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Sustainable strategy for the implementation of energy efficient smart public lighting in urban areas: case study in San Sebastian

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ABSTRACT

Public lighting connects hundreds of millions of streetlights with access to power across the globe, being responsible for 19% of global electricity usage, 30% - 50% of a typical city's energy bill and the already exceeding levels of CO2 emissions. Consequently, this represents a priority issue for cities in their strategy towards sustainability. In this framework, the momentum for smart public lighting is growing as its implementation represent quick wins (such as increase security and safety, improve mobility, increase the attractiveness of public spaces, or improve quality of life for citizens) with a massive impact on energy savings and maintenance, and can be achieved through low-cost connectivity. This paper discusses the effectiveness, efficiency, and feasibility of any city establishing a smart public lighting infrastructure network. With this aim, a pilot intervention in San Sebastian's public lighting network is presented together with a holistic analysis based on the Value Creation Ecosystem (VCE) and the City Model Canvas (CMC) to visualise how such plans may offer public value with a long-term and sustainable approach. Additionally, relevant, and fundamental patterns and recommendations are provided, which may help other public managers effectively implement this service and scale-up its use and business model.

1. INTRODUCTION

Public lighting is a critical public service that affects social wellbeing on multiple levels from crime prevention to mobility by enabling high visibility, which is imperative for the interaction of road users (Sánchez-Balvás et al, 2021; Mohandas et al., 2019; Steve Fotios 2018; van Bommel 2015; Peña-García, et al, 2015; Addy et al., 2004; Painter, 1996; Lynch et al., 1988); and it represents almost 40% of the energy consumed in European cities (Ozadowicz and Grela, 2014; and Gutierrez et al. 2015). The high energy consumption associated with public lighting lies in the business model offered in most European cities, which relies upon offering light all night to ensure visibility. Besides, the technology and facilities in place are obsolete and inefficient leading to poor quality lighting and light pollution and adding to energy consumption and maintenance costs (Green, Perkins, Steinbach, & Edwards, 2015; Sanchez-Sutil & Cano-Ortega, 2021).

Consequently, many systems are switching to LED (Light Emitting Diode) technology for high quality, efficient and low-maintenance lighting. According to The Northeast Group (2017), 89% of the planet's 363 million streetlights will adopt LED by 2027. However, the same source estimates that only 29% of those will have smart features that allow an on-demand light service (e.g. control management and sensors). Hence, these systems will remain with an inefficient business model offering light all night.

Smart public lighting integrates sensor and control with information and communication technologies to improve the efficiency of the system and reduce energy consumption (Castro et al., 2013; Todorović, & Samardžija, 2017; Petritoli et al., 2019b; Al Irsyad, Halog, & Nepal, 2019; Dwiyaniti & Nitisasmita, 2019; Sutopo, 2020). Examples of these readily available technologies include LED lighting and hardware solutions (e.g. light controller and lamp driver) (Ożadowicz & Grela, 2017; Lee et al., 2019), remote on-off control (Caponettoet et al., 2008; Liu

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et al., 2009; Lin, 2009; Mohamaddoust et al., 2011, Marino et al., 2017), smart street lighting control systems with intelligent streetlight management (Elejoste et al., 2013, Liu et al., 2017) or detection of moving objects (Srivatsa, et al, 2013), dimming or scheduling functions (Abdalaal et al., 2019). These solutions can be implemented through low-cost connectivity (Pasolini, et al., 2019) and have a massive impact on energy savings and maintenance (Shahzad et al., 2016; Soh et al., 2018; Khatavkar et al., 2017; Mahoor et al., 2017), which are the two main drivers to adopt smart public lighting in cities (Polzin et al., 2018). Furthermore, if energy savings and operation and maintenance costs are accounted for, the paybacks on the invested capital are short, ranging from 4 to 8 years (Cacciatore et al., 2017).

Beyond economising lighting, the network system offers opportunities for new smart city applications by integrating different services (Jin et al. 2016) and creating opportunities for innovation . On the one hand, servicer monitoring can offer real-time data about mobility and the environment, turning a traditional service into a source for real-time data. On the other hand, smart lighting offers great synergies among the stakeholders in city planning (e.g. local administration, energy suppliers and utility companies) (Riva Sanseverino et al., 2016), being able to integrate broadband connectivity, traffic light control, traffic management, smart parking, electric vehicle charging stations, air quality and noise monitoring or pedestrian footfall sensing (Cho et al., 2019).

This technology and the successful trials and large-scale implementation support the growing momentum for smart public lighting (Valentová, M. et al, 2015; Petritoli et al., 2019a; Dizon & Pranggono, 2021). Relevant testbeds include Barcelona, Copenhagen, and Chicago. In 2012, Barcelona published its Lighting Masterplan with 10,000 smart LED lamp posts including movement sensors and dimmers to save energy, remote management, free Wi-Fi for the citizens and air and noise pollution data collection. Copenhagen's 2014 lighting master plan involved 20,000 LED lamps and remote management and control, leading to savings of 65%. Chicago's smart lighting program launched in 2017 and entailed 270,000 LED lamps in 4 years, including a monitoring and control system to improve maintenance with real-time updates in case of an outage.

These testbeds demonstrate that it is feasible to create safer public spaces while reducing electricity consumption and costs and, consequently, decrease CO_2 emissions. For this reason, public lighting is a central piece in the EU's strategy towards sustainable cities (Jin et al. 2016). However, the question remains how can municipalities implement smart public lighting efficiently? This is one of the issues addressed in the 5-year research and development project REPLICATE (**Re**naissance of **Pl**aces with **I**nnovative **C**itizenship **A**nd **TE**chnologies) funded by the EU's Horizon 2020 Research and Innovation programme. This project aimed at deploying energy efficiency, mobility and ICT solutions in three lighthouse cities: Bristol (UK), Florence (Italy) and San Sebastian (Spain).

This study aims to propose a framework for the implementation of smart public lighting building on the pilot experience in San Sebastian within the scope of the REPLICATE project.

This study proposes a framework for the implementation of smart public lighting in cities from a business perspective that has been validated through the pilot experience in the municipality of San Sebastian (within the scope of the REPLICATE project). This framework or holistic city strategy was developed using the City Model Canvas (CMC) to assess the net balance of the policies and actions involved in the new business model and the Value Creation Ecosystem (VCE) to construct the business model network. The pilot experience allowed identifying the key elements for the replication and scaling-up of the intervention and provided valuable insight on how to transform city lighting infrastructure into a smart and energy-efficient asset, thus contributing to a more modern, efficient, accessible, and safer public spaces in cities.

2. METHODOLOGY

The research methodology selected to meet the objectives is the case study method. This research strategy is an empirical inquiry that investigates a contemporary phenomenon focusing on the dynamics of the case within its real-life context (Roth, S., 1999). It is an ideal method when the research aims to find answers to "why" and "how" types of questions when it is not possible to control the behavioural events (Teegavarapu et al, 2008).

While other methods focus on certain specific phases of research like (1) problem definition, (2) formation of hypothesis, (3) data collection or (4) data analysis etc, the case study is an all-encompassing method that covers all these phases .

3. CASE STUDY

3.1. *Selection of the city*

The case study was selected from the pilot implementations carried out in public lighting of the city of San Sebastian to provide a smarter, more efficient, environmentally friendlier, and more cost-effective system.

The municipality of San Sebastian (Donostia in Euskera) is the capital of the province of Guipuzcoa in the autonomous community of the Basque Country in northern Spain. It has a population of approximately 188,000 people. Despite being a relatively small city, San Sebastian has gained importance as one of Spain's main tourist destinations due to its coastal scenery and renowned cuisine (it has the second-highest number of Michelin-starred restaurants per capita in the world). The EU designated San Sebastian as the 2016 European Capital of Culture, which is a recognition of the city's cultural richness. Other services, especially in commerce and transport, are also important drivers of the city's economy.

San Sebastian has been internationally acknowledged for driving forward numerous smart city initiatives. In 2010, the Spanish government granted San Sebastian the title of City of Science and Innovation, IDC (an international firm specialising in information technology) ranked San Sebastian in the top 5 Spanish smart cities in 2011 due to its trajectory of developing smart city projects, and the EU granted the CIVITAS awards to San Sebastian in 2012 for innovative and sustainable urban mobility initiatives.

In terms of the public lighting system, San Sebastian counts with over 30,000 street light points with an annual cost of € 3.5 million due to energy consumption and € 1.8 due to maintenance. Like most cities in the world, San Sebastian still partially relies on old conventional technology. The term 'old technology' refers to HPSV light generation which stands for High-Pressure Sodium Vapour. The refurbishment conducted in the past consisted of more efficient but still conventional technology. Recently, the city started switching from conventional lamps to LED lamps; however, these did not include intelligent features.

3.2. *City values and needs*

San Sebastian has set several goals for its future public lighting infrastructure, which include (1) increasing the safety of public spaces and roads by providing high quality and optimal lighting level for pedestrians, cyclists, and drivers, (2) improving the energy efficiency of the services and (3) reducing operational and maintenance costs. Besides, the city is eager to simplify the installation and operation of municipal services.

These goals could be easily meet with an intelligent lighting network. The remote control system of the network would reduce the energy consumption, environmental impact and costs of operation and maintenance. High-quality products that are easily replaceable and adaptable to the lampposts should be used to keep the maintenance costs to a minimum and ensure the sustainability of the solution from an environmental standpoint.

Implementing a project of such a scale does not come without hurdles and reluctance. In Europe, the tendency is to change the old technology (high-pressure sodium vapour or mercury vapour lights, among others) for LED technology to reduce energy consumption and discarding the possibility of implementing a smart management system that has a greater impact on the efficiency of the service. This is undoubtedly linked to the high initial investment for purchasing and installing the smart lampposts. Besides, San Sebastian must follow specific design criteria to maintain a uniform urban landscape in certain areas of the city (i.e., historical areas). In most cases, the traditional lighting designs cannot be adapted to incorporate the new technologies.

4. CITY BUSINESS MODEL FOR SMART PUBLIC LIGHTING PROJECTS

Many cities, like San Sebastian, are eager to explore the opportunities offered by smart public lighting to overcome the rigid, expensive, and inefficient approach of the traditional network and incorporate smart features to the service that meets the needs of the citizens. Hence, this section presents the City Model Canvas (CMC) and the Value Creation Ecosystem (VCE) through which the city defined the strategy for implementing the smart public lighting in to create energy-efficient, cleaner, safer, and more liveable spaces for citizens.

4.1. City Model Canvas

The business model canvas (BMC), as proposed by Osterwalder and Pigneur (2010), visually represents the elements of a business model and the potential interconnections and impacts on value creation (Wallin et al., 2013, Bocken et al., 2014) to align profit and purpose to support more sustainability-oriented value creation model. Joyce & Paquin (2016) and Díaz-Díaz et al. (2017) extended the original BMC by adding the environmental and social layer to create a triple bottom line assessment accounting for environmental and social values which were not implicitly considered in the BMC canvas's (mainly profit or economic value-orientated) (Upward, 2013; Coes, 2014). When taken together, the three layers of the business model explicitly show how an organization generates multiple types of value – economic, environmental and social.

More recently, Timeus, Vinauxa & Pardo-Bosch (2020) replaced several blocks of the canvas with others that are more closely related to public operations and proposed a framework called the City Model Canvas (CMC). The CMC is composed of fourteen blocks, divided into four main areas, as seen in Fig. 8:

1 value proposition,
2 producing value (key partnerships, key activities and key infrastructure and resources),
3 delivering value (buy-in support, deployment and beneficiaries), and
4 the triple-layered bottom line (budget costs, environmental costs, social risks, revenue streams, environmental benefits and social benefits).

According to Pardo-Bosch, Cervera & Ysa (2019) and Pardo-Bosch et al. (2021), the CMC represents a useful tool that city councils and public administrations can use to assess, from a holistic perspective, the net balance of their policies and actions when designing new business

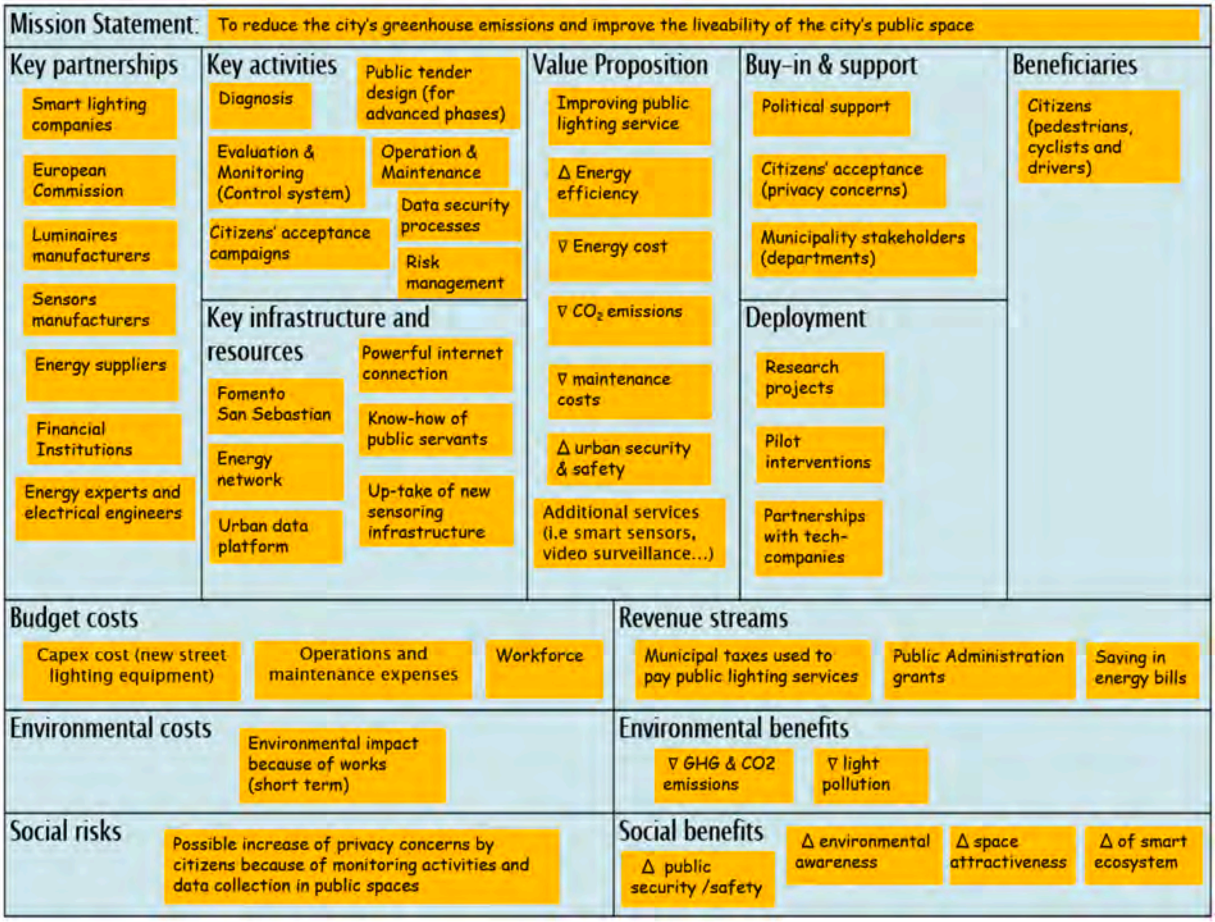

Fig. 1. City business model of smart public lighting services in San Sebastian.

models which can deliver on multiple objectives.

San Sebastian's city model canvas for smart public lighting interventions

The city strategy aims at reducing greenhouse emissions and improving the liveability in the city through smart public lighting services. The CMC presented in Fig. 1 enables cities like San Sebastian to straightforwardly organise their resources and activities to create and deliver public value to their citizens in a way that is economically viable, socially inclusive, and environmentally sustainable.

The *value proposition* of the model is to improve the public lighting system and implement new services taking advantage of the existing infrastructure. Particularly, it focuses on light management optimisation through the installation of LED lighting technology, the implementation of remote-control management and the transformation of the electrical infrastructure into a communication network. Following the values and needs of San Sebastian, three aspects are key to the model and pilot:

- cutting costs due to energy consumption and, consequently, reducing light pollution and CO_2 emissions;
- decreasing maintenance costs by using an intelligent remote management system; and
- extending the services in the existing infrastructure by including sound systems, sensors and video surveillance among others.

The successful deployment of the business model relies on *key partnerships* with suitable stakeholders, *key activities* and *key infrastructure and resources* that sustain the implementation.

Relevant partners for this business model include funding or sponsoring institutions (e.g. European Commission and other public administrations) that facilitate the deployment through research and pilot projects; technical suppliers (i.e. smart lighting companies, sensor manufacturers and technology companies); energy experts, suppliers and electronic engineers that provide technical advice and support, especially, in the implementation phases.

The model also envisages a wide range of activities spanning from diagnosis and market research to operation and maintenance as well as data security process (see all activities in Fig. 1). An essential activity reflected on the model is the public or citizen acceptance campaign, which aims at advertising the intervention, describe its main features, address any privacy concerns and obtain feedback. This publicising campaign is paramount to obtain the citizen's buy-in and, hence, the approval of the future beneficiaries (pedestrians, cyclists, and drivers).

The support of the public administration is the most valuable resource in the implementation of the model as it sets favourable conditions for the development of the research and pilot projects. The know-how of the municipality technicians is also key to manage the service and ensure successful implementation (educational and training programmes on the new technologies may be required). Regarding infrastructures, aside from a powerful internet network structure and servers to enable connectivity and data transfer and storage, the operational headquarter is central for managing the operation of the entire system and for solving any possible incident.

As previously mentioned, *acceptance* of the intervention is vital. The politicians' buy-in will facilitate the public investment needed to transition from the conventional lighting system to the new one after the initial pilot project. For that, the payback of the investment is crucial in the decision-making. Public acceptance is addressed through the citizen acceptance campaign previously described. Commonly, the resistance in the early stages is linked to privacy concerns that are alleviated by explaining the commitment of the model to strictly follow general data protection regulations (GDPR) and work with anonymous and aggregated data that are not strictly related to safety and security objectives.

The sustainability of the business model focuses on the triple bottom line: *costs/revenues, environmental costs/benefits*, and *social risks/benefits*. Cities have two main revenue sources:

- municipality taxes used to pay the smart street lighting services, and
- grants from other public administrations.

Besides these sources of *revenue*, the business model highlights savings for the Municipality. These saving are related to the reduction of the infrastructure and operating and maintenance costs. The optimisation and remote-control management of the service will allow reducing workforce, times and resources. However, the highest saving will be the reduction in the municipality energy bills due to the use of smart LED lighting. The *budget cost* is related to the capex costs —expenditure in new lampposts and technologies— and opex costs —operating expenses for the correct function of the service. During the implementation phases, the capex cost will be much higher than the opex ones.

The *environmental impacts* are highly positive, being the most important ones the decreasing of CO_2 and GHG emissions and the lighting pollution. Regarding environmental costs, there is just a short impact on energy use during street lighting works.

Finally, the business model includes the *benefits and risks* of the intervention. Increased public safety, environmental awareness among the citizens, more attractive public spaces and an improved smart social ecosystem in the city are the main benefits highlighted by the model. Against these benefits, the identified social risk is a potential increase in privacy concerns, which can be mitigated. Hence, the potential risk is largely outbalanced by the benefits of the intervention.

4.2. *Value Creation Ecosystem*

An ecosystem is an interconnected set of services enabling users to fulfil a variety of needs in one integrated experience. Analysing the implications of innovative business models in multifaceted environments like public lighting requires a comprehensive approach to ensure that all the stakeholders obtain a benefit (Madina, Zamora & Zabala, 2016).

Such an approach must be carried out assessing:

- Industry opportunities and outlook to understand how much value is on the table (relevant factors include market size, growth potential, competitive strategy, and profitability).
- City strengths to evaluate if there is a natural owner of a given opportunity (important factors include the customer base, access to valuable data, relevance to the core business, capabilities and existing partnerships, networks and sister companies to leverage).

Pardo-Bosch, Cervera & Ysa (2019) propose the integration of these factors using a tool called the Value Creation Ecosystem (VCE), which is based on Allee (2000), to construct the business model network. VCE connects each actor with as many nodes as necessary, thus each relation of a node A (actor A) with a node B (actor B) generates two links: one which indicates the value that actor A creates for actor B, and another one from actor B to actor A which represents the value that A captures from its relation with B (this would represent the payback).

In the case of cities, and particularly, the public lighting system, the analysis of the VCE allows answering important questions such as: What are the activities needed to create value for the ultimate beneficiaries? Who are these ultimate beneficiaries? What actors/stakeholders are necessary to develop these activities? And what are the values captured? Although other models, such as e3-value (Gordijn, 2002), also attempt to somehow value those factors, in this manuscript the VCE will be used.

San Sebastian's value creation ecosystem (VCE) for smart public lighting interventions

This section presents the VCE needed for transforming the traditional public lighting system into a smart one (see Fig. 2). The municipality should act as the project owner for public lighting interventions. Due to the complexity of running this type of projects from scratch, it is recommended to have financial support from a public administration (e.g. European Commission) and share the role of project promoter with a

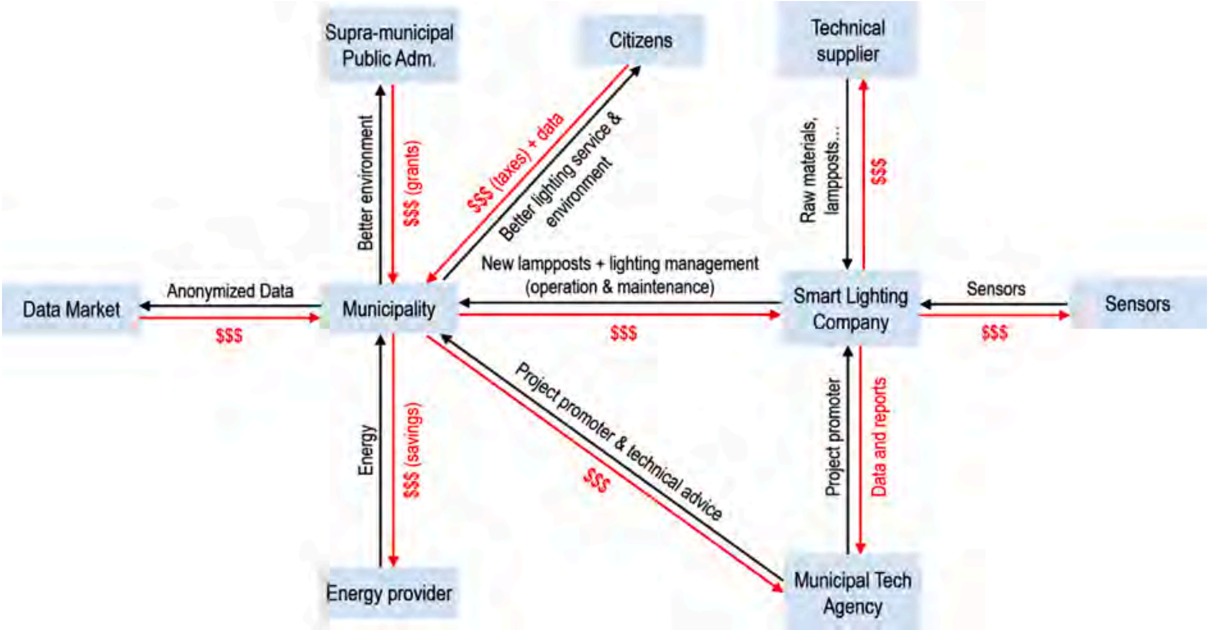

Fig. 2. Theoretical value creation ecosystem for smart public lighting services.

municipal agency (e.g., Fomento San Sebastian in the case of San Sebastian), to safeguard the public interest and the technical rigour that the city requires.

The municipality, through a public tender based on a competitive dialogue, contracts the installation of smart lampposts, the operation and maintenance of the smart public lighting service to a private company, identified in the VCE as Smart Lighting Company —Leycolan S.A. L. in the case of San Sebastian. Leycolan is a local technology-based company that designs, manufactures, and installs hardware and software components for the management of road and industrial lighting.

The smart lampposts, sensors and other materials could be provided by technology suppliers and sensor manufacturers if they are not manufactured by the Smart Lighting Company. Through this network of stakeholders, the municipality generates value for the citizens, who benefit from an improved lighting service and environment (i.e., pedestrians, cyclists and drivers). The municipality receives revenues from the taxpayers and commercialisation from the anonymized data could contribute to the payment of the smart public lighting services, the costs of which are significantly reduced due to the energy savings.

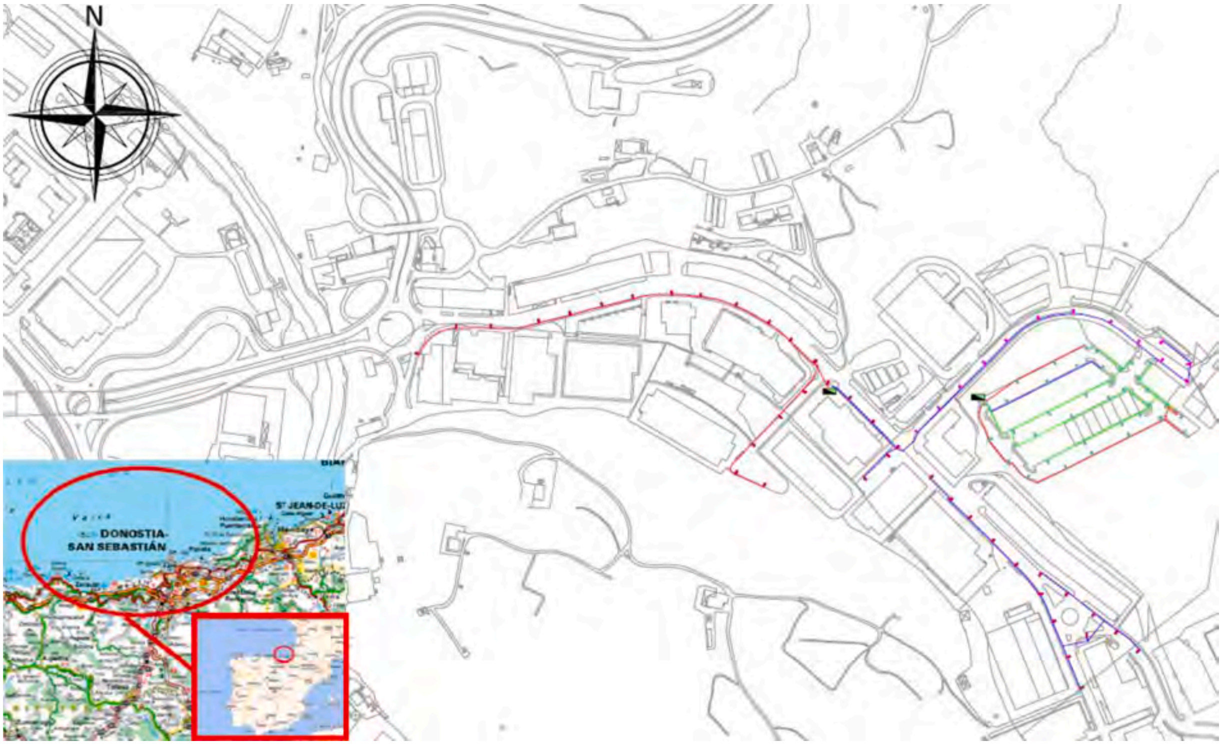

Fig. 3. Area covered in the pilot project and electrical circuits.

5. IMPLEMENTATION OF A SMART PUBLIC LIGHTING STRATEGY WITHIN REPLICATE PILOT PROJECT

5.1. Definition of the Pilot Project

The Urumea Riverside district (see Fig. 3) in San Sebastian is selected for the implementation of the pilot. The district covers three sites with a surface area of approximately 200 hectares: a residential area, an industrial park with over 300 companies employing 4,500 citizens and the largest natural park in the city (Ametzagaina Park). This pilot serves as a demonstrator for the implementation of the strategy in the whole city.

The pilot project was co-designed by the municipality and Leycolan, which was a partner in the REPLICATE project and was responsible for the implementation of the smart lighting in the pilot.

After a thorough analysis of the power grid infrastructure, the electrical circuits and the lighting needs, the proposal consisted of replacing the existing 90 lampposts of the area by 90 smart lampposts according to the following criteria (figure 4):

- Fifty-two conventional 250 W lamps for 120 W and 100 W LED lamps from Philips (SMD Led Modules) in the white area of figure 4, called from now on zone A.
- Thirty-eight 150 W lamps for 100 W LED lamps from Leycolan (SULKA model) with COB LED technology in the area shaded in green and delimited by a dashed line in figure 4, called from now on zone B

The incorporation of two LED lamps (SMD Led Modules and SULKA model) in the pilot study responds to a request from the municipality of San Sebastian, who wanted to assess the performance of both types.

The pilot project also entailed the installation of an intelligent remote-control system with two central cabinets, one for zone A, providing the power and control to its 52 lamps, and the second one for zone B providing the power and control to its 38 lampposts. Besides, the pilot implemented one control node in every lamppost and one concentrator at every control cabinet of each circuit. Each concentrator enables the communication among the different lamps. The communication takes places from each lamp to the concentrator (and viceversa) and from the concentrator to the server of the system. Fig. 4 presents an overview of the pilot project.

The LED technology, concentrator and control nodes convert the street light grid into a LAN ((Local Area Network) network over the power grid covering the street light installation grid. Every lamppost is an intelligent point where it is possible to connect an IP device that can work over the internet and promote IoT activities in the area. For example, the system can control every light point, monitor energy consumption, manage calendars, and regulate (DIM) the lights according to real-time needs. The communication is carried through the existing power line for the supply of energy to the lampposts. Therefore, no additional costs are generated.

To make the system more intelligent, specific detection systems are installed in some posts. These systems are composed of four wide-angle detection radars and 12 vision detection cameras to manage light regulation as needed by pedestrians and drivers, ensuring safety and efficiency.

The pilot also included 6 × 2 IP audio services, 4 IP vision cameras (2 for the Municipality police, and 2 for streaming viewing cameras, which are used for monitoring and surveillance of the state of the roads and spaces in the industrial park), 2 rain sensors, 1 vehicle counter and 2 energy meters. These devices enable the assessment of the real-time performance of the lighting service, regulation of the lights, and using the sound system to issue evacuation notices in the event of a risk of unexpected flooding caused by the rising of the river.

Fig. 5. Lampposts with different features: a) without IP services (System –control node is installed inside the pole); b) c) audio IP and video IP; d) e) vision detection devices; (f) (g) Chip On Board (COB) Led Light, vision detection and (h) (i) LED COB, System inside Pole, vision IP device, vision detection.

As with the previous system, the new intelligent system turns the lights on and off based on an astronomical clock that modifies the operating hours according to the needs of each period of the year. However, in general terms, from 9:00 to 18:00, the lights are turned off. From 18:00 to 22:00 the lights do not dim regardless of the absence of pedestrians or vehicles, thus working at 100% of their power. However, the new smart public lighting infrastructure allows activating presence detection from 22:00 to 9.00 and dimming the lights as required. In the presence of users, the lights are dimmed to 60% of their power and in the absence of users to 40%. Additionally, from 22:00 to 9:00, the rain sensor detection ensures visibility in case of rain by dimming the lights only to 60% of their power.

5.2. Pilot's outputs analysis: results and impacts

The effectiveness of the pilot was assessed by comparing the new smart public lighting against the existing lampposts. Hence, the project established a baseline monitoring in Zones A and B for 16 months - from January 2016 (month 1) to April 2017 (month 16) – before the installation of the new smart lampposts in May 2017 (month 17). The intervention was then monitored for another 44 months until December 2020 (month 60).

Figs. 6 and 7 present the power consumption —in kW— in Zones A and B, respectively. It is easily noticeable that from the moment in which the smart lampposts were installed (month 16 - identified with a broken line in both figures, 6 and 7) there is a general decrease in energy consumption. The reduction is constant and maintained over the months, despite the logical seasonal oscillation.

The effects of covid-19 were relatively low in the pilot because the industrial park where it is located remained operative most of the lockdown. However, it is important to mention that the pandemic affected zones A and B of the pilot unevenly. In zone A (figure 6), although the effect was modest, the lowest consumption of the entire historical series was registered in month 53, when Spain was under a total lockdown and even the companies were forced to stop their activity. With the reopening of the business's activities (month 54) the consumption in this zone was recovered. In zone B (figure 7), instead, the covid-19 pandemic did not affect the energy consumption because in this area of the pilot there are some essential companies that did not cease to operate during the total lockdown.

Fig. 8 presents the accumulated power consumption month by month from 2016 to 2020 for both zones. In both graphs, the implementation of the smart lighting features in May 2017 (month 4) leads to a change in the slope of the accumulated consumption (if compared to 2016) and it is parallel to the curves from subsequent years up to 2020. According to data, the measure implemented represents cumulative consumption savings of 43% in zone A at the end of the year in 2017 (only 8 months after the implementation) and around 75% in 2018 (74%), 2019 (77 %) and 2020 (76%).

In zone B, the measure implemented represents a cumulative consumption saving of 29% in 2017 (only 8 months after the implementation) and around 55% in 2018 (55%), 2019 (62%) at the and 2020 (50%). Fig. 8b shows an increase in energy consumption in Zone B in the year 2020 compared to years 2018 and 2019, which is due to the increase in the levels of lighting in the area at the request of the businesses operating in the area due to safety reasons. The lower savings in zone B are explained by the pre-existing lighting infrastructure in that area, which was newer and, therefore, more efficient. The nominal reduction of the power of the light was from 150 W in HPSV technology (conventional) to 100 W in LED, plus the detection system. Despite the smaller savings, the lighting system installed in May 2017 in zone B is as efficient as the system in zone A. In fact, the accumulated power consumption during the last three years is 13,733.6 kW in zone A and 8,913.3 kW in zone B. In addition, it is estimated that the actions taken

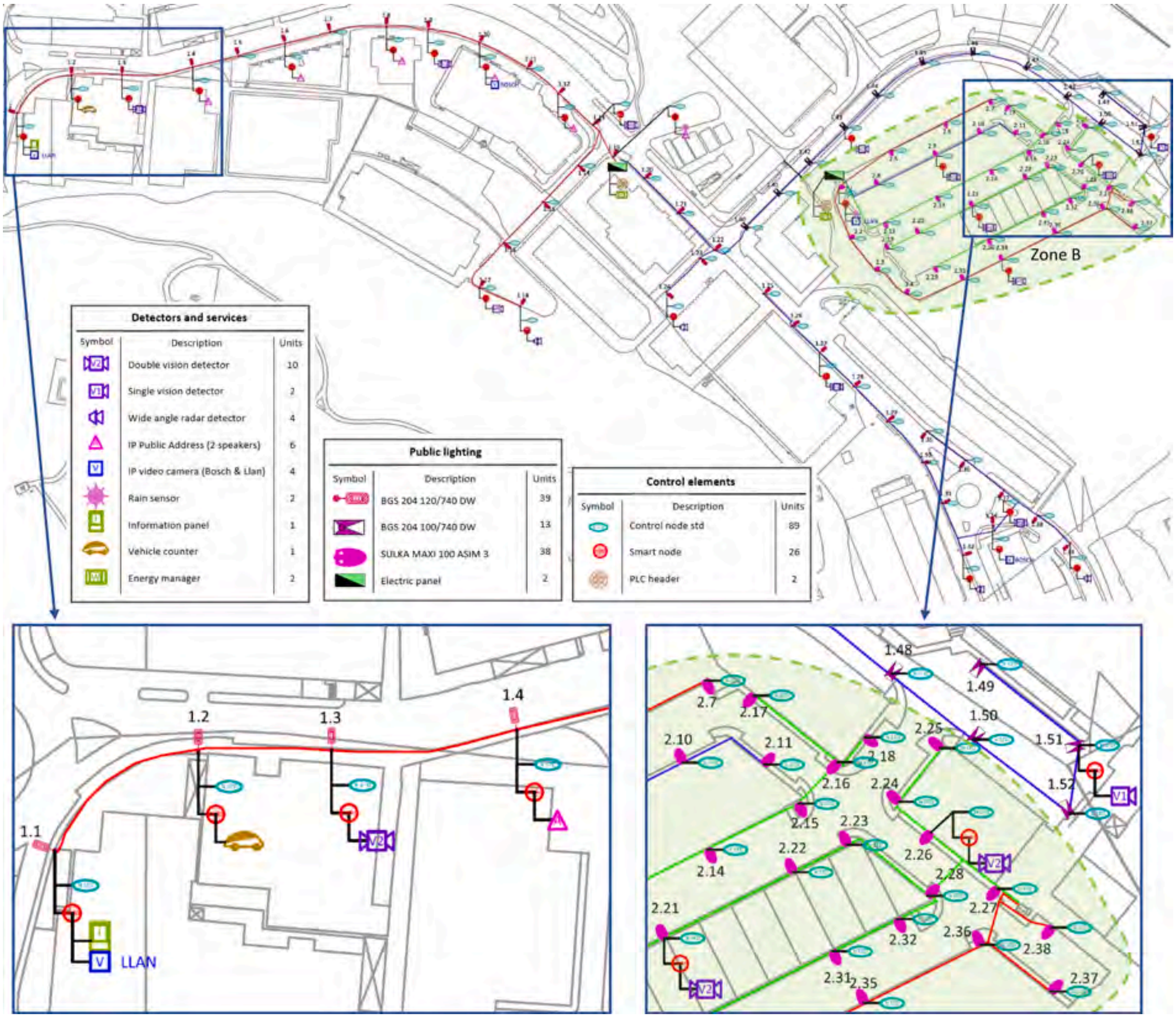

Fig. 4. Pilot intervention: zone A in white background and zone B shaded in green and delimited by a dashed line.

within the pilot reduced the emissions around 20 tCO_2/year.

The reduction in power in both zones means that the existing wiring is less wearable, safer and sufficient to hold other power supplies. Additionally, the power supply costs were also reduced (fixed costs) due to the contracted power fee. Maintenance costs and work have been reduced and are expected to continue to decline in the coming years due to the enhanced lifetime of the products installed, and the system alerting on the installation issues by remote control (avoiding the need for a visit to the site to check the issues).

In addition to the performance analysis, the study of the economic viability of the solutions is paramount for the replacement of the public lighting system in a city. Hence, two technical solutions or models, namely LED technology (LED) and smart technology (SMART) are herein compared with the previous situation (PS). Each solution is described below:

- The previous situation (PS) model, which implies to keep operating with the same old lamppost without making any change, therefore it just considers maintenance and energy costs, without considering investment cost. As the previous solutions of zone A and zone B were different, they will be represented by PSA and PSB respectively.
- The LED model also considers replacing the old lamppost with new ones that use LED technology, thus involving a significant investment plus maintenance and energy costs.
- The SMART model was the solution implemented in the pilot project of San Sebastian. It combines LED luminaires with the installation of cutting-edge technologies based on sensors and data management, which optimizes the investment made, maximizing the environmental, economic, and managerial benefits, improving the public service.

Table 1 presents the main average costs (investment, maintenance, and energy consumption costs) per unit of lamppost. All those costs were allocated based on the experience of the city and according to the data obtained in zone A and zone B of the pilot. Comparing the LED and SMART solution with the PS, it is possible to estimate the annual savings per lamppost in euros and in percentage for both zones, which are considered for the analysis as revenues. The payback and the net present value (NPV) are the economic feasibility parameters used for the assessment.

The payback shows that the municipality of San Sebastián should recover the initial investment of installing smart lamppost in an approximate interval of 4 to 7 years, depending on the age of the replaced lampposts (remember that the original lampposts of zone A were older than those of zone B), which is a short period of time if it is compared with other urban projects and just a bit higher to the interval presented by LED solution. However, the NPV —calculated with a 5% discount rate at year 25, which is its average lifetime— is higher for the SMART solution. This solution should generate in savings between 2,500

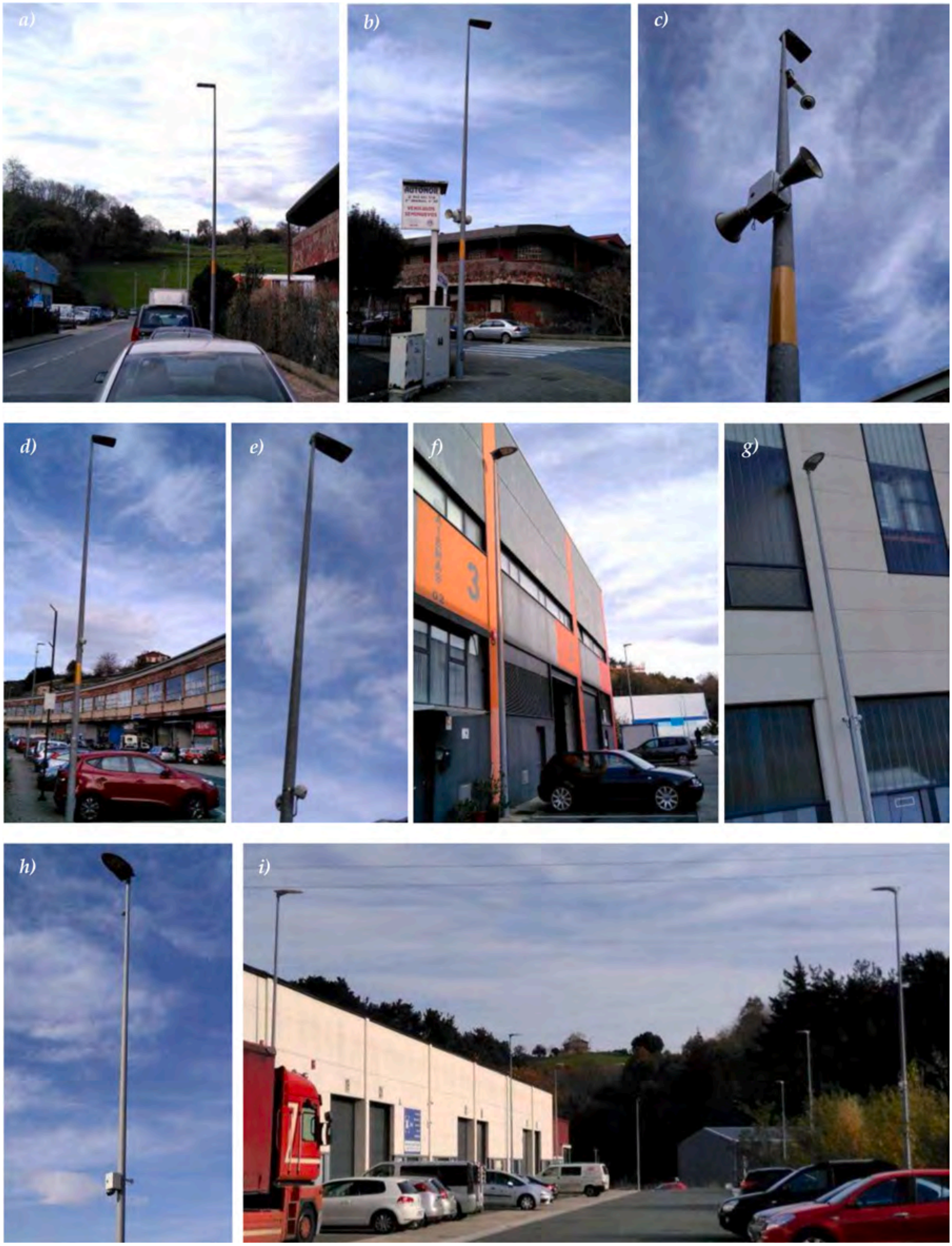

Fig. 5. shows the lampposts with different smart features installed within the scope of the pilot intervention.

€ and 1,500 € per lamppost approximately in 25 years, which is a very promising result that encourages to replicate this solution in other European locations.

6. SCALE-UP STRATEGY FOR SMART PUBLIC LIGHTING PROJECTS

Based on previous sections' outcomes and learning, a strategy to scale-up the smart public lighting intervention from a pilot level to the municipality level is herein presented. The strategy, composed in the form of 12 steps that municipalities should follow, relies on a strong collaboration between municipalities and industrial partners. Fig. 9 presents an overview of the scale-up strategy.

1 *Analysis* of the existing public lighting system and identification of the needs.

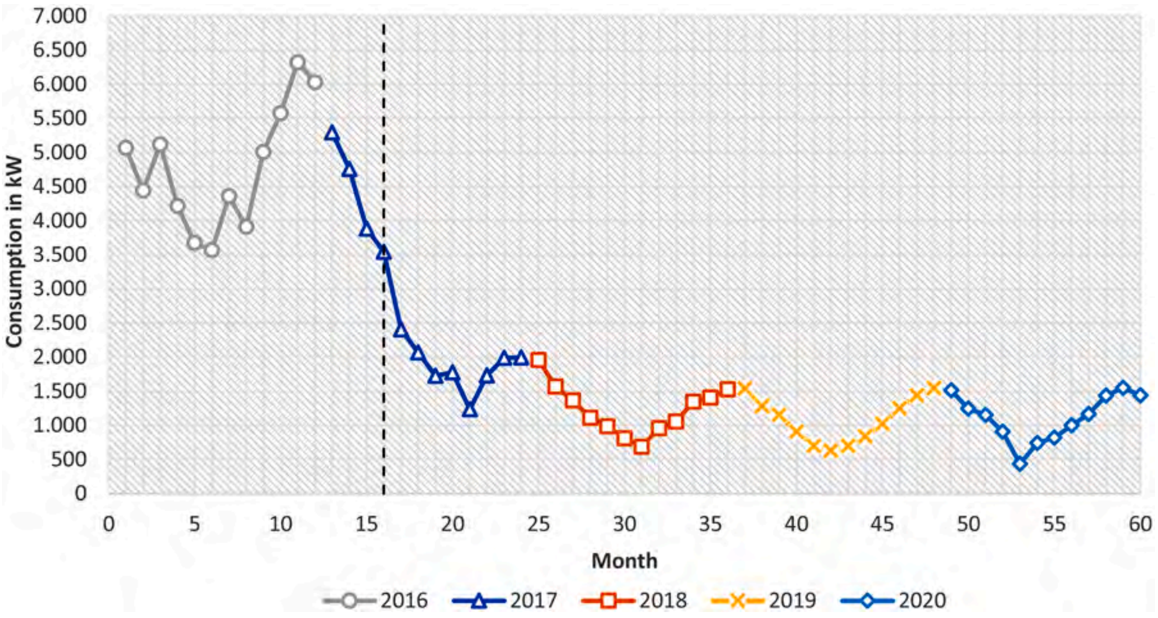

Fig. 6. Evolution of power consumption from 2016 to 2020 in zone A of the pilot.

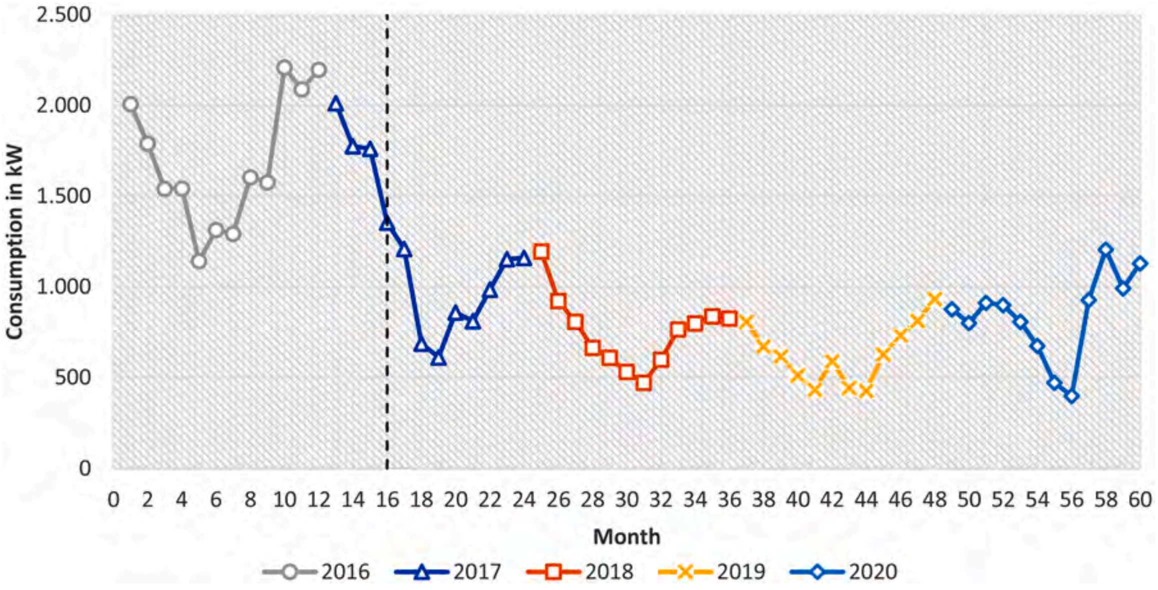

Fig. 7. Evolution of power consumption from 2016 to 2020 in zone B of the pilot.

2 Definition of *future specification* for public lighting (including infrastructure, light, sensors, etc.) and the design of the lamppost (according to the regulations of the municipality).
3 Mapping *stakeholders* accounting for local partners to empower local business and create synergies that impact at multiple levels in the municipalities (economically, socially and environmentally).
4 Identification of *funding and financing schemes* (both public and private ad different territorial levels) that enable the long-term viability and sustainability of the intervention.
5 *Informative campaigns* for citizens and potential stakeholders addressing economic, environmental, and social benefits. The economic benefits should be quantified and presented in terms of energy efficiency and reduction in operation and maintenance costs. Other aspects such as luminosity, safety and biodiversity should also be addressed in the campaign.
6 Running a public procurement based on a competitive dialogue with the stakeholders previously identified for installing and managing the smart public lighting. This selection process aims at identifying desirable partnerships that can be promoted as a city and assessing the service that will be delivered.
7 Establishment or *constitution of a public-private partnership*[1] *(PPP)*, which should enable to replicate interventions in smaller cities with fewer resources and infrastructure. Besides, this could also be a financing source by using a sharing risk model.

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[1] PPP is an “ongoing agreement between government and private sector organisations in which the private organisation participates in the decision-making and production of a public good or service that has traditionally been provided by the public sector and in which the private sector shares the risk of that production” (Forrer, Kee, Newcomer, & Boyer, 2010)

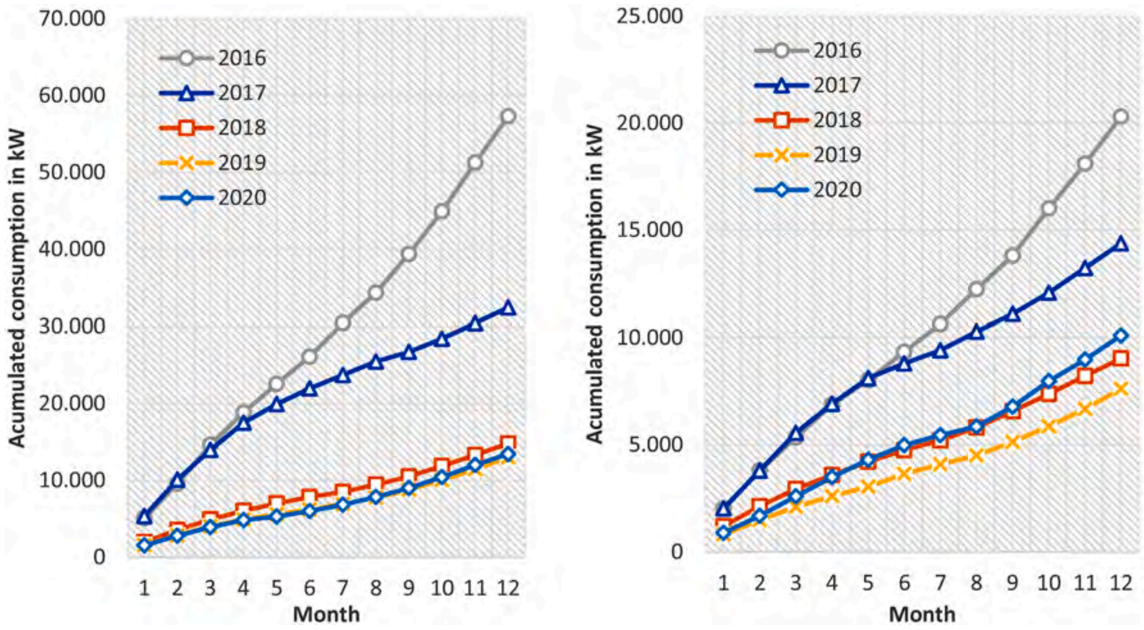

Fig. 8. Accumulated power consumption month by month for 2016 to 2020: a) zones A and b) zone B.

Table 1
Main lighting costs by type of technology (per unit).

	ZONE A			ZONE B		
	PSB	LED	SMART	PSA	LED	SMART
Total cost investment per unit (€)	**0.00**	**450.00**	**550.00**	**0.00**	**450.00**	**550.00**
Differences in investment vs CS		-450.00	-550.00		-450.00	-550.00
Annual cost of maintenance (€)	**55.00**	**14.00**	**17.00**	**55.00**	**14.00**	**17.00**
Savings in maintenance €/year/lamppost vs CS		41.00	38.00		41.00	38.00
Savings in maintenance in % vs CS		75%	69%		75%	69%
Annual energy cost (4,100 hours year) (€)	**149.24**	**51.73**	**37.35**	**76.12**	**51.73**	**37.35**
Savings in energy €/year/lamppost		97.51	111.89		24.39	38.77
Savings in energy in %		65.34%	74.97%		32.04%	50.93%
Total cost of service (maint. + energy) (€)	**204.24**	**65.73**	**54,35**	**131.12**	**65.73**	**54,35**
Savings operation €/year/lamppost vs CS		138.51	148.69		65.39	76.77
Savings operation in % vs CS		68%	73%		50%	59%
PAYBACK (years)		**3.25**	**3.70**		**6.88**	**7.16**
NPV in 25 years (€)		**2,287.76**	**2,535.75**		**1,306.29**	**1,554.28**

8 In parallel, definition of a *Prioritization model* (Pujadas, Pardo-Bosch, Aguado-Renter, & Aguado, 2017; Roigé, Pujadas, Cardús, & Aguado, 2020; and Pardo-Bosch, Aguado & Pino, 2019) to assess the replacement lamppost projects and to select (the municipal budget is limited) those with the greatest potential in terms of economic viability, environmental sustainability, and social inclusion.
9 Identification and *definition of projects* to be implemented in the city or across the region.
10 *Selection of projects* through the prioritization model.
11 *Lamppost replacement* according to the roadmap established by the prioritization model.
12 *New infrastructure management* through the PPP model, which is based on indirect administration under rigorous control procedures and strong synergy between the municipality and the industrial partner.
13 The implementation process should be closed loop. In other words when a project is finalised a new project should be selected and implemented. Private managers should be involved to help municipalities improve the efficiency of the system. In this indirect management style, it is crucial to focus on the outcomes rather than the outputs.

7. CONCLUSIONS

This manuscript presents the principal needs and challenges that cities are facing when deploying a smart public lighting network and identifies governance recommendations and key elements to define a sustainable and feasible strategy. Thus, the paper provides insights that enable Public Administrations to transform their lighting infrastructure into a smart, valuable, energy-efficient and sustainable asset that will make urban areas more accessible and ensure that the city itself is safer, more modern, efficient and attractive.

The transformation towards the adoption of smart public lighting faces different barriers. Among these barriers, the high upfront cost could represent the most significant for cities. In this regard, the case study of San Sebastian presented in this manuscript shows that considering the economic savings in energy, operation and maintenance costs, the paybacks on invested capital are worthwhile, between 4 and 7 years. The smart public lighting potential savings and competencies represent strong factors to encourage cities to engage in it. Beyond economizing lighting, the network system offers opportunities for new smart city applications by integration of different services (and raises opportunities for improvement and innovation.

Even though the payback periods for this type of interventions are

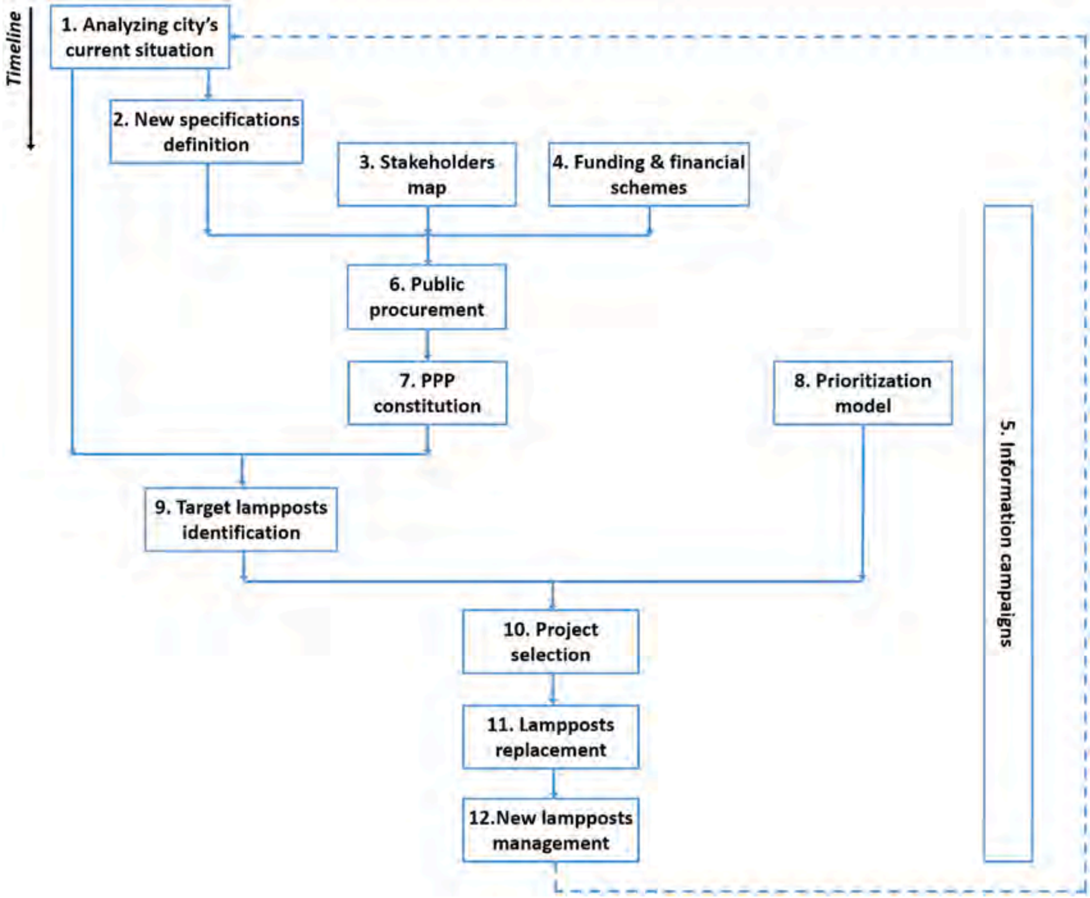

Fig. 9. Scale-up strategy for smart public lighting projects.

quite short from the point of view of a municipal budget, the high investment needed for replacing the existing lamppost could delay the implementation of this type of projects. One of the solutions to tackle such barriers is to share the investment risk using proper business models that promote the social benefits and environmental protections, encouraging the participation of public and private actors, both as main stakeholders and beneficiaries, as well as encouraging local business.

Moreover, a holistic analysis at the city level from a business perspective through the Value Creation Ecosystem (VCE) and the City Model Canvas (CMC) has been presented. Both tools offer complementary information and are useful to visualise from a comprehensive perspective, how a city can offer value to the public with a long-term approach.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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