected devices and appliances for LV networks.
Interference analysis	Analyse **potential interference sources** to mitigate signal degradation.	Identify **sources of noise** along power lines to ensure quality PLC communication in LV networks.
Propagation modelling	Estimate **signal attenuation** using radio wave propagation models.	Develop **PLC-specific propagation models** to predict signal behaviour along power lines in LV networks.
Resource management	Optimize **antenna orientation**, transmit power, and **frequency allocation**.	Optimize parameters **like signal modulation, data rates, and power levels** for reliable LV communication.
Visualization and reporting	Visualization of **coverage maps**, signal strength, and network performance.	Show **LV coverage area, link quality**, and network performance.

These described features will be needed to be provide from the future specific tools for the deployment of BPL-LV. However, this Project has more basic requirements and will not develop so many features but more essential ones that will be described in *Chapter 4. Description of the Model*.

3.6. CONCLUSIONS OF CHAPTER 3.

This chapter has described the potential of Power Line Communications (PLC) and, more specifically, the broadband PLC (BPL) technology that holds the promise of revolutionizing power distribution systems. The description of the state of the art of this technology has covered various dimensions and delved into its integration within the power distribution grid.

Firstly, it has been necessary to understand telecommunications protocols through an introduction to the OSI model. This conceptual framework has provided a basis for understanding how data is transmitted across networks and how the distinct layers contribute to seamless communication. Having acquired this knowledge, it has been easier to introduce the next section that included telecommunication expertise.

The next section was focused on PLC and the diverse protocols used in both narrowband and broadband PLC. These protocols do not only make easier data transmission but also enable several applications. The importance of describing these protocols relies on how they enable the connection between the energy and the information worlds, therefore enabling utility companies to optimize their operations and customer service.

After that, the description of the different electric equipment that belongs to the LV grid are given to understand the electrical constraints that the telecommunications system deployment may face. Each of the mentioned elements play a crucial role in the successful integration of BPL technology. Besides that, other essential resource for this deployment is the Geographical Information Systems (GIS) that empowers energy distribution systems with the capability to visualize, analyse, and plan their infrastructure. The synergy between GIS and BPL assists in identifying deployment areas and also in optimizing the positioning of equipment for maximum coverage and efficiency.

Finally, the benchmark of similar projects has led to the understanding of the E.ON's approach and how the conclusions drawn in its field trials can help i-DE to acquire knowledge that is adapted and implemented to its grid to achieve a deployment plan that is eventually more efficient than other that are already underway.

Chapter 4. DESCRIPTION OF THE MODEL

The introduction of this new telecommunication solution over the low voltage grid has the main aim of achieving the real-time data collection so the end-user can manage and have information of their energy consumption with a waiting time of less than 1 minute [83]. By deploying a network of broadband PLC, the data collection from the smart meters in real-time will be possible. To complete this desired scenario, it is required to make changes in the low voltage grid topology that may affect the configuration and structure of the elements that have been presented in section *3.3. Power Distribution System*: secondary substations that may include new base nodes for telecommunications, low voltage lines that may be injected with BPL, street fuse boxes that may incorporate additional elements as repeaters, etc. This chapter will explain in detail the changes that are required. After that, the experience and knowledge acquired from the field trials will be summarized to show how were they carried out and what are the constraints that have showed up during this process. The goal of this analysis of the field trials is to obtain conclusions from this experience that can be used for the developing of the specification that is the result of this Project. After the deployment of the BPL-LV network is already explained and defined, the last section of this chapter will go deeper into the configuration of the PRIME v1.4. network: differences between this and the previous version of NB-PLC and how these new features make possible the planning of the channels that can be used to optimize the narrowband communication.

4.1. DESCRIPTION OF THE PROPOSED LV GRID TOPOLOGY.

Currently, BPL is used in medium voltage for 25.900 secondary substations' main communication. Now, the goal is to expand this technology in the low voltage grid. The innovation Project of i-DE regarding the deployment of BPL consists of a combination of telecommunications technologies: BPL in low voltage to communicate the secondary substations (SS) to the house connection boxes (HCB), and PRIME v1.4 solution to communicate these HCB to the Smart Meters (SM). This coexistence of narrowband and broadband PLC is feasible thanks different frequency ranges used by the technologies that are much higher for BPL solution than for NB-PLC as explained in section *3.2. Power Line Communications (PLC)*.

There are two main goals that are pursued by this change of topology that suggests this Project: first one is to bring the broadband PLC network closer to the SMs. Before, the BPL network just reached the SS, but this new approach of LV grid wants this technology to reach the end-users: until the SFB or the SM centralizations [3]. 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 networks that gathers hundreds of SMs to smaller and more efficient ones that include dozens of SMs. To a better understanding of this desired change of topology, *Figure 44* and *Figure 45* shows the "before and then" of the LV grid configuration that is aimed by this Project. The same infographic has been attached as *Annex VI – LV Grid Topology Transformation*. This document was a requirement of one of the responsible of the working team who oversees the BPL-LV deployment. The main constraint for the creation of this infographic was to include realistic images of the actual equipment being used in the field trials so the scheme is as precise as possible and represents the status of the new LV grid created for this field trials. Also, the scheme needed to be as simple as possible while keeping the technical accuracy.

As seen in *Figure 44*, the common topology now 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 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

[3] To review the difference of the bonding installations depending on the number of users or type of building to know when there is directly a SFB after the SS or when there is a centralization of SMs, *Figure 38* illustrates different scenarios and can serve as a reference to understand the different case studies.

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.

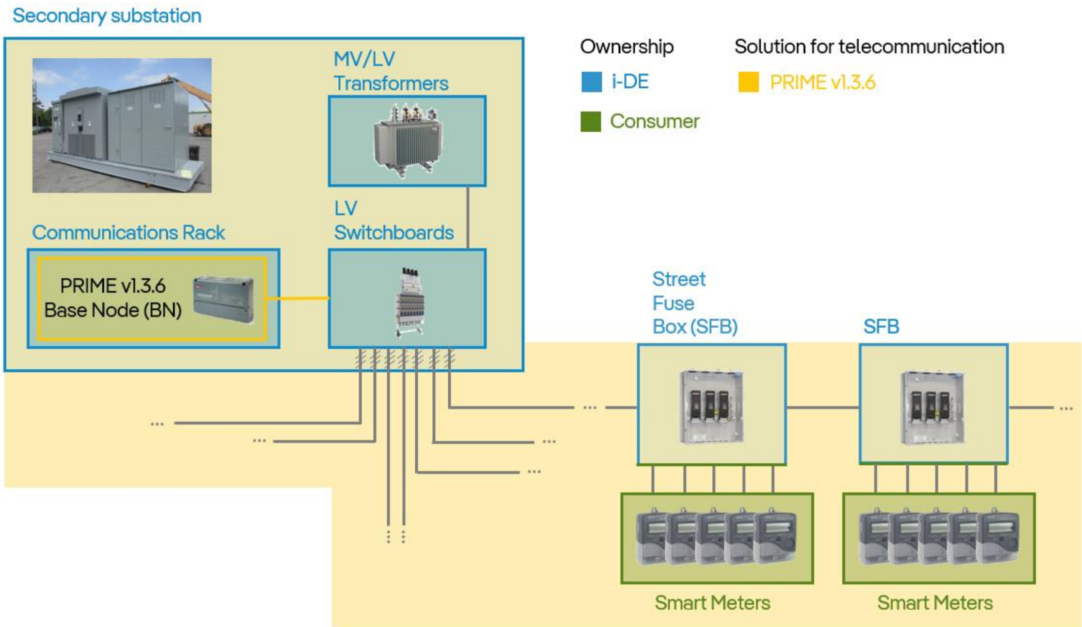


Figure 44: LV architecture before: PRIME v1.3.6 network. [Own preparation]

In the new paradigm of low voltage grid, there is a combination of PRIME v1.4 – that is an evolution of the previous version as explained in section *2.2.3. New Solutions for Telecommunications* – 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 as well as a PRIME v1.4 base node to communicate – using DLMS through PRIME as 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 45*. The main difference between these two PRIME v1.4 base nodes is that the supplied by ZIV is triphasic while the other is monophasic. 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 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 also provides the reduction of latency that is the aim of this deployment.

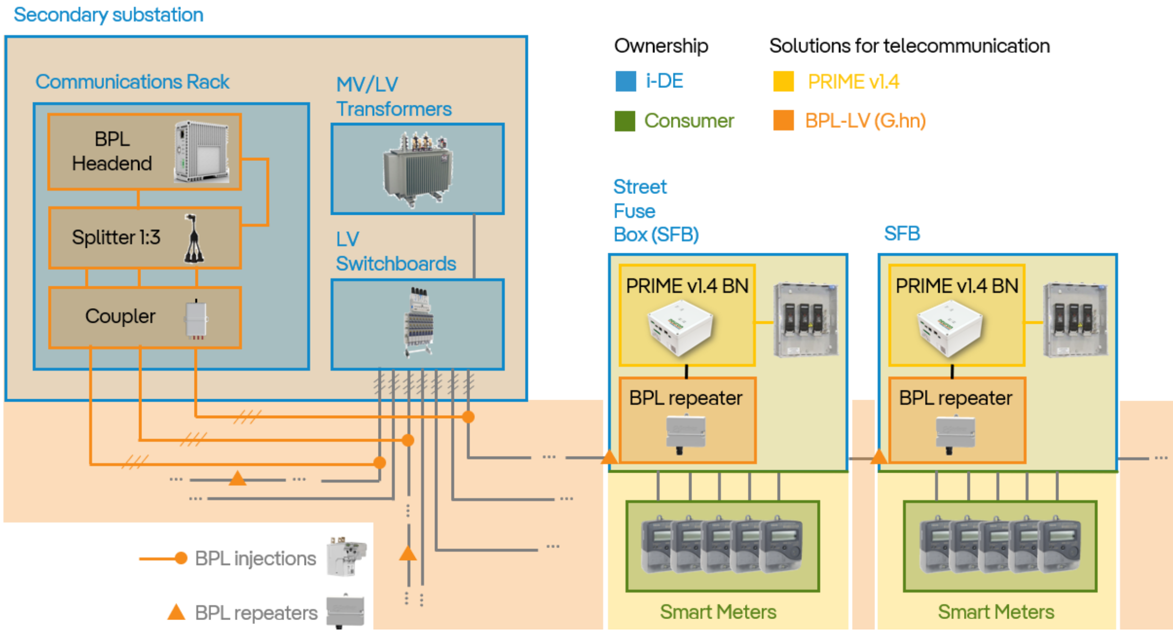


Figure 45: LV architecture after: PRIME v1.4 and BPL networks. [Own preparation]

For a better understanding of the main differences involved in the transformation of previous LV grid topology to the new one, *Table 16* summarizes them.

Table 16: Solutions for telecommunications: before vs. then. [Own preparation]

	Traditional (*Figure 44*)		Suggested (*Figure 45*)	
	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

The objective with this new topology is to **communicate through BPL those SFBs where there are at least 5 smart meters**. To do so, the BPL master equipment – represented as BPL Headend in *Figure 45* – is installed in the SS and it is fed at 24 – 48 V_{DC}. The USB-B port of the headend is connected to a splitter that can have 2 (splitter 1:2) or 3 (splitter 1:3) outputs depending on the number of injections that are needed in the low voltage lines of that SS. The outputs of the splitters are connected to couplers, that have likewise other 3 outputs that serve as 3 cables to inject the selected LVL with BPL. These injections can be done through two methods [84] that have been represented in *Figure 46*: using the AMI sensor or with a *Niled*. The second option is used if the first option is not possible and when the SS is not floodable. When the first 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. The three cables coming out of the coupler are connected with *Nileds* or with the AMI sensor to the three phases and of the LVLs.

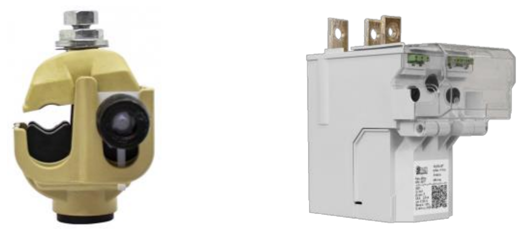


Figure 46: Alternatives for BPL injection: Niled (left) and AMI sensor (right).

Although there are currently criteria to choose the type of injection, this selection is leading to problems between the diverse working teams involved in the Project. The main discussion is between the "Standardization of Secondary Substations" and the "Telecommunications" departments. The first one favors the *Niled* solution because it avoids changes in the SFB structure and the installation of new base nodes and repeaters in the SFB may led to difficulties in standardizing. On the other hand, the *Niled* has the disadvantage of the deterioration of the LVLs' isolation that becomes perforated, and the insulation gets affected. Furthermore, removing the *Niled*, requires isolating it again by for instance vulcanizing it.

Regarding the BPL repeaters, they are installed in the target SFBs if there is enough space, in the overhead lines, or in the SM centralizations when there are more than 5 SM. Also, in the cases where the target number of SM is not reached but the target SFB. The injection of the BPL repeaters to the rest of LVL is also done with *Nileds* or AMI sensors following the same criteria as before. The presence of BPL repeaters produces a decrease of transmission losses with respect to the cases where there is no repeater in the SFB.

4.2. DESCRIPTION OF THE FIELD TRIALS.

The field trials started with the deployment of BPL-LV in 25 different secondary substations: 3 in San Agustín de Guadalix (Madrid), 3 in Rafelbunyol (Valencia), and 19 in Zalla (Biscay). This way, conclusions from different regions – centre, northern east, and north respectively – can be drawn. This may be relevant for the deductions as each region is characterised by different LV grids as explained in section 2.2.1. Iberdrola as a DNO. For instance, LV grid in the East and Centre regions present a high number of smart meters per unit area. On the other hand, the North region is much less filled. These 25 SS corresponding to the phase 0 of the deployment plan will involve 374 target SFBs. After that, 4.788 SFBs will be included in the six following phases. The prevision for this deployment plan is to reach the total of 349 SS and 4.723 SFB by the end of 2024. The description of these phases and the expected number of injected SS are summarized in Table 17. As shown, additionally to the first 3 cities, another 37 cities will be sequentially included in further phases.

Table 17: Phases of the BPL-LV deployment. [83]

		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**

4.2.1. SELECTION OF THE TARGET SECONDARY SUBSTATIONS.

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 17*, was developed in a previous Master's Thesis carried out by J. Berzal Hernández with the title of *"Broadband PLC Deployment in the Low Voltage Grid"* (Universidad Pontificia de Comillas, Madrid. August 2022). The selection process in this Project follows the scheme in *Figure 47*. The parameters that have been determinant for the selection of the SS will be described in this section.

Figure 47: Procedure for target SS selection. [51]

For the first step that consists of the selection of the set of SS that may be eligible for the field trials, the following sequence of decisions shown in *Figure 48* 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.

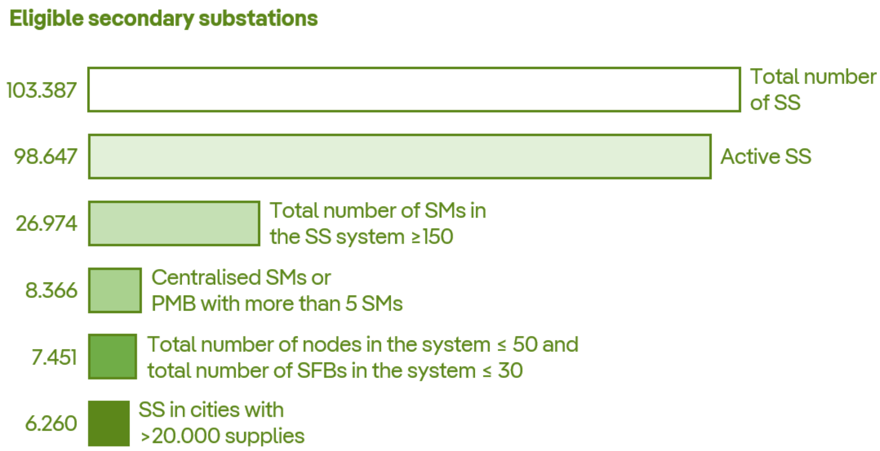


Figure 48: Criteria to select the eligible SS for the field trials. [Own preparation]

As explained in *Figure 47*, 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.

4.2.2. VERIFICATION OF THE BPL-LV DEPLOYMENT PERFORMANCE.

As mentioned in section *3.5. Benchmark of Similar Projects,* the process of deployment needs a detailed supervision of each of the injected secondary substation. 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. This section will explain what these parameters are.

a. Source: *GridValue.*

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 possible 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. However, there are already features that can be measured and visualized through this program that looks as in *Figure 49*.

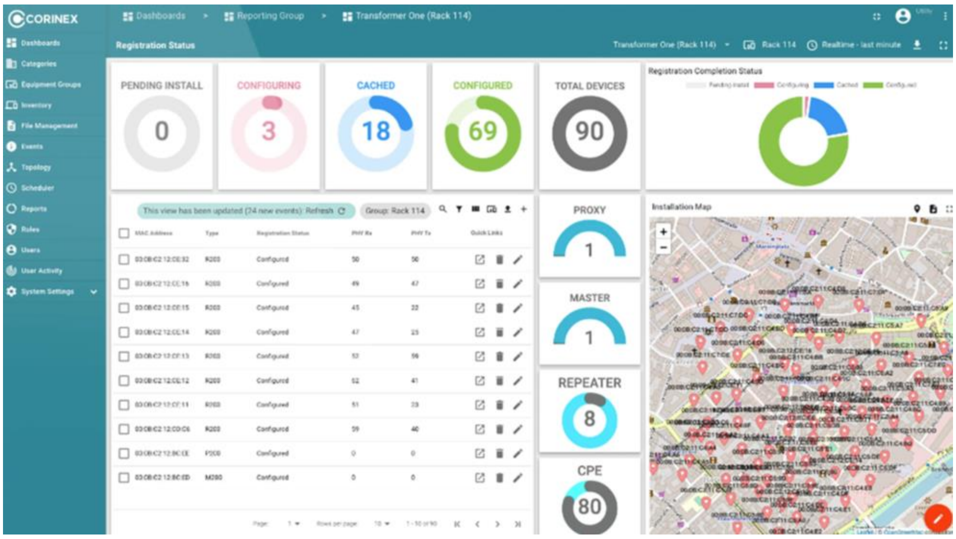


Figure 49: Screenshot of the GridValue software. [78]

Data representation in dashboards makes easier for the audience to interpret the energy data that is collected. This is feasible because of the integration of *GridValue* with the GIS, resulting maps as the shown in *Figure 49* 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 following:

- **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. This parameter measured in *GridValue* indicates the percentage of time that the telecommunication network is functional and transmitting data without interruptions. 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 over the telecommunications systems. These speeds are measured in bits per second (bps) and usually reaches the magnitude of Mbps. These parameters assess the efficiency and performance of the data communication infrastructure and help to identify bottlenecks and points 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.

The analysis that is carried out in this software to analysis the performance of the telecommunication system in the power distribution system allows the download of the following data, whose relevance will be explained below.

- **Code of the SS** to unequivocally identify them.
- **Name of the SS** that is commonly used within the working teams.
- **WAN communication** that determines the telecommunications of the SS with its MV grid. As explained in previous section, this parameter is relevant since target SS are preferable not to have BPL over their MV grid to avoid interferences with the potential deployment of BPL over LV grid.
- **Initial number of repeaters**: since the explained criterion is that those SFB with more than 5 SMs will include a BPL repeater, there is a count that specifies the number of initial repeaters that will be needed for this deployment per each SS.
- **Deployed repeaters**: it is a count of the repeaters that are already deployed per each SS.
- **Pending number of repeaters**: starting from the initial number of repeaters that may be required, the pending repeaters that are actually required for the deployment will be computed following the next equation:

  $$Pending\ Rep. = Inital\ Rep. - Deployed\ Rep. - Non\ viable\ installations$$

  The main reasons for an installation not to be suitable are that the concrete SFB has not been found or it is no accessible (i.e., is not possible to unlock the lock), the SFB has not enough space for the repeater installation, or the communication link is not achieved according to the verifications after the deployment.

  The information about the count of repeaters in the phase 0 of the field trials has been summarized in *Figure 50*. As shown, the progress of the deployment in the 25 SS of the phase 0 of the Project is already completed in terms of repeaters installation as there is currently no pending repeaters to install. As shown, phase 0 of this deployment plan has involved the deployment of 346 BPL repeaters.

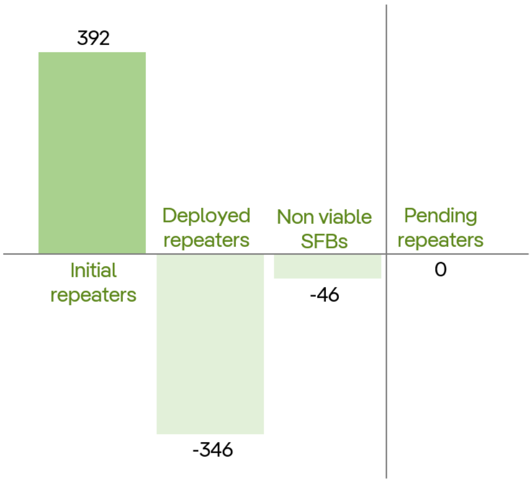


Figure 50: Count of repeaters. Source: GridValue. [Own preparation]

- **Availability of the repeaters**: after the installation of the BPL repeaters, it is necessary to check its accurate functioning. *GridValue* checks the following relation:

$$Availability\ (\%) = \frac{Operational\ time\ (s)}{Total\ time\ (s)} \cdot 100$$

Apart from the individual availability of each BPL repeater, there are other measured parameters such as the number of BPL repeaters that are below the 50, 80, 90, and 95% of availability in terms of absolute number of repeaters and the percentage that this number means compared with the total number of repeaters of each SS. The results from this analysis for the phase 0 of the deployment plan have been gathered in *Table 18*. Based on these results, it is possible to compute the number and percentage of repeaters that are above these values. These computed results will be valuable for setting criteria to determine if the performance is proper enough, as it will be defined in next section.

Table 18: Results of the availability analysis. Source: GridValue. [Own preparation]

Repeaters' availability	Repeaters per SS with each % of availability (count)	Repeaters per SS with each % of availability (percentage)
< 50%	47	14%
< 80%	58	17%
< 90%	61	18%
< 95%	78	23%
≥ 50%	299	86%
≥ 80%	288	83%
≥ 90%	285	82%
≥ 95%	268	77%

b. Source: *Grafana*.

Grafana is a software that serves to visualize data that is collected from the deployed equipment. It allows the customization of dashboards that represent the performance of these 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 example and 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. On the other hand, 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 this latency.
- **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.

Since these parameters are relevant to determine if the performance of the BPL-LV deployment is appropriate enough, *Grafana* has been customized to show them as in the example *Figure 51* that the RTT [ms] of the low voltage lines of certain SS is measured in real time so this value is obtained for each of the LVLs. Similar to that, *Figure 52* shows the percentage of lost packets per each of the LVLs of certain SS.

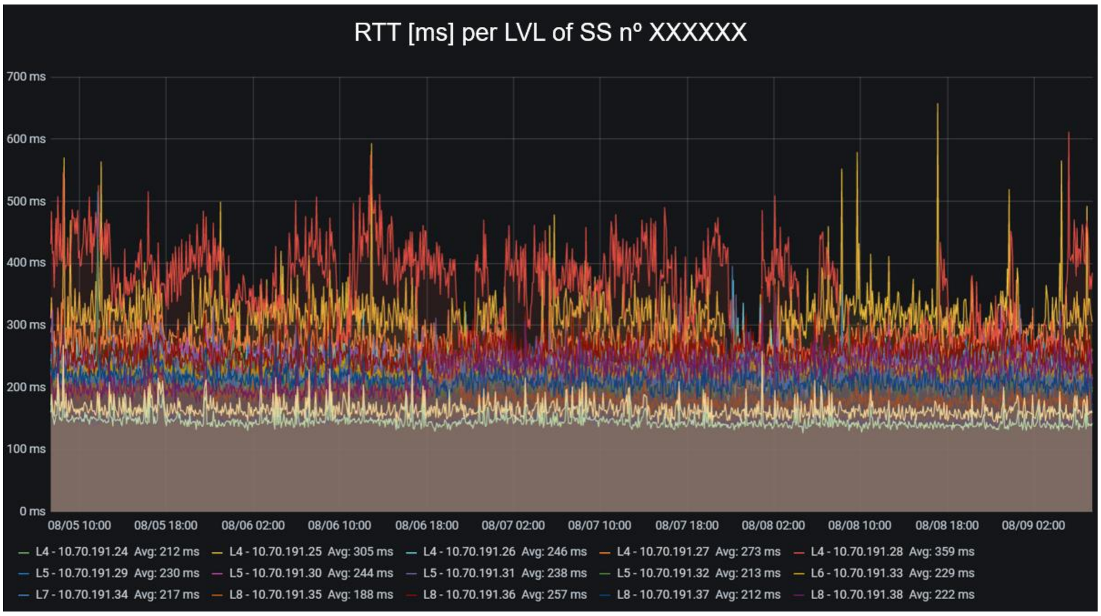


Figure 51: Ping analysis for the LVLs of a SS: RTT [ms]. Source: Grafana.

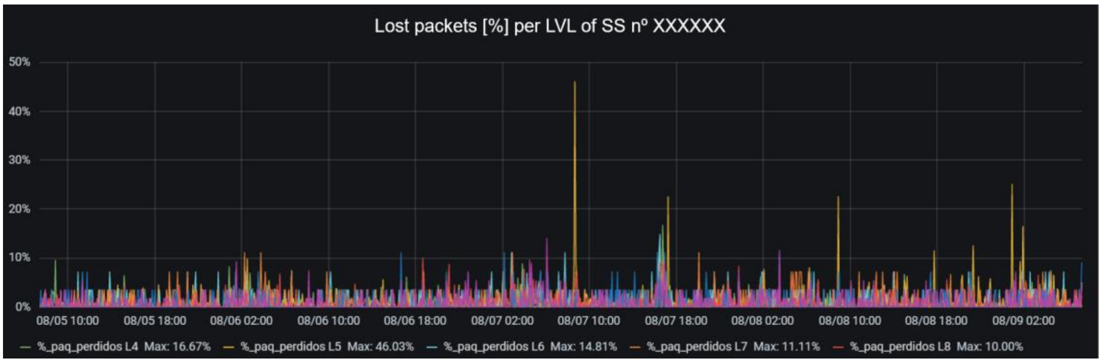


Figure 52: Ping analysis for the LVLs of a SS: Lost packets [%]. Source: Grafana.

To understand the meaning of these dashboards, some of the conclusions that can be drawn from analysis *Figure 51* and *Figure 52* will be explained. Firstly, by reading the legend of the graphics, this SS has been injected with BPL-LV in 5 of its LVLs: L4, L5, L6, L7, and L8. This concrete SS has 7 active LVL, so the **injected lines represent around the 70%** of the total. Furthermore, each LVL has respectively 5, 4, 1, 1, and 4 SFBs per line that make 15 SFBs with BPL repeaters compared to the total 29 SFBs that belong to this SS, meaning that more than the **50% of the SFBs of this SS have BPL-LV equipment**. From *Figure 51*, average RTT per line is respectively 279, 231, 229, 217, and 220 ms; being the **average RTT of all the lines 235 ms**. On the other side, the **average percentage of lost packets is 12,9%** excluding L5, that has clearly suffered an interruption of the communication.

4.3. BPL-LV NETWORK: CONCLUSIONS FROM FIELD TRIALS.

Once the model of the proposed new LV grid topology has been explained, the devices that take part of the field trials have been described, and the criteria of selection of the SS has been justified, and the verifications that the field trials require to carry out have been listed, it is possible to understand and draw conclusions from the field trials. This section will specify what are the criteria that the field trials have empirically show. In other words, what are the processes and deployment measures that are better taken to ensure a reliable connection with the highest value of availability. Besides that, the specific KPIs that are desired to be measured after the BPL-LV deployment will be indicated in this section.

4.3.1. CRITERIA FOR THE BPL INJECTION.

The objective of the BPL-LV deployment is to identify the target SFBs and inject with BPL as many low voltage lines as possible to expand the BPL (G.hn) network in order to cover the widest area that includes the maximum number of endpoints and therefore improve the telecommunication for the maximum number of final clients. To do so, the first requirement is to describe that **target SFBs are those with at least 5 SMs**.

After that, the field trials have provided knowledge about two main subjects: which lines require BPL-LV injection and in which cases it is necessary to install additional BPL repeaters. As mentioned in section *4. Description of the Model*, BPL repeaters are installed in all the target SFBs which will also include a PRIME v1.4 base node.

a. Selection of injectable LVLs.

First, it is important to identify those LVLs that share a sufficient long cable section. When various LVLs share at least 30 or 40 m, they are studied together as a “cable bundle”. For each cable bundle, it is recommended to inject BPL in that LVL whose target SFB is located as far as possible. In fact, when the target SFB is located closer than 50 m from the SS, it is advised not to inject that LVL.

One of the most relevant parameters that influence the availability of the communication between devices is the distance between the SS and its SFBs. In other words, the LVL length. It has been proved that a LVL length of more than 150 m is associated with connection and availability problems. This distance is just indicative since other parameters such as the cable age, its type, and the number of splices and branches – mentioned in section *3.3.2. Low Voltage Lines* – need to be considered.

Apart from the LVL length, other constraint to consider is the signal reduction provoked by the overuse of the telecommunication network. Because of this reason, it is not recommended to inject more than 4 LVLs per SS. This restriction allows the attenuation to not exceed 6 dB. Therefore, there will be the need to select those LVL that

b. Identification of additional repeaters.

As explained, additional repeaters will enable the signal to be stronger and reach the desired locations and equipment. Therefore, this additional equipment will enable the BPL network to be as extensive as planned in the LV grid designing process. The lack of communication that leads to the necessity of these BPL repeaters may be due to signal attenuation related to excessive distances.

BPL repeaters will be installed in all the target SFBs whereas additional BPL repeaters may be required in some SFBs that are not target. This happens when the target SFB is further than 150 m[4] from the SS but shares the same LVL with a SFB that is not target but it is closer to the SS than the target one.

In addition to this information, there is an established hierarchy to choose the optimal placement of the additional BPL repeaters that is stated below:

1. No target and no problematic SFB sharing the same LV line as a problematic SFB.
2. No target and no problematic SFB sharing the same cable bundle as problematic SFB.
3. Additional BPL repeater installed in the SS directly connected to the problematic LVL.

[4] Target SFBs that are further than 150 m from the SS are defined as *“problematic SFBs”*.

4.3.2. KPIs OF THE BPL-LV DEPLOYMENT PERFORMANCE.

As explained in section *3.5.2. The Experience of E.ON*, after the deployment of the BPL-LV it is necessary to check if the process has been actually successful. As it is an empiric method, there is the need to set key performances indexes (KPIs) to verify the accuracy of the communication between devices in the telecommunication network. The parameters that are relevant in a telecommunication system have been described in section *4.2.2. Verification of the BPL-LV Deployment Performance*. Now, these KPIs that the working team needs to check in the following weeks after the deployment have been gathered in *Table 19*.

Table 19: KPIs to check after the BPL-LV deployment. [Own preparation]

	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.

As shown in *Figure 51* and *Figure 52*, currently the communications are not reaching these KPIs. However, since this Project is still in a trial phase, the KPIs may be adapted to the reality and may change to be looser so the measured parameters are within the limits. This decision will be responsibility of the working team leading the field trials of the Project.

4.4. NB-PLC NETWORK: SELECTION OF PRIME CHANNELS.

PRIME v1.4 has some features that requires some further planification compared to the previous version of this standard. 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. It is the case demonstrated in *Figure 53* where a spectrogram of a photovoltaic inverter has been represented. This example is relevant since PV inverters are elements with increased presence in the power distribution grid related to the increase of renewable energies installation. This spectrogram shows that the inverter introduces narrowband interference within the analysed band. This phenomenon will be stronger as more PV inverters will be added to the distribution grid. The interferences can be detected from the brighter colours of the spectrogram that are wider at frequencies below 100 kHz and more pronounced in the PRIME v1.3.6 band between 42 and 89 kHz.

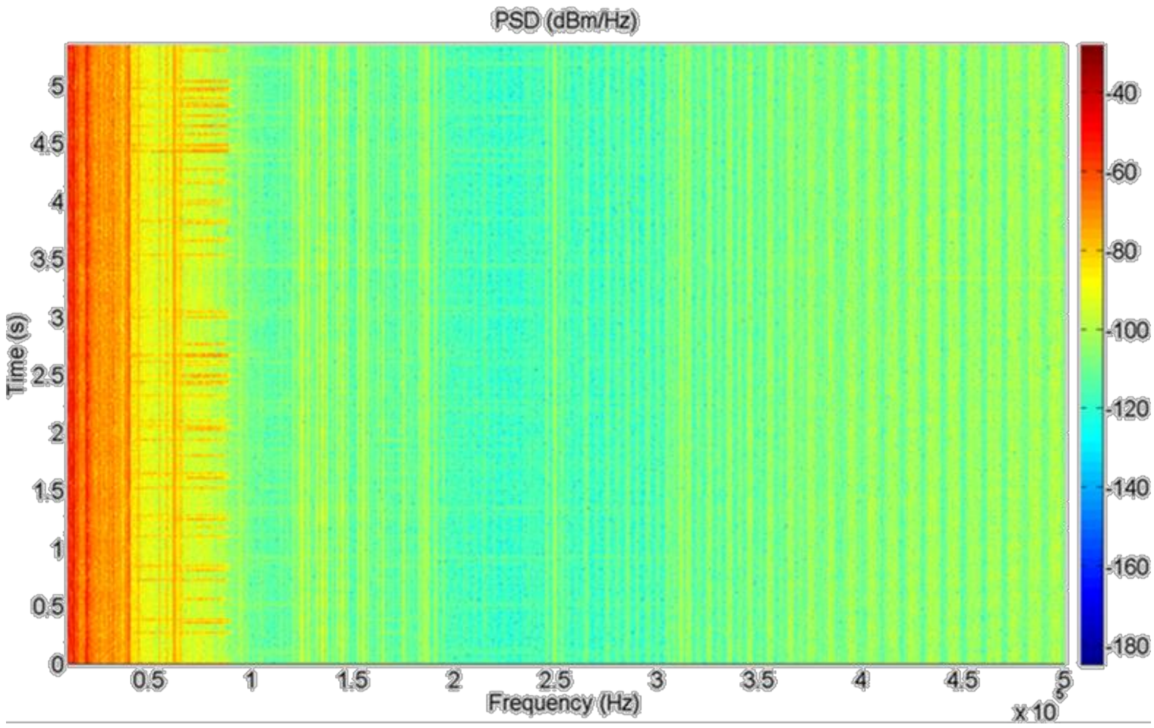


Figure 53: Spectrogram – PV inverter. [85]

Annex III – CENELEC Frequency Band has presented the existent influence of the frequency in the variation of impedance of the power lines [58]. Besides the changes in impedance represented in *Figure 69*, *Figure 54* shows the drop in the PLC received signal that is directly related with the grid impedance meaning that lower impedances reduce the received signal. Furthermore, related to the presence of PV inverters in the grid, these elements introduce harmonics in the frequencies between 8 and 80 kHz and therefore interfere in the PLC signal transmission.

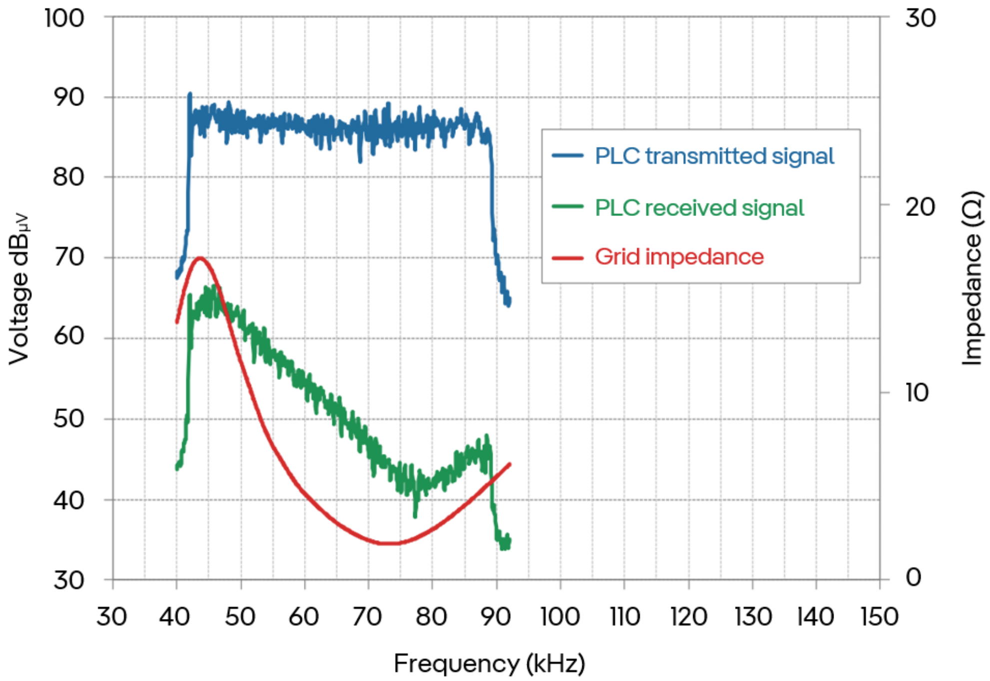


Figure 54: Frequency influence. [86]

On the other hand, PRIME v1.4 is multichannel while PRIME v1.3.6 was single channel. This new feature makes necessary to plan the use and distribution of the available frequency band for the different low voltage lines and PRIME networks in each of the telecommunication systems established per each secondary substation. Regarding these 8 channels of the new version of the PRIME standard, only 6 of them are actually available for PRIME v1.4. This phenomenon is represented in *Figure 55* 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 55* 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.

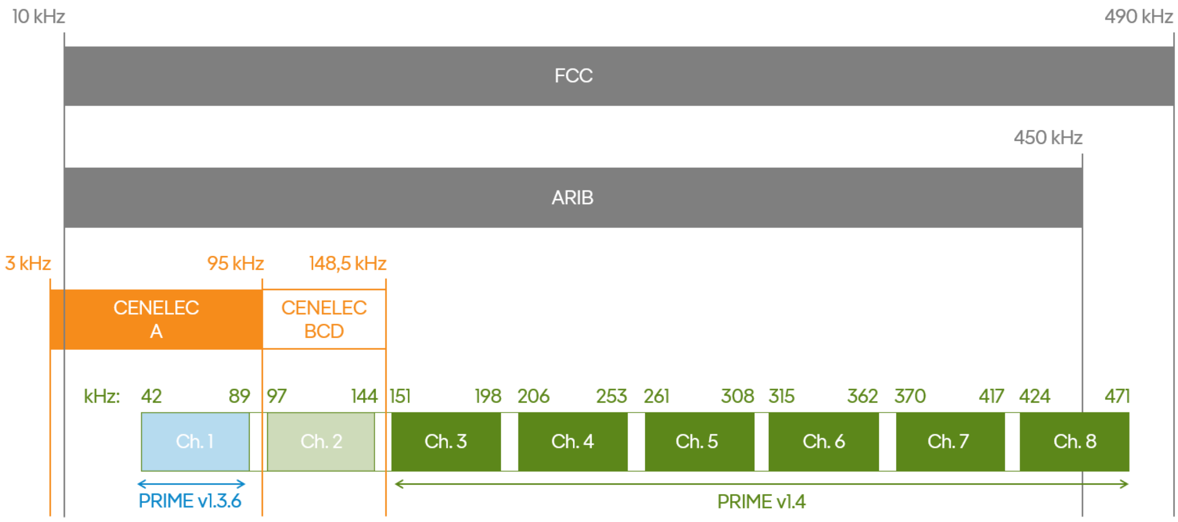


Figure 55: Frequencies band for NB-PLC - Available channels for PRIME v1.4. [Own preparation]

Despite the availability of 6 channels, the field trials have only checked the reliability of some of them. More concretely, as mentioned in section *2.2.3. New Solutions for Telecommunications,* PRIME v.1.4 base node supplied by Neuron was tested in more than 130 secondary substations using channels 5 and 7, while ZIV's base node has been tested in three SS operating in channel 5.

4.4.1. THE FOUR-COLOUR THEOREM.

In order to reduce the interferences in the frequencies used for narrowband PLC, it is possible to take advantage of the existence of different channels to plan a combination of them that ensures the most efficient utilization of the available spectrum. The objective therefore is to design a planification to allocate the 6 available adjacent channels to the different low voltage lines in the power distribution system.

To do so, it is possible to apply graph theory to develop an approach for this decision-making process that allocates the channels. The relevance of graph theory lies in the fact that vertices and edges can represent a variety of entities, making it applicable to a diverse range of problems. Through graph theory, highly complex networks – such as power distribution networks – can be simplified into a problem of nodes and connections.

a. Basic concepts of graph theory.

Graph theory is a mathematical discipline that examines the properties of graphs. According to this theory, a graph is a pair (G) comprising a non-empty set of vertices (V) and a set of edges (A), so G = (V, A). Graphs are visually represented using points (vertices) connected by lines (edges) [88]. The precursor of graph theory was Leonhard Euler, who solved the first related problem in 1736 inspired by the structure of Konigsberg (East Prussia). This city was divided into four different regions because of the Pregel River, and it counted on seven different bridges that connected these regions [88], as shown in *Figure 56*.

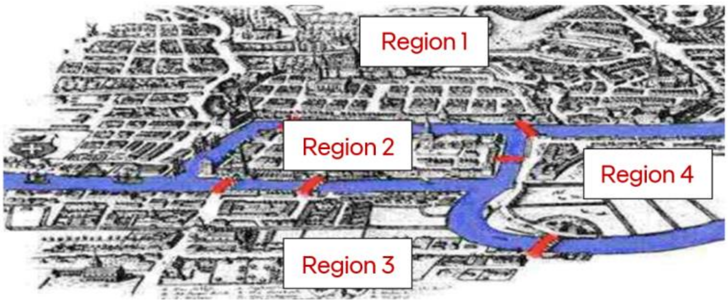


Figure 56: Konisberg in 1736.

Based on this context, Euler wondered if there was a possibility to design a route that would start at a point, cross each of the seven bridges once, and return to the starting point. Euler resolved this question by utilizing a graph, where the vertices represented the four areas into which the city was divided, and the edges represented the seven bridges connecting them. To solve this question, Euler simplified the city's structure and depicted it as a network of nodes and connections like the represented in *Figure 57*, which can be considered as the first graph, which mathematical deduction can be defined as a set of vertices V = {a, b, c, d} representing the four regions and the set of edges A = {a1, a2, a3, a4, a5, a6, a7} representing the seven bridges of the city.

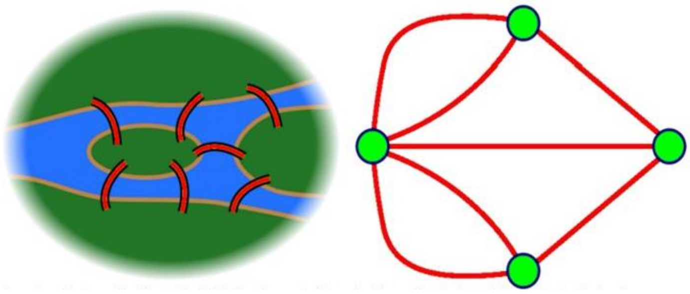


Figure 57: "The Seven Bridges of Konisberg" graph. [89]

Subsequently, other scientists like Gustav Kirchhoff in 1845 and Francis Guthrie in 1852 employed graph theory to develop their own theories. Kirchhoff published the laws that enable the calculation of voltage and current across different points and connections in an electrical circuit. In Guthrie's case, he proposed the Four-Color Theorem, which it is part of the graph colouring theorems and states: *"Given any two-dimensional map with contiguous regions, it is possible to colour it with four different colours in such a way that adjacent regions would not be the same colour"*. The graph colouring defines the smallest number of colours needed to colour a graph as $\chi(G)$. Based on that, the Four-colour theorem can be described as in the following equation: $\chi(G) \leq 4$.

This theorem can be also represented as a graph like in *Figure 58*. To do so, the regions are represented as vertices and the edges are those that connect adjacent regions. The theorem was ultimately proved in 1970 by Kenneth Appel and Wolfgang Haken by using a computer.

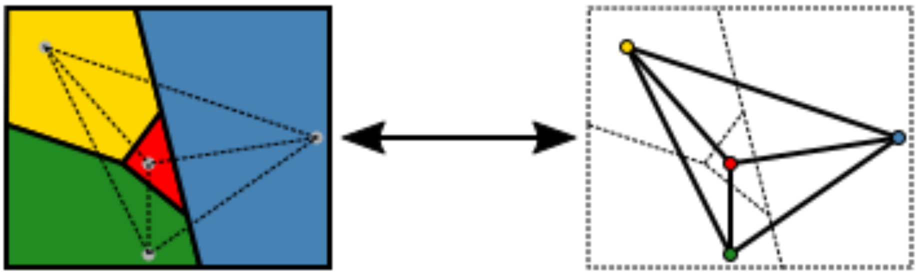


Figure 58: Four-colour theorem and its graph representation. [90]

To apply this theorem to face the challenge of avoiding interferences among adjacent channels, each channel would simulate a colour and the geographical areas to “get coloured” would be the areas covered by the PRIME v1.4 networks belonging to each SS.

By employing the Four-Colour Theorem as a guiding principle, it is evident how a theoretical abstraction can offer insights into creating more robust and efficient NB-PLC networks.

4.4.2. PRIME v1.4 CHANNELS PLANIFICATION.

The similarities of the Four-Colour theorem with the PRIME channel allocation are represented in *Figure 59*. The main concept to considers is that to avoid interferences, the objective is to assign different frequencies or channels to adjacent areas or PRIME v1.4 networks belonging to the same secondary substation.

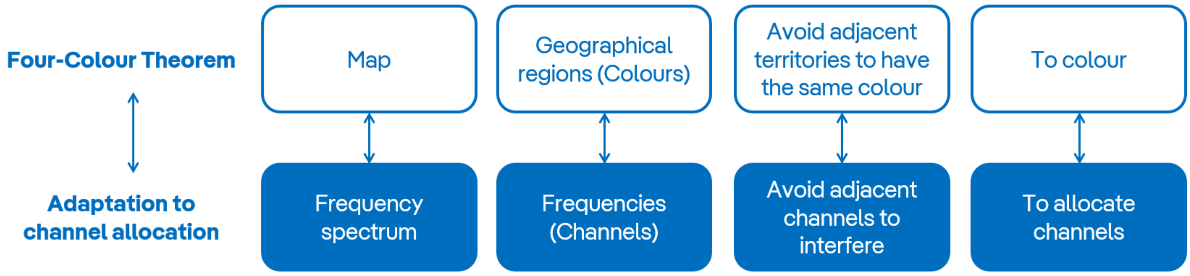


Figure 59: Application of Four-Colour Theorem to channel allocation. [Own preparation]

The design of the algorithm that assigns the channels need to be based on graph theory concepts and optimization techniques. One effective algorithm for this purpose may be the "Greedy Graph Colouring Algorithm" that **iterates** through the nodes (communication channels) and assigns colours (frequencies) in a way that adjacent nodes (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. The step-by-step representation of this algorithm use has been represented in *Figure 60*.

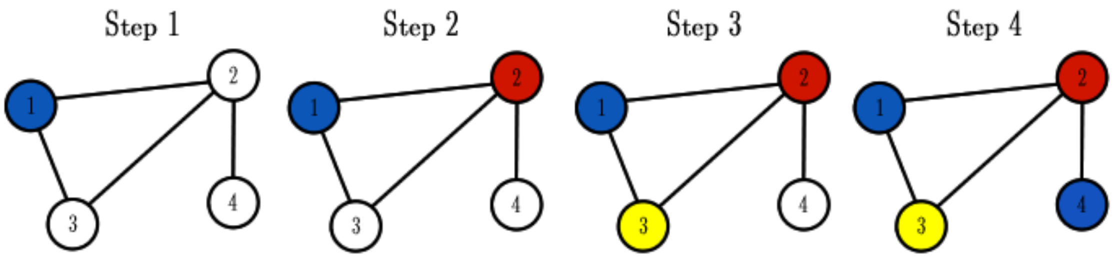


Figure 60: Step-by-step of Greedy Colouring Algorithm. [91]

a. Greedy Graph Colouring Algorithm.

This introduced algorithm does not ensure the use of the minimum number of colours (channels) but it provides an upper limit on the number of colours that are needed [92]: *"Greedy graph colouring algorithm never uses more than d+1 colours where d represents the highest degree of any vertex within the graph under consideration"*. One demonstration of this statement is *Figure 61*, where the same algorithm would provide two different solutions, one that required the use of one additional colour with respect to the other.

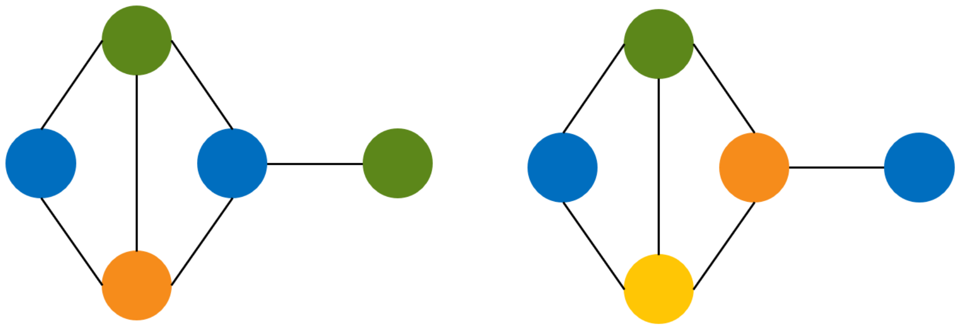


Figure 61: Two solutions for the Greedy graph colouring algorithm. [Own preparation]

Figure 61 also proves that the order in which the colours (channels) are selected is relevant for the final solution. The most common approach to state an order to follow is the known as *Welsh-Power Algorithm* that suggests the following steps [93]:

1. Calculate the degree of each vertex. In other words, the number of edges that end in each vertex 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.

An example that clarifies this iterative process has been explained in *Annex VII – Welsh-Powell Algorithm*. Furthermore, an implementation of this algorithm developed in Python3 has been attached in *Annex VIII – Greedy Colouring Algorithm.*

b. Further considerations for PRIME v1.4 channel allocation.

Apart from iterative as developed in previous section, 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 19* are required to be met to ensure an accurate and valuable telecommunication and connection of the equipment compromised in the PRIME v1.4 network. As in the BPL example with *GridValue* and *Grafana*, this performance can be checked through simulation and field trials. 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 channel allocation efficiency 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.

4.5. CONCLUSIONS OF CHAPTER 4.

This chapter has served to flesh out the idea of BPL-LV deployment that had been theoretically described in previous chapters. As mentioned before, there is not a variety of field trials developed by diverse companies. Despite this, this Project is innovative, and its progress is active and dynamic. In fact, the switch from theory to actual deployment and performance is relying of the conclusions daily obtained from the field trials, that are currently providing valuable insights into the real-world dynamics of the deployment. Another step for the formalization of the deployment has also been introduced in this chapter: the use of performance measurement tools such as *GridValue* and *Grafana*, and the establishment of KPIs to serve as a reference of the expected performance to be compared with the actual one. These KPIs, as the Project indeed, are dynamic and will be continuously informed by the evidence of the new deployed field trials.

After defining the deployment and expected KPIs for the BPL-LV implementation, this chapter also completes the "new network" planning by exploring approaches that can be adapted from the mathematical field to help optimize the allocation of channels that PRIME v1.4 offer. The most suitable methodology has appeared to be the adaptation of the Four-Colour Theorem that provides efficiency to the channel allocation problem since it avoids adjacent channels to share adjacent PRIME networks and therefore avoiding interferences between these adjacent channels.

By combining the BPL-LV deployment insights obtained from the field trials and the mathematical approach to allocate NB-PLC channels, the Project is now closer to the practicality than before. After this chapter, there is a holistic objective view of the deployment process. The paradigm shift in the low voltage grid topology points out the dynamic nature of this deployment. By introducing BPL technology into both low voltage lines and medium voltage grids and complementing it with the enhanced capabilities of NB-PLC PRIME v1.4, it is possible to obtain low voltage networks that can support the new features that are expected and that the traditional power distribution systems could not offer. In the subsequent sections of this thesis, these insights will transition into quantifiable results, forming the base for the actual deployment patterns for this Project.

Chapter 5. RESULTS OF THE RESEARCH

The previous chapter has focused on the description of the model, the requirements for the new grid topology, and the description of the field trials that are in progress and from which it is possible to obtain relevant insights. This knowledge is combined in this chapter with the information obtained from the vast databases of Iberdrola in order to design the tool that will serve to standardize the BPL-LV deployment. This mentioned empiric conclusions that were described in *4.3. BPL-LV Network: Conclusions from Field Trials*, are now used to design the specifications that will be needed for developing this tool to automatize the BPL-LV deployment. According to the usual policy of i-DE, regarding code programming, the common way of proceeding is to rely on third parties. That is the reason why developing the specific tool that executes the program is out of the scope for this project. Despite this, the actual purpose is to design the specification sheet that will help those third parties to develop a tool that provides the accuracy and performance that i-DE requires for its deployment. Although there are various methods to describe an automatization process so the third parties can develop a program from it, the most common in these cases is to use flow diagrams, so that is what it will be for this chapter.

Besides these specifications, a very significant result that has been obtained from the analysis of the databases that are involved in this Project is the list of required equipment that will be necessary in the deployment. This outcome is relevant since it may help the working team to plan their budget and overview the quantity of equipment that it will be required in each specific phase of the work. In this chapter, the list will be described this necessary equipment as well as its justification and the quantity divided into the different phases of the Project. Furthermore, as the analysis of the data has revealed some important information about the LV grid downstream the SS in the cases where the SS is part of the field trials, this chapter will include some essential percentages that symbolize the grid configuration will be computed and described.

5.1. BPL DEPLOYMENT: TECHNICAL SPECIFICATION.

5.1.1. DECISION TREE: BPL-LV DEPLOYMENT.

A study has been carried out in order to identify which are the variables that cause the greatest impact on the deployment of the system. Even though, each individual secondary substations and its related electrical components and devices may need to be studied separately, the main goal of this section is to investigate the influence of these significant variables with the aim to establish a standard process for the deployment of BPL over LV, improving its automatization and therefore the efficiency of the deployment itself.

This study of the empiric information from the field trials, has allowed to build the following diagram based on the impact of the variables that have been stated before. As it can be observed from *Figure 62*, the BPL deployment would vary whether a single cable is involved, or it is a cable bundle. Furthermore, different actions would be taken depending on the distance between the SFB_T and the SS or the number of BPL injections that the studied SS already had considering the restrictions described in *4.3.1. Criteria for BPL injection.* This diagram that will serve as a technical specification is also attached as *Annex IX – BPL over LV Deployment.* for better reading. Besides that, in order to provide more detail to the information given in the diagram, here there are some clarifications:

- LVL_T refers to the Low Voltage Lines that have a SFB_T connected.
- SFB_T are the Street Fuse Boxes that have at least 5 Smart Meters.
- When two or more cables share at least 30 m of length, it is considered as a Cable Bundle.
- When two or more cables share less than 30 m of length or take different directions, they are considered as independent cables. They are studied separately even when coming from the same Secondary Substation (SS).
- Regarding an independent cable, if the distance between a SS and its SFB_T is lower than 50 m, no action is needed.
- In case of a Cable Bundle with more than one LVL_T, injection would take place in the LVL_T that has its SFB_T furthest from the SS, as long as it is not further than 150 m.

- In the event of a SFB_T distanced more than 150m from its SS without a SFB in between, the LVL_T would not be injected unless it involves an Overhead Line.
- No more than four LVL_T would be injected for the same SS. In case of having more than four LVL_T in a SS, injections would take place in the LVL_T that has its SFB_T furthest from the SS, as long as this distance is shorter than 150 m.

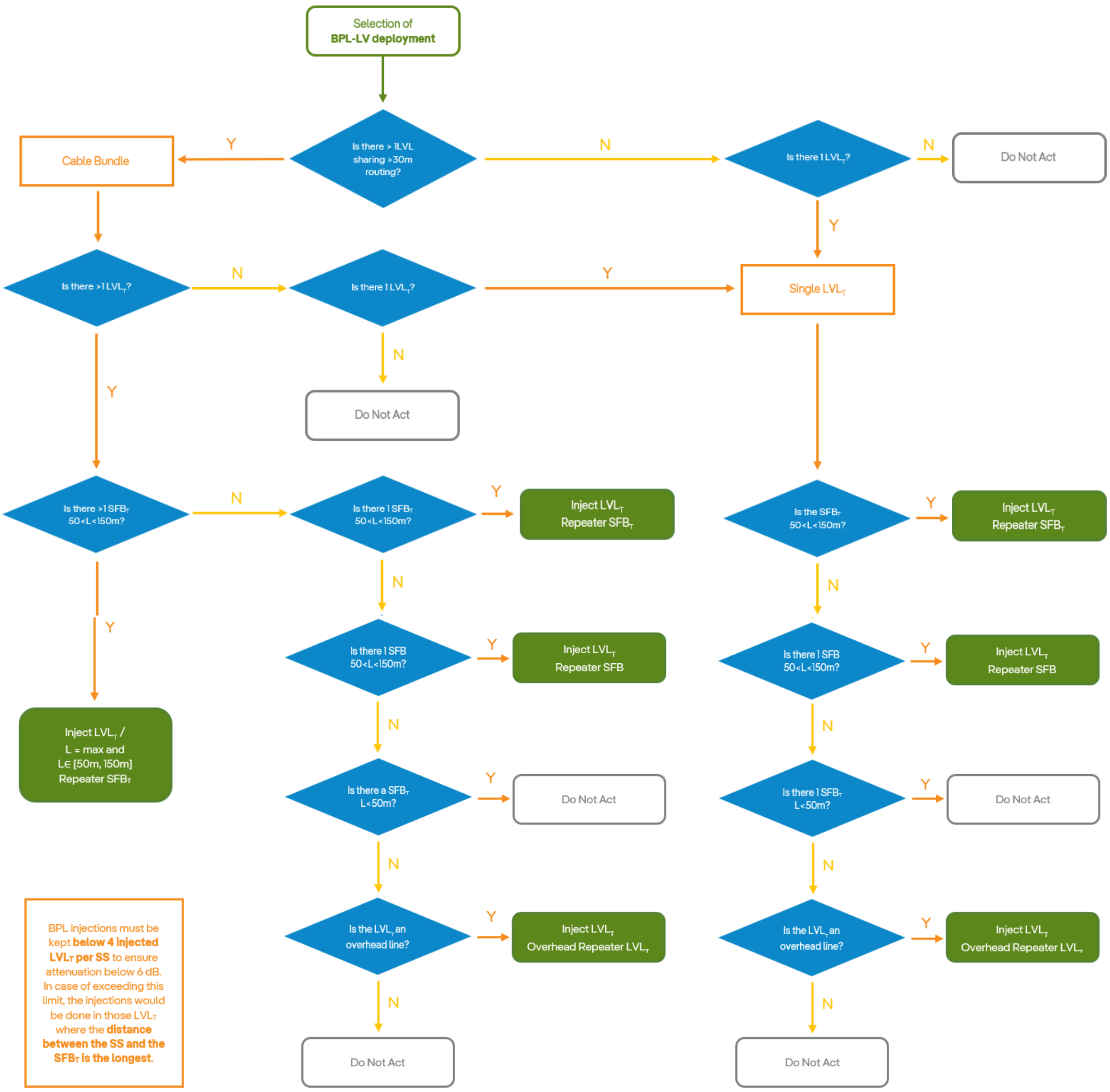


Figure 62: Decision tree - BPL over LV deployment.

5.1.2. DECISION TREE: BPL INJECTION SOLUTION.

As mentioned in *4.1. Description of the Proposed LV Grid Topology*, the preferred injection solution for BPL in LV is to use the LV-AMI sensor rather than to inject it with a Niled. This AMI sensor would not supervise the injected LVL as the supervision card is substituted by a dummy card. This is done to take advantage of the intermediate phases used by the advanced supervision card to connect the BPL injection through them.

However, before this current preference, the favoured BPL injection solution 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 the following 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 these risks are associated with the use of Niled [84]:

- **Risk of short-circuit** if a flooding occurs in the SS: as the insulation has got 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. This is the main reason why Niled injection is not recommended for those SS that are floodable. In example, underground SS and SS that are located in basements.
- **Risk of "hot points**": these 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 phenomena makes that the use of Niled requires to ensure that the SS is perfectly sealed and that in the case where the conductor and insulation gets perforated and the Niled is later removed, this cable gets repaired by vulcanizing it and reassuring its insulation or even changing it for other cable that is new and keeps its insulation. On the other hand, the use of AMI sensors limits the supervision of the LVL so the aim is to develop an equipment that allows the connection of the both applications: supervision and BPL injection.

Because of these reasons, the criterion now is to only use Niled to inject in the cases when the LV switchboard is not standardized so it is not compatible with the AMI sensor without the supervision card and when the SS is not at risk of flooding. These criteria have been represented as a decision tree in *Figure 63.* 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.

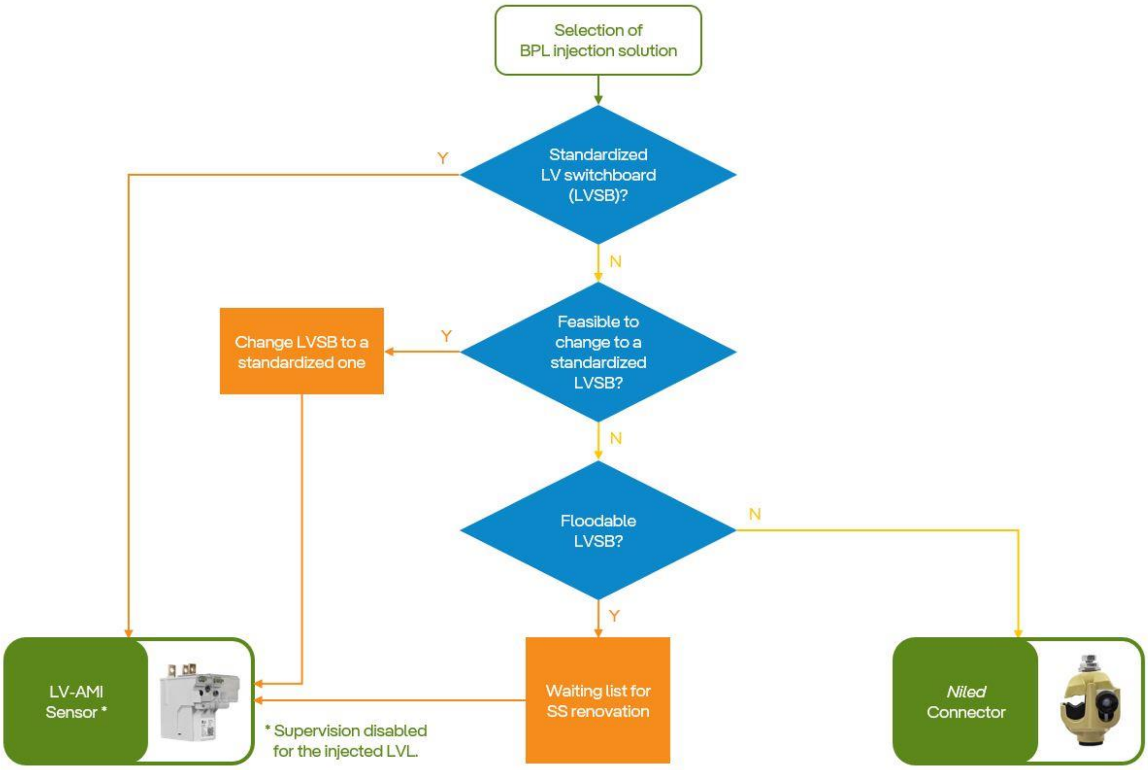


Figure 63: Decision tree - BPL injection solution.

5.2. LIST OF REQUIRED EQUIPMENT.

In section *4.1. Description of the Proposed LV Grid Topology*, the new structure of the power distribution grid has been represented in *Figure 45*. As shown, this new topology requires the installation of new equipment and the related purchasing of these new material. Among the new devices that will be necessary there are: BPL headends, BPL repeaters, splitters, couplers, *dummy* cards, and PRIME v1.4 base nodes. This section will serve to illustrate the number of new devices that will be required to gather for the field trials that have already started and that have been defined in *Table 17* of section *4.2. Description of the Field Trials.*

That plan suggests the deployment of BPL-LV in **349 SS** by the end of 2024. Based on the list of selected SS – whose selection process is explained in *4.2.1. Selection of the Target Secondary Substations* – it is possible to obtain the information about the configuration of the LV grid downstream the secondary substation. After the analysis of this data, some extra knowledge was acquired about the magnitude of the deployment has been acquired. For instance, that there are **4.723 of target SFB** associated to the 349 SS. Additionally, it was possible to find out the number of target lines per SS. This data about which LVL belongs each target SFB to is represented in *Figure 64*.

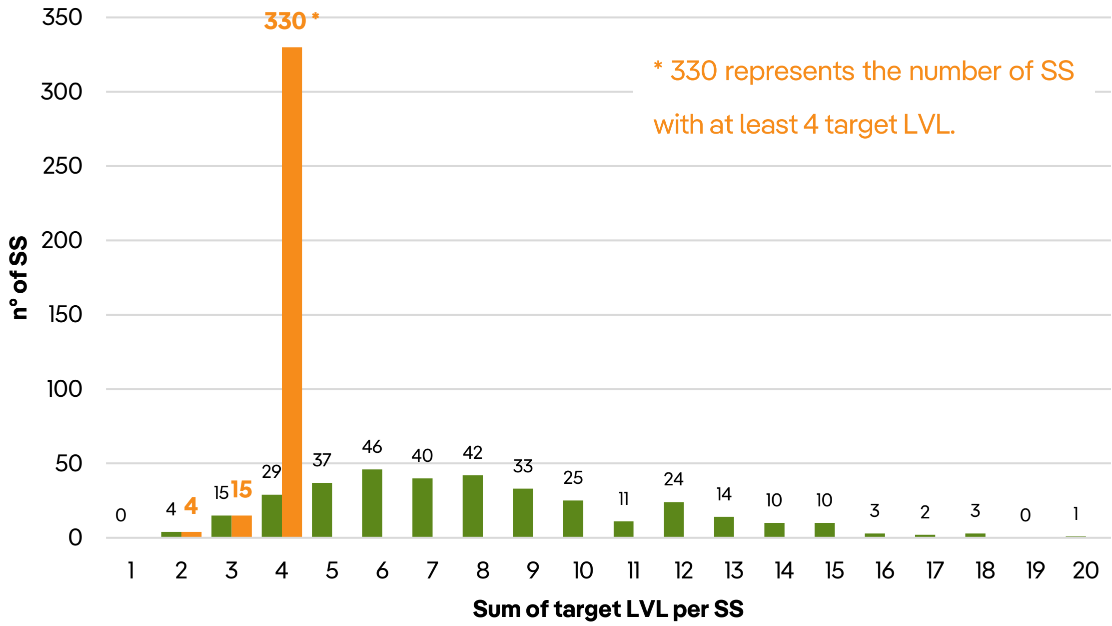


Figure 64: Classification of SS according to their nº of target LVL.

As shown in *Figure 64*, the green series represents the number of SS that has the quantity of target LVL declared in the x-axis. As seen, the rank of the number of target LVL per SS goes from 2 to 20. Besides that, the orange series represents the number of SS that has respectively 2, 3, and 4 or more target LVL. This restriction of 4 target LVL is due to the constraint of avoiding the BPL injection in more than 4 LVL per SS to avoid attenuation above 6 dB. This information is relevant since the number of target LVL will consequently determine the number of splitters, the necessity of splitters type 1:2 or type 1:3, and the quantity of required couplers for the deployment. Another insight from this *Figure 64* is **that 48,52 % of the target LVL will be injected with BPL**. This value is obtained considering there is a total of 2.830 target LVL belonging to those 349 SS and computing that the total of injected lines is 1.373 considering that those SS with more than 4 LVL will only be injected in 4 of them.

Lastly, the database of the grid inventory has also revealed the classification of SS according to their type of building and LV switchboard. The summary of this classification is represented in *Figure 65*, where the SS coloured in blue represent those floodable SS while the green ones are the standardized and non-floodable SS. As learnt from previous section, this classification is relevant since it will determine the solution to inject BPL in the LVL. In the case of floodable SS – **136 floodable SS in total** – these injections will be carried out using Niled while the rest of the SS that are standardized and non-floodable – 213 in total – will need *dummy* cards for the AMI sensors of those to-inject LVL so the supervision can be removed and substituted by these cards.

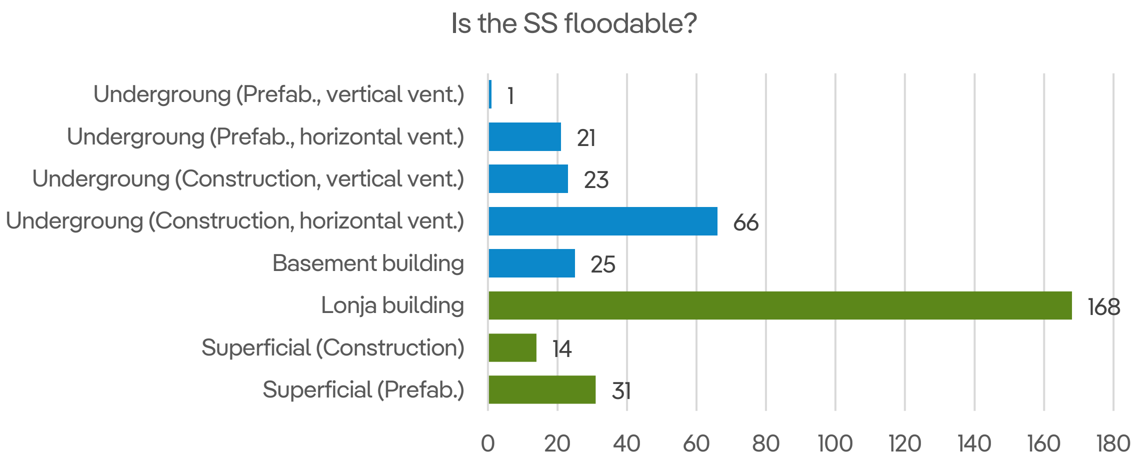


Figure 65: Classification of SS according to their type. [Own preparation]

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 20 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 20: 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%

The conclusions from this equipment analysis have been summarized in *Table 21* that shows the devices that are required for the new LV grid. Each of them is associated with an element that is already installed and whose quantity is known and therefore the total number of new devices can be computed and found out.

Table 21: List of equipment. [Own preparation]

Equipment	Quantity per SS_T	Multiplier (description)	Multiplier (value)	Total
BPL Headend	1	SS_T	349	349
BPL Repeater	1	SFB_T	4.723	5.152
	1	SFB no target but necessary (9,08% of SFB_T)	429	
PRIME v1.4 Base Node	1	SFB_T	4.723	4.723
Splitter 1:2	1	$SS_T / \sum LVL_{inj} \leq 2$	4	664
	2	$SS_T / \sum LVL_{inj} \geq 4$	330	
Splitter 1:3	1	$SS_T / \sum LVL_{inj} = 3$	15	15
Coupler for injected lines	2	$SS_T / \sum LVL_{inj} \leq 2$	4	1.373
	3	$SS_T / \sum LVL_{inj} = 3$	15	
	4	$SS_T / \sum LVL_{inj} \geq 4$	330	
***Dummy* card**	1	Standardized SS_T	213	213
Niled	1	No standardized SS_T or floodable SS_T	136	136

This information is obtained from a previous analysis of the deployment strategy that is theoretically planned today. However, the application of the specifications developed in previous sections and the deployment of the equipment will provide the actual number of devices that will be required. Despite this, these estimations could help the working team to plan the purchases based on the knowledge of which SS is part of each phase of the deployment process.

To design the definitive list that defines the quantity of equipment per phase, first *Table 22* gathers the number of electrical components involved in each phase (SS, SFB, LVL, etc.). Also, the type of SS that will later determine the solution for the BPL injection. As seen, although phases are balanced in terms of number of SS to be involved in each phase (c. 55), the number of target SFB is increasing with the phases. This happens because big, concentrated cities such as Madrid, Valencia, and Castellón are included from phase 2. These cities will require the deployment of more BPL repeaters as there are more clients and therefore more SFB both common and target because of the high population density there.

Table 22: Count of electrical components 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

* Note that there is some equipment with more than one line per phase. This is the case of the BPL repeaters, the splitter 1:2, and the coupler. Following the structure of the previous *Table 21*, the total equipment has in these cases been computed by the addition of various scenarios. For instance, in the case of BPL repeaters, first line corresponds to the ones that are required for each of the target SFB while the second line corresponds to the ones that will be installed in SFB that are not target but are necessary to ensure the reliable connection. In the case of the splitters 1:2, first line corresponds to those SS that will be injected in 2 LVL and the second lines to those SS that will be injected in 4 LVL and therefore will need 2 splitters 1:2 per SS, so this reason

Table 22 gives the information about the electrical components that are involved in each phase and because the required telecommunication equipment is dependant of these figures, now it is possible to design *Table 23* that gives an overlook of the required quantity of equipment per phase.

Table 23: List of equipment per phase. *[Own preparation]*

	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	66	454	550	814	948	1.070	821
		8	41	48	74	86	97	75
PRIME v1.4 Base Node	4.723	66	454	550	814	948	1.070	821
Splitter 1:2 *	664	1	1	1	0	0	0	1
		80	100	98	110	100	108	104
Splitter 1:3	15	4	3	3	1	3	0	1
Coupler *	1.373	2	2	2	0	0	0	2
		12	9	9	3	9	0	3
		80	200	196	220	200	216	208
***Dummy* card**	213	6	16	25	24	17	24	24
Niled	136	19	38	28	32	36	30	30

The information from *Table 23* can help to design an accurate budget for the Project and each of its phases just by knowing the unit price of each one of the required elements and equipment. Unfortunately, this budget cannot be attached in this document because the unit price of these elements is not public since the Purchases department and the corresponding supplier negotiate these prices until they both reach an arrangement that defines a framework and establish an agreement between the utility and the supplier to get the required material for a certain deployment as in this case. This *"Framework Agreement"* is confidential and may include some benefits or savings due to the huge volume of equipment that is needed by the utility.

5.3. CONCLUSIONS OF CHAPTER 5.

Based on the foundation developed in the preceding chapters, the current chapter delves into the tangible outcomes of the research, which contribute to shape the strategy of BPL over LV deployment. The previous chapter has qualitatively described the model of the new LV grid and the field trials that are an essential part for this Project to obtain relevant conclusions. On that basis, this chapter joins these empirical conclusions and the data from the Iberdrola's inventory that has been analysed in order to design a specification that serves to develop a tool to standardize and therefore improving the efficiency of the BPL-LV deployment. In other words, the conclusions described in section *4.3. BPL-LV Network: Conclusions from Field Trials* are transformed in this chapter into valuable information and insights that will be useful for the further progress of this Project and its 6 phases.

More concretely, this chapter contains the flow diagram that serves to automatize two essential procedures that are part of the BPL-LV deployment: the selection of the low voltage lines that need to be injected, and the injection solution that is more suitable for each of these injections. These two relevant processes have been deeply analysed to finally be able to design these diagram flows that serve as the example for the future programmers to develop the desired tool that will finally contribute the deployment process.

Furthermore, apart from the mentioned specifications, the other significant outcome of this chapter, the list of required equipment for the following phases, not only will help to enhance the efficiency to plan the expected budget for the deployment process. Besides that, this chapter includes the categorization of equipment per phase, what provides insight of the quantities of the required devices at different stages. This categorization not only enables the project team to anticipate demands, plan purchases, and streamline logistical operations, but also it will contribute to the formulation of a systematic approach for managing the necessary components in following phases or trials.

These two elements: the technical specification that will be needed for the actual deployment of the technology together with the logistic information about how many devices or equipment will be needed for this deployment makes this process more standardized and therefore easy to be carried out.

Chapter 6. CONCLUSIONS AND FUTURE WORKS

6.1. CONCLUSIONS OF THE PROJECT

The first chapters of this Thesis have focused on the transformation that the energy sector is undergoing. It is especially important the information gathered in chapter 2 about the specific progress that the electricity sector is experiencing. The description of all the new features that the consumers require to the power distribution grid points out the unavoidable necessity of the electrical grid to embrace the advancements provided by the development of new telecommunication solutions in order to make the grid suitable for the integration of the new technologies that are yet part of the present and that means a change of paradigm for the electrical sector and the power distribution companies.

After having give an overview of this evolution that is currently happening, chapter 3 has focused on the particular technology that is the matter of this Project: power line communications that use both narrowband and broadband depending on the applications. This chapter is relevant since is establishes the framework within this Project is being developed. Furthermore, to provide more information not only about the technology in general but about the progress of this Project in particular, the chapter ends with the insights that have been obtained in other field trials of BPL-LV deployment. These insights and the conclusions that are gathered from these trials are essential for the active management of the develop of this Project itself.

Chapter 4 eventually provides the detailed information about how the deployment of the BPL over LV is going to happen. This chapter offers relevant awareness of the Project and the infographics that describe the transformation of the LV grid will be especially relevant for some teams that are not involved in the deployment itself but will need to know about the new configuration of the grid. An example of this it is the workers in charge of the grid maintenance that may start to receive alarms and notifications of the new equipment potential failures and need to learn how the LV grid going to be.

In fact, the supervision and control of the new grid will require the use of new plataforms as the described in this chapter (i.e., Grafana and GridValue). In order to provide an overview of what are the expected key performance indexes that the responsible of controlling the operation needs to supervise, a table that gathers the main parameters that are expected from a reliable communication among the deployed equipment has been provided based on empiric measurements combined to be as realistic as possible. These parameters, as well as other results from this Project are subject to changes as this is an active Project that acquires knowledge on a daily basis that needs to be implemented as it was a system with feedback loop that learns from its outputs.

Apart from the BPL-LV deployment, it exists the parallel deployment of NB-PLC to include the features of PRIME v1.4 in the new grid. As this technology provides a wider frequency band and the possibility to use different channels that will have a positive impact for the reduction of signal interferences, this chapter also has provided an approach that could be used to program the allocation of the channels. This methodology consists on sequentially allocate them avoiding two adjacent PRIME v1.4 networks to share the same or adjacent channels based on the Welsh-Powell Algorithm.

Finally, this Thesis concludes with the specification that will be needed to program the tool that will allow the automatization for the deployment of the new power distribution grid. Based on the knowledge acquired from the analysis of the large databases that Iberdrola gathers regarding its electrical and telecommunication systems inventory, together with the study of the different conclusions and insights provided from the supplier and learnt from previous field trials, it has been possible to establish some common patterns that can be applied for the deployment. Furthermore, a detailed analysis of the LV grid configuration downstream the SS has suggested some figures that help to understand the number of SFB involved in the Project as well as the necessities in terms of logistics and procurement that this Project entails.

The idea is that once the tool is already developed and these diagrams have helped to know what is the BPL injection strategy that better suits each one of the SS, this information will be represented in a GIS such as Mapinfo. This way, when a deployment is about to be carried out, it would be possible to select the target SS in Mapinfo and verify the information of the equipment and injection strategy that will be needed for that specific SS in order to standardize the deployment process and therefore make it more efficient, scalable, and robust.

6.2. 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.

6.2.1. BENCHMARK OF POTENTIAL SUPPLIERS

As defined in *3.5. Benchmark of Similar Projects*, following the example of *E.ON*, i-DE is relying on Corinex as its supplier for the required BPL-LV equipment. Corinex is probably the world leader in BPL as it has developed remarkable partnerships not only with *E.ON* but also with other key players in the industry such as *Stromnetz* Hamburg, *Stromnetz* Berlin, or *westnetz,* that are tier 1 utilities in Europe [77].

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 in order to increase the resilience of the procurement process by counting on the most qualified suppliers in the industry.

6.2.2. CHANGES IN THE REGULATION

As explained in section *2.2. The Role of Iberdrola*, the 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 actually 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.

Chapter 7. BIBLIOGRAPHY

7.1. BIBLIOGRAPHY CHAPTER 1

[1] J. Berzal, *"Broadband PLC Deployment in the Low Voltage Grid"*. Escuela Técnica Superior de Ingeniería ICAI, Universidad Pontificia de Comillas. August 2022.

[2] A. Sendín, J. Matanza and R. Ferrús, *"Smart Grid Telecommunications: Fundamentals and Technologies in the 5G Era"*. IEEE Press and Wiley. 2021.

[3] J. Matanza, *"Improvements in the PLC Systems for Smart Grids Environments"*. Escuela Técnica Superior de Ingeniería ICAI, Universidad Pontificia de Comillas. October 2013.

[4] J. P. Chaves et al., *"La Digitalización de las Redes Eléctricas de Distribución en España"*. Instituto de Investigación Tecnolócia (IIT), Universidad Pontificia de Comillas and Fundación Naturgy. September 2021.

[5] i-DE, *"Resultados Alcanzados"*.

[6] N. Šajn, *"Electricity 'Prosumers'"*. European Parliamentary Research Service. November 2016.

[7] H. Nalinakshan, M. Hoffman and H. Le, *"Partnering up: why the time has come for telcos and utilities to collaborate more closely than ever"*. PwC Publications. December 2022.

[8] J. González-Ramos et al., *"Upgrading the Power Grid Functionalities with Broadband Power Line Communications: Basis, Applications, Current Trends and Challenges"*. Sensors, Vol. 22, No. 12. January 2022.

7.2. BIBLIOGRAPHY CHAPTER 2

7.2.1. SUBSECTION 1

[9] A. Sendín, J. Matanza and R. Ferrús, *"Smart Grid Telecommunications: Fundamentales and Technologies in the 5G Era"*. IEEE Press and Wiley. 2021.

[10] Electrical Technology blog, *"SCADA Systems for Electrical Distribution"*. September 2015.

[11] N. S. Živic, *"Evolution of Smart Metering Systems"*. University of Siegen, Germany. 23rd Telecommunications fortum (TELFOR). November 2015.

[12] P. Mlynek et al., *"Narrowband Power Line Communication for Smart Metering and Street Lightning Control"*. Brno University of Technology, Czech Republic. International Federation of Automatic Control (IFAC). 2015.

[13] *Kersting* Iluminación y Energía, *"Medidor electromecánico monofásico DD866"*. EAN 7807371028649.

[14] ZIV Making the Smart Grid Real, *"5CTM – Contador Monofásico Inteligente. PLC PRIME"*.

[15] Unabiz, *"Modbus Reader – SigFox transmission"*.

[16] Southern California Edison, *"Smart Energy Program Terms and Conditions"*. July 2018.

[17] Southern California Edison, "*Rebates Incentives & Savings Tips: Summer Discount Plan"*.

[18] Titan Energy, *"What is Peak Demand and How It Affects You"*. 2023.

[19] Comisión Nacional de los Mercados y la Competencia (CNMC), *"Liquidación Provisional 14/2020 del Sector Eléctrico"*. 2020.

[20] W. H. Fleischer, *"A Comparative Analysis in the Relationship between the Economy and Environmental Protection"*. Revista Economică 66:5. Lucian Blaga University of Sibiu. January 2014.

[21] Valley Clean Energy, *"Flattening the Curve"*. December 2017.

[22] California ISO, *"Daily Renewables Watch for 10/22/2016"*. Renewables and emissions reports. October 2016.

[23] U.S. Department of Energy, *"Confronting the Duck Curve: How to Address Over-Generation of Solar Energy"*. Office of Energy Effiency & Renewable Energy. October 2017.

[24] K. Ahmed, Notes on *"Electric Vehicles"* for module EE803: "Power Electronics for Transmission and Distribution Networks". University of Strathclyde. January 2023.

[25] M. Nour et al., *"Review of Positive and Negative Impacts of Electric Vehicle Charging on Electric Power Systems"*. Energies 2020, 13, 4675. September 2020.

[26] Virta Global, *"The state of EV charging infrastructure in Europe by 2030"*. May 2022.

[27] Schmidt Automotive Research, *“Western Europe annual new BEV passenger registrations”.* 2021.

[28] Bloomberg New Energy Finance (Bloomberg NEF), *“Hitting the EVs inflection point”.* May 2021.

[29] J. A. Martínez Gutiérrez, *“Vehículo Eléctrico: Análisis y Prospectiva de Factores Tecnológicos y Económicos”*. Universidad de Valladolid. March 2013.

7.2.2. SUBSECTION 2

[30] Comisión Nacional de los Mercados y la Competencia (CNMC), *“Listado de Comercializadoras de electricidad”.* 2023.

[31] Iberdrola España, *“Datos operativos y otras cifras relevantes”*. 1S 2023.

[32] Presentación de resultados 1S 2023. July 2023.

[33] i-DE, *“Sobre i-DE: Conócenos”*. 2 023.

[34] Informe de Innovación 2020-2022.

[35] Proyectos de Innovación en Europa. 2023.

[36] Proyectos de Innovación en España. 2023.

[37] Creara, Energy Experts, *“Tipos de contadores para la monitorización de los consumos”.* February 2018.

[38] PRIME Alliance, *“PRIME Alliance Principal Members”.*

[39] i-DE, *“STAR Project General Vision”.* July 2016.

[40] i-DE, *“Iberdrola Deployment Overview in Spain”.* Control Systems and Telecommunications. June 2015.

[41] Iberdrola: Nuestra actividad en Redes Inteligents, *“Proyecto STAR: un referente mundial de eficiencia en inversiones en redes y contadores inteligentes”.* 2023.

[42] Riick, *“Optic fibre service options”.* Wikimedia Commons, Creative Commons. April 2007.

[43] H. Remmert. *“¿Qué son el CBRS y el LTE privado y cuáles son los casos de uso?”*. Soluciones Celulares, Digi Internacional. September 2018.

[44] PRIME Alliance, *“PRIME v1.4 Specifications”.*

[45] R. Ayala Arranz, *“Novedades de Telecomunicaciones. Sesión a CSDs”.* (Internal Use of i-DE). Red Acceso Digital. June 2023.

7.3. BIBLIOGRAPHY CHAPTER 3

7.3.1. SUBSECTION 1

[46] L. Cucala, *"Divide et impera: OSI layer stack".* Notes on *"Switching and Protocols stack"* for module: "Telecommunications 101". University of Comillas – ICAI. September 2021.

[47] Iberdrola España, *"Curso de Telecomunicaciones en entornos eléctricos – Capítulo 1: Introducción".* March 2013.

[48] J. D. Day and H. Zimmerman, *"The OSI reference model".* Proceedings of the IEEE, Vol. 71, No. 12. December 1983.

7.3.2. SUBSECTION 2

[49] Iberdrola España, *"Curso de Telecomunicaciones en entornos eléctricos – Capítulo 2: Nivel Físico".* March 2013.

[50] A. R. Ndjiongue and H. C. Ferreira, *"Power Line Communications (PLC) Technology: More Than 20 Years of Intense Research".* Transactions on Engineering Telecommunications Technologies. July 2019.

[51] J. Berzal, *"Broadband PLC Deployment in the Low Voltage Grid".* Escuela Técnica Superior de Ingeniería ICAI, Universidad Pontificia de Comillas. August 2022.

[52] A. Kumar, *"A Review on Cognitive Radio for Next Generation Cellular Networks and its Challenges".* American Journal of Engineering and Applied Sciences. March 2017.

[53] G. López et al., *"Noise Sources, Effects and Countermeasures in Narrowband Power-Line Communications Networks: A Practical Approach".* Journal Energies. 2017.

[54] L. R. M. Castor et al., *"The Smart Grid Concept in Oil & Gas Industries by a Field Trial of Data Communication in MV Power Lines".* Journal of Microwaves, Optoelectronics and Electromagnetic Applications, Vol. 15, No. 2. June 2016.

[55] B. D. Rivero and A. M. Moncayo, *"Diseño y Análsis de una Red de Banda Ancha usando Tecnología BPL".* Escuela Superior Politécnica del Litoral, Ecuador. 2011.

[56] A. Peralta, *"BPL (Broadband over Power Line): una alternativa para brindar el servicio de internet de alta velocidad".* INGENIUS, Revista de Ciencia y Tecnología. 2010.

[57] R. Jayaparvathy, *"A low-cost AMR technology based on power line signaling".* International Journal of Applied Engineering Research. January 2015.

[58] I. Hakki Cavdar and E. Karadeniz, *"Measurements of Impedance and Attenuation at CENELEC Bands for Power Line Communications Systems".* Journal Sensors, 8, 8027-8036. December 2008.

[59] G. Díaz Moral, *"Análisis del Rendimiento del Estándar BPL OPERA con Datos Empíricos".* Escuela de Ingeniería de Bilbao. July 2018.

[60] Maxim, *"The History of the IEEE P1901.2 Standard".* EEWeb. Aspencore Network. August 2013.

[61] PRIME Alliance Technical Working Group (TWG), *"PRIME v1.4 White Paper".* April 2020.

[62] R.A. Bustillo, *"Banda Ancha sobre Red Eléctrica o BPL".* Andean Lawyers, ICT Legal Consultants in Latin America. 2008.

[63] International Telecommunications Union (ITU), *"GSTP-HNSG: Technical Paper on the Use of G.hn Technology for Smart Grid".* 2020.

7.3.3. SUBSECTION 3

[64] A. Sendín, J. Matanza and R. Ferrús, *"Smart Grid Telecommunications: Fundamentales and Technologies in the 5G Era".* IEEE Press and Wiley. 2021.

[65] R. Cossent, Notes on *"Enhanced LV network observability and data analyses"* for module: *"*Operation and Planning of Distribution Systems". University of Comillas – ICAI. May 2022.

[66] A. Sendín, Notes on *"Electric Power Systems"* for module: "Telecommunications for Smart Grids". University of Comillas – ICAI. December 2021.

[67] Europacable, *"An Introduction to Medium and Low Voltage Cables in Distribution Networks as support of Smart Grids".* Brussels, June 2014.

[68] Manual Técnico de Distribución i-DE, *"Especificaciones particulares para instalaciones de alta tensión (hasta 30 kV) y baja tensión".* MT 2.03.20. Ed. 11. May, 2019.

[69] Notes on "*Transmission and Distribution lines"* for module: "Technology and Electric Engineering". Universidad de Alcalá. May 2019.

[70] Reglamento Electrotécnico de Baja Tensión (REBT), ITC-BT-13. March 2023.

7.3.4. SUBSECTION 4

[71] Kang-Tsung Chang, *"Geographic Information System".* Wiley Library. March 2019.

[72] N. Rezaei et al., *"Role of GIS in Distribution Power Systems".* World Academy of Science, Engineering, and Technology 60. January 2009.

7.3.5. SUBSECTION 5

[73] Corinex, *"Smart Grid Products"*. 2023.

[74] J. F. Segalotto, *"Towards a Truly Smart Grid: The Case for Broadband over Power Line"*. PRIME Alliance and International Data Corporation. IDC #EUR148113621. August 2021.

[75] Corinex, *"E.ON chooses Corinex broadband over powerline technology for their smart metering rollout"*. Business Wire. January 2018.

[76] Corinex, *"Broadband over power lines: Reimaging grid resilience with BPL"*. 2023.

[77] Corinex, *"Smart grid solution: Enabling grid modernization for a smart energy future"*. 2023.

[78] Corinex, *"GridValue Energy Management System"*. 2023.

[79] Corinex, *"PRIME Alliance standardizes BPL Smart Meter Gateway solution for grid management"*. November 2022.

[80] C. Beard and W. Stallings, *"Wireless Communication Networks and Systems"*. Pearson Education Limited. 2016.

[81] C&C Wireless Telecom Products and Services, *"Planifación y Optimización de RF: Construir mejores redes RAN"*. 2021.

[82] J. Laiho et al., *"Radio Network Planning and Optimisation for UMTS"*. IEEE Press and Wiley. Second Edition. 2006.

7.4. BIBLIOGRAPHY CHAPTER 4

[83] R. Ayala Arranz, *"Novedades de Telecomunicaciones. Sesión a CSDs".* (Internal Use of i-DE). Red Acceso Digital. June 2023.

[84] R. Ayala Arranz, *"Pruebas de inyección BPL BT en SAG".* Telecomunicaciones. Red Acceso Digital. August 2023.

[85] I. Fernández Pérez et al., *"Análisis de las emisiones indeseadas en las Bandas Cenelec A y FCC y su influencia sobre las comunicaciones PRIME".* III Smart Grids Congress. January 2021.

[86] J. González Ramos, *"Análisis del Impacto de los Efectos de Canal en las Comunicaciones Narrowband PLC según el Estándar PRIME".* Escuela de Ingeniería de Bilbao, Universidad del País Vasco. July 2019.

[87] I. Fernández Pérez et al., *"Comparison of Measurement Methods of LV Grid Impedance between 9 and 500 kHz".*

[88] J. García Miranda, *"Introducción a la teoría de grafos".* Universidad de Granada. 2006.

[89] Notes on *"Teoría de grafos".* Resources of University of Pamplona. 2012.

[90] K. Appel, "*The Solution of the Four-Color-Map Problem".* Scientific American 237 (4) pp. 108 – 121. 1977.

[91] T. Ribeiro, *"Understanding Grapgh Coloring (vertex): a greedy approach".* December 2015.

[92] *"Graph Colouring: Set 2 (Greedy Algorithm)".* Geeks for Geeks. February 2023.

[93] M. Leblanc, Notes on *"Vertex Coloring: Welsh-Powell Algorithm"* for module: "Planning & Scheduling". 2004.

Chapter 8. ANNEXES

ANNEX I – SUSTAINABLE DEVELOPMENT GOALS

The Sustainable Development Goals (SDG) are an initiative of the United Nations that were established in September 2015 at the Development Summit. It aims to develop a plan of action based on sustainable progress and with the priority of ensuring prosperity for all the people and the planet. To achieve this goal, *2030 Agenda* was designed and put into effect on 1 November 2016. Its official title is "Transforming our world: the 2030 Agenda for Sustainable Development" and it defines the Sustainable Development Goals, which are summarised in *Figure 66* and will be briefly explained below.

Figure 66: Sustainable Development Goals.

Unlike their predecessors – the Millennium Development Goals (MDG) –, the SDG include climate change, innovation, social inclusion and responsible consumption, and are not only targeted at the poorest countries but apply to the whole world.

I.1. ALIGNMENT OF THIS PROJECT WITH THE SDG.

One of the importance of this Project lies on the giving solution to an existing problem. Furthermore, knowing the SDGs, it is clear to link them with the Project's own objectives. SDGs are divided into three dimensions and so will be the objectives of this Project. These dimensions are environmental, social, and economic. Because of the nature of this Project, it will focus on the three of them as it will be explained in this section.

Firstly, the deployment of this technology in the low voltage distribution network will allow the evolution of smart grids and will enable the use of trend technologies such as electric vehicles, distributed generators, batteries, as well as the existence of prosumers. This deployment is necessary since these technologies need a real-time monitoring that may not be possible without broadband PLC. Because of this, the results of this Project will have a positive impact on the industry of the electricity distribution as it is innovative and improves the infrastructures (**SDG 9**). Following within the economic dimension, considering that this Project will enable the development of the mentioned technologies and their related economies, it can be said that it will contribute to a sustainable economic growth (**SDG 8**) that lies on those technologies that assure a sustainable use of the resources.

In the same way, this sustainable economic growth will be directly related to a sustainable growth of human settlements (**SDG 11**) that will be inclusive since everyone will be benefited from the improvement of the communications in the distribution network and it will help to the actual possibility to reach the desired integration of renewable generation, electric vehicles, etc. to achieve in the development of sustainable cities.

The upgrade in technology that the deployment of BPL can achieve will allow the sustainable presence and integration of renewable distributed generation, this is why this Project is aiming to encourage the existence of affordable, reliable, sustainable, and modern energy for all (**SDG 7**).

Lastly, as this Project is developed thanks to the collaboration between two leading companies in each own sector: Comillas – education and investigation – and Iberdrola – electricity distribution, commercialisation, and generation –, this can be understood as a partnership oriented to work for the goals (**SDG 17**).

I.2. TARGETS OF THIS PROJECT IN RELATION WITH THE SDG.

Based on the explanation of how this Project is contributing to the SDGs, this section will list the concrete targets that will be covered. Once it is mentioned that the involved goals are 7, 8, 9, 11, and 17, this Project will contribute to:

Target 7.2: Increase of global percentage of renewable energy.

Target 7.3: Improvement in energy efficiency.

Target 8.2: Diversification, innovation, and upgrade for economic productivity.

Target 8.4: Improvement of resource efficiency in consumption and production.

Target 9.1: Development of sustainable, resilient, and inclusive infrastructures.

Target 9.3: Upgrade of all industries and infrastructures for sustainability.

Target 9.5: Enhancement of research and upgrade of industrial technologies.

Target 9.C: Universal access to information and communications technology.

Target 11.6: Decrease of the environmental impact of cities.

Target 17.6: Knowledge sharing and cooperation for access to technology, and innovation.

Target 17.17: Encouragement of effective partnerships.

For a better understanding and vision of how this Project aligns with the Sustainable Development Goals in different dimensions, a summary of what has been developed in this chapter is presented in *Table 24*.

Table 24: Summary of SDG Involvement of the Project.

SDG dimension	Goal	Role	Alignment with the Project
Environmental dimension	**7.** Access to affordable, reliable, sustainable, and modern energy for all.	Secondary	The deployment of BPL will allow the integration of renewable distributed generation.
Economic dimension	**8.** Sustained, inclusive, and sustainable economic growth and decent work for all.	Secondary	Innovation and upgrade of technologies that will lastly contribute to the economic growth.
	9. Industry, innovation, and infrastructures.	Primary	Reliability on the development of BPL supports the innovation in the electric sector.
Social dimension	**11.** Inclusive, safe, resilient, and sustainable human settlements	Tertiary	The integration of renewable energies will contribute to the existence of more sustainable cities.
	17. Revitalise the Global Partnerships for the Goals	Primary	Partnership between *Comillas* and *Iberdrola* for the aforementioned goals.

ANNEX II – OFDM

Orthogonal Frequency Division Multiplexing is a digital modulation technique used in telecommunications to transmit data over multiple subcarriers simultaneously, allowing high-speed and efficient data transmission.

The representation of OFDM is shown in *Figure 67* where it is illustrated that the available spectrum is divided into a number of orthogonal subcarriers (called *Users* in *Figure 67*). These subcarriers are closely spaced and modulated with independent data streams.

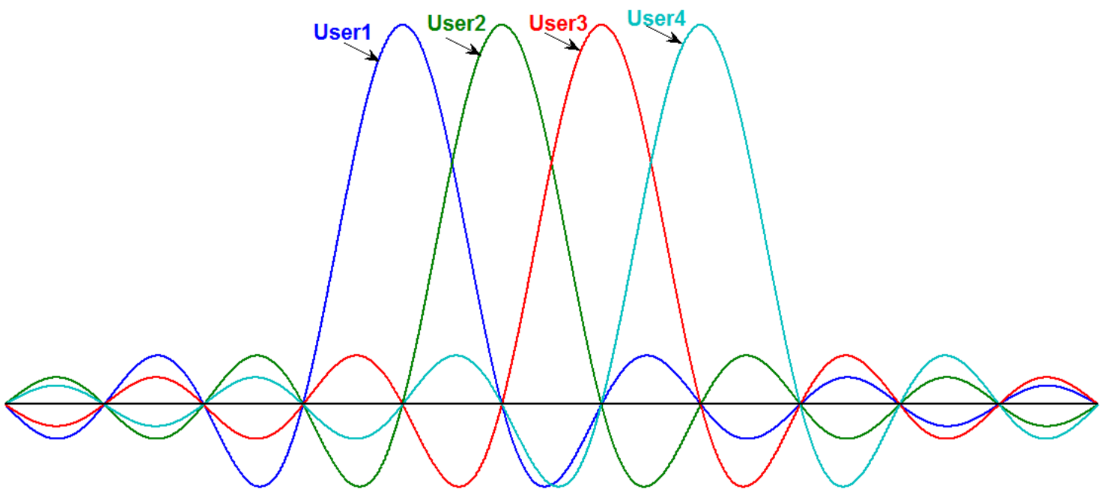


Figure 67: Representation of OFDM. [52]

The modulation is called *Orthogonal* because the subcarriers are orthogonal one with each other, meaning that their frequency spectra do not overlap. This feature makes possible the minimization of interferences between subcarriers.

ANNEX III – CENELEC FREQUENCY BAND

CENELEC (*Comité Européen de Normalisation Électrotechnique*) is the European Committee for Electrotechnical Standardization in which Spain and the UK takes part. It was founded in 1973 and it is responsible for standardization in electrical engineering.

This organization established in 2011 (standard EN-50065) that the frequency ranges available for NB-PLC are from 3 to 148.5 kHz. They defined this frequency band as CENELEC band and divided it into four different sub-frequencies as represented in *Figure 68* [57]. It is especially important for this Project the definition of the CENELEC-A frequency band as it is the band in which PRIME v1.3.6 operates. After that, with the upgrade to PRIME v1.4, higher frequencies are being explored in order to find bands with less interferences. By doing that, FCC (10 – 490 kHz) and ARIB (10 – 450 kHz) frequency bands are being suggested for the PRIME v1.4 operation. More specifically the band from 42 to 472 kHz that is divided into 8 different channels that can be used independently.

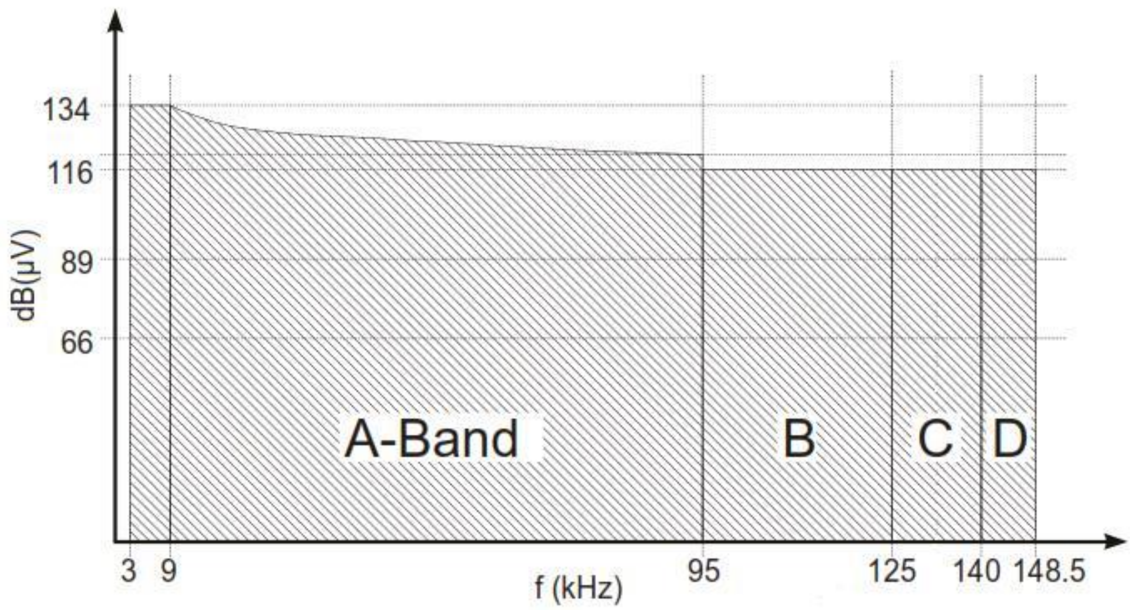


Figure 68: PLC Signal Limits specified in CENELC Standard EN-50065.

Although there is a wide range of frequencies that can be used in NB-PLC, it is important to consider its relation with the impedance of the power lines [58], as the results shown in *Figure 69* corresponding to measurements in rural power lines.

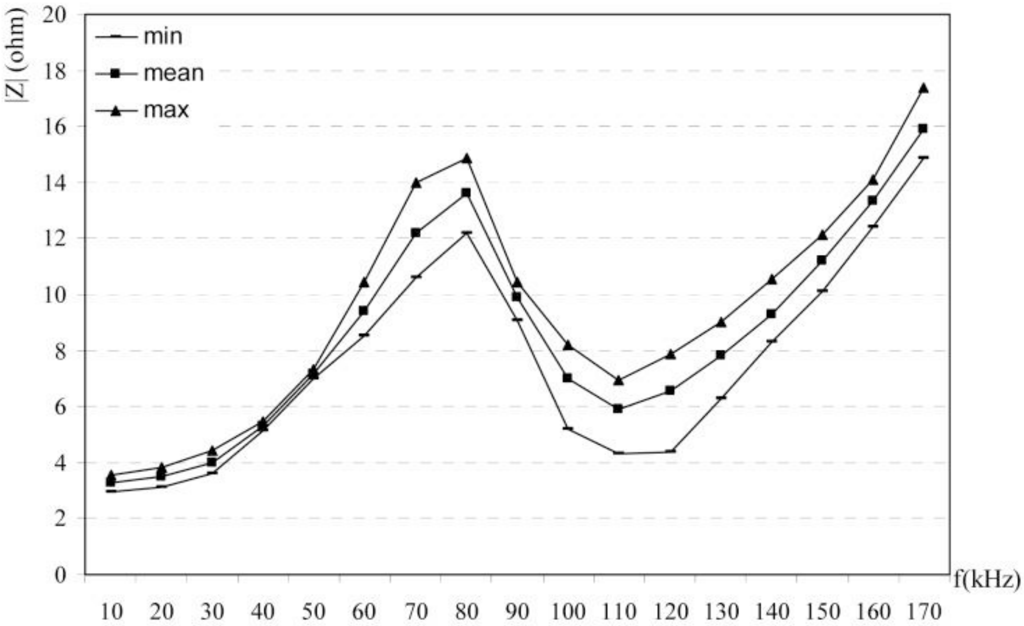


Figure 69: Relation between impedance of the line and frequency of transmission. [58]

ANNEX IV – SFB STANDARDIZED SCHEMES

ITC-BT-13: Street Fuse Boxes (SFB)

The topology of the Street Fuse Box (SFB) will be selected taken into account:

- Standardized schemes by the REBT (see Section 1).
- Standardized schemes used in each power distribution company (see Section 2 for i-DE).

Section 1: Standardized SFB schemes by REBT.

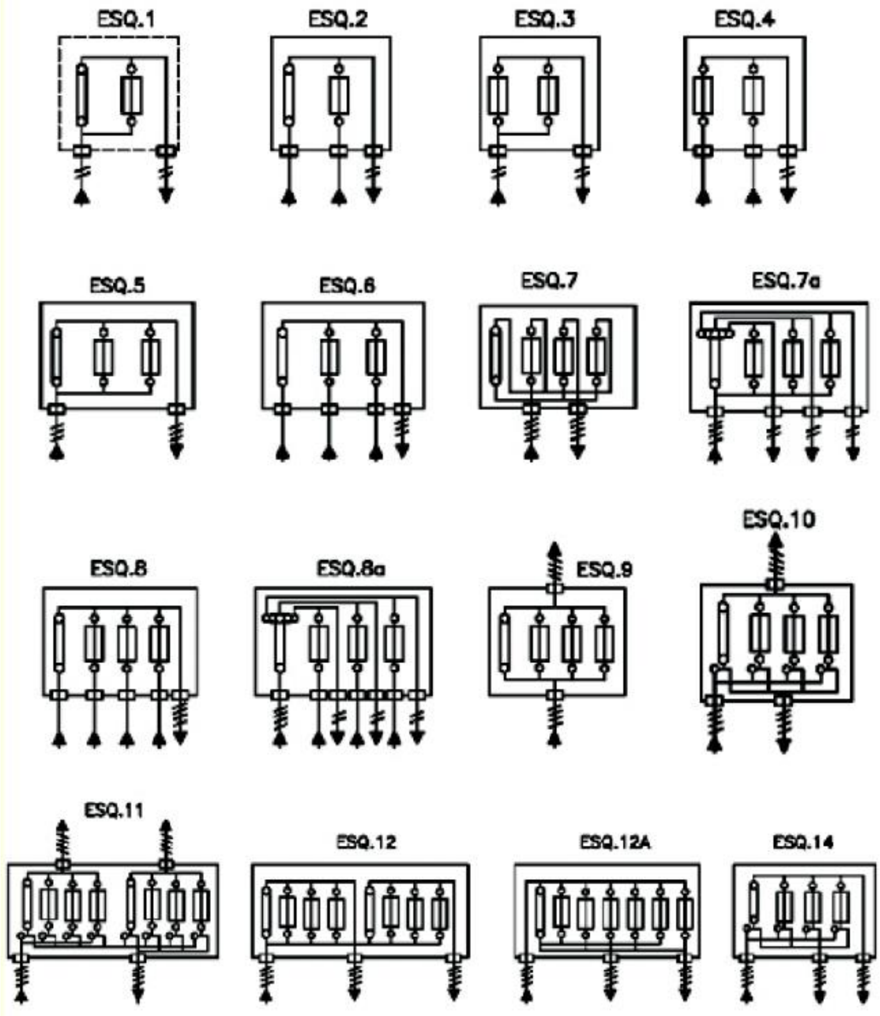


Fig. 1: Standardized SFB schemes.

1.1. Legend of the schemes.

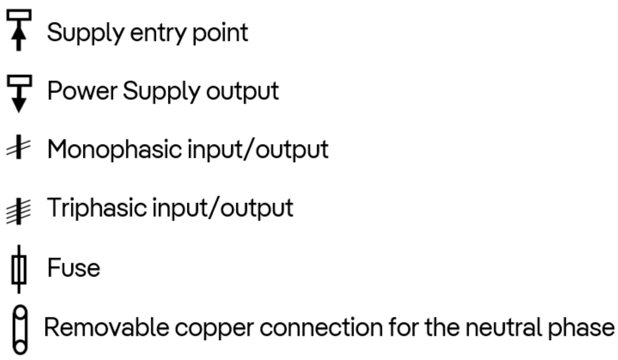


Fig. 2: Legend of the SFB schemes.

1.2. Nomenclature of the SFB.

The SFB are named according to the following nomenclature: *CGP-a-b/c/d*

Where:
- · a: Number of the scheme (according to Section 1).
- · b: Nominal current of the fuses in one circuit.
- · c: Nominal current of the fuses if there was a second one.
- · d: Maximum current rating.

Note 1: The most common nominal currents for the SFB are: 40 A, 100 A, 160 A, 250 A y 400 A.

Note 2: The nomenclature can also include the acronym that defines the type of fuse holder, i.e. "CUB" for Closed Unipolar Load-Break Bushing.

Section 2: Standardized SFB schemes used by i-DE.

According to the Iberdrola's standard NI 76.50.01, July 2010 (6th Ed.), the standardized SFB schemes that the company has agreed to use and install are the following.

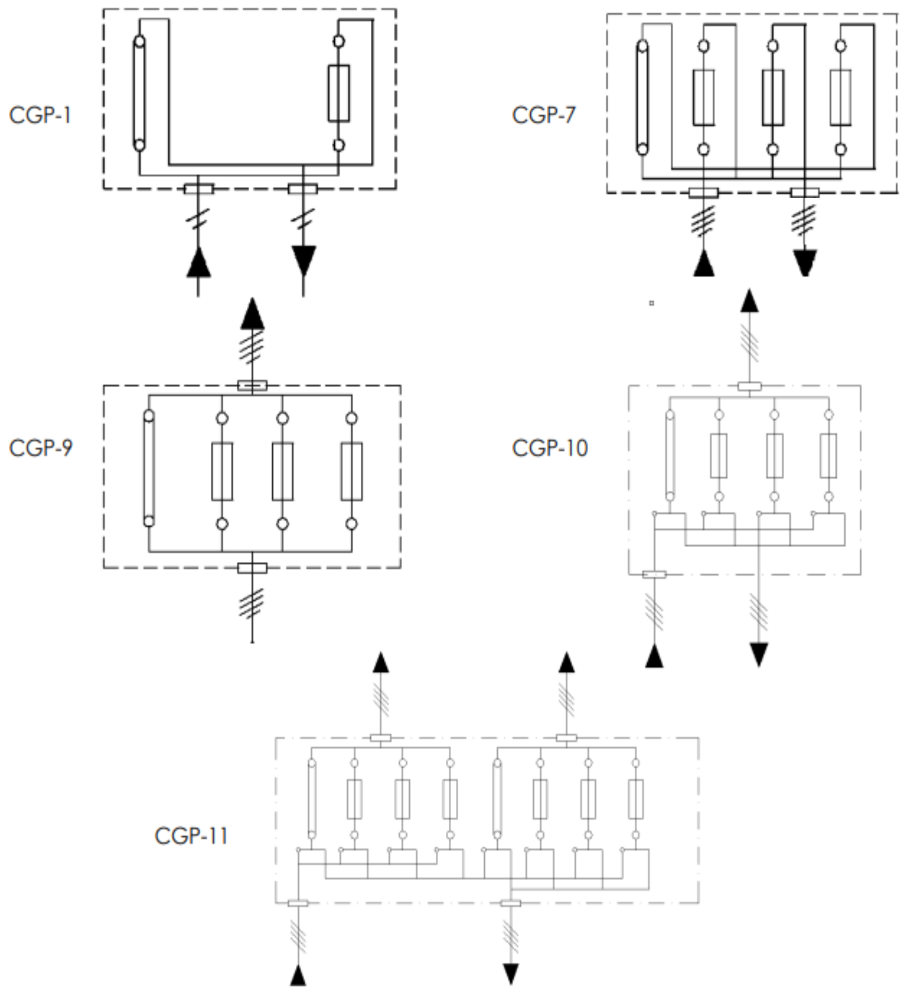


Fig. 3: Standardized SFB schemes used by i -DE.

2.1. Selection of the type of SFB.

Characteristics of the CGP

The main characteristics of each SFB have been gathered in *Table 1*. As seen, every SFB name starts with "CGP" because it is the Spanish acronym for SFB: "Cuadro General de Protección", and it is the real nomenclature used by Iberdrola in their inventories, etc.

Table 1: Main characteristics of the standardized SFB.

Name	Fuses			Use	Code
	Holder		I-max (A)		
	Number	Size			
CGP-1-100	1	00 (CUB)	100	O	7650004
CGP-7-100	3	00 (CUB)	100	O	7650005
CGP-1-160	3	00 (CUB)	160	O	7650006
CGP-7-250	3	1 (CUB)	250	I / I	7650010
CGP-7-400	3	2 (CUB)	400	O / I	7650011
CGP-9-250	3	1 (CUB)	250	I	7650013
CGP-9-400	3	2 (CUB)	400	I	7650014
CGP-10-250	3	1 (CUB)	250	I	7650018
CGP-11-250	3	1 (CUB)	250	I	7650019

Note 3: As it is shown in *Table 1* and specified in *Fig. 3*, scheme 1 corresponds to a monophasic power supply meanwhile schemes 7, 9, 10 y 11 correspond to a triphasic power supply.

Note 4: Column "Use" refers to the location in which the SFB can be placed. Here, "O" refers to "Outside" while "I" refers to "Interior". In the case of "Interior use", the SFB needs to be protected from severe weather conditions.

Triphasic power supply

In the cases where there is triphasic power supply, the most common schemes are 7 and 9. Their characteristics and differences have been gathered in *Table 2*.

Table 2: Most common schemes for triphasic supply.

	Scheme 7	Scheme 9
Supply entry point	Lower part	Lower part
Power Supply output	Lower part	Upper part
Outdoors	Suitable (if weatherproof enclosure in the upper part)	Unsuitable (flush-mounted installation)
Underground networks	Suitable	Suitable
Overhead networks	Suitable	Suitable (flush-mounted installation)

ANNEX V – LV NETWORK CHARACTERISATION

IBERDROLA

GUÍAS BÁSICAS

GRUPO: Procesos y Tecnología
SUBGRUPO: Telecomunicaciones

Negocio de Redes

TITULO: **Caracterización de red BT para despliegue BPL.**

BPL-BT_01

ORGANISMO EMISOR: **PROCESOS Y TECNOLOGÍA** FECHA: 19/07/2023 REVISION: 0

HOJAS 12

ÍNDICE

Preparado Comprobado Aprobado

CONTROL DE REVISIONES

REVISION	FECHA	MOTIVO	HOJAS REVISADAS

1. OBJETO

Este documento recoge las consultas que se requieren para poder hacer una caracterización de la red de baja tensión (BT) que incluya los datos necesarios para la toma de decisiones sobre las inyecciones de *Broadband Power Line Communications* (BPL). El objetivo final es tener toda la información necesaria para completar el **despliegue de BPL en la red de BT**.

2. ALCANCE

La información que se necesita para caracterizar la red BT proviene de dos fuentes principalmente:

- *MapInfo Professional 12.0.*
- Base de Terceros (BD3) de Genesis.

Como se entiende que la consulta de la BD3 de Genesis puede hacerse de forma general y a través de distintos *softwares* (i.e. Microsoft Access, Oracle, etc.), se aportará la información necesaria para poder hacer esas consultas y se deja a preferencia de cada usuario el método para obtener los parámetros de salida deseados.
En caso de no tener procedimiento preferido, se aconseja seguir el tutorial de "Acceso a la Base de Datos de Terceros" reflejado en la Guía Básica con título "Proceso de caracterización de la red para el despliegue de BPL en BT" cuyos pasos principales se han replicado en este documento: ver Anexo *4.2. Acceso a la BD3 de Genesis.*

Por el contrario, como *MapInfo* es un programa creado para las particularidades de la red de baja tensión de i-DE, se explica en la sección *3. DESARROLLO* el **procedimiento a realizar para extraer la información necesario para caracterizar la red de BT y obtener las variables que son decisivas para hacer las inyecciones de BPL que hagan posible su despliegue**.

Observación:
Los parámetros que se obtienen de *MapInfo* se han obtenido a través de cálculos realizados por el equipo a cargo de esta herramienta y se basan en datos recogidos en Genesis. Se deben descargar desde *Mapinfo* porque no se ha realizado el volcado de datos de dichos cálculos a otra base de datos. El resto de los datos – los no procesados provenientes directamente de Genesis – podrán obtenerse según las consultas especificadas en la sección *4. ANEXOS.*

3. DESARROLLO

En esta sección, se describe el procedimiento para conseguir descargar el archivo *.csv* que almacena la información propia de cada cuadro de baja tensión (CT) que se considera necesaria para la caracterización de la red de BT para el despliegue de BPL en dicha red.

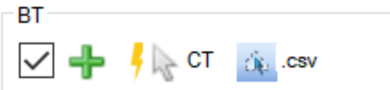
3.1. Procedimiento para la obtención de los datos propios del CT.

1. Iniciar la aplicación.
2. En el Menú de inicio, seleccionar: "Abrir el último entorno de trabajo: SICOID-19.wor".
3. Selecciones en el panel de la izquierda según preferencias de visualización:
   * Para la obtención del mencionado archivo .csv, sólo sería necesaria la selección de la Red de Baja tensión (apartado b); sin embargo, se especifican otras visualizaciones por si ayudan a la visualización de la red y a la comprensión del entorno del CT que se quiere analizar.

   a. Red de Media Tensión: SIGRID > MT/AT/MT > [Primer recuadro]
   b. Red de Baja Tensión: SIGRID > BT > [Primer recuadro]
   c. Vista de satélite / ortofoto: Cartografía > IGN PNOA.

4. Búsqueda del CT que se quiere analizar.
   a. Por nombre del CT: en el menú de la izquierda, clicando el símbolo de la lupa. Esta opción requiere, también, conocer la provincia en la que se encuentra dicho CT.
   b. Por código del CT: en el menú de la izquierda, clicando el símbolo de la lupa con un "1".

5. Descargar el archivo .csv para el CT seleccionado.
   a. Hay que asegurar que el recuadro de la sección SIGRID > BT está seleccionado.
   b. Con el símbolo de la flecha "Seleccionar" clicado (ver barra superior), elegir el CT que se desea analizar.
      * Para confirmar que la selección se ha hecho correctamente, comprobar en la barra inferior que tras el título "Selecionando:" aparezca el elemento "Instalación".
   c. Clicar en el símbolo de .csv como el que se muestra a continuación.



   d. Aceptar en el cuadro de diálogo que aparece avisando que se va a procesar 1 instalación.

3.2. Datos que se obtienen en la descarga de Mapinfo.

Para cada CT, el archivo que se obtiene muestra una fila por cada CGP correspondiente a dicho CT. Además, hay filas que guardan las bifurcaciones (denominadas BF) en *MapInfo* y que se representan en el plano como cruces.

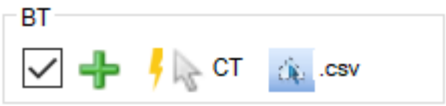
Los campos que se obtienen en esta descarga de datos se especifican a continuación:

cod_usuario	nombre	num_linea	cod_cgp	num_abona
ID_USUARIO del CT.	Nombre con el que se identifica el CT.	Línea BT del CT en la que se encuentra la CGP.	Cógido de la CGP.	Número de clientes en cada CGP.

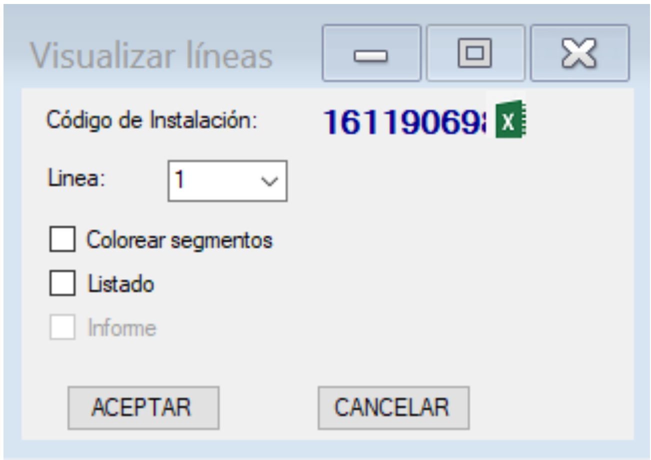
modelo	distanciaCT	distanciaCGPproxima	codigoCGPproxima
Esquema de la CGP.	Distancia de la CGP al CT.	Distancia de la CGP a la anterior en la misma línea.	Código de dicha CGP anterior en la misma línea.

3.3. Consulta particularidades de las líneas de baja de tensión de cada CT.

MapInfo permite la consulta individual de la información para cada línea BT. Para ello, en el recuadro de BT, seleccionar el símbolo de la flecha junto al rayo.



Con esa opción seleccionada, elegir el CT que se desea visualizar en detalle. De esta manera, aparecerá un cuadro como el siguiente:



Este cuadro permite la visualización de cada línea, para hacer uso de él:

1. Elegir línea que se desea analizar: seleccionarla en el desplegable.
2. Colorear los segmentos que componen dicha línea: seleccionar “Colorear segmentos”.
3. Obtener la información y parámetros que se tienen de cada línea: seleccionar “Listado”. Con esta opción, se creará una tabla que recoge los datos que se obtienen en la descarga del .csv completo (que se ha explicado en el apartado anterior) pero en este caso sólo para la línea seleccionada.

4. ANEXOS

4.1. Consultas de BD3 de Genesis.

Este anexo contiene un resumen de las consultas que se tienen que hacer en la Base de Terceros (BD3) de Genesis para obtener los datos que se consideran necesarios para el despliegue de BPL en BT que provienen de esta fuente.

Cada sección contiene el nombre de las tablas que se necesitan consultar, los campos que se necesitan para relacionarse con otras tablas y esas relaciones entre campos. Además, se incluye la selección de parámetros que se debe hacer para obtener la información necesaria. El tratamiento de colores que se ha hecho para estas tablas es el siguiente:

TÍTULO	Título de tabla utilizada en la consulta.
TÍTULO	Campo de la tabla utilizada en la consulta.
TÍTULO	Título de tabla de donde se obtienen parámetros de salida.
Número	Campos que se utilizan como parámetros de salida.
Nota	Aclaración sobre tipo de unión distinta a la estándar.

* Las uniones, si no se especifica serán de tipo 1:
Incluir sólo las filas donde los campos combinados de ambas tablas sean iguales.

Nota: En la primera tabla que se especifica en cada una de las consultas, la titulada como "Entrada" aparece siempre una con denominación "CTs". Esta tabla corresponde a la lista de CTs que se quiere analizar refiriéndose a ellos con el ID_USUARIO (no el código G3E_FID) que les corresponde; es decir, se trata de una tabla de n filas y 1 columna en la que cada fila es el ID_USUARIO del/de los CTs de los que se quiere extraer la información.

Consulta G3E_FID

Obtiene el código G3E_FID correspondiente a cada CT (del que previamente sólo se sabe ID_USUARIO).

Entrada	Campo IN	Campo 1 IN	Tabla 1	Campo 1 OUT	Campo 2 IN	Tabla 2
CTs	ID_USUARIO	ID_USUARIO	GENESIS_EXT_CT_ALF	COD_MUNICIPIO	COD_MUNICIPIO	GENESIS_EXT_V_L_MUNICIPIO_VL

Campo	ID_USUARIO	G3E_FID	NOM_NOMBRE	NOM_MUNICIPIO
Tabla	CTs	GENESIS_EXT_CT_ALF	GENESIS_EXT_CT_ALF	GENESIS_EXT_V_L_MUNICIPIO_VL
Orden	-	-	-	-

Consulta Datos_CTs

Obtiene información general del CT: ID, nombre, municipio, tipo de solución de comunicaciones, tipo de CT, n° clientes, n° líneas BT y n° CGPs.

Entrada	Campo IN	Campo 1 IN	Tabla 1	Campo 1 OUT	Campo 2 IN	Tabla 2
CTs	ID_USUARIO	ID_USUARIO	GENESIS_EXT_CT_ALF	COD_MUNICIPIO	COD_MUNICIPIO	GENESIS_V_L_MUNICIPIO_VL
				Campo 1 OUT	Campo 3 IN	Tabla 3
				COD_CLA_CT	COD_CLA_CTM	GENESIS_EXT_V_E_CLA_CTM_VL

Campo	ID_USUARIO	NOM_NOMBRE	NOM_MUNICIPIO	TIP_SOL_COM	DES_DESCRIPCION	CAN_CLIENTES
Tabla	GENESIS_EXT_CT_ALF	GENESIS_EXT_CT_ALF	GENESIS_V_L_MUNICIPIO_VL	GENESIS_EXT_CT_ALF	GENESIS_EXT_CT_ALF	GENESIS_EXT_CT_ALF
Orden	-	-	-	-	-	-

Campo	CAN_LINEA_BT	CAN_CGP_LINEA_BT
Tabla	GENESIS_EXT_CT_ALF	GENESIS_EXT_CT_ALF
Orden	-	-

Consulta CAN_CUADROS

Completa la información del CT (Datos_CTs) añadiendo el valor de cantidad de cuadros BT que contiene.

Entrada	Campo IN	Campo 1 IN	Tabla 1
CTs	G3E_FID	ID_PADRE_CT	GENESIS_EXT_CUADRO_BT_ALF

Campo	ID_USUARIO	NUM_TRAFO: G3E_FID
Tabla	CTs	GENESIS_EXT_CUADRO_BT_ALF
Total	Agrupar por	Cuenta
Orden	Ascendente	-

Nota - Tipo de unión
3: Incluir TODOS los registros de 'CTs'
y sólo aquellos registros de 'GENESIS_EXT_POS_TRAFO_ALF' donde los campos combinados sean iguales.

Consulta CAN_TRAFOS

Completa la información del CT (Datos_CTs) añadiendo el valor de cantidad de transformadores que contiene.

Entrada	Campo IN	Campo 1 IN	Tabla 1	Campo 1 OUT	Campo 2 IN	Tabla 2
CTs	G3E_FID	ID_PADRE_CT	GENESIS_EXT_POS_TRAFO_ALF	G3E_FID	ID_PADRE_POS_TRAFO	GENESIS_TRAFO_ALF

Campo	ID_USUARIO	NUM_TRAFO: G3E_FID
Tabla	CTs	GENESIS_EXT_POS_TRAFO_ALF
Total	Agrupar por	Cuenta
Orden	Ascendente	-

Nota - Tipo de unión
3: Incluir TODOS los registros de 'CTs'
y sólo aquellos registros de 'GENESIS_EXT_POS_TRAFO_ALF' donde los campos combinados sean iguales.

Consulta Lin_CGPs

Obtiene información por cada línea BT del CT: CGPs en cada línea, n° de clientes (1F y 3F) por líneas y distancias (aéreas y subterráneas) de dichas líneas.

Entrada	Campo IN	Campo 1 IN	Tabla 1	Campo 1 OUT	Campo 2 IN	Tabla 2
CTs	ID_USUARIO	ID_USUARIO	GENESIS_EXT_CT_ALF	G3E_FID	ID_PADRE_CT	GENESIS_EXT_LINEA_BT_ALF
	Campo 2 OUT	Campo 3 IN	Tabla 3	Campo 3 OUT	Campo 4 IN	Tabla 4
	G3E_FID	ID_PADRE_LINEA_BT	GENESIS_EXT_CGP_ALF	COD_MUNICIPIO	COD_MUNICIPIO	GENESIS_EXT_V_L_MUNICIPIO_VL

Campo	ID_USUARIO	NOM_MUNICIPIO	NUM_LINEA_BT_PADRE	ID_CAJA	CAN_CLIENTES	CAN_CLIENTES_TRIF
Tabla	GENESIS_EXT_CT_ALF	GENESIS_EXT_V_L_MUNICIPIO_VL	GENESIS_EXT_CGP_ALF	GENESIS_EXT_CGP_ALF	GENESIS_EXT_CT_ALF	GENESIS_EXT_CT_ALF
Orden	-	-	-	-	-	-

Campo	LONG_A_LINEA_BT	LONG_S_LINEA_BT	CAN_DIST
Tabla	GENESIS_EXT_LINEA_BT_ALF	GENESIS_EXT_LINEA_BT_ALF	GENESIS_EXT_CGP_ALF
Orden	-	-	-

Consulta Segmentos

Divide las líneas BT de cada CT para dar información de los segmentos en los que están dividas: nº y código de segmentos y longitud total.

Entrada	Campo IN	Campo 1 IN	Tabla 1	Campo 1 OUT	Campo 2 IN	Tabla 2
CTs	G3E_FID	ID_PADRE_CT	GENESIS_EXT_LINEA_BT_ALF	G3E_FID	ID_PADRE_LINEA_BT	GENESIS_EXT_SEG_LINEA_BT_ALF

Campo	ID_USUARIO	NUM_LINEA	G3E_FID
Tabla	CTs	GENESIS_EXT_LINEA_BT_ALF	GENESIS_EXT_LINEA_BT_ALF
Orden	-	-	-

Campo	LONG_A_LINEA_BT	LONG_S_LINEA_BT	G3E_FID	LONG_TOT
Tabla	GENESIS_EXT_SEG_LINEA_BT_ALF	GENESIS_EXT_SEG_LINEA_BT_ALF	GENESIS_EXT_SEG_LINEA_BT_ALF	GENESIS_EXT_SEG_LINEA_BT_ALF
Orden	-	-	-	-

Consulta Canalizaciones

Para los segmentos canalizados (subterráneos), da información de esas canalizaciones: número, código y longitud total.

Entrada	Campo IN	Campo 1 IN	Tabla 1	Campo 1 OUT	Campo 2 IN	Tabla 2
CTs	G3E_FID	ID_PADRE_CT	GENESIS_EXT_LINEA_BT_ALF	G3E_FID	ID_PADRE_LINEA_BT	GENESIS_EXT_SEG_LINEA_BT_ALF
	Campo 2 OUT	Campo 3 IN	Tabla 3	Campo 3 OUT	Campo 4 IN	Tabla 4
	G3E_FID	G3E_FID_1	GENESIS_EXT_RELACION_N_M_ALF	G3E_FID_2	G3E_FID	GENESIS_EXT_CANALIZ_ALF

Campo	ID_USUARIO	NUM_LINEA	G3E_FID	LONG_A_LINEA_BT	LONG_S_LINEA_BT	G3E_FID
Tabla	CTs	GENESIS_EXT_LINEA_BT_ALF	GENESIS_EXT_LINEA_BT_ALF	GENESIS_EXT_SEG_LINEA_BT_ALF	GENESIS_EXT_SEG_LINEA_BT_ALF	GENESIS_EXT_SEG_LINEA_BT_ALF
Orden	-	-	-	-	-	-

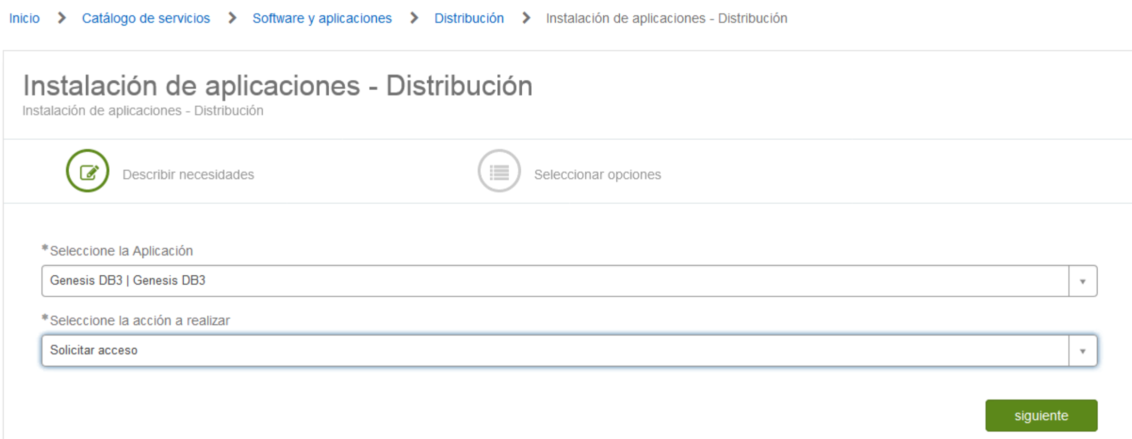
Campo	LONG_TOT	G3E_FID	LONG_TOT
Tabla	GENESIS_EXT_SEG_LINEA_BT_ALF	GENESIS_EXT_CANALIZ_ALF	GENESIS_EXT_CANALIZ_ALF
Orden	-	-	-

4.2. Acceso a la BD3 de Genesis.

En esta sección se detallará el proceso para acceder a las tablas recogidas en la Base de Datos de Terceros mediante el programa Microsoft Access. Para mayor detalle, referirse a la wiki en la que se puede encontrar material adicional como manuales y videotutoriales.

e. Solicitud de acceso a la base de datos.

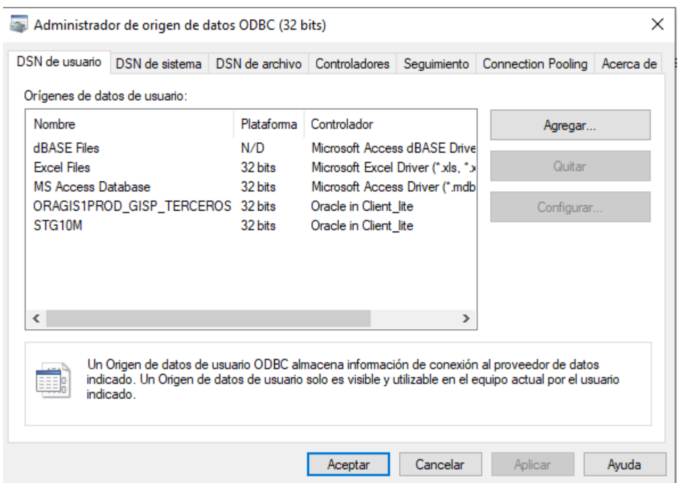
Para dar acceso al usuario a la BD de Terceros, es necesario realizar una petición a través del portal ITNow realizando la siguiente petición:



Una vez aprobada la petición por el supervisor correspondiente, se hará efectiva el alta en un máximo de 24h.

f. Configuración de la conexión OBDC.

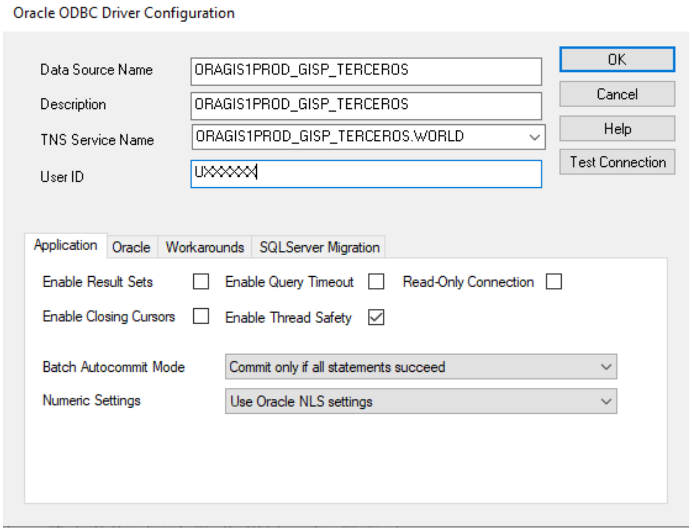
Para configurar la conexión es necesario acceder a la aplicación "ODBC Data Sources 32 Bits" mediante la barra de búsqueda o accediendo a Inicio > Panel de control > Sistema y seguridad > Herramientas administrativas> Origenes de datos OBDC. Se abrirá una ventana similar a esta:



En esa imagen, se encuentra ya configurado el acceso a la BD de Terceros. El proceso seguido para configurarlo de esta forma es el siguiente:

DNS Usuario > Agregar > Elegir "Oracle in Client_Lite" o "Oracle en OraClient11g_home"

Una vez seleccionado, configurar de la siguiente manera:



Configurando el User ID con el usuario para el que se haya solicitado acceso a la base de datos.

c. Base de Datos de Terceros preconfigurada.

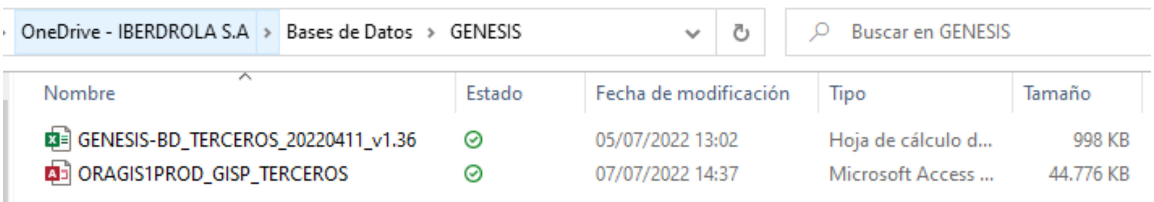
Para acceder a la base de datos, existe en la wiki la siguiente carpeta comprimida con las tablas en formato Access.

BD Access preconfigurada:

BD3-Produccion.zip

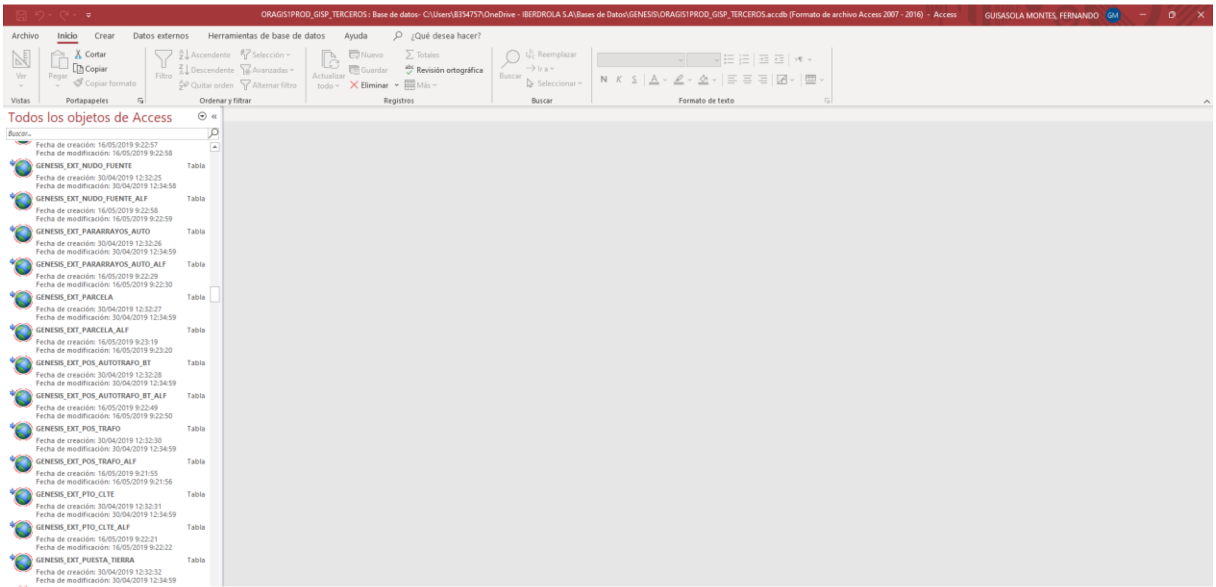
Descargando dicho archivo y descomprimiendo se obtiene acceso a todas las tablas de la DB de Terceros. Es recomendable descargar el archivo Excel "GENESIS-BD_TERCEROS_XXX_vXX" en su versión más actualizada de la sección "Conexión y acceso" de la misma wiki.

El resultado con ambos archivos descargados es el siguiente:

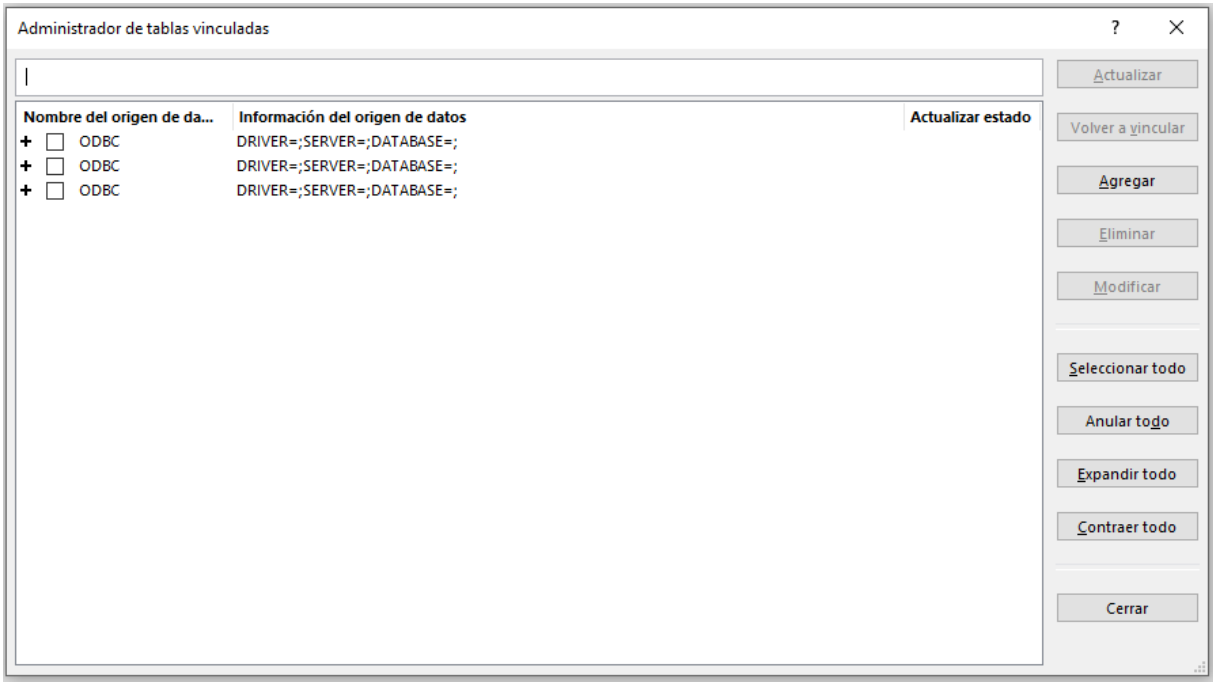


d. Actualización de las tablas de la BD de Terceros.

Una vez abierta la base de datos deberá tener un aspecto similar a este:



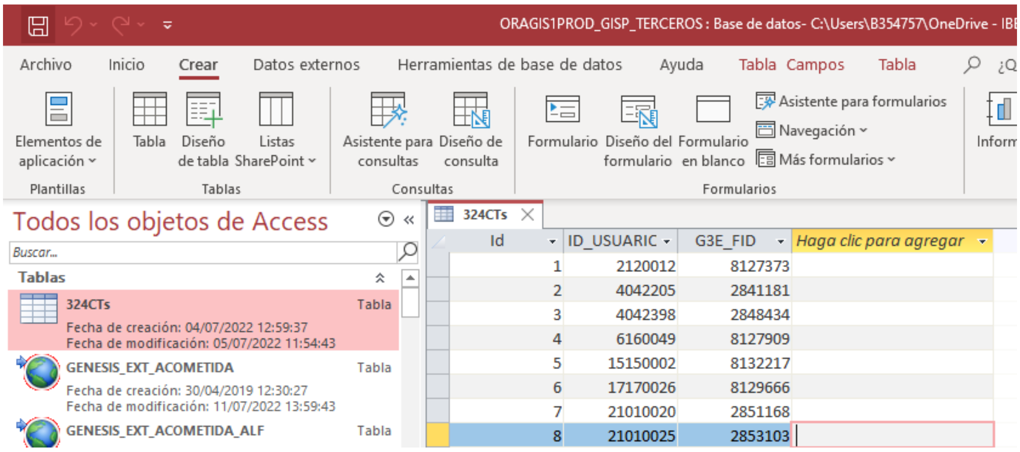
En la sección “Todos los objetos de Access” haciendo clic derecho sobre las tablas y seleccionando “Administrador de Tablas Vinculadas” aparece la siguiente ventana:



Buscando por nombre la tabla que se quiera actualizar se pueden seleccionar tantas tablas como se necesiten actualizar antes de realizar una consulta.

e. Creación de una tabla nueva

Para crear una nueva tabla como es el caso de la tabla “324CTs” que se utilizará más adelante, es necesario ir a la pestaña “Crear” y seleccionar “Tabla”.



Esta tabla en concreto es una lista de CTs que quieren analizarse refiriéndose a ellos con su ID_USUARIO; es decir, se trata de la tabla titulada “CTs” (tabla “Entrada” en la especificación de las consultas que se han hecho en la sección *3.1. Consultas de BD3 de Genesis).*

Otra forma de crear tablas es importándolas directamente de un archivo en la pestaña “Datos Externos”. Para ello, seleccionar “Nuevo Origen de datos” y elegir tipo de archivo y directorio.

f. Realizar una consulta básica

Para realizar las consultas usando directamente las tablas y campos tal y como se ha especificado en la anterior sección:

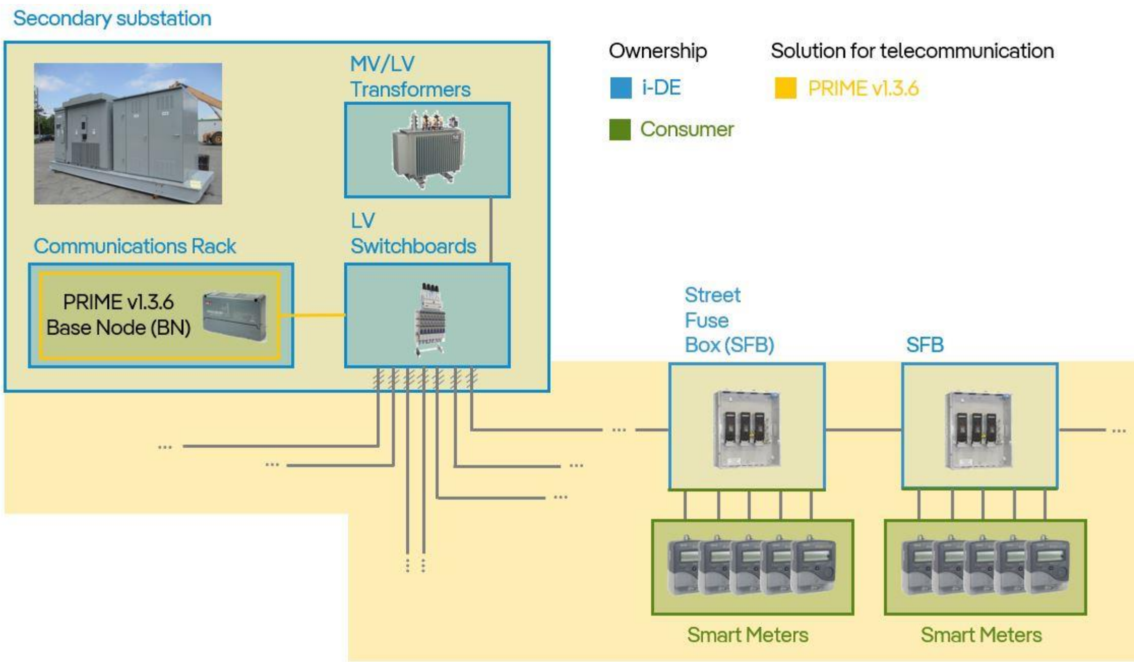
1. Crear consulta: Menú superior “Crear” > “Diseño de consulta.
2. En la esquina inferior derecha, asegurarse de que se ha seleccionado la opción para realizar la consulta seleccionando directamente las tablas deseadas.

3. En el menú lateral izquierdo, buscar y seleccionar las tablas que se necesitan (coloreadas en verde oscuro en la anterior sección).
4. Buscar los campos que se requieran (Campo IN y Campo OUT en la anterior sección) dentro de los parámetros de cada tabla. Seleccionar el parámetro de salida y unirlo al de entrada de la siguiente tabla.
5. Para la selección de parámetros de salida que se desean, en el menú inferior, escribir los campos tal y como se han especificado en la anterior sección (*3.1. Consultas de BD3 de Genesis*).
6. Seleccionar “Ejecutar” en el menú superior y esperar a la creación de la base de datos.

ANNEX VI – LV GRID TOPOLOGY TRANSFORMATION

LV grid now.

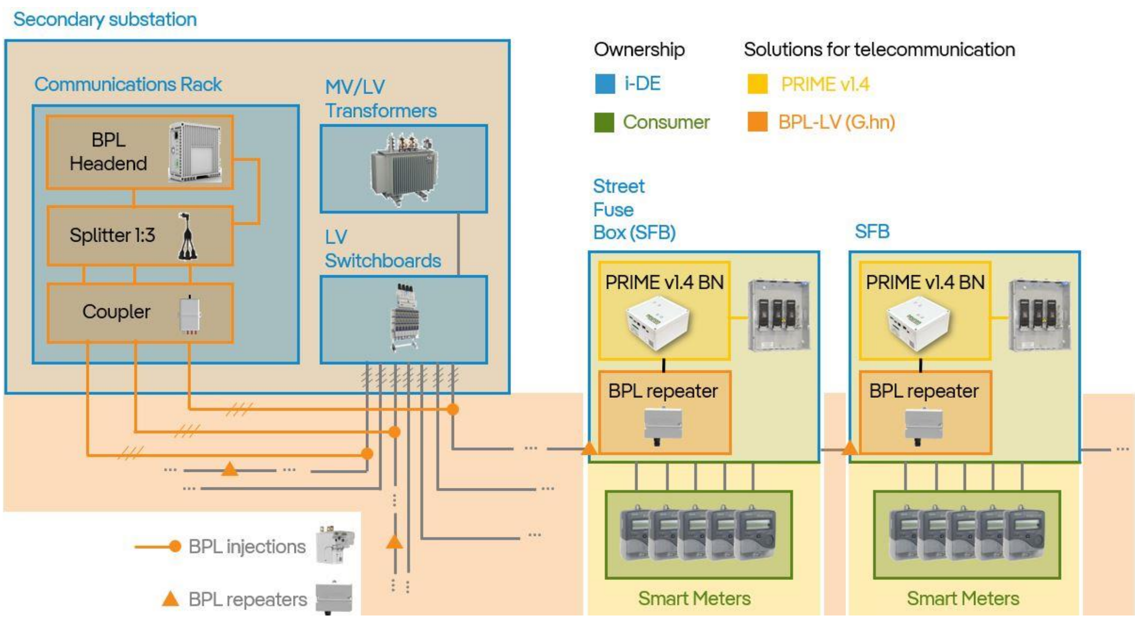
· PRIME v1.3.6 network from the secondary substation to the smart meters.



LV grid after the BPL over LV deployment.

· Broadband PLC (BPL) from the secondary substation to the street fuse boxes.

· Narrowband PLC (PRIME v1.4) from each street fuse box to its smart meters.



ANNEX VII – WELSH-POWELL ALGORITHM

The stated steps to follow the *Welsh-Power Algorithm* has been described in section *4.4. NB-PLC Network: Selection of PRIME Channels.* Based on them, this annex will take an example graph to explain the step-by-step of this algorithm that ends solving the colouring problem as represented in *Figure 70*.

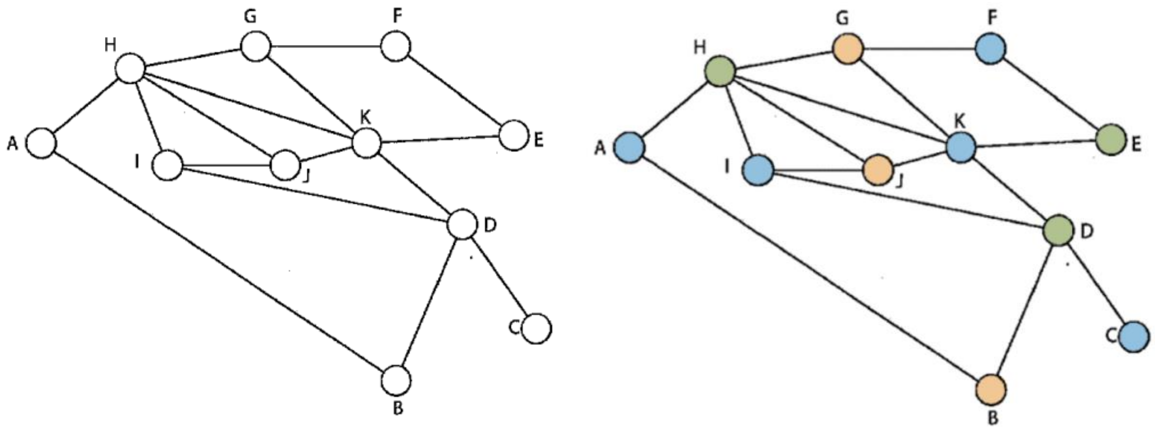


Figure 70: Graph to describe the Welsh-Powell Algorithm. [93]

Steps 1 and 2: Calculate the degree of each vertex (the number of edges that end in each vertex of the graph) and list the vertices in order of descending degree.

Vertex	A	B	C	D	E	F	G	H	I	J	K
Degree	2	2	1	4	2	2	3	5	3	3	5
Order	7th	8th	11th	3rd	9th	10th	4th	1st	5th	6th	2nd

Steps 3 and 4: Colour the first vertex in the list with colour 1 (green in *Figure 70*) and go down the list to colour every vertex not connected to the coloured ones above.

1st = vertex H: Colour 1.

2nd = vertex K: No colour 1 because it connects with H.

3rd = vertex D: Colour 1.

4^{th} = vertex G: No colour 1 because it connects with H.

5^{th} = vertex I: No colour 1 because it connects with H.

6^{th} = vertex J: No colour 1 because it connects with H.

7^{th} = vertex A: No colour 1 because it connects with H.

8^{th} = vertex B: No colour 1 because it connects with D.

9^{th} = vertex E: Colour 1.

10^{th} = vertex F: No colour 1 because it connects with E.

11^{th} = vertex C: No colour 1 because it connects with D.

Step 5: Repeat the process on the uncoloured vertices with the new colours.

5.a. Colour 2 (blue in *Figure 70*).

2^{nd} = vertex K: Colour 2

4^{th} = vertex G: No colour 2 because it connects with K.

5^{th} = vertex I: Colour 2.

6^{th} = vertex J: No colour 2 because it connects with I.

7^{th} = vertex A: Colour 2.

8^{th} = vertex B: No colour 2 because it connects with A.

10^{th} = vertex F: Colour 2.

11^{th} = vertex C: Colour 2.

5.b. Colour 3 (orange in *Figure 70*).

4^{th} = vertex G: Colour 3.

6^{th} = vertex J: Colour 3.

8^{th} = vertex B: Colour 3.

ANNEX VIII – GREEDY COLOURING ALGORITHM

The annex develops the *Python3* implementation to colour graphs as the represented in *Figure 71*. The objective is to apply the Greedy colouring algorithm to solve this problem and obtain two different solutions that prove that the application of this algorithm is not unequivocal depending on the vertices' numeration.

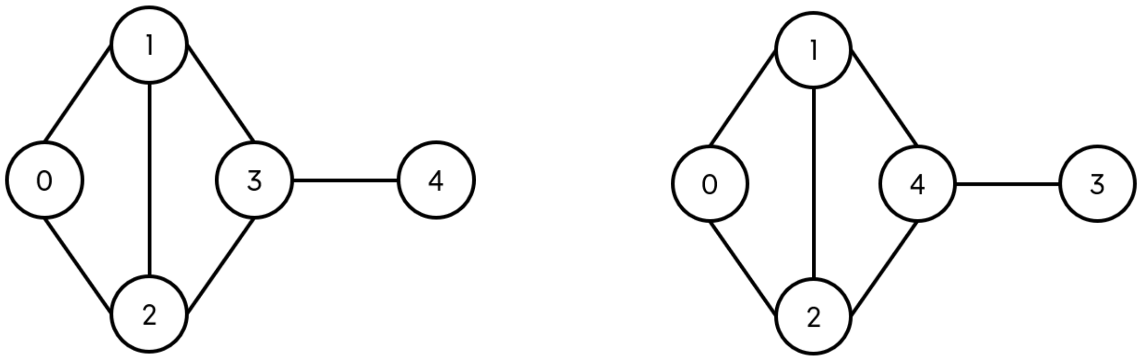


Figure 71: Uncoloured graphs before colouring algorithm implementation. [Own preparation]

VIII.1. PYTHON3 PROGRAM.

```
# Python3 program to implement greedy algorithm for graph coloring

def addEdge(adj, v, w):

    adj[v].append(w)

    # Note: the graph is undirected
    adj[w].append(v)
    return adj

# Assigns colors (starting from 0) to all
# vertices and prints the assignment of colors
def greedyColoring(adj, V):

    result = [-1] * V

    # Assign the first color to first vertex
    result[0] = 0;
```

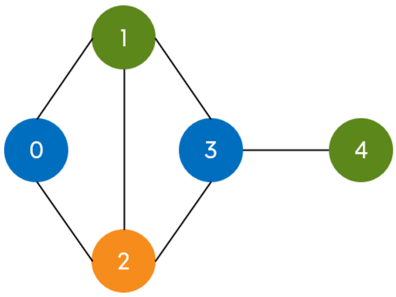
```
     # A temporary array to store the available colors.
    # True value of available[cr] would mean that the
    # color cr is assigned to one of its adjacent vertices
    available = [False] * V

    # Assign colors to remaining V-1 vertices
    for u in range(1, V):

        # Process all adjacent vertices and
        # flag their colors as unavailable
        for i in adj[u]:
            if (result[i] != -1):
                available[result[i]] = True

        # Find the first available color
        cr = 0
        while cr < V:
            if (available[cr] == False):
                break

            cr += 1

        # Assign the found color
        result[u] = cr

        # Reset the values back to false
        # for the next iteration
        for i in adj[u]:
            if (result[i] != -1):
                available[result[i]] = False

    # Print the result
    for u in range(V):
        print("Vertex", u, " --->  Color", result[u])

# Driver Code
if __name__ == '__main__':

    g1 = [[] for i in range(5)]
    g1 = addEdge(g1, 0, 1)
    g1 = addEdge(g1, 0, 2)
    g1 = addEdge(g1, 1, 2)
    g1 = addEdge(g1, 1, 3)
    g1 = addEdge(g1, 2, 3)
```

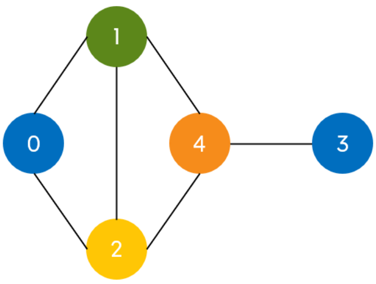
```
g1 = addEdge(g1, 3, 4)
print("Coloring of graph 1 ")
greedyColoring(g1, 5)

g2 = [[] for i in range(5)]
g2 = addEdge(g2, 0, 1)
g2 = addEdge(g2, 0, 2)
g2 = addEdge(g2, 1, 2)
g2 = addEdge(g2, 1, 4)
g2 = addEdge(g2, 2, 4)
g2 = addEdge(g2, 4, 3)
print("\nColoring of graph 2")
greedyColoring(g2, 5)
```

VIII.2. PYTHON3 OUTPUT.

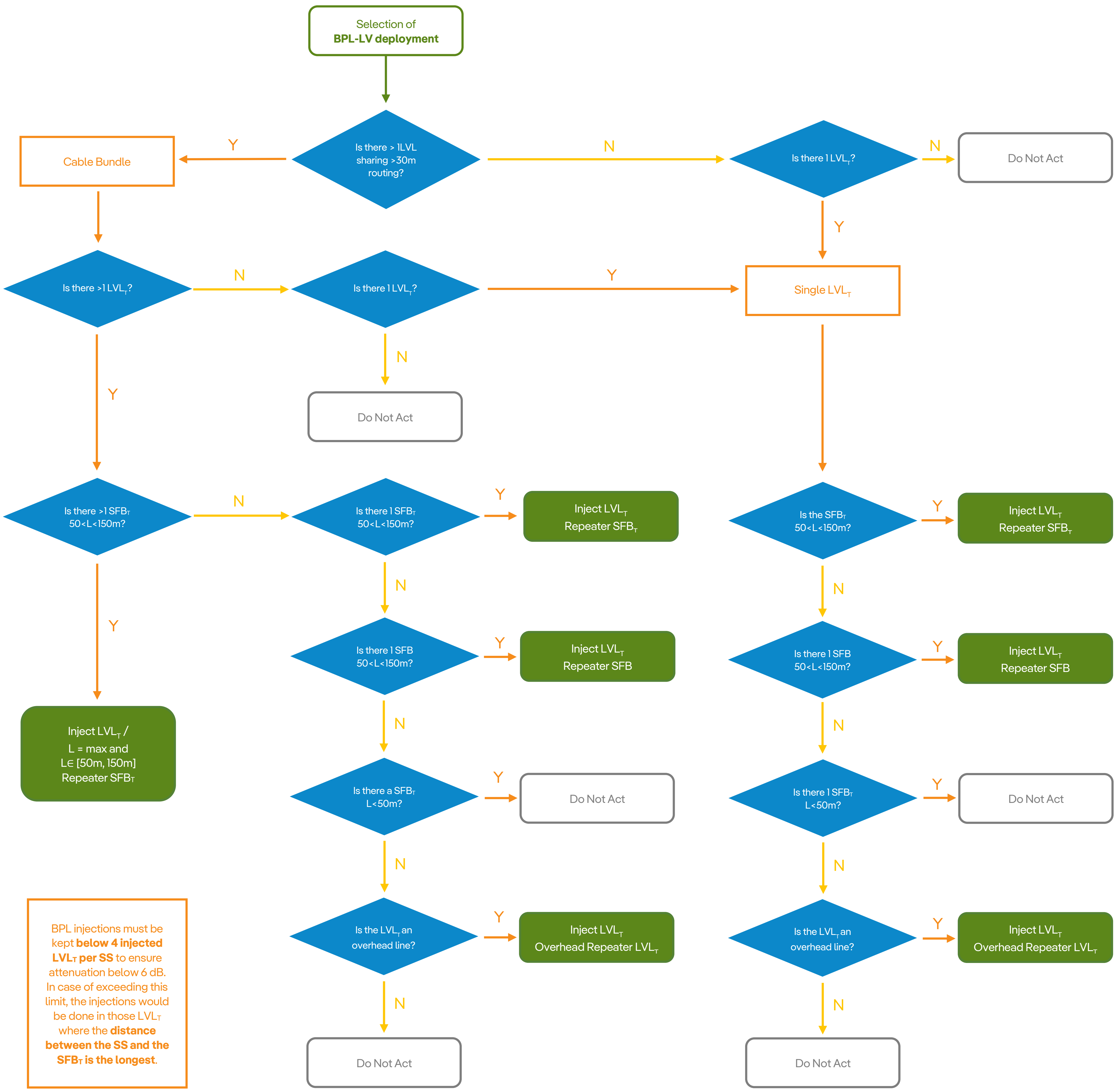
```
Coloring of graph 1
Vertex 0 --->  Color 0
Vertex 1 --->  Color 1
Vertex 2 --->  Color 2
Vertex 3 --->  Color 0
Vertex 4 --->  Color 1
```

```
Coloring of graph 2
Vertex 0 --->  Color 0
Vertex 1 --->  Color 1
Vertex 2 --->  Color 2
Vertex 3 --->  Color 0
Vertex 4 --->  Color 3
```

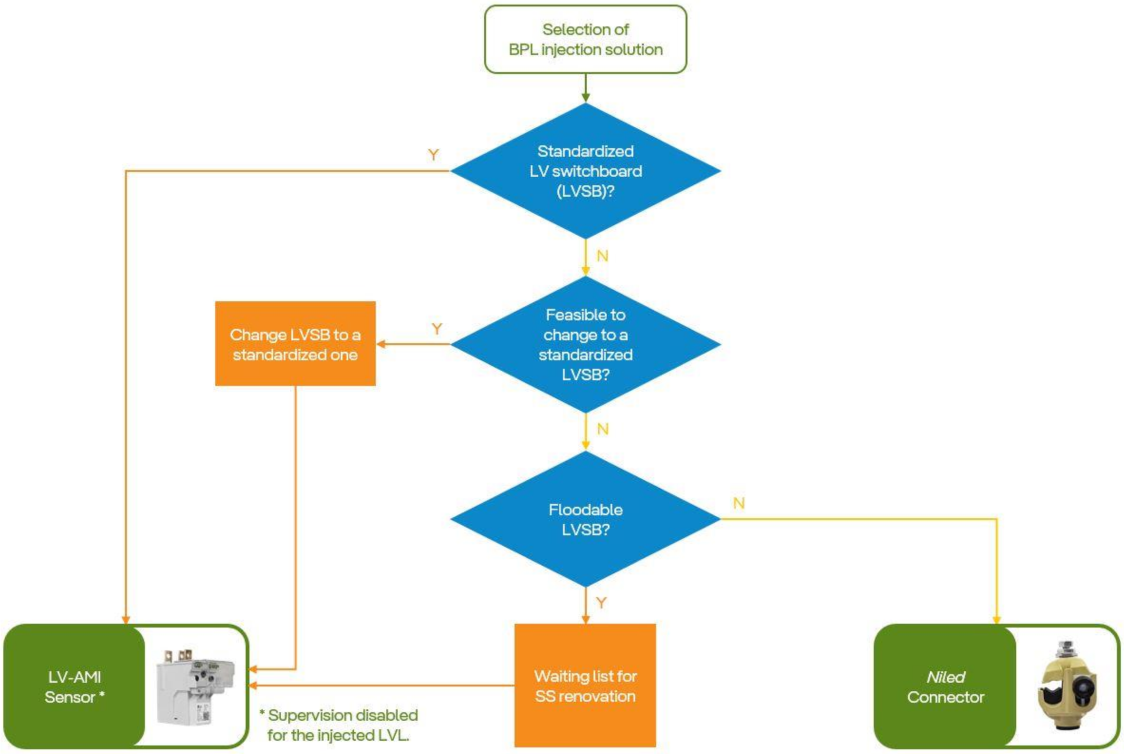




ANNEX IX – BPL OVER LV DEPLOYMENT.


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
Is the SFB_T 50<L<150m?
Y
Inject LVL_T Repeater SFB_T
Y
Inject LVL_T / L = max and L∈ [50m, 150m] Repeater SFB_T
N
Is there 1 SFB 50<L<150m?
Y
Inject LVL_T Repeater SFB
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 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
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**.

ANNEX X – BPL INJECTION SOLUTION


Selection of
BPL injection solution
Standardized
LV switchboard
(LVSB)?
Y
N
Feasible to
change to a
standardized
LVSB?
Y
Change LVSB to a
standardized one
N
Floodable
LVSB?
N
Y
LV-AMI
Sensor *
Waiting list for
SS renovation
Niled
Connector
* Supervision disabled
for the injected LVL.