ESCUELA TÉCNICA SUPERIOR DE INGENIERIA (ICAI)

MÁSTER EN INGENIERÍA INDUSTRIAL

BUSINESS MODELS FOR ELECTRIC VEHICLES CHARGING INFRASTRUCTURES

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MODELOS DE NEGOCIO ASOCIADOS A LAS INFRAESTRUCTURAS DE RECARGA DE VEHÍCULOS ELÉCTRICOS

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RESUMEN

En los últimos años han aparecido cada vez más factores que impulsan un desarrollo acelerado de los vehículos eléctricos, como la excesiva dependencia del petróleo, el aumento de los precios de la gasolina o la creciente amenaza del calentamiento global. Por lo tanto, es necesario promover esta tecnología para cumplir con las tasas de reducción de CO_2 impuestas por los gobiernos, evitar sanciones por emisiones y cumplir con la creciente preocupación social por el medio ambiente.

En este contexto, han surgido muchas políticas tanto a nivel europeo como nacional, asignando fondos para promover la eficiencia energética. Todas estas iniciativas gubernamentales y la creciente concienciación sobre la sostenibilidad han convertido la penetración del vehículo eléctrico en un punto clave de la política actual para iniciar lo que se conoce como la 'transición energética'. Cabe destacar el Paquete de Energía y Cambio Climático con objetivos para 2020, el Marco 2030 y la Hoja de Ruta 2050, con objetivos de reducción de emisiones, aumento de la penetración de energías renovables y aumento de la eficiencia energética. En el caso concreto de la Comunidad de Madrid, destacan dos políticas. Por un lado, el Plan Energético Horizonte 2020, que está en línea con los objetivos propuestos por la UE para ese mismo año. Por otro lado, el Plan de Calidad del Aire y Cambio Climático ('Plan A'), cuyo principal objetivo es conseguir una ciudad sostenible que garantice la salud de los ciudadanos ante el reto de la contaminación atmosférica.

En resumen, los vehículos eléctricos todavía tienen problemas y desafíos que superar, como el tiempo de carga, la corta duración de la batería o el acceso a puntos de recarga fuera del hogar. Aun así, los gobiernos de todo el mundo están tratando de superar las barreras existentes y acelerar el mercado para este sector, y la investigación de la industria en esta área se encuentra en constante crecimiento. En este contexto, se realiza un análisis de la viabilidad de la instalación de infraestructuras de recarga en la estación de Plaza de Castilla, coincidiendo con que se trata del final de línea de muchos autobuses públicos y también de un lugar frecuentado por coches particulares de trabajadores, para obtener una visión general de la rentabilidad del proyecto.

El objetivo del proyecto es maximizar la rentabilidad obtenida mediante la instalación de sistemas de recarga eléctrica en una estación de autobuses, que tanto los coches particulares

como los autobuses pueden utilizar para cargar sus baterías y obtener beneficios económicos, mediante una formulación MIP (Mixed Integer Programming).

Para ello, se modela el 'routing' y 'charging scheduling' estratégico tanto de los autobuses como de los potenciales usuarios privados, empleando un 'unit commitment' para hacer una representación realista de su comportamiento. Un bus estará en ruta sólo si su variable de decisión asociada está activada, de la misma manera que tiene que ocurrir para que se esté cargando. Los usuarios privados pueden cargar cuando haya puntos de carga disponibles, y el número de usuarios se estima heurísticamente con la curva de adopción futura del coche eléctrico como principal medio de transporte.

Para garantizar la calidad del servicio de autobuses la demanda debe ser satisfecha a lo largo de todo el horizonte temporal y para cada una de las líneas, por medio de autobuses de gasolina, eléctricos o por una combinación de ambas tecnologías.

En términos de inventario de la batería del autobús, la carga se modela como un aumento en el inventario, y la descarga o autobús en movimiento como una disminución en el mismo. La viabilidad del 'routing' de los autobuses se ve limitada por el nivel de inventario, de manera que una ruta no puede iniciarse si no hay suficiente energía para terminarla.

Por último, el número óptimo de puntos de recarga que deben instalarse en la estación viene determinado por el número de autobuses y usuarios privados que cargan al mismo tiempo, siempre que no se sobrepase el límite superior. Los puntos de carga serán ocupados en primer lugar por los autobuses, y sólo cuando haya espacios libres disponibles, los coches privados podrán cargar.

A lo largo de la exposición de los resultados queda claro que se esperan flujos de caja positivos cuando Plaza de Castilla se convierta en una estación de autobuses electrificada, donde se podrá cargar su flota de autobuses y donde los usuarios privados serán una oportunidad para aumentar la rentabilidad del proyecto. Se analizan dos escenarios diferentes: por un lado, el de la estación equipada con puntos de carga rápida y, por otro, el de la carga semi-rápida. Para ambos casos, se ha comprobado que los autobuses funcionan según lo previsto y se ha llevado a cabo un análisis comparativo de rentabilidad.

En cuanto a la calidad del servicio, se verifica que se cumple el perfil de demanda para ambos escenarios. El tiempo se considera en intervalos de 30 minutos, ya que esta medida permite alcanzar el compromiso necesario entre precisión y convergencia del problema. En cuanto a la carga de los autobuses eléctricos, se observa que se realiza principalmente durante la noche, permitiendo a los usuarios privados cargar durante el día maximizando así los beneficios económicos para la estación.

Con respecto al inventario de la batería de cada uno de los buses, se verifica que el nivel de carga varía de manera coherente según su comportamiento. Además de todo lo que concierne a los autobuses, se obtiene el número de coches particulares que se cargarían diariamente en la estación, así como su distribución a lo largo de todos los periodos.

En el análisis de flujo de caja, se estudian los beneficios de la implantación para ambos escenarios. Se concluye que la instalación de puntos de carga semi-rápidos ofrece una mayor rentabilidad a los 20 años que los de carga rápida. Aun así, esta diferencia no es significativa ya que los beneficios en ambos casos estarían en torno a los 31 millones de euros. El factor determinante para elegir uno u otro sería la prioridad dada a los costes sobre el tiempo de carga. Los puntos de carga semi-rápidos implican menores costes de instalación, pero también el doble de tiempo de carga. Por el contrario, los puntos de carga rápida son más caros, aunque permiten períodos de carga más cortos.

En cuanto al grado de penetración eléctrica que supondría cada tecnología, el porcentaje es ligeramente superior en el caso de recarga rápida, aunque ambos valores se sitúan en torno al 59%. Este resultado tiene sentido, ya que un tiempo de carga más corto permite aumentar el número de autobuses eléctricos que se pueden cargar en la estación.

Respecto al número de puntos de carga que maximizarían los beneficios, el programa determina que cada una de las 53 dársenas de la estación debe estar equipada con uno. Se trata de un negocio rentable que se amortiza en poco tiempo y, desde el punto de vista económico, valdría la pena instalar tantos puntos de carga como fuera posible, incluso si hubiera más espacio disponible.

En base a los resultados obtenidos, se concluye que el Ayuntamiento de Madrid debería instalar el máximo número de puntos de recarga en la estación de autobuses de Plaza de Castilla. De esta forma obtendrá el máximo beneficio económico y penetración eléctrica en la flota de autobuses públicos, en línea con las medidas de sostenibilidad promovidas en el 'Plan A'. Como se ha explicado anteriormente, se trata de un plan para combatir la contaminación atmosférica de la ciudad y los impactos del cambio climático.

Para alcanzar sus objetivos, una de las principales líneas de acción del 'Plan A' es la promoción de la movilidad sostenible. La ampliación y renovación de la flota de transporte público forma parte de esta política, cuyo objetivo es lograr una clasificación de 'cero emisiones' para el 100% de todos sus vehículos. Para apoyar esta medida, también se está promoviendo la expansión de la red de carga eléctrica, ya que es esencial para satisfacer la demanda de la creciente tecnología de bajas emisiones. Por ello, en este sentido, la instalación de cargadores en Plaza de Castilla parece un buen punto de partida para llevar a cabo esta política, esperándose además una alta rentabilidad a lo largo de todo el ciclo de vida del proyecto.

Business Models for Electric Vehicles Charging Infrastructures

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Abstract

In recent years, more and more factors driving an accelerated development of electric vehicles have emerged, such as an excessive oil dependency, rising gasoline prices or the growing threat of global warming. It is therefore necessary to promote this technology, to meet the CO_2 reduction rates imposed by governments, avoid penalties for emissions and comply with the increasing social concern for the environment.

In this context, many policies have emerged at both European and national level, allocating funds to promote energy efficiency. All these government initiatives and the increasing awareness of sustainability have turned the penetration of the electric vehicle into a key point of the current policy to begin what is known as the 'energy transition'. It is worth highlighting the Energy and Climate Change Package with objectives for 2020, the 2030 Framework and the 2050 Roadmap, with targets for reducing emissions, increasing the penetration of renewable energies and increasing energy efficiency. In the specific case of the Community of Madrid, two policies stand out. On the one hand, the Energy Plan 2020 Horizon, which is in line with the objectives proposed by the EU to achieve by 2020. On the other hand, the Air Quality and Climate Change Plan ('Plan A'), whose main objective is to achieve a sustainable city that guarantees the health of citizens in the face of the challenge of atmospheric pollution.

In short, electric vehicles still have problems and challenges to overcome, such as charging time, short battery life or access to recharging outside homes. Even so, governments around the world are trying to overcome existing barriers and accelerate the market for this sector, and industry research in this area is constantly growing. Within this context, an analysis of the feasibility of installing charging infrastructures in Plaza de Castilla station, coinciding with the fact that it is the end of the line of many public buses and also a place frequented by private workers' cars, is conducted to get an overview of the profitability of the project.

The aim of the project is to maximize the profitability obtained by installing electric charging facilities in a bus station, which both private cars and buses can use to charge their batteries and obtain economic benefits, by using MIP (Mixed Integer Programming) formulation.

The strategic routing and charging scheduling of both buses and potential private users is modelled by using a unit commitment in order to make a realistic representation of their

behavior. A bus will be on route only if the decision variable associated is activated, the same way it has to happen for it to be charging. Private users can charge when there are available charging points, and the number of users is estimated heuristically with the curve of future adoption of the electric car as the main means of transport.

In order to guarantee the quality of the bus service, the demand of buses should be satisfied across the whole horizon of time and for every line by gasoline buses, electric buses or a combination of both technologies.

In terms of bus battery inventory, bus charging is modeled as an increase in inventory, and the discharge or moving bus as a decrease in it. The feasibility of the routing of the buses is constrained by the inventory level, where a route cannot be started if there is no sufficient energy to finish it.

Finally, the optimal number of charging points to be installed in the facility is determined by the number of buses and private users charging at the same time, when the upper-bound is not exceeded. Charging points will be occupied first by buses, and only when there are free spaces available, private cars will be able to charge.

Throughout the discussion of the results it becomes clear that positive cash flows are expected when Plaza de Castilla is converted into an electrified bus station, where its bus fleet can be charged and where private users are an opportunity to increase the profitability of the project. Two different scenarios are analyzed: on the one hand, station equipped with fast charging points and, on the other, with semi-fast charging ones. For both cases, the buses have been found to operate as expected and a comparative profitability analysis has been carried out.

With regard to the quality of service, it is verified that the demand profile is met for both scenarios. Time is considered at 30-minute intervals, as this measure allows the necessary compromise between accuracy and convergence of the problem to be met. As for the charging of the electric buses, it is observed that it is mainly performed during the night, allowing private users to charge during the day and maximizing the economic benefits for the station.

With respect to the battery inventory of each of the buses, it is verified that the level of charge varies in a coherent way according to its behavior. In addition to all that concerns buses, the number of private cars that would be charged daily at the station is obtained, as well as their distribution over all periods.

In the cash flow analysis, the benefits of the implementation for both scenarios are studied. It is concluded that the installation of semi-fast charging points offers greater profitability after 20 years than the fast charging ones. Even so, this difference is not significant since the benefits in both cases would be around 31 million euros. The determining factor for choosing one or the other would be the priority given to costs over charging time. Semi-fast charging points entail lower installation costs, but also double the charging time. Conversely, fast charging points are more expensive, although they allow for shorter charging periods.

As for the electrical penetration rate that each technology would entail, the percentage is slightly higher in the case of fast charging, although both values are around 59%. This result makes sense, as a shorter charging time allows for an increase in the number of electric buses that can be charged at the station.

Regarding the number of charging points that would maximize the benefits, the program determines that each of the 53 docks of the station should be equipped with one. This is a profitable business that pays for itself in a short period of time, and economically speaking it would be worthwhile to install as many charging points as possible, even if there were more space available.

Based on the results obtained, it is concluded that the City Council of Madrid should install the maximum number of charging points at the Plaza de Castilla bus station. This way it will achieve the greatest economic benefit and electrical penetration in the public bus fleet, in line with the sustainability measures promoted in the 'Plan A'. As explained above, this is a plan to combat the city's air pollution and the impacts of climate change.

To achieve its objectives, one of the major lines of action of 'Plan A' is the promotion of sustainable mobility. The expansion and renewal of the public transport fleet is part of this policy, which aims to achieve a zero-emission classification for 100% of all vehicles. To support this measure, the expansion of the electrical charging network is also being promoted, as it is essential to meet the demand for the growing low-emission technology. Therefore, in this sense, the installation of chargers in Plaza de Castilla seems a good starting point for carrying out this policy with a high profitability expected for the whole project life cycle.

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1. INTRODUCTION

In recent years, more and more factors driving an accelerated development of electric vehicles have emerged, such as an excessive oil dependency, rising gasoline prices or the growing threat of global warming. It is therefore necessary to promote this technology, to meet the CO_2 reduction rates imposed by governments, avoid penalties for emissions and comply with the increasing social concern for the environment [1].

Against this background of environmental concern, the European Union has already set ambitious greenhouse gas emission reduction targets. In 2050, its economy is expected to be less or no longer dependent on energy consumption from sources emitting these gases. This target has been defined as the reduction of GHG emissions between 80 and 95% with respect to 1990 emissions by the year 2050, and therefore the transport industry must be involved to achieve these figures [2].

The transport sector represents a critical share of greenhouse gas emissions, as seen in the figure below. Based on the historical trend, it is estimated that emissions from transport will increase by 84% by 2030, and that is why the contribution of electric vehicles is expected to help reduce these emissions in the long term. The number of electric vehicles sold globally has increased rapidly from 45,000 units in 2011 to more than 300,000 in 2014, giving an idea of the pace of growth in this sector.

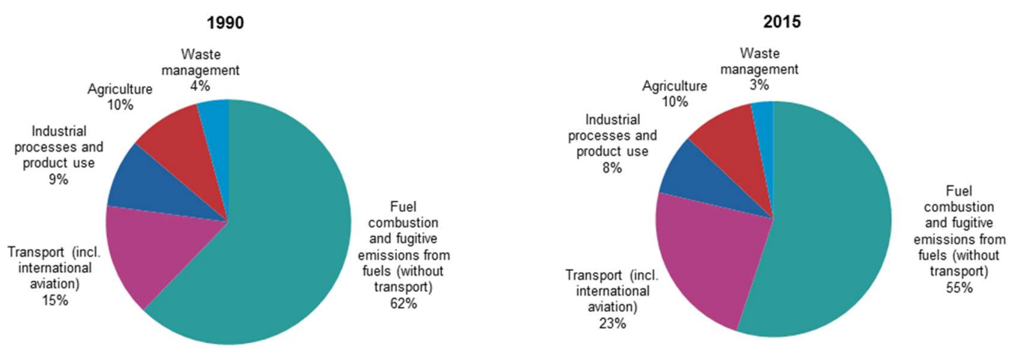


Figure 1.1. Greenhouse gas emissions share, analysis by source sector, EU-28, 1990 and 2015 [3].

Despite this, research and development in this field must continue to progress in order to overcome the barriers that still hinder massive market penetration. The future development of the industry must deal with three key obstacles: vehicle cost, performance and charging infrastructure. On the one hand, electric vehicles are not yet competitive in price with the conventional ones that offer the same services, nor are they competitive in terms of refueling time or autonomy. In addition, the availability of public recharging points is scarce, and the installation of private charging posts is difficult. Further work is therefore still needed on these aspects [2].

In Europe, all vehicles are encouraged to achieve emissions of 95 gCO_2/km by 2021, but this regulation is more favorable to electric vehicles with ‘super credits’ and the omission of their emissions upstream. In addition, several levels of charging equipment for electric vehicles have been installed in European countries to improve the value proposition of this sector and increase the confidence of its users. Some of them have even set energy targets, offered major tax incentives to consumers, installed charging infrastructures and even implemented other support policies to promote the deployment of this technology [4].

In Spain, more and more initiatives are emerging to comply with European and national legislation on air quality. Specifically, in Madrid, the so-called ‘Plan A’ was approved last year, including 30 measures to reduce pollution and greenhouse gases. This proposal revolves around four main axes: low-emission urban management, adaptation to climate change, public awareness and sustainable mobility [5].

Within this last block is where initiatives to promote electric vehicles and low emission technologies in general emerge. As deduced from the following figure, there is still a long way to go before electric mobility in our country becomes a reality, and that is why this subject is presented as a promising field.

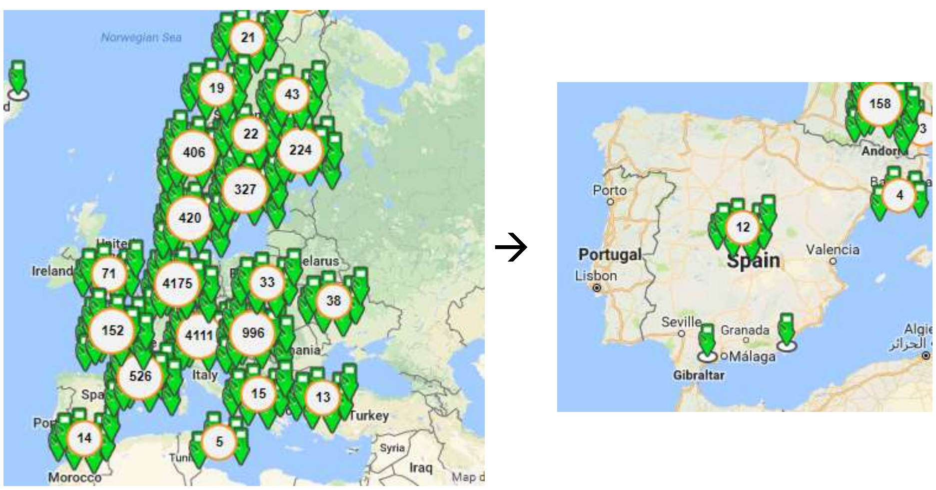


Figure 1.2. Recharge stations for EV in Europe vs. Spain [6].

As part of the promotion of low emission technology, the city council intends to act on strategic fleets (buses, taxis, municipal service fleets), and it is expected that the Municipal Transport Company (EMT) will have a fleet of low emissions by 2020. This ambitious objective will require restructuring of the public transport sector and the establishment of electricity recharging infrastructures to enable it to operate.

Motor vehicle registrations for alternative energy sources other than gasoline and diesel have increased by 51,4 percent in the third quarter of 2017 in Europe, compared to the same period in 2016. It should also be noted that Spain has been the country that has grown most between July, August and September throughout the continent, with 90,7 percent more registrations. However, there is still a long way to go to reach countries like Norway, the only country where 1 in 3 cars registered is an electric-powered car **[7]**.

In short, electric vehicles still have problems and challenges to overcome, such as charging time, short battery life or access to recharging outside homes. Even so, governments around the world are trying to overcome existing barriers and accelerate the market for this sector, and industry research in this area is constantly growing. Therefore, this field is presented as a good starting point to investigate and deepen it.

The project will start with a review of chargibng infrastructures at European level, including existing business models, available services and customers. In addition, there will also be a review of the state of the art of energy policies and a comparison of Spain with the rest of the countries. An economic study will then be carried out for two cases, public recharging of private cars and also public transport fleets.

Specifically, an analysis will be performed to check the feasibility of installation of charging infrastructures in Plaza de Castilla station, coinciding with the fact that it is the end of the line of many public buses and also a place frequented by private workers' cars.

2. EV Policy Drivers

After nearly a century of domination of the internal combustion engine in the transport sector, the electric vehicle is now experiencing rapid growth in both established and emerging markets. The large-scale adoption of this technology promises to bring about significant changes for society, and not only in terms of the means used for transport. Also in terms of economies, moving away from the dominance of oil, and in the so-called social conscience of the population, creating concern about the issue of environmental footprint [8].

In this regard, many policies have emerged at both European and national level, allocating funds to promote energy efficiency. All these government initiatives and the growing awareness of sustainability have led to electric vehicle penetration becoming a key point of current policy. However, in order to meet this objective there are a number of challenges that both the automobile industry, the large electrical industry and society have to overcome.

2.1. Energy Policy

Energy has always played a central role in human activity and has served as the basis for social development. This role is often underestimated by citizens, who are not aware of its vital nature and, above all, of the limitation of energy resources, its costs and its consequences for the environment. Despite this, an increasing social, political and economic concern has arisen in recent years about the impact that the current energy model could have. There is a broad scientific consensus on the problem of climate change, and international energy policy is acting in this direction.

The International Energy Agency (IEA) was created after the first major energy crisis in 1973 to coordinate the energy policies of developed countries and defend their common interests. This world reference organization in the sector is responsible for issuing annual reports on the international energy problem, emphasizing the unsustainability of the current energy model and the urgency for all countries to take action on it.

In the transition towards a new energy model, the IEA points out that the main resource available to humanity is energy saving and efficiency. Its potential is enormous, both because of the technological advances of recent times and because of the environmental awareness that makes it the focus of society. Another pillar on which the reduction of emissions must be based is renewable energies, which must gain ground from fossil fuels.

In response to international warnings, certain policies are being implemented, with Europe at the forefront, to begin what is known as the 'energy transition'. This is a change that will take place over a long period of time and whose ambitious goal will be to achieve a low-carbon economy [9].

2.1.1. European Energy Policy

Historically, economic and technological development has been associated with greenhouse gas (GHG) emissions, such as carbon dioxide, methane and nitrogen oxides, although this trend has increased significantly in recent times. Despite this, no attention had been paid to the consequences that these emissions could have on our environment until relatively recently.

The scientific community warns that, in the absence of an urgent global action, climate change could have irreversible impacts. Therefore, one of the major challenges of today's society is to decouple emissions from economic growth, making fossil fuels cease to act as a pillar of development.

Coal, natural gas and petroleum products are the main contributors to emissions (Figure 2.1), and they are present in most sectors. Their high calorific value, low cost, availability and transport and storage capacity have turned them into the preferred resources. This is why a change in the pattern of energy production is necessary if neutrality in emissions is to be achieved. In this sense, the European Union has led decarbonization policies, setting ambitious targets for reducing GHG emissions so that by 2050 its economy will not be dependent on the sources that produce this type of gases **[10]**.

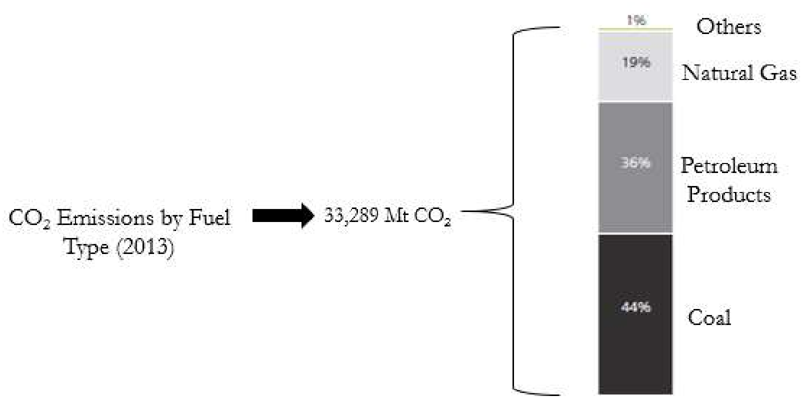


Figure 2.1. CO_2 emissions by fuel type (2013) Importance of the contribution of fossil fuels **[11]**.

Until 2007, when the Treaty of Lisbon was signed, energy played a negligible role in the Treaties and was not a political priority for the institutions of the European Union. The initiatives that have been taken on this subject up to then were opportunistic and motivated only by specific circumstances, such as the 1973 oil crisis, and were abandoned when they were no longer necessary. The impact on policy and standards of the Green (1995) and White (1995) Papers and the New Green Paper (2000) was limited.

The Treaty of Lisbon represents the beginning of the development of a committed and permanent energy policy by the European Union, providing on the one hand a solid legal framework for action on the energy issue, but also a set of concrete objectives. From this point on, energy policy is reflected in provisions, among which the Energy and Climate Change Package with objectives for 2020 stands out for its pioneering nature [9].

In addition, the European Union has set ambitious emission reduction targets of between 80 and 95% by 2050, with respect to 1990 levels. In order to achieve these objectives, a number of benchmark policies and intermediate milestones have been set in place, allowing decarbonization to be progressively achieved:

- **Energy and Climate Change Package 2020:** as already mentioned, it established the basis for achieving the environmental objectives endorsed by the European Council in 2007. It includes three key objectives within the 2020 target package:
  - Reduction of GHG emissions by 20% compared to 1990 levels.
  - 20% renewable energy share in final energy consumption, and 10% of conventional fuels replaced by biofuels in the EU.
  - 20% improvement in energy efficiency compared to the baseline scenario, taking 1990 as a reference year.

- **2030 Framework:** it was established to follow up the previous Energy Package and was adopted in 2014 including the following measures:
  - Reduction of greenhouse gas emissions by 40% compared to 1990 levels.
  - 27% share of renewable energies in final consumption, reviewed in 2020 for a possible increase to 30%.
  - 27% improvement in energy efficiency compared to the baseline scenario, taking 1990 as a reference year.

- **2050 Energy Roadmap:** it was presented in 2011, and established a number of targets in line with the European emission commitment to be met by developed countries:
  - Greenhouse gas emissions reduced by 80% compared to 1990 levels, achieving a reduction of 40% in 2030 and 60% in 2040.
  - Encourage the contribution of all sectors.
  - Make the transition viable and economically feasible.

Table 2.1 summarizes the European Union's energy objectives and highlights the specific short-term objectives for Spain, assuming that the percentage of reduction in comparison with 1990 is the same as the European average.

	TARGETS 2020	TARGETS 2030	TARGETS 2050
GHG Emissions (compared to 1990)	**-20%** **+30%**	**-40%**	Between **-80%** and **-95%**
Renewables Penetration on Final Energy	**20%** (10% renewable origin in transport)	**27%** (review in 2020 with the intention of increasing the target to 30%)	N/A
Energy Efficiency	**20%** savings compared to 1990 trends	**27%** savings compared to 1990 trends	N/A

Table 2.1. EU energy targets for 2020, 2030 and 2050 **[10]**.

The 2016 Paris Agreement, reached at the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC), establishes a commitment by the signatory parties to achieve two goals: emissions neutrality between 2050 and 2100, and containment of the global temperature increase below 2°C as compared to the pre-industrial level. Although not legally binding, the parties reached an agreement to prepare, communicate and maintain national contributions, implementing measures to achieve the objectives **[10]**.

2.1.2. SPANISH ENERGY POLICY

The antecedents of energy planning in Spain are the National Energy Plans of 1983 and 1991. After the liberalization of the electricity sector in 1997, these Plans were followed by the three planning instruments: The Electricity and Gas Sector Plans of 2002, 2005 and the current one of 2008-2016.

At the same time, the Energy Efficiency Strategy in Spain 2004-2012 was carried out, which was developed through two Action Plans. In accordance with European directives, the Energy Saving and Efficiency Plan 2011-2020 was drawn up and subsequently replaced by the National Energy Efficiency Action Plan 2014-2020, currently in force. To this context, we must add the specific regulations on renewable energies, which include the Renewable Energy Plan 2005-2010 and the subsequent Renewable Energy Plan 2011-2020 **[9]**.

Thanks to this planning, Spain contributes to the fulfilment of the European Union's objectives for the energy transition, in accordance with the Community directives. Although it is on track to meet the 2020 targets, the renewable energy penetration target will require additional effort.

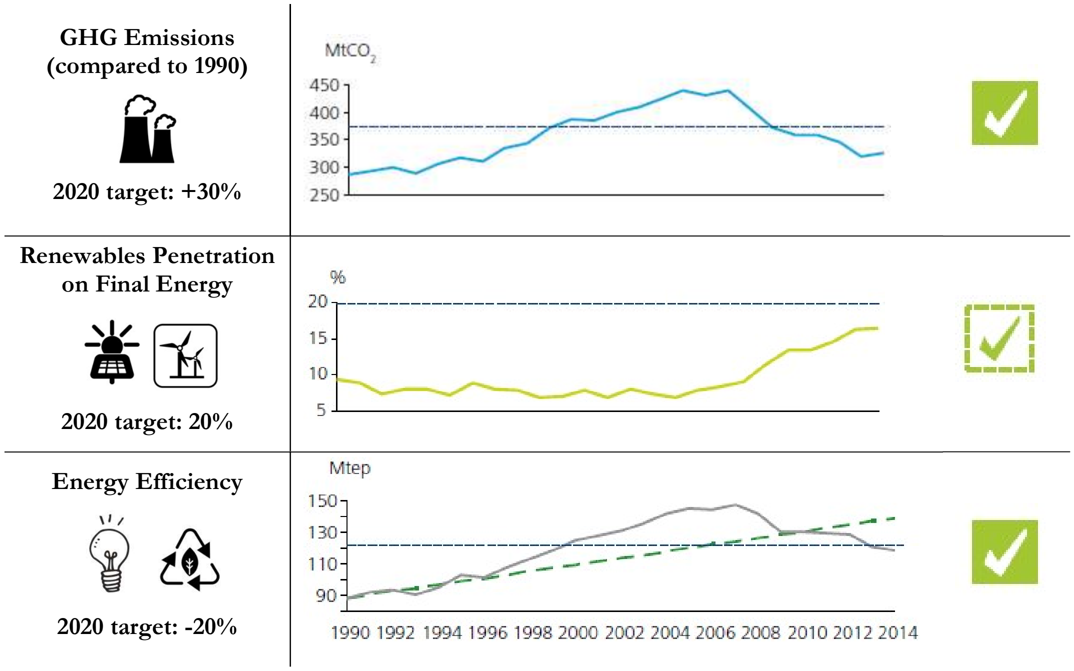


Figure 2.2. Analysis of the fulfilment of environmental objectives imposed for Spain within the framework of the European Union until 2020 [10].

The development of renewable energy resources in recent years has been remarkable. In terms of final energy, renewables now account for 17.1% of consumption, and there is a gradual approach to the 20% target set for 2020. However, poor regulation of clean electricity production premiums has led to unregulated growth in some technologies, resulting in a general reform of the system in 2014 to regulate electricity production from renewable sources, cogeneration and waste. In any case, the development of renewables will continue, in accordance with European guidelines and because they constitute the most solid alternative to fossil fuels.

In terms of energy efficiency Spain has made positive progress in recent years. Energy intensity, which is an indicator representing the amount of energy needed to produce each unit of GDP, has evolved favorably recently, with a consequent improvement in the energy efficiency of the economy. Spain is more efficient than the European average [9].

The emission reduction target in Spain (30%) is different from that of the European Union (20%), since those countries that were more industrialized in 1990 must make a greater effort than the rest. The majority of GHG emissions in Spain come from energy uses (Figure 2.3), which is why the change in the forms of energy generation and consumption in the period up to 2050 is essential to meet the emission reduction targets. Although the economic crisis that shook the country led to a reduction in energy demand, a change in the current energy model is necessary to achieve the long-term goals [10].

	Electric Generation	Petroleum Refining	Road Transport	Other Transports	Residential	Services	Industry	Others	Non-energetic Sectors	
$MtCO_2$ Equivalent	58	12	75	5	17	12	42	19	82	**322**
Percentage	18%	3,7%	23,3%	1,6%	5,3%	3,7%	13%	5,9%	25,5%	**100%**

Figure 2.3. Breakdown of emissions in Spain by sector in 2013 [10].

To this end, a series of actions for the decarbonization of the system are established, which are classified into three categories:

- **Reduction in the consumption of petroleum products:** to carry out an electrification of the demand and use energy vectors with lower emissions. The promotion of the electric vehicle plays an important role here, and the goal of 100% penetration by 2050 makes it a very interesting field. A modal shift from heavy transport to rail and natural gas or electrification and gasification of the residential, service and industrial sectors would be other forms of transition.

- **Development of a generation park based on renewable energies:** in order to ensure that the generation mix in 2050 is up to 90% or 100% renewable (compared to 38% in 2015), all new generation capacity installed must be clean, except in certain scenarios of an increase in demand.

- **Implementation of energy efficiency measures:** in this section, the adoption of the electric vehicle, among other measures, becomes particularly important due to its greater efficiency compared to a conventional vehicle. It is necessary to ensure that the trend in energy intensity is decreasing.

In addition to the environmental benefits resulting from the decarbonization of the energy model, there are other positive impacts:

- **Less energy dependence on foreign sources:** practically 100% of the oil consumed by the current Spanish economy comes from abroad, and almost 100% of the natural gas comes from other countries as well. If these imports are drastically reduced by 2050, it is to be expected that their costs will also fall.

- **Lower electricity prices for the consumer:** although the installation of clean generation will require significant investments from consumers, these costs will be offset by higher demand. In addition, other factors must be taken into account, such as the gradual reduction of grants for renewable energy plants or the amortization of the tariff deficit.

- **Increased energy efficiency:** generation based on renewable energies leads to high energy efficiency and therefore lower energy consumption by consumers **[10]**.

In this context of commitment to achieving the objectives proposed by the EU, both the Spanish Government and the local authorities are taking measures to promote a process of energy transition that is economically viable and technically feasible. The first point is key due to the high cost of the electricity bill that Spain already has, and the second is not easy to achieve due to the unpredictable pace of progress of some technologies **[12]**.

2.1.3. Madrid Energy Policy

The Community of Madrid has a population of 6.4 million inhabitants, with a high population density, a fairly small territory, a significant economic activity that contributes one sixth of the national GDP, the highest GDP per capita in Spain and a low potential for energy resources. All this makes the Community a unique case in the national territory, with a reduced indigenous production and high energy consumption, where energy is a key factor for its development.

Therefore, it is necessary to promote policies that encourage energy efficiency, increase energy production in the region and improve energy infrastructures. And if all the specific characteristics of the Community are added to the pollution problems that the capital has recently been suffering from, it would also seem necessary to propose some measures to guarantee the health of its citizens under these conditions. As a result, two of the key Plans that the subsequent work will fall under emerge **[9]**.

- **Energy Plan of the Community of Madrid 2020 Horizon**

The International Energy Agency highlights the importance of promoting energy efficiency improvements, attributing them a 50% potential to meeting emission reduction targets. As mentioned above, there is an EU Directive on energy efficiency, which provides for stringent measures in all sectors. On a national and regional level, these guidelines must be followed, and this is why the Madrid City Council has presented in 2017 the Community of Madrid Energy Plan Horizon 2020.

The summary of the objectives of this Plan is as follows:

- Fulfillment of the energy demand with high levels of security and quality in the supply, reinforcing the existing infrastructures.
- Improvement in energy consumption efficiency, with a decrease in energy intensity in 2020 of around 10% of consumption compared to the baseline scenario.

- 35% increase in renewable energy production and over 25% increase in total energy production.

The guidelines proposed to achieve this are classified into two groups: cross-cutting ones, which affect various sectors and technological applications, and sectoral ones.

The cross-cutting actions include the following:

- **Promulgation of an Energy Saving and Efficiency Law in the Community of Madrid:** this Law will ensure the permanence of energy efficiency policies, which should be applied to all actions carried out by the regional and local administrations in their different fields of action.
- **Awareness-raising and educational activities:** the Community of Madrid is aware of the importance of this need, and therefore carries out a campaign under the name Madrid Saves with Energy.
- **Training:** training activities are a fundamental element and therefore training courses are carried out for professionals in the different technical and energy fields.
- **Promulgation of regulations:** mandatory regulations in different sectors and regulatory areas.
- **Inspections:** guidelines to ensure compliance with the regulations.
- **Promotion of energy services:** Energy Service Companies are entities that provide energy services or energy efficiency improvement in a user's facilities and face some economic risk in doing so. The actions to be carried out are mainly oriented towards the public sector.
- **Energy Audits:** the obligation to carry out an energy audit every four year to all large companies is stipulated.
- **Implementation of the UNE-EN ISO 50.001 standard:** its aim is to identify and manage energy uses properly, involving all workers in efficient areas. It is voluntary and is applicable to any public or private entity.
- **Promotion of energy labelling:** to establish eco-design requirements for energy-related products and to indicate the consumption of energy and other resources by these products through labelling and other standardized information.
- **Support for R&D&I:** it will be developed through the Cluster of Renewable Energies and the Madrid Institute of Advanced Studies. It combines public and private support for science and directs research towards market demands.
- **Collaboration with City Councils and Business Associations:** collaboration with these entities will be deepened through actions and agreements in different sectoral areas.

The sectoral actions are focused on the following fields: building, public services, industry, energy transformation and transport. For this study, the actions proposed for the latter are particularly important.

The transport sector accounts for almost half of the region's total final energy consumption, and this determines the importance of the measures to be taken to improve its efficiency. In addition, 97.5% of this sector's consumption corresponds to oil derivatives, which implies an enormous dependence on a single source, and the consequent strategic vulnerability in prices. On the other hand, this situation determines the great environmental impact of the sector, which is manifested in the bad indices of atmospheric pollution in Madrid.

To this end, two action steps are proposed:

- **Modal shift towards more efficient means of transport:** this includes the actions that contribute to the promotion of more efficient means of transport.
  - **Promotion of rail transport:** rail transport is much more efficient than road transport, however, when comparing Spain with the rest of Europe the difference is devastating, with a rail freight transport rate much lower than the European average.
  - **Development of Sustainable Urban Mobility Plans** in all municipalities with more than 50.000 inhabitants: these plans aim to achieve greater participation of the most efficient means of transport and the use of vehicles with alternative energy sources.
  - **Prioritization of public transport over private transport:** this will be achieved through restrictions on the latter, especially on the least efficient and most polluting vehicles. Also, by improving the quality and comfort of public transport.
  - **Provision of platforms reserved for public transport by bus:** this will be done by extending the bus lanes on the one hand and providing radial highways with reserved platforms with reversible lanes for intercity buses on the other.
  - **Expansion of the network of car parks:** a complementary measure to the increasing restrictions on the use of polluting private vehicles.
  - **Promotion of bicycle use:** this will be based on increasing the number of kilometers of cycle paths, promoting bicycle hire, installing bicycle parking spaces and carrying out information campaigns.

- **Promotion of vehicles with alternative energy sources:** electric vehicles save more than 50% of energy compared to conventional vehicles and, in addition, combustion vehicles have high emissions. For this reason, it seems clear that an energy revolution in the automotive industry must be promoted. The most relevant actions in this area are:
  - **Promotion of gas vehicles:** on the one hand, agreements with gas distribution companies and municipalities will be signed so that more free access supply points are available. In addition, a Gas Vehicle Renewal Plan will be implemented and the use of gas in urban and interurban buses will be promoted.
  - **Promotion of the electric vehicle:** a Plan for the Installation of Electric Vehicle Recharging Points in garages will be implemented, and cooperation with

City Councils will be provided to install medium-quick recharging points in easily accessible places.

- **Prioritization of parking and traffic for efficient vehicles:** initiatives such as parking and even circulation in areas with restricted access will be extended, as well as the reservation of spaces and lower costs for clean vehicles at certain points.
- **Incentive Plan for the Madrid Autotaxi:** the aim is to achieve the progressive renewal of the taxi fleet by efficient vehicles until 2020.
- **Renewal of the city bus fleet:** buses using biodiesel will be replaced by vehicles using alternative fuels or the installation of filters to reduce emissions.
- **Renewal of the intercity bus fleet:** the aim is to renew more than 50% of the fleet to efficient vehicles by 2020.
- **Renewal of institutional fleets** with energy efficiency criteria.

- **AIR QUALITY AND CLIMATE CHANGE PLAN IN MADRID**

With the so-called 'Plan A' the city council aims to achieve a sustainable city, which guarantees the health of citizens against the challenge of air pollution, reduces greenhouse gas emissions and strengthens the city against the impacts of climate change. The time frame of Plan A includes two horizons, 2020 for the achievement of the air quality objectives required by the regulations and a longer-term horizon, 2030, for the necessary energy transition and consolidation of a low-emission city model **[13]**.

The legal framework for air quality at European level is laid down in two directives:

- **Directive 2008/50/EC** of the European Parliament and of the Council, of 21 May 2008, on ambient air quality and cleaner air for Europe.
- **Directive 2004/107/EC** of the European Parliament and of the Council, of 15 December 2004, relating to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air.

The Spanish legal system has incorporated European legislation through a series of laws and royal decrees, in the same way that the local regulations of Madrid have done so through the adoption of ordinances.

The general objectives of Plan A are specified in the fulfilment of other specific objectives that allow a quantitative evaluation of the development of the Plan, and that respond to the fulfilment of obligations to which the city of Madrid must respond immediately. These objectives are translated into the following commitments:

- To comply with European and national air quality legislation.
- To achieve air quality standards for suspended particles in accordance with the World Health Organization's guideline value.

- To achieve a reduction of more than 40% in the total GHG emissions of the municipality of Madrid by 2030, in comparison with 1990.
- To meet the commitment of a 50% reduction in GHG emissions from urban mobility by 2030, in comparison with 2012.
- To develop an adaptation strategy to the effects of climate change, reducing urban vulnerability to the risks associated with global warming.

To achieve these objectives, the Plan promotes four action lines:

1. **Sustainable mobility:** Priority actions are focused on the road network and public space to reduce the intensity of private car traffic, the promotion of public transport and active modes of mobility (pedestrian and cyclist). A zero-emission Central Area is defined, and there are also measures aimed at the vehicle fleet to achieve greater efficiency and technological innovation. In addition, electric mobility and shared mobility are promoted.
2. **Urban regeneration:** The urban regeneration and neighborhood rehabilitation strategies promoted by the Madrid City Council, together with energy efficiency actions, the promotion of distributed generation, the use of renewable energies and measures aimed at reducing emissions from the residential, commercial and institutional sectors, set the path towards a low-emission urban management.
3. **Adaptation to climate change:** Interventions aimed at increasing the city's resilience to the effects of climate change are promoted. The implementation of nature-based solutions to combat urban heat island, biodiversity loss or water management during heavy rainfall episodes is proposed.
4. **Public Awareness:** Awareness-raising among citizens on the problems of air pollution and climate change is promoted. Also, consciousness about the impacts on the environment and on people's health, as well as about the tools that citizens can use to build a more sustainable and healthy city.

The most outstanding actions focused on sustainable mobility include the following:

- **Expansion and renewal of the EMT fleet:** to contribute to the improvement of local air quality, the EMT will renew its fleet with low emissions buses, mainly powered by Compressed Natural Gas (CNG). In addition, in order to promote the de-carbonization of public transport and make progress on the road to electro-mobility, it will renew its fleet of electric vehicles and increase it in the coming years. To do so, it will create the necessary energy supply infrastructures. The aim is to achieve ZERO (electric), ECO (gas and hybrid) classification for all buses in 100% of the fleet.
- **Electric vehicle charging network and alternative fuel supply:** to drive the transformation of the fleet towards less polluting vehicles, it is essential that the supply networks meet the demands of technologies with a lower environmental impact. The main objective is to support the development of the electric vehicle which, due to its absence of direct emissions at the place of use, must play a leading

role in the renewal of the city's vehicle fleet and the reduction of emissions from road traffic. It is necessary to promote the development of charging solutions that will give a definitive boost to the use of electric vehicles. The expansion and improvement of the alternative fuel supply network (CNG, LPG) is contemplated as a complementary objective.

2.2. Status of the Electric Vehicle in Spain

Fossil fuels are still the main source of energy today. Despite its high pollution rate, dependence in Spain is 98%, compared to the European Union average of 73%. Against this background, research into cleaner energy has gained momentum in recent years. The so-called clean energies are timidly gaining ground in our daily lives [14].

An example of this is that, in the last year, cities like Madrid have been forced to take urgent measures to alleviate the pollution caused by traffic, so that electric vehicles have become a principle of solution. In fact, one of the benefits of the electric car versus the fuel car is the amount of greenhouse gas emissions that it produces. In the case of those whose energy source is electricity, they emit between 24 and 70 grams of CO2/km, while conventional fuel cars produce an average of 130 grams of CO2/km.

Institutions and private companies have launched initiatives to encourage the use of this type of vehicle and electric cars charging points became part of street furniture some years ago. At the same time, several private companies have seen a business opportunity in sustainable initiatives such as shared mobility vehicles, as will be explained below.

The urgency to reverse or at least slow down climate change and the harmful effects of greenhouse emissions has forced us to set a threshold with clear objectives: the year 2020. In fact, the Government of Spain expects that there will be at least 110.000 electric vehicles in our country this year. So far, 8.645 vehicles were registered in 2017. In addition, the Executive has committed itself to reducing greenhouse emissions by 10%.

Their combination of energy and environmental efficiency make electric vehicles the clearest example of the move towards a more sustainable and rational mode of transport deemed necessary and desirable by today's societies. Spain is especially well placed to meet all the technical and business needs of this sector, coupled with the political will to socially consolidate the use of electric vehicles [15].

- **Strategic Position**

The characteristics of the Spanish vehicle production, specialized in low range and with models similar to the electric proposals, make it more compatible than in other countries. Moreover, Spain has an excellent geostrategic situation, with direct, fast and economic access to:

- The other main European automobile markets (Germany, France, Italy and United Kingdom)
- The new emerging markets in North Africa.

In addition, Spain is located in the top five electricity producing countries of the European Union, making it one of the most attractive places for the development of electric vehicles.

➢ **Competent Charging Tariff**

In some cases, the electric vehicle charging installation requires a meter for each charging station, as well as a tariff adjusted to its purpose. Considering that the domestic consumer will charge the vehicle mainly at night, an hourly discrimination rate where the energy consumed during the night is cheaper than during the day seems the best option. Some years ago, the Government introduced the Electric Vehicle tariff or 2.0 DHS tariff. This tariff has three periods of consumption with different prices, being the super-valley period (1h-7h) the ideal period for charging electric vehicles at the best price [16].

In the figure below, there is a comparison in terms of energy billing price for the different tariffs offered to the small consumer. The benefits of discriminatory hourly tariffs are clear if most of the consumption is made in the first half of the day. Within them the differences are very small, but it is clear how the one that is divided into three periods is better for the charging of vehicles that will consume mainly in super-valley period [17].

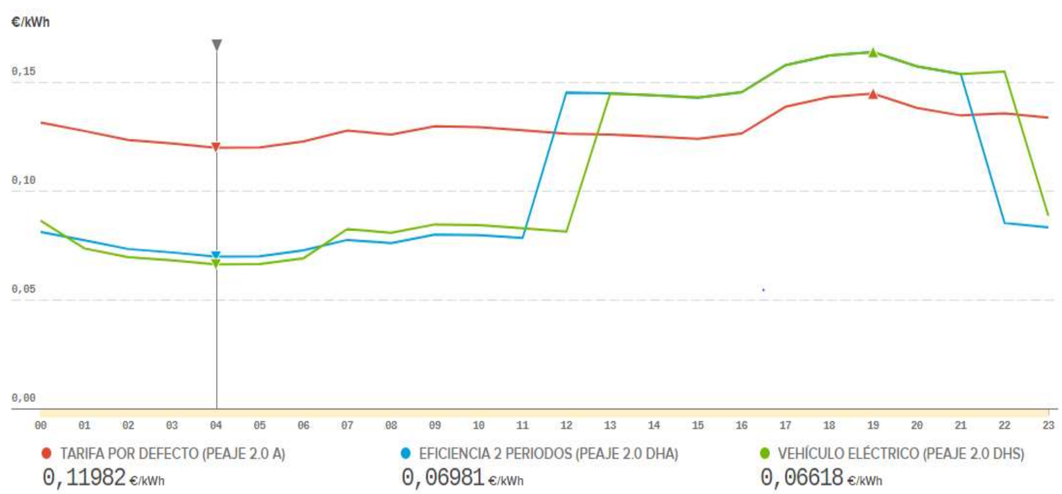


Figure 2.4. Comparison of the price of energy billing in super-valley period [18].

➢ **Experience**

Spain has an extensive experience in the automotive sector, both in terms of vehicle production and automotive parts and accessories development. The Spanish vehicles production plants are among the most competitive in Europe and the world, and at the same time have proven to be very flexible, allowing them to adapt quickly to new market niches. Also, Spain has a consolidated network of technology centers with highly qualified personnel, which are breaking new ground in the development of electric cars.

- **Components Access**

Spain has a wide and competitive automotive components industry, with companies dedicated to R&D in projects related to electric vehicles. In Spain there are 12 companies registered as manufacturers or distributors of batteries, although only two of them are manufacturing in Spain. The two main competitive advantages in this regard are:

- The high weight and hazardous nature of batteries means high logistical costs. The proximity of manufacturers is therefore a key competitive factor.
- A relevant factor in the development of lithium batteries is the battery control electronics. Lithium batteries, specific for electric vehicles, require complex electronics for more effective use.

- **Purchase Intention**

The intention to purchase electric or hybrid vehicles in Spain is higher than the average for other European countries. In this sense, social acceptance is another of the key factors for the development of this technology.

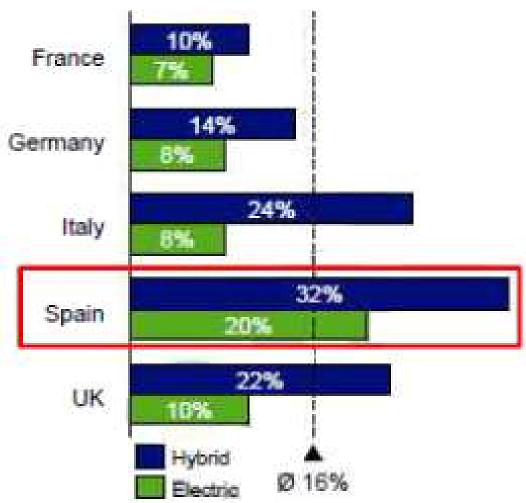


Figure 2.5. Purchase intention of electric and hybrid vehicles [15].

2.2.2. Charging Scenarios

To understand the different scenarios that the electric vehicle charging process could involve, a classification is made taking into account the location and access to the charging point. These factors are defined according to the type of property in which it takes place, and the following cases are distinguished: charging point in public areas, private areas with public access and private areas with private access.

- **Public areas:** these are municipal, regional or national properties with public access. This means that the charging station or point must be accessible to all citizens, but it does not mean that the energy consumed must be free of charge. However, the possibility that the distribution company will take over the infrastructure does not seem unreasonable, as it is a public good. For the moment, the problem lies in finding the way in which the Distribution Operator invests in this type of infrastructure, and in discovering the way in which the customer pays for it.
- **Private areas with public access:** these areas include car parks or charging stations ('electrolineras'). In them, the owner can choose to commercialize the service himself, outsource it to other companies or sell the license to do so. There would also be other cases, such as an office or business building, where the owner could choose to provide this service free of charge. The cars would be parked there for many hours, and different types of on-site generation could be integrated.
- **Private areas with private access:** these are all areas with restricted access to a certain number of owners of electric vehicles. For example, this group includes single-family houses with private garages or apartment buildings with their own parking spaces. The most logical thing is that in this case the vehicle's charging infrastructure is owned by the user, and therefore he has to bear its costs [19].

One way to go further is to classify these scenarios according to the intermediary in charge of providing the final product, as well as according to the level of sophistication in the communication, control and optimization of the battery charging process:

LOCATION		AGENT		CONTROL	
Home	**HO**	Supplier-Aggregator	**SA**	Uncontrolled Charging	**UCO**
				Controlled Charging	**CCO**
Private Property	**PR**	Charging Point Manager	**CPM**	Vehicle-to-Home	**V2H**
				Vehicle-to-Building	**V2B**
Public Property	**PU**	PEV Supplier-Aggregator	**PEVSA**	Vehicle-to-Grid	**V2G**

Table 2.2. Classification of charging modes for electric vehicles [19].

In Spain, the role of demand aggregation is only reflected in the regulatory framework of the electric vehicle through the figure of the charges manager, and it is still necessary to promote a legislation that regulates this figure to analyze its potential and facilitate its implementation [20].

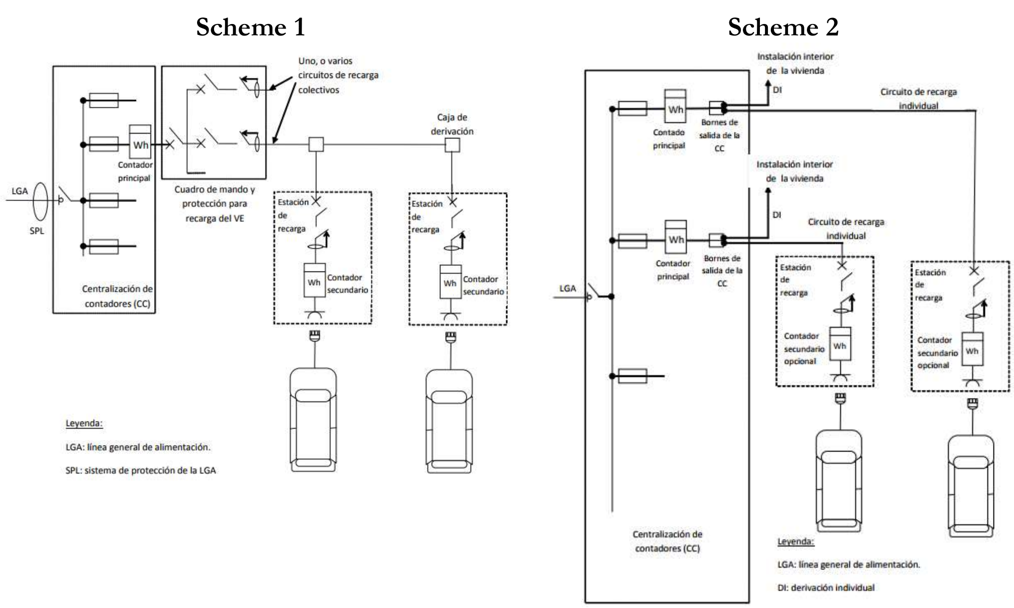
In the context of domestic charging of electric vehicles, it is particularly important to consider the figure of the 'supplier-aggregator', who could be a person with the qualifications to act as such. It is an agent that acts as an intermediary between the electricity company and the consumers, and that specializes in supplying a very flexible charge of electric vehicle fleets [19].

According to Royal Decree 647/2011, those agents whose objective is to carry out the activity of charges manager must prove their legal, technical and economic capacity. In other words, they must demonstrate their capacity to sell and buy electricity, comply with the technical and safety regulations in the facilities where the activity is to be carried out, have the necessary authorizations to perform the charging, have signed an access toll contract with the distribution company for each connection point and present, for each of the facilities, the guarantee deposit corresponding to the access toll contract with the distribution company [21].

2.2.3. Infrastructure for the EV

For each of the existing charging scenarios, the (ITC) BT-52 establishes a series of requirements that must be met for the installation. There are four possible standardized schemes for the supply of charging stations:

1. Collective or main scheme with a central meter at the source of the installation.
2. Individual scheme with a common meter for the house and the charging station.
3. Individual scheme with one meter for each charging station.
4. Scheme with additional circuit or circuits for electrical vehicle charging.



Scheme 3 **Scheme 4**

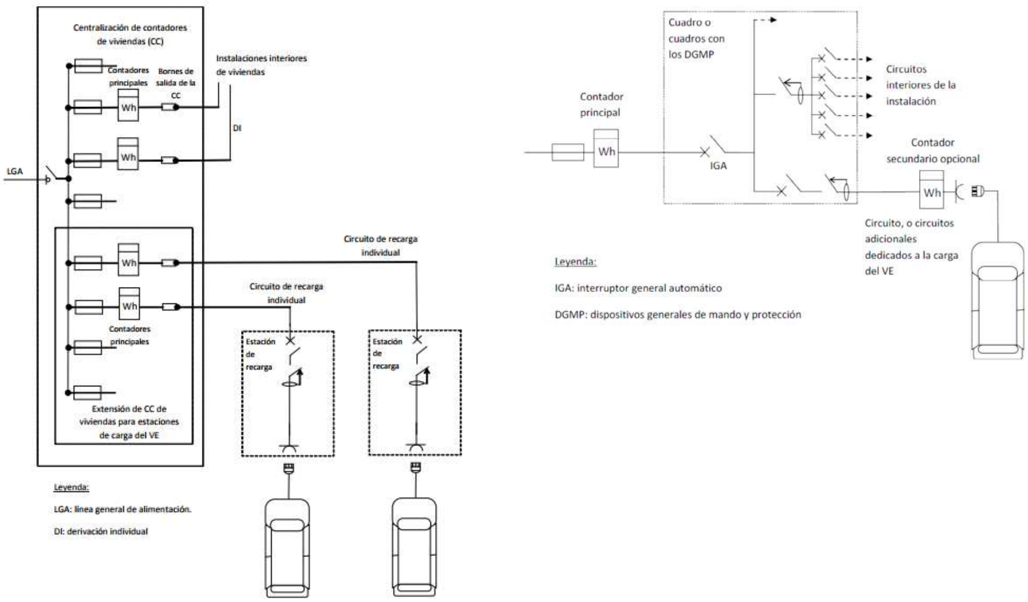


Figure 2.6. Standardized schemes for charging stations power supply [22].

Depending on the type of property, the installations must meet a number of requirements according to the defined schemes:

- **Installation in parking lots for single-family homes**: in new single-family homes with an area designed to house an electric vehicle, an exclusive circuit will be installed for its charging. This circuit will follow installation scheme 4.

  The power supply of this circuit can be single-phase or three-phase, and the installed power will respond to the power forecast per charging station. To avoid imbalances, single-phase circuits shall not have an installed power greater than 9.200 W, and when single-phase stations are connected in a three-phase circuit, they shall be distributed in the most balanced way possible among the three phases.

- **Installation in car parks or collective parking lots in buildings:** the installations for the electrical vehicle charging will follow any of the described schemes. Different schemes may be used in the same building as long as all the requirements laid down in the regulations are met.

  Both in new and existing installations, and in order to facilitate the use of the selected electrical diagram, the general protection boards can be located in the rooms enabled for this purpose or in common areas. Installations in newly constructed buildings shall be equipped with at least one electrical pre-installation for electric vehicle charging in order to facilitate the subsequent use of any of the possible installation schemes.

- **Other charging facilities:** this group includes self-service charging stations, which are intended for the use of untrained persons, or charging stations with assistance for their use. This type of station will follow schemes 1, 3 or 4 as described above [22].

2.2.4. Charging Options

There are now three types of charging for electric vehicles, which vary according to their maximum power, the current they use and the average charging time:

- **Slow charging:** it is the most common due to its simplicity and is compatible with all vehicles on the market. The charge is made using single-phase alternating current at 230V, 16A and 3.6kW maximum power. It only involves connecting the vehicle to a standard plug, and the charging time varies between 5-8 hours. This type of charging is recommended for private garages, whether communal or single-family.

- **Semi-fast charging:** it is not very widespread up to now. Charging is made through a single-phase alternating current of 230V, 32A and 8-14 kW, allowing a charging time of between 1.5-3 hours, or with three-phase alternating current of 400V, up to 63A and 22-43 kW, getting to charge a battery in 30 minutes. This type of charging is aimed at fleet car parks, cinemas, shopping centers or street charging points.

- **Fast charging: it requires a complex electrical installation.** The charging is made through a direct current of up to 600V and 400A, reaching 240kW of power. At maximum power, it allows to charge a battery up to 80% in 5-30 minutes. With 500V alternating current, up to 250A and 220 kW, it achieves charging times of 10 minutes for 80% capacity. This type of charging is intended for the so-called 'electrolineras', as well as service stations that offer electric charging [23].

2.2.5. Initiatives to Promote Electric Vehicles

Both public and private institutions and companies have launched initiatives to encourage the use of this type of vehicle and the charging points for electric cars.

In the specific case of the Community of Madrid, Plan A and the Energy Plan Horizon 2020 stand out as public initiatives. Both proposals are focused on achieving a sustainable city, and to this end they promote the electric vehicle as one of the key points to achieve their objective. With regard to private initiatives, some of the most important are explained below.

- **Charging Infrastructures**

Iberdrola has launched its new 'Smart Mobility' plan to boost electric mobility. As part of this initiative, it plans to install a total of 25,000 charging points for electric vehicles in Spain by 2021. Most of them, 16,000, will be installed in homes and the remaining 9,000 in companies that want to offer this service to their employees or customers. 'Smart Mobility' is a complete global solution that includes the acquisition of the charging point, its installation and guarantee, the possibility of checking and operating it in real time and remotely through a simple application, as well as the supply contract that is adapted to each customer **[24]**.

Endesa, has also developed a complete solution with the most advanced technology intended for charging electric cars. The 'Endesa Charging Points' offer the necessary infrastructure to charge the battery of the electric vehicle, with the maximum security and in a comfortable way from the home garage. There are also external charging points where the batteries can be charged. The installation of the 'Charging Point' is free of charge, provides unlimited repair service (both for the point and the installation) and a full warranty **[25]**.

In the case of the oil companies many of them are changing their policies, due to the latest developments in an increasingly pro-electric car industry. In this sense, they see the charging business as a possible strategy to adapt to the new times. In our country there is a good example of this with the IBIL charge manager. This company focuses on the development of a fast charging network at Repsol service stations with coverage throughout Spain **[26]**.

Tesla's network of Superchargers offers free fast chargers for the benefit of customers who purchased one of its electric cars. The Spanish Supercharger network currently has 21 stations, to which Tesla will soon add 16 additional Superchargers. With them, a total of 37 stations for more than two hundred connections allow Spanish Tesla users to quickly charge their electric vehicle during long-distance journeys. With only 30 minutes connected, the Tesla car will have about 250 kilometers of extra autonomy. A complement to the Superchargers is Tesla's Destination Charging network, which allows customers to charge their vehicles while they are 'on the go' in places like shopping malls or hotels **[27]**.

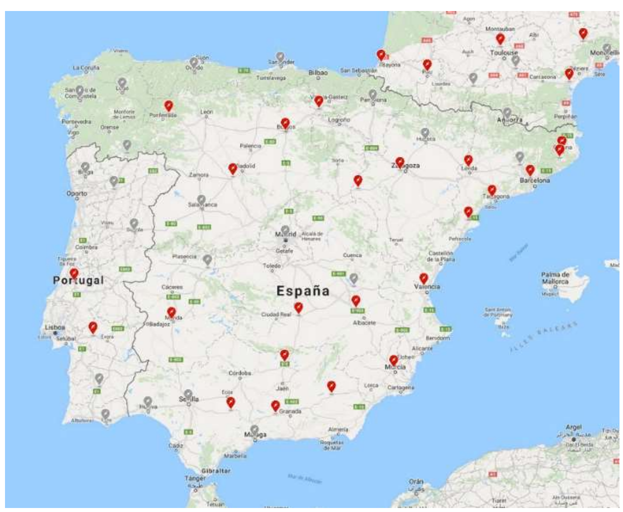


Figure 2.7. Existing Superchargers (red) and planned or under construction (grey) in Spain **[27]**.

- **Shared Mobility**

Several private companies have seen a business opportunity with sustainable initiatives such as shared mobility vehicles. This is a service that offers both motorcycles and cars for rent for short periods of time at multiple locations. The nearest vehicle is identified and booked via an app. The cost of the service depends on the time of use.

First came the electric cars (carsharing) in 2015, with companies such as Car2Go, Emov or Zity; and in 2017 they were followed by motorcycles (motosharing) thanks to Muving or eCooltra. Today, there are already 1.480 electric carsharing cars and 615 motosharing vehicles in Madrid, and according to Car2Go calculations, each one is rented 16 times a day on average [14].

Company	Vehicle	Rental Rate	Vehicle Model	Autonomy	Fleet	Operating Radius	Capacity
CAR2GO	Car	0,21€/min 59€/day	Smart Fortwo	160 km	500 vehicles	Inside the M-30	2 persons
emov	Car	0,24€/min 69€/day	Citroën C-ZERO	150 km	600 vehicles	Inside the M-30 and surroundings	4 persons
ZITY	Car	0,26€/min 55€/day	Renault Zoe	403 km	500 vehicles	Inside the M-30 and surroundings	5 persons
MUVING	Motorcycle	0,21€/min	Torrot L1 (49 c.c.) Torrot L3 (125 c.c.)	65 km	700 vehicles	Inside the M-30 and surroundings	2 persons
eCooltra	Motorcycle	0,24€/min	Govec (50 c.c.)	40 km	1000 vehicles	Inside the M-30 and surroundings	2 persons

Table 2.3. Shared mobility services comparison [28] [29].

- **Other Electric Vehicle Charging Initiatives**

'Metrolinera': Since 2011, Metro de Madrid has developed the Train2car project in collaboration with various institutions. The aim of this initiative is to take advantage of the energy generated as a result of the braking of the metro units, resulting in the so-called 'metrolineras'. It is a charging post, which uses the converted electrical energy from the movement of the Metro de Madrid wagons in the long phases of deceleration and braking. Accumulators located in the station itself are responsible for storing the energy beforehand, and then carrying it to the supply post, located outside the metro station. This energy is transported under voltage conditions equivalent to those of a rapid charge. The first 'metrolinera' was opened in Spain in 2014, and Train2Car's promoters plan to install up to 150 more in the coming years throughout the Metro network [30].

'Ferrolinera': This is a project developed by Adif, which aims to promote the development of urban electric mobility. This is done by taking advantage of the energy generated during the braking of trains and the integration of auxiliary support systems based on renewable energies, through charging points for electric vehicles connected to the railway network. The aim is to convert the railway network into the largest chain of charging points for electric vehicles, given that the project foresees the installation of up to 1.500 charging facilities in railway stations in Spain. These points will supply the energy of the electrical substations that supply the catenary of the train lines, the energy recovered from the braking of the trains and the photovoltaic energy available in the canopies of the parking areas [31].

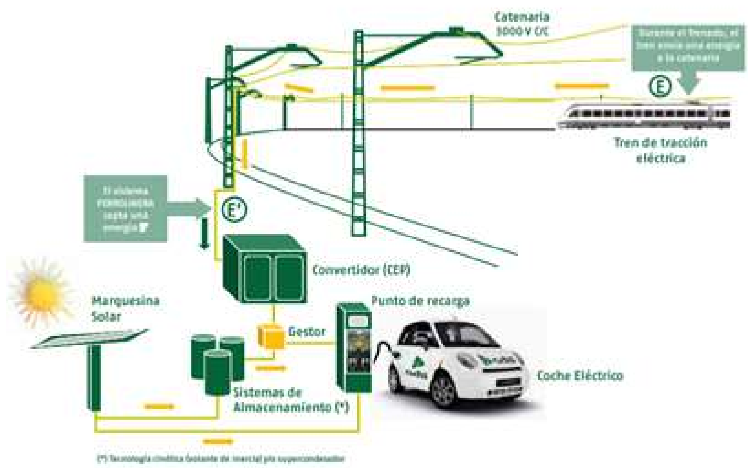


Figure 2.8. Connection of Electric Vehicle to the Railway catenary [31].

2.3. STATUS OF THE ELECTRIC VEHICLE IN EUROPE

The EU is strongly committed to eliminating carbon technologies. To this end, electric vehicles are one of the alternatives chosen to be fostered. The policies they are pursuing promote [32]:

- Progress in the use of electricity and renewable technologies.
- Provision of the infrastructure required for electric vehicles, such as charging points.
- Implementation of legislation that limits the amount of carbon dioxide per kilometer allowed for new cars.

The electric car still has a long way before it becomes a real alternative and achieves sales numbers closer to those of traditional vehicles. However, little by little it is starting to take off, and in Europe we are already talking about sales of 135.369 electric cars compared to the 90.996 registered in 2016, which represents a growth of 48.8%, according to data published by the European Association of Vehicle Manufacturers. These numbers are expected to increase to the point where more than 600.000 electric vehicles are expected to be sold in Europe by 2020 [33].

Spain is one of the European countries with the lowest representation of electric vehicles in terms of sales (0.32% share of the passenger car market), well below the European average, which is 1.7%. Norway is by far the European country with the highest percentage of electric cars in the market. In terms of 2017 registrations, Norway is back at the top of the list.

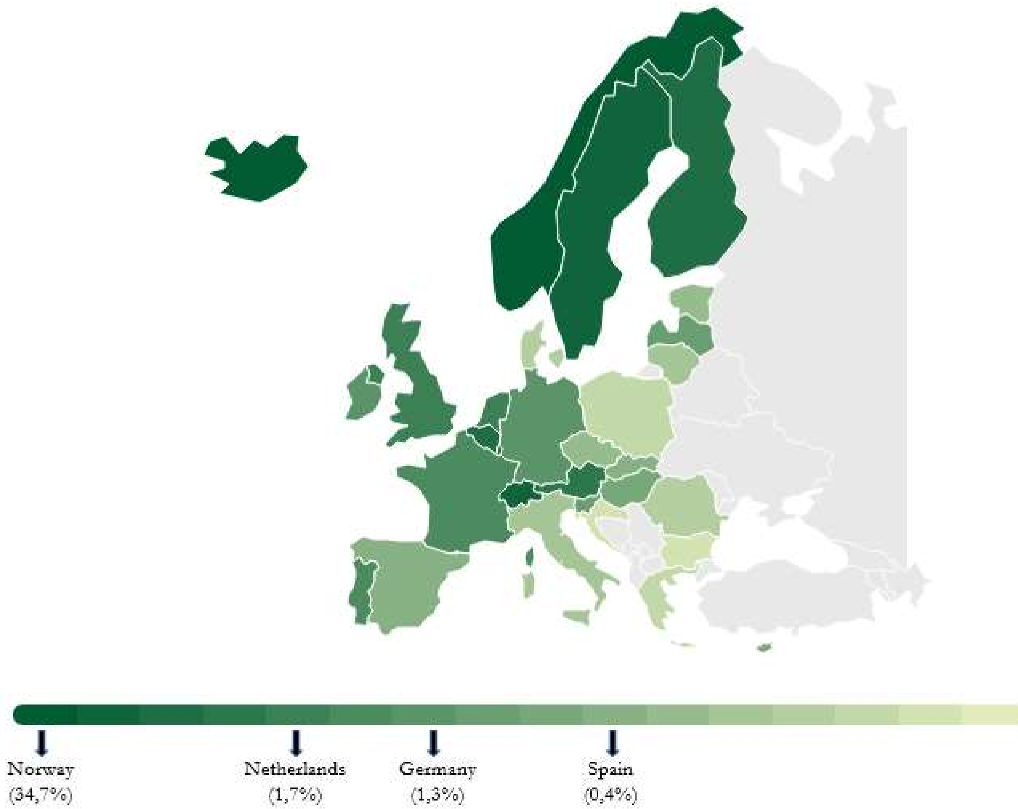


Figure 2.9. Market share of electric cars in Europe with respect to total vehicles.

2.3.2. ELECTRIC VEHICLE IN NORWAY

As already mentioned, Norway is a model country for the speed and efficiency with which the automotive fleet is changing. In this sense, the difference with the rest of the countries lies in a very complete set of incentives for the population [32].

The subsidy for the purchase of electric vehicles is what seems to mark the turning point. As a result of this help, the prices of these cars are practically the same as those of traditional ones. Some other favorable measures have to do with the possibility of driving on public bus lanes, the reduction in taxes or the benefits in parking and charging costs. Electric vehicle users do not pay for this electricity: thanks to the good functioning of the country's renewable energy sources, such as wind, the kilowatt is very cheap and the government can afford this expense. In addition, the network of car plugs is widespread, and there are fast charging points on many roads.

2.3.3. Electric Vehicle in Netherlands

In the Netherlands, several initiatives are under way to achieve a 55% reduction in pollutant emissions by 2030. The government hopes to achieve this mark with the gradual introduction of the electric car, and the disappearance by 2030 of diesel and gasoline models, as well as hybrids. This 4-billion-euro emissions reduction project also includes measures to further increase the use of bicycles and the closure of all coal-fired power plants by 2030 **[34]**.

At the moment there are no details of what measures the Dutch government will put in place, but it is expected that incentives such as the significant tax deductions for electric cars, which only pay 7% VAT (25% for the rest), in addition to investment in public charging infrastructure, will be maintained. These are two of the pillars of this technology.

2.3.4. Electric Vehicle in Germany

The electric car market in Europe continues to grow, and although Norway had a huge advantage in sales of these vehicles, there are already signs of a new country starting to reign in the sector. Germany, which already leads the way in the sale of plug-in models, is about to become the third largest global market for electric cars after China and the United States.

The German government aims to reach the number of one million electric cars circulating in the country by 2020. To boost this, it just announced that it will offer an incentive consisting of a 5.000 € public bond for the purchase of an electric vehicle. The plan will run until 2020 and will apply a bonus reduction of 500 € each year for each passing year **[35]**.

This measure complements previous public initiatives such as the designation of free parking spaces reserved for electric cars in city centers and the privileged authorization for these vehicles to use the bus lane. In addition, the government plans to fund 15.000 new charging stations across the country and to provide grants for research to develop the batteries technology. Its goal is to help maintain the technological leadership of the German industry.

2.4. Conclusions

After almost a century of domination of the internal combustion engine in the automotive sector, the electric vehicle market is growing rapidly. Many policies have emerged at both European and national level, allocating funds to promote energy efficiency. All these government initiatives and the increasing awareness of sustainability have turned the penetration of the electric vehicle into a key point of the current policy.

As a response to international warnings, a number of policies have been developed, with Europe at the forefront, to begin what is known as the 'energy transition'. It is worth highlighting the Energy and Climate Change Package with objectives for 2020, the 2030 Framework and the 2050 Roadmap, with targets for reducing emissions, increasing the penetration of renewable energies and increasing energy efficiency.

In this context of commitment to achieving the objectives proposed by the EU, both the Spanish Government and the local authorities are taking measures to promote a process of energy transition that is economically viable and technically feasible. In the specific case of the Community of Madrid, two policies stand out. On the one hand, the Energy Plan 2020 Horizon, which is in line with the objectives proposed by the EU to achieve by 2020. On the other hand, the Air Quality and Climate Change Plan ('Plan A'), whose main objective is to achieve a sustainable city that guarantees the health of citizens in the face of the challenge of atmospheric pollution.

As already mentioned, the electric vehicle is one of the key solutions for achieving the sustainability objectives set by the EU, and for slowing down the growing social concern for the environment. Spain has an advantage in this regard, as it is a country that is particularly well placed to meet all the technical and business needs of this sector, and also has the political will to socially consolidate the use of electric vehicles.

In addition, current legislation provides for regulation of electric vehicles. On the one hand, standardized schemes are established for the supply systems of charging stations according to the type of ownership of the facilities, which may be public areas, private areas with public access or private areas with private access. On the other hand, the role of demand aggregation is recognized through the figure of the 'load manager', which is an agent that acts as an intermediary between the electricity company and the consumers. Even so, it is still necessary to promote a legislation that regulates this figure to facilitate its implementation, as it is particularly important in the field of domestic charging of electric vehicles.

Besides the public institutions, private firms are also implementing initiatives to encourage the use of this type of vehicle and promote electric car charging points in our country. Companies such as Iberdrola and Endesa have approved plans for the installation of charging points for households, with supply contracts adapted to the new customer needs. Also noteworthy are Tesla's network of Superchargers throughout the country and oil companies such as Repsol, which are progressively adapting to the new times and investing in the future of electric mobility at their service stations. Another interesting initiative is the shared mobility of motorcycles and electric cars, a sustainable and cost-saving proposal for transportation.

In terms of Europe's overall picture in this area, Norway stands out for the speed and efficiency with which its automotive fleet is changing. It seems that the difference with the rest of the countries lies in a very complete set of incentives for the population, both for the purchase of vehicles and for their use. Germany, however, is following it closely and is about to become the third largest global market for electric cars. Its targets in figures are very ambitious, and it is also announcing interesting measures to promote the penetration of the electric car in the market.

Spain still lags behind in these aspects, but the new policies that promote energy efficiency are gradually beginning to pay off, turning the electric vehicle into one of the key actors in achieving it.

As already mentioned, in the specific case of the Community of Madrid, 'Plan A' includes the encouragement of sustainable mobility as a core line of action to achieve its objectives. This measure involves renewing the city's fleet of public buses, replacing them with low-emission ones, and at the same time promoting the recharging network for clean fuel vehicles. However, there is still no bus station in Madrid prepared to meet the recharging needs of an eco-friendly fleet, such as an electric one.

In this context of novelty and advantageous political framework, the study of the profitability and operation of a supposed station fully equipped with electric recharging points is presented as an opportunity. The reasons for choosing the city of Madrid to carry out the analysis are, on the one hand, the possibilities offered by its size and population, and also the political support derived from 'Plan A'. More specifically, the Plaza de Castilla station is chosen because it is the end of line for many buses and a point frequented by private cars of workers, which will also be included in the analysis to contemplate a scenario that allows for the benefit of all citizens. The results obtained from the analysis will serve to study the feasibility of a real project of this kind, and also the profitability that would involve for both users and public institutions.

3. Mathematical Formulation

The case of study consists on a MIP (Mixed Integer Programming) problem where the objective is to stablish the scheduling of the buses, the number of charging points and the potential private users, when transforming a bus station into an electric one. The aim is to maximize the cash flow profits obtained by installing electric chargers in a bus station, where both private cars and buses could charge and benefit from the difference in prices between consuming electricity and gasoline. The modeling or complex representation of the reality is done through deterministic formulation, where all the parameters are known in advance with certainty and the objective is to choose the best alternative to achieve the maximum economic performance.

The optimization model consists on:

1. **Sets** or dimensions of the variables, which are lines of buses, buses, periods of time (30 min interval), technology of the bus (gasoline or electric) and charging type (fast and semi-fast charging).
2. **Parameters** or data researched in advance, which are the timetables of the buses (public information of EMT **[36]**), charging duration, cost of infrastructures and heuristic estimation of the potential private users.
3. **Variables** or decisions, which are the scheduling of the bus and its charge, number of private users that charge and number of charging points. Other variables, such as the battery inventory level, are implemented to make a realistic representation of the behavior of the buses.
4. **Objective Function** or performance of the model, measures the profitability obtained with the charging schedules of the buses and the number of private users that charge. The costs associated to the electric bus station are the installation of the charging points.
5. **Constraints** or feasibility region of the problem, introduced to make a realistic representation of the operation of the bus station by modelling the movement and charging of bus and private users.

To sum up, the Table 3.1 gives a perspective of how the case of study is modelled.

STEP 1 [Data Research]	***STEP 2 [Optimization]***	***STEP 3 [Output]***
▫ Bus Timetable	▫ **Sets**	▫ Charging Scheduling
▫ Estimation of Potential Private Cars	▫ **Parameters**	▫ Bus Scheduling
▫ Cost of Infrastructure	▫ **Variables**	▫ State of Battery
▫ Charging Durations	▫ **Objective Function**	▫ Number of Charging Points
▫ Degree of EV Penetration	▫ **Constraints**	▫ Potential Private Cars' Users Coverage
▫ Location		▫ Cash Flow

Table 3.1. Resolution process of the optimization problem.

The mode of operation of the buses and private cars consists of constraining their movement to have a full charge of the battery, and this is achieved by revising the state of charge of the battery every time period. The quality of the bus service is guaranteed by solving the most unfavorable case for the whole year.

In terms of toolkit used, a combination of GAMS and Excel is adopted to solve the business case of the EV facility. GAMS or General Algebraic Model System is a high-level modeling tool for optimization problems, that gives the user great flexibility to adapt the model to new situations. Excel is principally used to introduce, process and interpret the data and outcome of the problem.

3.2. SETS

The sets of the model are the dimensions that all the variables can have. The case of study is based on Plaza Castilla Station, as it is shown in the map it is located in the north of Madrid Figure 3.1.

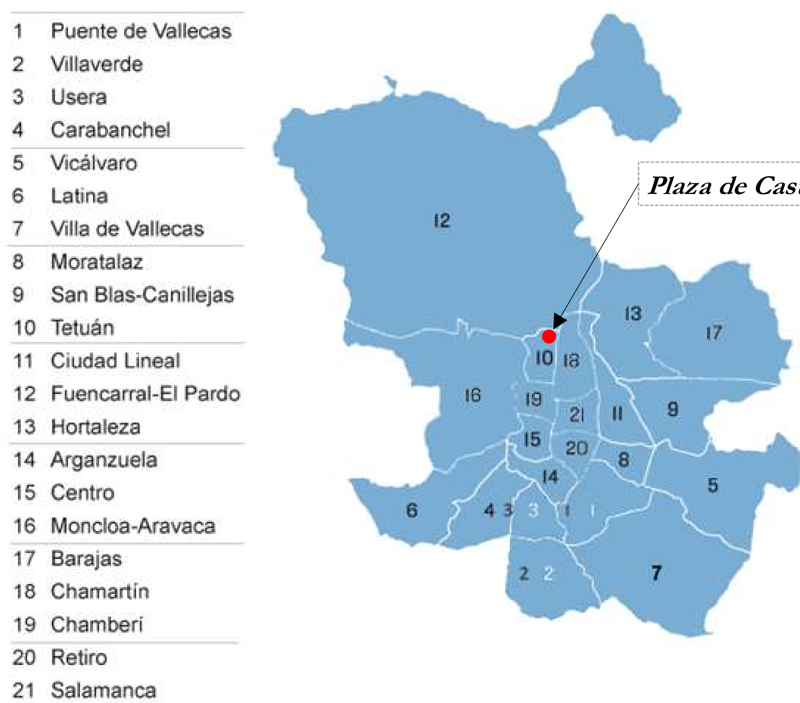


Figure 3.1. Case study bus station location.

In terms of the dimensions, there are 58 bus lines in Plaza de Castilla and the number of periods for a 30 min time window in a whole day of operation are 48.

The definition of the sets is explained subsequently in Table 2.2.

Sets	
Name	Definition
p	Periods of time in the case study, a day of operation is divided into 48 periods of 30 min.
l	Bus Lines in Plaza de Castilla.
b	Buses dimension.
e	Type of bus, distinguishing between gasoline and electric.
s_e	Subset of electric buses.
t	Type of charging, both fast and semi-fast electric charging.

Table 3.2. Sets of the case of study.

The number of buses necessary for every line are estimated by using the frequency and the time cycle [36] needed to complete the line, resulting in:

$$N^{o}\ of\ Buses = \frac{Full\ Route\ [2\ Cycles]}{Frecuency} + 1\ Emergency\ Bus \qquad \text{Eq. 3.1.}$$

As an example of the calculation with data coming from the EMT webpage, the bus line 724 of Plaza de Castilla with a frequency of 30 min and a duration of 120 min for a round trip is chosen. Consequently, 4 buses are needed to maintain the schedule and 1 extra for emergencies, resulting 5 buses for the line 724.

The other 58 lines of Plaza de Castilla are estimated in Table 3.3.

	b1	b2	b3	b4	b5	b6	b7	b8
L149	1	1						
LT62	1	1						
LSE704	1	1						
L27	1	1	1					
L70	1	1	1					
L135	1	1						
L67	1	1	1					
L129	1	1						
L177	1	1						
L175	1	1	1					
L176	1	1	1					
L49	1	1	1					
L107	1	1						
L42	1	1						
L173	1	1						
L174	1	1	1					
L134	1	1	1					
L178	1	1	1					

L151	1	1	1					
L153	1	1	1					
L155B	1	1	1					
L155	1	1	1					
L157	1	1	1					
L157C	1	1	1					
L152C	1	1	1	1				
L154C	1	1	1	1				
L181	1	1	1					
L185	1	1	1	1				
L182	1	1	1	1				
L183	1	1	1					
L184	1	1	1					
L159	1	1	1					
L156	1	1	1					
L161	1	1						
L721	1	1						
L722	1	1	1					
L724	1	1	1	1	1			
L726	1	1	1	1	1	1		
L725	1	1	1	1	1	1		
L195	1	1						
L197	1	1	1	1	1			
L714	1	1	1					
L712	1	1	1	1				
L713	1	1	1	1				
L716	1	1	1	1				
L194	1	1	1					
L196	1	1						
L199	1	1						
L191	1	1	1					
L193	1	1	1	1				
L876	1	1	1	1				
L171	1	1	1					
LN103	1	1						
LN102	1	1	1					
LN101	1	1	1					
LN701	1	1						
LN702	1	1						

Table 3.3. Buses per line in Plaza de Castilla or subset of buses and lines.

3.3. PARAMETERS

The data included in the model as a parameter is deterministic, this is, known in advance with certainty and no probability.

Parameters		
Name	Definition	Units

$Demand_{p,l}$	Demand of buses per bus line and period or real representation of the timetable.	[# of buses]
$DurationR_l$	Duration of the routes of the buses.	[# of periods]
$DurationC_t$	Charging duration depending on the technology, fast or semi-fast.	[# of periods]
$DurationCPU_t$	Charging duration for Private Users depending on the technology, fast or semi-fast.	[# of periods]
$DischargeDur$	Discharge duration for electric buses.	[# of periods]
$PotentialP$	Number of potential private users that could charge in the electric facility installed.	[# of buses]
ρ	Grade of penetration or percentage of electric buses.	[%]
$\overline{NCP}$	Maximum number of charging points that could be installed.	[# of charging points]
$benPU$	Benefit that comes from the private users' charging.	[€]
$benB_e$	Benefit per route provided by an electric bus.	[€]
cost_t	Cost of the charging point.	[€]
$WACC$	Interest rate.	[%]

Table 3.4. Parameters of the case of study

$Demand_{p,l}$, the demand of buses represents the number of buses per line that should be in movement at the same time in order to guarantee the frequency and quality of the service. An aggregation of the demands of Plaza de Castilla every 30 min, which is the time window selected for the case of study, is presented in the next figure.

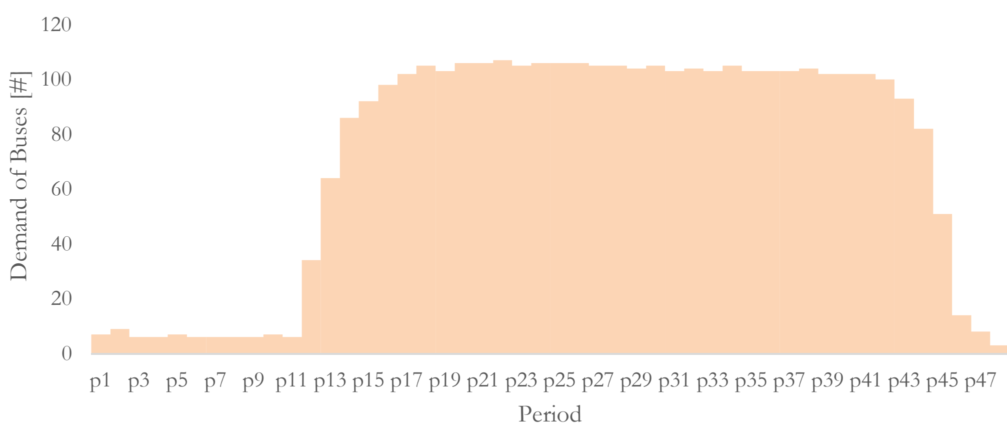


Figure 3.2. Demand of buses in Plaza de Castilla by aggregating the schedules [36].

For the duration of the routes or $DurationR_l$, an estimation or rounding of the time that appears on the schedules of every line is done to determine the number of 30-minute periods needed to complete a whole cycle of each line.

L149	1	L153	2	L725	5
LT62	1	L155B	1	L195	11
LSE704	1	L155	1	L197	4
L27	1	L157	1	L714	2
L70	1	L157C	2	L712	3
L135	1	L152C	2	L713	3
L67	1	L154C	2	L716	2
L129	1	L181	4	L194	9
L177	1	L185	3	L196	8
L175	1	L182	4	L199	4
L176	1	L183	2	L191	3
L49	1	L184	4	L193	3
L107	1	L159	1	L876	3
L42	1	L156	1	L171	2
L173	1	L161	2	LN103	2
L174	1	L721	2	LN102	1
L134	1	L722	2	LN101	1
L178	1	L724	4	LN701	2
L151	1	L726	5	LN702	2

Table 3.5. Duration of the route of each bus line in Plaza de Castilla, which is two times the cycle of the route (round trip) [36].

Charging the buses and private electric vehicles requires time ($DurationC_t$ and $DurationCPU_t$), which depends on the technology of the charging point. In the case study, slow charging is discarded since it reduces the flexibility needed for guaranteeing the quality of the service without incrementing the number of buses. According to [23], semi-fast charging with three-phase current of 32 A is estimated in 1 hour, which is 2 periods of 30 min, and fast charging with DC is between 5 and 30 min, so it is taken 1 period of 30 min to charge. Figure 3.3. represents the number of periods needed for fast and semi-fast charging.

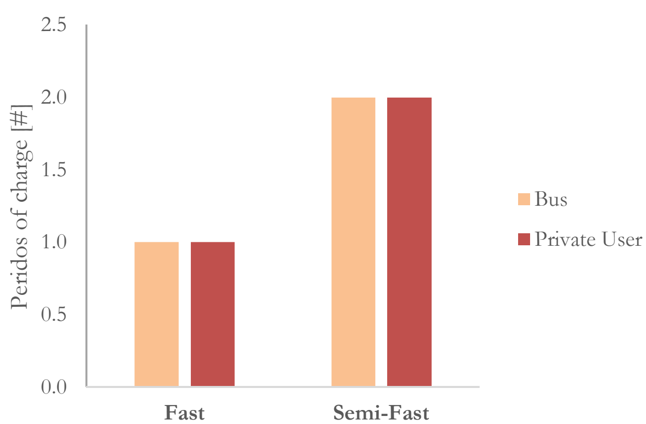


Figure 3.3. Charging time duration depending on the technology.

$PotentialP$ or potential private users of the electric charging points installed in the case of study is estimated by using the number of EV that were bought in 2017 and the population of the districts that could be affected by the installation in this area. Moreover, a projection to the future is calculated by using the S Curve or Adoption Curve, where Madrid could be resembled as an early adopter of the electric vehicle.

The districts affected by Plaza Castilla Bus Station represent the 30% of the total population of Madrid. As a result, a total of 20000 EVs could charge there. However, it is supposed that only 10% of those cars would be willing to charge in the bus station, resulting in a total daily demand of ~2000 cars.

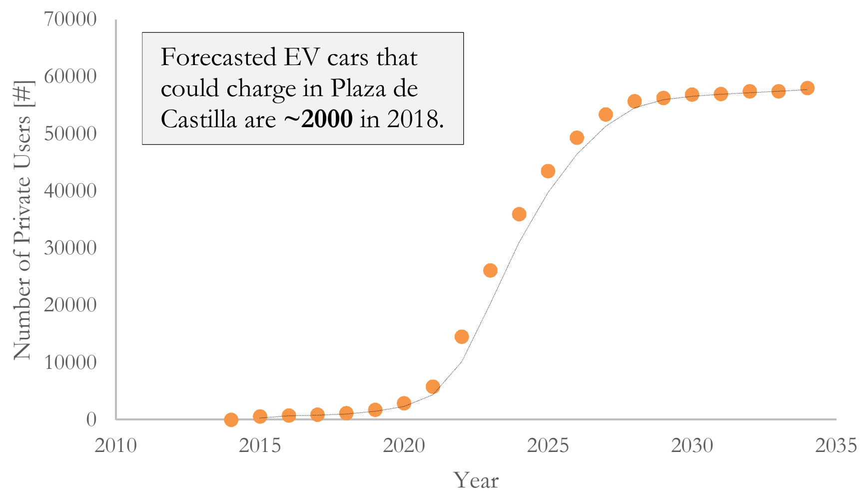


Figure 3.4. Potential private users' estimation in Plaza de Castilla for 2018.

In order to quantify the number of potential users per period, a daily usage curve is heuristically obtained, resembling to the electric demand curve. The number of potential private users is obtained by multiplying the usage curve and the 2000 cars that are estimated daily, represented in Figure 3.5.

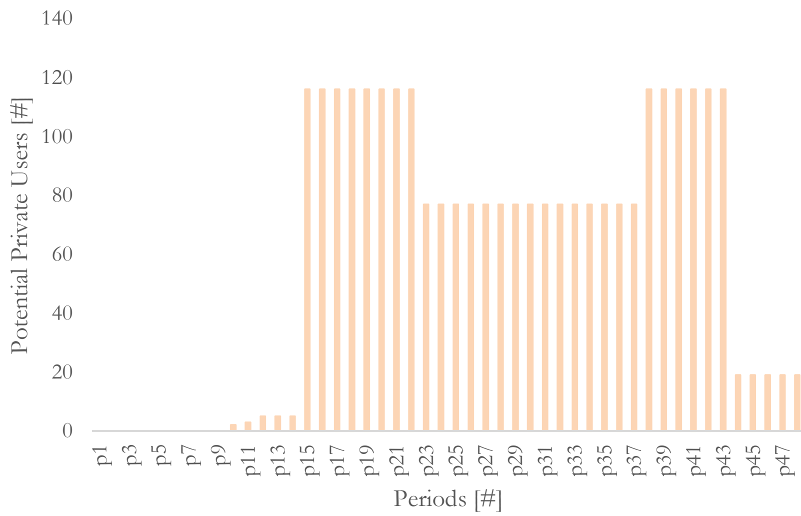


Figure 3.5. Potential Private Cars curve.

ρ, grade of adoption or penetration of electric buses in the case of study is at least 10% of the fleet of buses. In the case of the bus station of Plaza de Castilla, where 195 buses are estimated to be scheduled, 20 buses will approximately be electric, and this will be traduced in monetary savings for the town hall of Madrid.

$\overline{NCP}$ or upper bound of the number of Electric Charging Points that could be installed is limited to the available space in the selected bus station. As an approximation, the available space is resembled as the number of docks in the station, being 53 in the case of Plaza de Castilla.

The positive cash flow or profits associated with the update of the bus fleet and the installation of charging points in a bus station are calculated as the savings that each bus could provide in each 30-minute period in route, which is 3.6 € or $benB$. Moreover, a benefit of 0.5 € or $benPU$ could be obtained for every private user charging in the facility by estimating the benefit in a 10% of the cost of charging a car.

Business Case Bus		
Gasoline Price	1.3	€/l
Electricity Price	0.12	€/kwh
CGN Price	0.7	€/kg
Gasoline Bus		
Fuel Tank	500	l Gasoline
Consumption	25	l/100km
Autonomy	2000	km
Electric Bus		
Battery Energy Cap.	376	kWh
Consumption	150.4	kWh/100 km
Autonomy	250	km

Business Case Car		
Price Electricity	0.12	€/kwh
Electric Car		
Battery Energy Cap.	40	kWh
Consumption	13.3	kWh/100 km
Autonomy	300	km
Cost Electric Bus	4.80	€/Car
Benefit [10%]	**0.48**	**€/Car**

Natural Gas Bus		
Gas Tank	200	kg
Consumption	28.6	kg/100 km
Autonomy	700	km
Cost Gasoline Bus	8.13	€/30 min
Cost Electric Bus	4.51	€/30 min
Cost Gas Bus	5.00	€/30 min
Savings Electric vs Gasoline	**3.61**	**€/30 min**
Savings CNG vs Gasoline	**3.13**	**€/30 min**
Savings Electric vs CNG	**0.49**	**€/30 min**

Table 3.6. Business case with the characteristics of electric buses **[37]**, gasoline buses **[38]**, CGN buses **[39]** and electric cars **[40]**.

It is important to highlight that the associated cost of changing the bus technology will be despised, since the bus fleet is already at the end of its useful life.

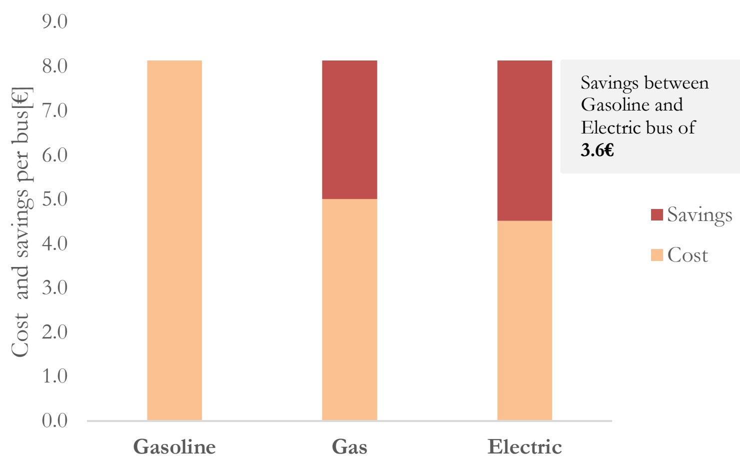


Figure 3.6. Cost and savings per bus for each 30-minute period depending on the technology with respect to gasoline.

cost_t or costs associated with the installation of the charging points depend on the type of technology installed, being much more expensive to install a fast charging facility. Fast charging (DC, 600V, 400A and 240kW) facilities cost around 50000 €, while semi-fast charging (3xAC, 400V, 32A and 22-43kW) installation costs about 3000 € **[41]**.

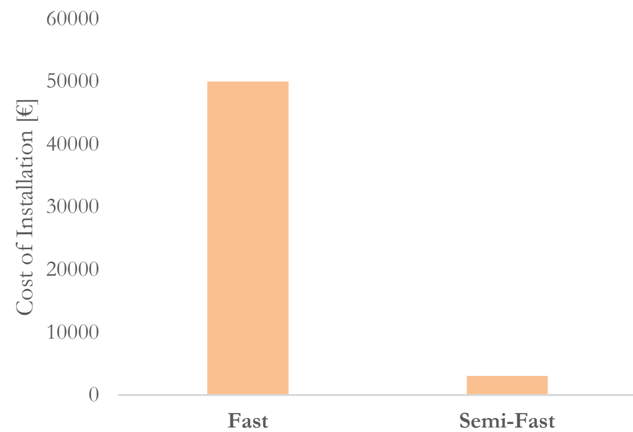


Figure 3.7. Installation cost of a charging point depending on the technology.

3.4. VARIABLES

The goal of the variables or decisions of the problem is to alter or control the performance of the objective function, which is a profitability maximization. As stated before, the problem is a combination of binary and continuous variables.

The main decisions that affect the objective function are the number of charging points installed in the bus station or NCP_t, the charging scheduling of the buses or $CB_{p,l,b,t}$ and the number of private users that will charge or $CPUS_{p,t}$ in the day of operation. The profitability of the project is divided into benefits minus cost, where the benefits come from charging buses and private users and the costs arise from the installation of charging points.

The continuous variables are presented subsequently:

Continuous Variables		
Name	Definition	Units
Ψ	Objective function in monetary terms.	[€]
$IBat_{p,l,b}$	State of the battery, as a percentage.	[%]
NCP_t	Number and type of charging points installed.	[#]
$CPU_{p,t}$	Number of private users charging.	[# of users]
$CPUS_{p,t}$	Number of private users that start charging.	[# of users]
$CPUE_{p,t}$	Number of private users that end charging.	[# of users]

Table 3.7. Continuous variables of the case of study.

All continuous variables are defined as positive variables.

$$IBat_{p,l,b}, NCP_t, CPU_{p,t}, CPUS_{p,t}, CPUE_{p,t} \geq 0 \quad \text{Eq. 3.2.}$$

$$\forall p, l, b, t$$

Except, for the objective function, which is a free variable.

$$\Psi \; free \quad \text{Eq. 3.3.}$$

The binary variables of the problem are:

Binary Variables		
Name	Definition	Units
$BR_{p,l,b,e}$	Decision variable for a bus in route.	[0-1]
$BO_{p,l,b,e}$	Decision variable for a bus starting a route.	[0-1]
$BI_{p,l,b,e}$	Decision variable for a bus ending a route.	[0-1]
$CB_{p,l,b,t}$	Decision variable for a bus charging.	[0-1]
$CS_{p,l,b,t}$	Decision variable for a bus starting to charge.	[0-1]
$CE_{p,l,b,t}$	Decision variable for a bus ending a charge.	[0-1]

Table 3.8. Binary variables of the case of study.

All binary variables belong to the 0-1 domain.

$$IBR_{p,l,b,e}, BO_{p,l,b,e}, BI_{p,l,b,e}, CB_{p,l,b,t}, CS_{p,l,b,t}, CE_{p,l,b,t} \in [0-1] \quad \text{Eq. 3.4.}$$

$$\forall p, l, b, e, t$$

3.5. Objective Function

The objective function or performance of the problem aims to maximize the cash flows obtained by changing a bus station into an electric charging facility where both the buses and the potential electric car users are the customers.

The objective function measures the cash flows that could be obtained by introducing charging points in a bus station, where electric buses are traduced in daily savings and private users are strictly indexed as a profit.

$$\max \Psi = \sum_{n=1}^{n=20} \frac{365 \cdot \sum_{p,l,b,e} benB_e \cdot BR_{p,l,b,e}}{(1+WACC)^n} + \sum_{n=1}^{n=20} \frac{365 \cdot \sum_{p,t} benPU \cdot CPUS_{p,t}}{(1+WACC^*)^n} - \sum_{t} \text{cost}_t \cdot NCP_t \quad \text{Eq. 3.5.}$$

3.6. Constraints

The constraints restrict the problem by establishing relationships between variables. They represent the feasibility area of the problem.

It is important to highlight that circular operators are introduced in order to reproduce a more realistic behavior of the charging process and the performance of buses, where the previous day of operation affects the subsequent one.

3.6.1. Bus Behavior

Bus performance constraints have been modeled the same way as a unit commitment of a power plant. This means that the behavior between periods is related to the previous ones. A bus is on route if its binary variable associated with the output has been previously activated, and its movement will be related to its status in the previous period. The following equation applies at the bus-line level, which is the level of detail that has been modeled in this case.

$$BR_{p,l,b,e} = BR_{p--1,l,b,e} + BO_{p,l,b,e} - BI_{p,l,b,e} \quad \text{Eq. 3.6.}$$

$$\forall p, l, b, e$$

The duration of the route determines the starting and ending point of the bus commitment, as shown in the following equation.

$$BI_{p++DurationRoute_l,l,b,e} \geq BO_{p,l,b,e} \quad \text{Eq. 3.7.}$$

$$\forall p, l, b, e$$

3.6.2. Selection of the Type of Bus Technology

Restrictions on the type of technology selection mean that only electric or petrol operation can be chosen. It becomes necessary to introduce a constraint for each variable that models the behavior of the bus in the selection of the technology.

$$\sum_{e} BR_{p,l,b,e} \leq 1 \qquad \text{Eq. 3.8.}$$

$$\forall p, l, b$$

$$\sum_{e} BO_{p,l,b,e} \leq 1 \qquad \text{Eq. 3.9.}$$

$$\forall p, l, b$$

$$\sum_{e} BI_{p,l,b,e} \leq 1 \qquad \text{Eq. 3.10.}$$

$$\forall p, l, b$$

3.6.3. Quality of Bus Service or Demand

In order to guarantee the quality of the current bus service, as well as the timetable that the buses follow for their journeys, an equation has been modelled to ensure this by means of a demand. The demand parameter is calculated as the number of buses on route for each time interval in the case study. The case study, as explained above, consists of the resolution of the most unfavorable day of the year.

$$\sum_{b,e} BR_{p,l,b,e} = Demand_{p,l} \qquad \text{Eq. 3.11.}$$

$$\forall p, l$$

3.6.4. Bus Charging Behavior

As well as the bus behavior restriction, the electric bus charging has been modeled as a unit commitment. In this case, the duration of the bus charging depends on the type of charging point, which can be fast or semi-fast. Slow charging is discarded due to its long duration, as the buses operate almost without interruption.

$$CB_{p,l,b,t} = CB_{p--1,l,b,t} + CS_{p,l,b,t} - CE_{p,l,b,t}$$ Eq. 3.12.

$$\forall p, l, b, t$$

$$CE_{p++DurationCharge_t,l,b,t} \geq CS_{p,l,b,t}$$ Eq. 3.13.

$$\forall p, l, b, t$$

3.6.5. Selection of the Charging Type

The restrictions on charging type selection mean that only fast or semi-fast charging can be chosen. Therefore, it is necessary to include a restriction for each variable that models the charging behavior of a bus in the charging type selection.

$$\sum_t CB_{p,l,b,t} \leq 1$$ Eq. 3.14.

$$\forall p, l, b$$

$$\sum_t CS_{p,l,b,t} \leq 1$$ Eq. 3.15.

$$\forall p, l, b$$

$$\sum_t CE_{p,l,b,t} \leq 1$$ Eq. 3.16.

$$\forall p, l, b$$

3.6.6. Feasibility of Bus Charging

The feasibility restriction on bus charging means that a bus that is in motion cannot be charging. Nor can it be in motion if it is charging.

$$\sum_t CB_{p,l,b,t} \leq (1 - BR_{p,l,b,e})$$ Eq. 3.17.

$$\forall p, l, b, e \in s_e$$

Another feasibility equation is introduced to limit the start or end of a charge in the same time period.

$$CS_{p,l,b,t} + CE_{p,l,b,t} \leq 1 \qquad \text{Eq. 3.18.}$$

$$\forall p, l, b, t$$

3.6.7. Bus Battery Status Inventory

By means of these equations, the aim is to quantify how much each of the bus batteries in all lines is charged at any given time. To do so, the bus charging is modeled as an increase in inventory, and the discharge or moving bus as a decrease in inventory.

$$IBat_{p,l,b} \leq IBat_{p--1,l,b} + \sum_{t} \frac{1}{DurationCharge_t} \cdot CB_{p,l,b,t} - \sum_{e \in s_e} \frac{1}{DischargeDur} \cdot BR_{p,l,b,e} \qquad \text{Eq. 3.19.}$$

$$\forall p, l, b$$

A bus cannot be moving if its inventory or charging status is zero, i.e., it is completely discharged.

$$IBat_{p,l,b} \geq \frac{1}{DurationR_l} \cdot \sum_{e \in s_e} BO_{p,l,b,e} \qquad \text{Eq. 3.20.}$$

$$\forall p, l, b$$

3.6.8. Charging Behavior for Private Users

As in previous restrictions, a unit commitment is used to model how the private users charge. These private users will mainly be cars. The difference with other behavioral constraints is that the variables of the equations are continuous.

$$CPU_{p,t} = CPU_{p--1,t} + CPUS_{p,t} - CPUE_{p,t} \qquad \text{Eq. 3.21.}$$

$$\forall p, t$$

$$CPUE_{p++DurationChargePU_t,t} \geq CPUS_{p,t} \qquad \text{Eq. 3.22.}$$

$$\forall p, t$$

3.6.9. Private Users' Potential

The number of private users is restricted by the parameter that estimates the future adoption of the electric vehicle as the main means of transport.

$$\sum_t CPU_{p,t} \leq PotentialP \qquad \text{Eq. 3.23.}$$

$$\forall p$$

3.6.10. Electric Penetration Rate

The number of electric buses expected at the bus station in the case study is constrained by the penetration rate parameter, which represents the electric adoption rate of the buses. The chapter of results will include a sensitivity analysis of the parameter to see how the cash flows evolve with it.

$$\sum_{l,b,e} BR_{p,l,b,e} \leq \rho \cdot \sum_l Demand_{p,l} \qquad \text{Eq. 3.24.}$$

$$\forall p$$

3.6.11. Charging Points

The number and type of charging points, including both fast and semi-fast charging, must be greater than or equal to the number of private users and buses being charged at the same time. Since buses represent greater profitability in the case of study and the quality of service must be guaranteed, the charging points will be occupied primarily by buses. Only when there are spaces available private cars will be able to charge.

$$\sum_{l,b} CB_{p,l,b,t} + CPU_{p,t} \leq NCP_t \qquad \text{Eq. 3.25.}$$

$$\forall p, t$$

The maximum number of charging points that can be installed is limited to the number of docks in the bus station of the case study.

$$\sum_{t} NCP_t \leq \overline{NCP} \qquad \text{Eq. 3.26.}$$

3.7. Conclusions

The case of study consists on a MIP (Mixed Integer Programming) problem, where variables can be continuous or binary. The objective of the case is to maximize the profits obtained by installing electric charging facilities in a bus station, which both private cars and buses can use to charge their batteries and obtain economic benefits.

A unit commitment is introduced to model the routing and charging of the buses scheduled in the bus station. This means that the behavior in the previous period will affect the subsequent one, and this is reflected in the equations, when establishing when the bus is in motion or charging. A bus will be on route only if the decision variable associated is activated, the same way it has to happen for it to be charging. In the latter case, the duration depends on the type of charging point, which can be fast or semi-fast. Also, the feasibility restriction on bus charging means that a bus that is in motion cannot be charging.

Another important feature for the charging process is to quantify the inventory level of the bus batteries in every line at any given time. For this, the bus charging is modeled as an increase in inventory, and the discharge or moving bus as a decrease in it.

In order to guarantee the quality of the bus service, the demand of buses should be satisfied across the whole horizon of time and every line by gasoline buses, electric buses or a combination of both technologies. This parameter is calculated as the number of buses on route for each time period. The restrictions on charging type selection mean that only fast or semi-fast charging can be chosen.

In the case of private users, a unit commitment is used again to model the charging process. The difference with other behavioral constraints is that the variables of the equations are continuous. The number of private users is restricted by a parameter that estimates the future adoption of the electric vehicle as the main means of transport.

The number of electric buses expected at the bus station is constrained by the penetration rate parameter, which represents the adoption rate of electric buses. The number and type of charging points, including both fast and semi-fast charging, must be greater than or equal to the number of private users and buses being charged at the same time. Charging points will be occupied first by buses, and only when there are free spaces available, private cars will be able to charge. This is because the quality of the service must be guaranteed and also because buses represent greater profitability in this case of study.

4. Analysis of Results

The analysis of results consists of several simulations in a bus station, where different types of electric chargers are installed to quantify in which case the maximum profit is reached. The bus lines and the space available for installing the charging points characterize the bus station. In addition, a comparative analysis of profitability and the electrical penetration rate according to the type of charge is carried out, as well as to check how the cash flows evolve with it.

The expected future cash flows serve as a guide for making a strategic decision on the number of charging points to be installed, in the facility in relation to the 'Plan A' of Madrid. Cash flows only cover the benefit of changing bus technology and do not include the cost of each new bus, as the fleet is already at the end of its life cycle.

The analysis of results is structured as follows:

Case 1. Plaza de Castilla Station with Fast Charging Points.

Case 2. Plaza de Castilla Station with Semi-Fast Charging Points.

Comparison of Cases. Comparison of Cash Flows.

4.1. Plaza de Castilla [Fast Charging]

This section analyzes the installation of fast charging points at the Plaza de Castilla bus station. On the one hand, it is verified that all the buses on the main lines at this station comply with the established timetables, thanks to the combination of electric and gasoline technology vehicles. On the other hand, the optimal charging schedule for electric buses is established, and it is checked that their battery level is modelled according to reality. Finally, the behavior of private users is predicted by giving an overview of how many cars could charge across the day of operation.

For the entire simulation, time is considered in 30-minute periods, due to the complexity of the problem and the lack of convergence with shorter intervals. As only fast charging is allowed in this case, the charging time is one period for any type of consumer.

4.1.1. Demand Compliance

Regarding the quality of service, it is verified that the demand profile is fulfilled. This case is a simplified representation of reality in which, as mentioned above, time is considered in half-hourly intervals. Although it does not offer the maximum detail, it allows to establish a realistic routing and charging scheduling for the buses. It should not be forgotten that replicating the planning for all the buses on a line is a complex task, because its resolution involves binary decision variables to determine when to make the route and to charge.

In this scenario, it is also proven that both electric and gasoline buses work as expected, with the best combination of both technologies to meet demand. When a bus is on route, charging, or stopped, the next available bus is immediately set in motion to meet the required service.

In addition, thanks to the use of circular operators in the modelling, those buses that have night routes are linked to what happened the day before. This provides a very accurate representation of what would happen in the real world.

Below is a graph showing the binary variable that decides whether or not a bus is on route for line 159. The combination of electric and gasoline buses for each of the periods of a day is shown, and how they alternate to meet the specified schedule and demand.

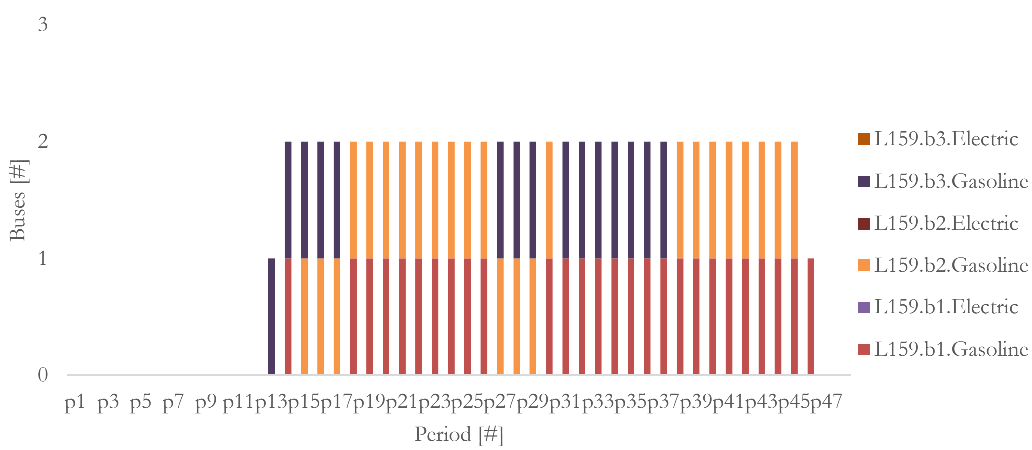


Figure 4.1. Combination of electric and gasoline buses per period to meet the demand of line 159.

4.1.2. Charge of Buses

To be able to complete their routes, electric buses must be sufficiently charged. To this end, they can be charged whenever space is available, taking precedence over private users at all times.

For this scenario, it is checked that most buses are charged when they are out of operation, i.e. during the night. In addition, as the maximum economic benefit is sought, this night charging schedule for buses is also beneficial in this respect, as it allows the charging of private cars during the day. The only times when charges are made during a line's operating hours are when demand is to be met by electric buses on lines where there are few.

All these behaviors in relation to the charging of buses serve to verify that the problem has been solved correctly, in an optimal way both in terms of economic benefit and quality of service.

The following table shows the charging periods during one day for each of the buses on line 185. This is the charging schedule that must be followed in order to effectively comply with their routes and, as mentioned above, it is shown how these charging periods are mainly concentrated during night-time hours.

	L185.b1	L185.b2	L185.b3	L185.b4	L185.b5
p1					
p2					
p3					
p4					
p5					
p6					
p7					
p8					
p9		1			
p10					
p11	1				
p12					
p13					
p14					
p15					
p16					
p17					
p18					
p19		1			
p20					
p21					
p22					
p23					
p24					
p25					
p26					
p27			1		
p28					
p29					
p30					
p31					
p32					
p33					1
p34					
p35					
p36					
p37					
p38					
p39					
p40					
p41					
p42					
p43	1				
p44					

p45		1			
p46				1	
p47					
p48			1		1

Table 4.1. Charging schedule during a day for each bus in line 185.

4.1.3. Inventory of Electric Bus Battery

The graph below shows an example of the route timetable, charging periods and battery inventory during a day of one of the buses of a main line in Plaza de Castilla. The most important thing about this figure is that it shows how the level of charge of the bus varies according to its behavior.

First of all, it is checked that the battery inventory of the bus drops correctly, as it does so every time it is in transit. In the same way, it increases during charging periods. On the other hand, it is observed that the bus does not make any complete discharge cycle while it is in motion. If this were to happen, the bus would not be able to complete the route due to a lack of energy, and the quality of service would not be guaranteed. To this end, the vehicle evaluates its battery inventory before beginning each route to determine if it is sufficient to complete it. If it is unable to do so, the bus must be charged in advance to meet its schedule.

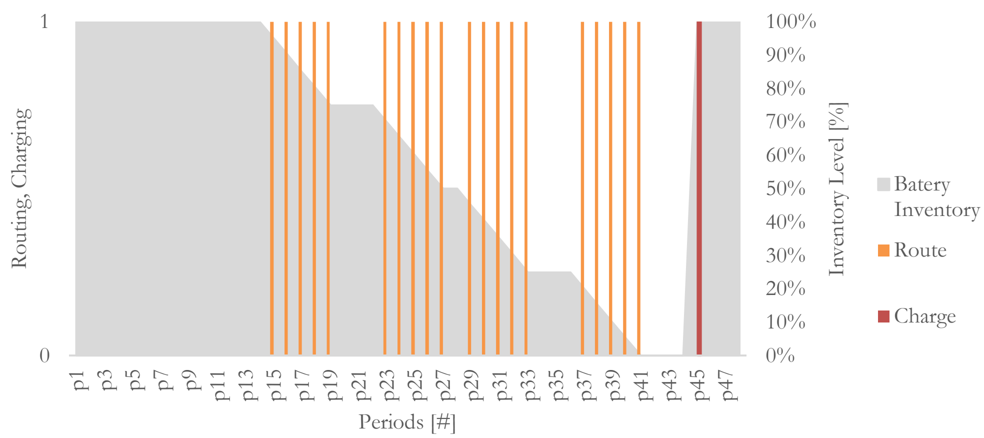


Figure 4.2. Route schedule, charging periods and battery inventory for bus 3 of line 726.

4.1.4. Private Users

As already mentioned, buses are mainly charged during the night hours. This is because most of them work during the day, and this way the quality of service is guaranteed. However, the fact that buses are charged at night also has economic benefits, as they leave room for cars to charge during the hours of the day when there are more potential private users.

The use of charging points by private cars means a positive cash flow for the station, which obtains revenue from each charge. Therefore, it is always sought to keep all charging points occupied, covering spaces with electric cars as long as they are not being used by buses.

Figure 4.3. represents the number of private users that charge in the day of operation; where private users could be understood not only as private cars, but also as taxis, trucks and other means of transport.

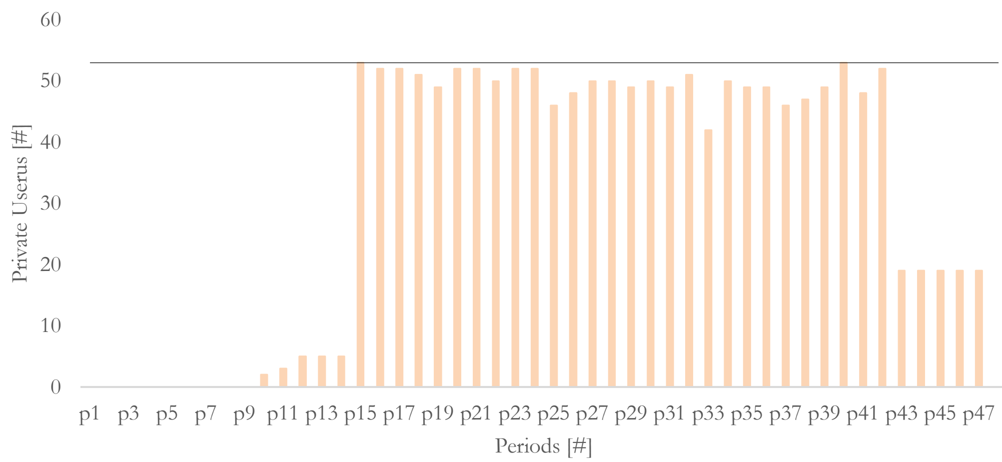


Figure 4.3. Number of private cars charged daily, and distribution according to periods.

4.2. Plaza de Castilla [Semi-Fast Charging]

Similarly to the previous case, this chapter analyses the installation of semi-fast charging points at the Plaza de Castilla bus station. First of all, it is verified that all the buses on the main lines of this station comply with the established schedules, thanks to the combination of electric vehicles and gasoline technology. Also, the battery level is checked to ensure that it is modelled according to reality, and the optimal charging program for electric buses is established. Finally, the behavior of private users is predicted by giving an overview of how many cars could charge across the day of operation.

For the whole simulation, the time is considered in 30-minute periods, due to the complexity of the problem and the lack of convergence with shorter timeframes. The charging time is two periods for any type of consumer, because in this case only semi-fast charging is allowed.

4.2.1. Demand Compliance

As for the quality of the service, it is checked that the demand profile is satisfied. This case is a simplified representation of reality in which, as mentioned before, time is considered in half-hourly periods. Although it does not offer the maximum detail, it allows to establish a realistic routing and charging scheduling for the buses. It is important to remember that the replication of the planning for all the buses on a line is a complex operation, as its resolution involves binary decision variables to determine when to make the route and to charge.

In this case, it is also clear that both electric and gasoline buses work as expected, with the best combination of the two technologies to meet demand. When a bus is on route, charging, or unable to move for whatever reason, the next available bus is immediately activated to perform the required service.

The graph below shows the binary variable that decides whether or not a bus is on route for line 157C. The combination of electric and gasoline buses is shown for each of the periods of the day, and also their alternation to meet the specified schedule and demand.

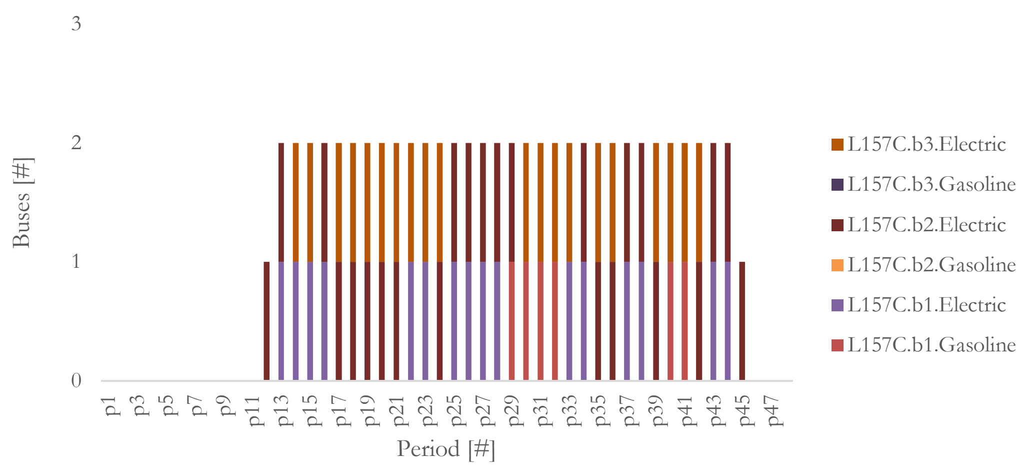


Figure 4.4. Combination of electric and gasoline buses per period to meet the demand of line 157C.

4.2.2. Charge of Buses

Electric buses must be sufficiently charged to be able to complete their routes. For this purpose, they can be charged whenever there is space available, with priority over private users at all times.

In this case, it is verified that most buses are charged when they are out of service, i.e. at night. In addition, as the maximum economic benefit is pursued, this night-time bus charging schedule is also beneficial in this respect, as it allows private cars to be charged during the day. The only cases in which they are charged during line operation hours are when demand must be covered by electric buses on lines where there are few.

The table below shows the charging periods for one day for each of the buses on line 191. This is the charging schedule that must be followed to effectively meet their routes and, as previously mentioned, it shows how these charging periods are concentrated primarily during night-time hours.

	L191.b1	L191.b2	L191.b3
p1			
p2			
p3			1
p4			1
p5			
p6	1		
p7	1		
p8			
p9			
p10			
p11			
p12			
p13			
p14			
p15			
p16			
p17			
p18			
p19			
p20			
p21			
p22			
p23			
p24			
p25			
p26			
p27			
p28			
p29			
p30			
p31			
p32			
p33			
p34			
p35			
p36			
p37			
p38			
p39			
p40			
p41			
p42			
p43			

p44			
p45			
p46		1	
p47		1	
p48			

Table 4.2. Charging schedule during a day for each bus in line 191.

4.2.3. INVENTORY OF ELECTRIC BUS BATTERY

The following graph shows an example of the route schedules, charging periods and the battery inventory of one of the buses of a main line of Plaza de Castilla for one day. The most significant thing about this figure is that it shows how the charge level of the bus changes according to its behavior.

First, it is verified that the battery inventory of the bus decreases correctly, as it does so every time it is moving. The same way, it increases during charging periods. On the other hand, it is noted that the bus does not perform any complete discharge cycle while on the move. If this were to happen, the bus would not be able to complete the route due to lack of energy, and the quality of service would not be ensured. For this, the vehicle evaluates its battery inventory before beginning each route to determine if it is sufficient to complete it. If it is not possible to do so, the bus must be charged in advance to meet its schedule.

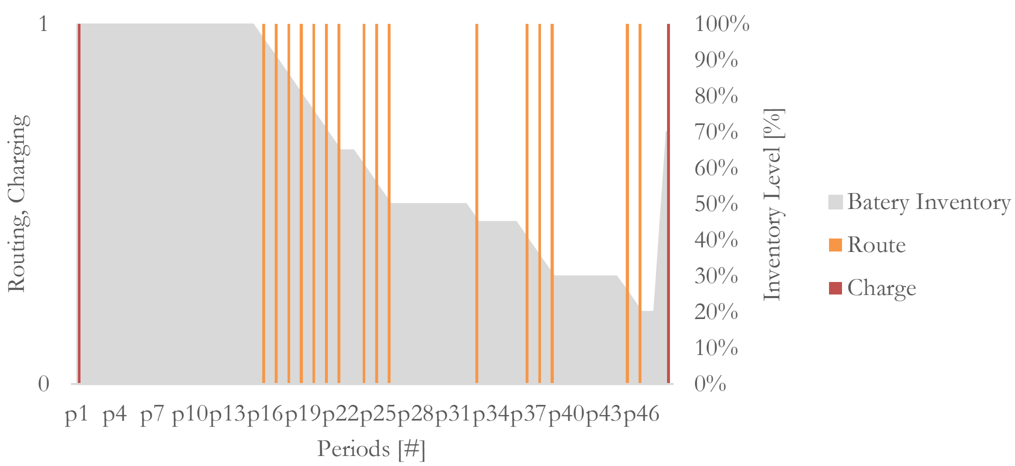


Figure 4.5. Route schedule, charging periods and battery inventory for bus 8 of line 725.

4.2.4. PRIVATE USERS

As already discussed, buses are mainly charged during the night hours. However, the fact that buses are charged at night also has economic advantages, as they leave room for cars to charge during the hours of the day when there are more potential private users.

The use of charging points by private vehicles results in a positive cash flow for the station, which receives revenue from each charge by covering the spaces with electric cars as long as they are not being used by the buses.

Figure 4.6. represents the number of private users that charge in the day of operation; where private users could be understood not only as private cars, but also as taxis, trucks and other means of transport.

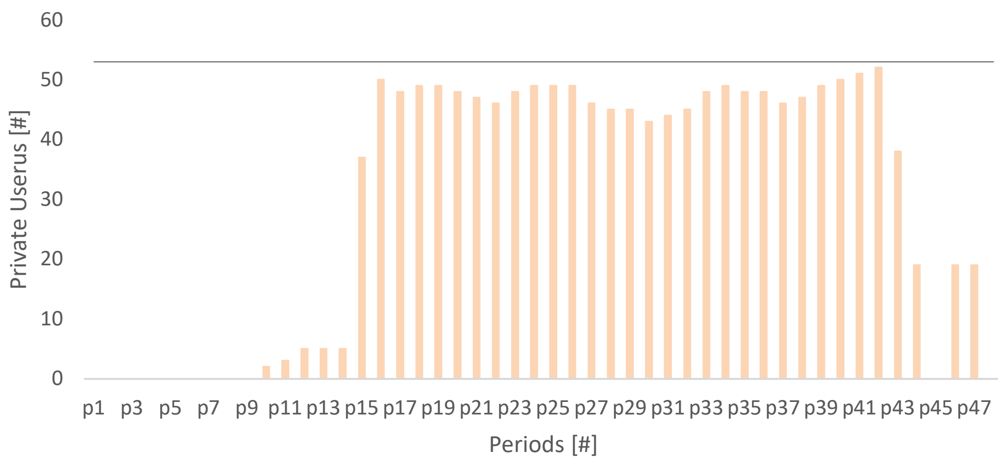


Figure 4.6. Number of private cars charged daily, and distribution according to periods.

4.3. Comparison of Cash Flows

This section compares the cash flow of the two case studies presented above, to determine which type of facility maximizes the benefits in terms of economics and electrical penetration. On the one hand, the profitability in euros of the installation of both fast and semi-fast charging points is analyzed. On the other hand, the penetration rate that the implementation of each type of installation would imply is determined, in line with the objectives of electric mobility that the Madrid 'Plan A' seeks to achieve for the coming years.

4.3.1. Profitability

The graphs below show the objective function values for both types of charging points. As described in the mathematical formulation section, this function aims to maximize the cash flows obtained by converting the bus station into an electrical charging facility, which can be used by both public bus fleets and private users. To calculate profitability, bus charging is translated into daily savings, while private car charging is considered as a profit.

It is important to clarify the concept of GAP, which is explained as the difference between the solution found for the objective function and the ideal one. The execution time in the simulation is exponential, and this makes it difficult to achieve a solution closer to the optimum. Therefore, for both simulations results are obtained with a certain GAP.

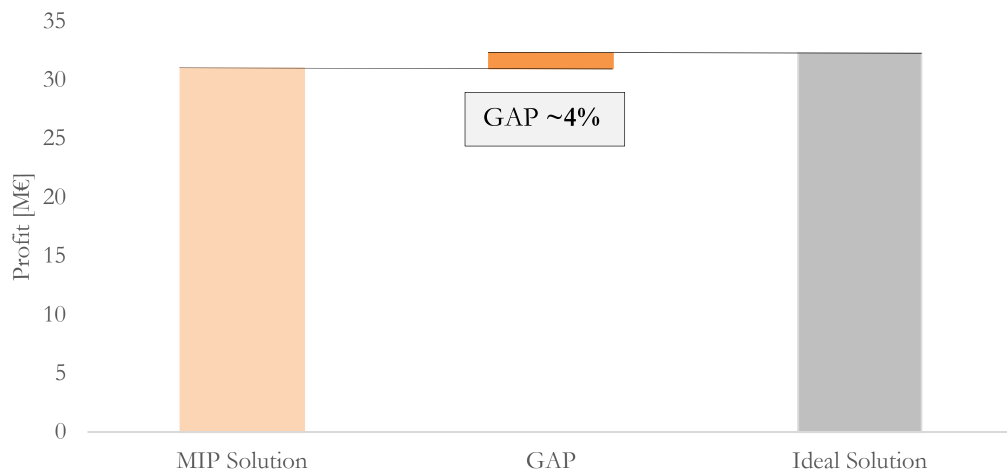


Figure 4.7. Value of the Objective Function for fast charging.

In the case of fast charging points, the expected profit over 20 years is 30.988.408 €, with a GAP of 4,02%.

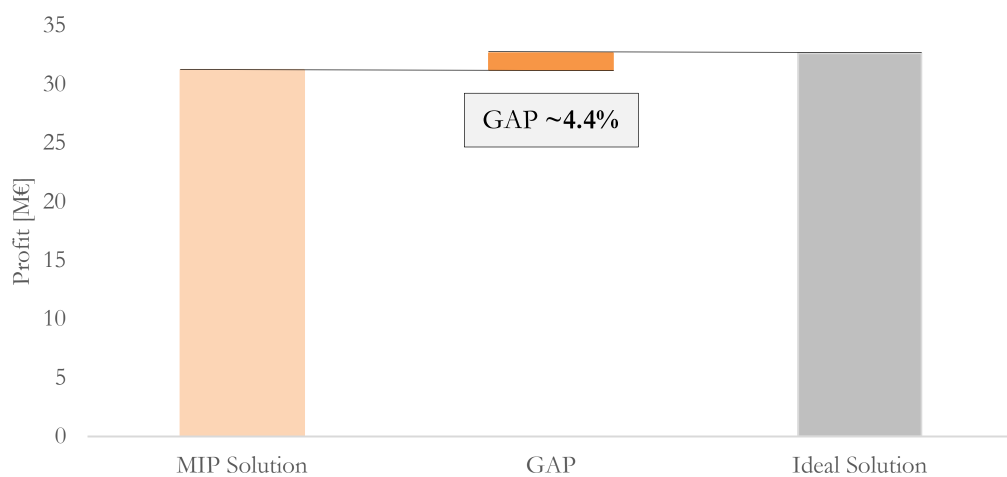


Figure 4.8. Value of the Objective Function for semi-fast charging.

In the case of semi-fast charging points, the expected profit over 20 years is 31.216.275 €, with a GAP in this case of 4,38%.

As noted, the economic benefits of installing semi-fast charging points are greater than in the case of fast charging systems. This is because the costs of installing this latest technology are still very high. Moreover, as there is a lot of margin for buses to charge at the times that suit them best, the charging duration is not a problem in this case.

However, even though the expected benefit of semi-fast charging is greater, this difference is not significant. Therefore, either of the two options would be valid for Madrid City Council, depending on the priority given to costs or charging time. Although semi-fast technology means twice the charging duration, the costs associated with installation are lower. Conversely, fast technology means higher costs, but less charging time and therefore greater potential profit from private users.

Finally, it should be noted that the difference in GAP obtained after the simulation of both scenarios is minimal, being 4.02% for the fast scenario and 4.38% for the semi-fast one.

4.3.2. Electric Penetration Rate

The following table shows a comparative summary of the electrical penetration rate that the installation of each technology would imply in the public bus fleet, as well as the number of charging points that would maximize the benefit for each scenario.

As noted, the electrical penetration rate is higher in the case of fast technology. This result makes sense, as a shorter charging time allows for an increase in the number of electric buses that can be charged at the station, thanks to greater time flexibility. In the future, when the electrical technology is more consolidated, and the batteries of the vehicles have more autonomy, the station could even become completely electric.

On the other hand, it is verified that the simulation maximizes the number of charging points to be installed in the station, so that the 53 docks of Plaza de Castilla should have one. If there were more space to install charging points, it seems logical to think that it would be cost-effective to install as many of them as possible. This is a profitable business that pays for itself in a short period of time, and the greater the number, the greater the benefits.

	Fast Charging	**Semi-Fast Charging**
Penetration Rate	59.1%	58.7%
Number of Charging Points	53	53
Power Installed	~12.7MW	~2.3MW

Table 4.3. Electric penetration rate and number of charging points according to the type of technology.

4.4. Conclusions

In this chapter, the results of the installation of charging points at the Plaza de Castilla bus station have been analyzed for two different scenarios: on the one hand, for fast charging points and, on the other, for semi-fast charging. For both cases, the buses have been found to operate as expected and a comparative profitability analysis has been carried out.

With regard to the quality of service, it is verified that the demand profile is met for both cases, in other words, the timetables established for the routes of each bus are respected. Time is considered at 30-minute intervals, as this measure allows the necessary compromise between accuracy and convergence of the problem to be met. In addition, it is verified that electric and gasoline buses are optimally combined to provide the best service.

As for the charging of the electric buses, it is observed that it is mainly performed during the night, coinciding with the hours when most of them are out of operation. This allows that during the day, when there are more potential private consumers, the cars can be charged, thus maximizing the economic benefits for the station. However, it can be observed that any time of the day when buses need to be charged, they will have priority over private users to guarantee their service.

With respect to the battery inventory of each of the buses, it is verified that the level of charge varies in a coherent way according to its behavior. Inventory decreases whenever the bus is in transit and increases during charging periods. The bus also evaluates its battery level before starting a route to ensure that it can cope with it. If this is not possible, the bus will be charged in advance.

In addition to all that concerns buses, the number of private cars that would be charged daily at the station is obtained, as well as their distribution over all periods. As already mentioned, the use of charging points by private users brings economic benefits, so the aim is to ensure that all of them are busy for as long as possible. This is achieved while respecting the priority of bus charging.

In the cash flow analysis, the benefits of the implementation for both scenarios are studied. It is concluded that the installation of semi-fast charging points offers greater profitability after 20 years than the fast charging ones. Even so, this difference is not significant since the benefits in both cases would be around 31 million euros. The determining factor for choosing one or the other would be the priority given to costs over charging time. Semi-fast charging points entail lower installation costs, but also double the charging time. Conversely, fast charging points are more expensive, although they allow for shorter charging periods.

As for the electrical penetration rate that each technology would entail, the percentage is slightly higher in the case of fast charging, although both values are around 59%. This result makes sense, as a shorter charging time allows for an increase in the number of electric buses that can be charged at the station.

Regarding the number of charging points that would maximize the benefits, the model determines that each of the 53 docks of the station should be equipped with one. This is a profitable business that pays for itself in a short period of time, and economically speaking it would be worthwhile to install as many charging points as possible, even if there were more space available.

Based on the results obtained, the City Council of Madrid should install the maximum number of charging points at the Plaza de Castilla bus station. This way it will achieve the greatest economic benefit and electrical penetration in the public bus fleet, in line with the sustainability measures promoted in the 'Plan A'. As explained in the energy policy section, this is a plan to combat the city's air pollution and the impacts of climate change.

To achieve its objectives, one of the major lines of action of 'Plan A' is the promotion of sustainable mobility. The expansion and renewal of the public transport fleet is part of this policy, which aims to achieve a zero-emission classification for 100% of all vehicles. To support this measure, the expansion of the electrical charging network is also being promoted, as it is essential to meet the demand for the growing low-emission technology. Therefore, in this sense, the installation of chargers in Plaza de Castilla seems a good starting point for carrying out this policy.

5. Conclusions

Many policies have emerged at both European and national level, allocating funds to promote energy efficiency. All these government initiatives and the increasing awareness of sustainability have turned the penetration of the electric vehicle into a key point of the current policy to begin what is known as the 'energy transition'. It is worth highlighting the Energy and Climate Change Package with objectives for 2020, the 2030 Framework and the 2050 Roadmap, with targets for reducing emissions, increasing the penetration of renewable energies and increasing energy efficiency.

In this context of commitment to achieving the objectives proposed by the EU, both the Spanish Government and the local authorities are taking measures to promote a process of energy transition that is economically viable and technically feasible. In the specific case of the Community of Madrid, two policies stand out. On the one hand, the Energy Plan 2020 Horizon, which is in line with the objectives proposed by the EU to achieve by 2020. On the other hand, the Air Quality and Climate Change Plan ('Plan A'), whose main objective is to achieve a sustainable city that guarantees the health of citizens in the face of the challenge of atmospheric pollution.

The electric vehicle is one of the key solutions for achieving the EU objectives, and for slowing down the growing social concern for the environment. Regarding the Spanish legislation for the regulation of the electric vehicle, standardized schemes are established for the supply systems of charging stations according to the type of ownership of the facilities, which may be public areas, private areas with public access or private areas with private access. On the other hand, the role of demand aggregation is recognized through the figure of the 'load manager', which is an agent that acts as an intermediary between the electricity company and the consumers. Even so, it is still necessary to promote a legislation that regulates this figure to facilitate its implementation, as it is particularly important in the field of domestic charging of electric vehicles.

In short, electric vehicles still have problems and challenges to overcome, such as charging time, short battery life or access to recharging outside homes. Even so, governments around the world are trying to overcome existing barriers and accelerate the market for this sector, and industry research in this area is constantly growing. Within this context, an analysis of the feasibility of installing charging infrastructures in Plaza de Castilla station, coinciding with the fact that it is the end of the line of many public buses and also a place frequented by private workers' cars, is conducted to get an overview of the profitability of the project.

The case of study consists on a MIP (Mixed Integer Programming) problem, where variables can be continuous or binary. The objective of the case is to maximize the profits obtained by installing electric charging facilities in a bus station, which both private cars and buses can use to charge their batteries and obtain economic benefits.

A unit commitment is introduced to model the routing and charging of the buses scheduled in the bus station. This means that the behavior in the previous period will affect the subsequent one, and this is reflected in the equations, when establishing when the bus is in motion or charging. A bus will be on route only if the decision variable associated is activated, the same way it has to happen for it to be charging. In the latter case, the duration depends on the type of charging point, which can be fast or semi-fast. Also, the feasibility restriction on bus charging means that a bus that is in motion cannot be charging.

Another important feature for the charging process is to quantify the inventory level of the bus batteries in every line at any given time. For this, the bus charging is modeled as an increase in inventory, and the discharge or moving bus as a decrease in it.

In order to guarantee the quality of the bus service, the demand of buses should be satisfied across the whole horizon of time and every line by gasoline buses, electric buses or a combination of both technologies. This parameter is calculated as the number of buses on route for each time period. The restrictions on charging type selection mean that only fast or semi-fast charging can be chosen.

In the case of private users, a unit commitment is used again to model the charging process. The difference with other behavioral constraints is that the variables of the equations are continuous. The number of private users is restricted by a parameter that estimates the future adoption of the electric vehicle as the main means of transport.

The number of electric buses expected at the bus station is constrained by the penetration rate parameter, which represents the adoption rate of electric buses. The number and type of charging points, including both fast and semi-fast charging, must be greater than or equal to the number of private users and buses being charged at the same time. Charging points will be occupied first by buses, and only when there are free spaces available, private cars will be able to charge. This is because the quality of the service must be guaranteed and also because buses represent greater profitability in this case of study.

The discussion of results of the analysis of the installation of charging points at the Plaza de Castilla bus station consists of two different scenarios: on the one hand, for fast charging points and, on the other, for semi-fast charging. For both cases, the buses have been found to operate as expected and a comparative profitability analysis has been carried out.

With regard to the quality of service, it is verified that the demand profile is met for both cases, in other words, the timetables established for the routes of each bus are respected. Time is considered at 30-minute intervals, as this measure allows the necessary compromise between accuracy and convergence of the problem to be met. In addition, it is verified that electric and gasoline buses are optimally combined to provide the best service.

As for the charging of the electric buses, it is observed that it is mainly performed during the night, coinciding with the hours when most of them are out of operation. This allows that during the day, when there are more potential private consumers, the cars can be charged, thus maximizing the economic benefits for the station. However, it can be observed that any time of the day when buses need to be charged, they will have priority over private users to guarantee their service.

With respect to the battery inventory of each of the buses, it is verified that the level of charge varies in a coherent way according to its behavior. Inventory decreases whenever the bus is in transit and increases during charging periods. The bus also evaluates its battery level before starting a route to ensure that it can cope with it. If this is not possible, the bus will be charged in advance.

In addition to all that concerns buses, the number of private cars that would be charged daily at the station is obtained, as well as their distribution over all periods. The use of charging points by private users brings economic benefits, so the aim is to ensure that all of them are busy for as long as possible. This is achieved while respecting the priority of bus charging.

In the cash flow analysis, the benefits of the implementation for both scenarios are studied. It is concluded that the installation of semi-fast charging points offers greater profitability after 20 years than the fast charging ones. Even so, this difference is not significant since the benefits in both cases would be around 31 million euros. The determining factor for choosing one or the other would be the priority given to costs over charging time. Semi-fast charging points entail lower installation costs, but also double the charging time. Conversely, fast charging points are more expensive, although they allow for shorter charging periods.

As for the electrical penetration rate that each technology would entail, the percentage is slightly higher in the case of fast charging, although both values are around 59%. This result makes sense, as a shorter charging time allows for an increase in the number of electric buses that can be charged at the station.

Regarding the number of charging points that would maximize the benefits, the program determines that each of the 53 docks of the station should be equipped with one. This is a profitable business that pays for itself in a short period of time, and economically speaking it would be worthwhile to install as many charging points as possible, even if there were more space available.

Based on the results obtained, the City Council of Madrid should install the maximum number of charging points at the Plaza de Castilla bus station. This way it will achieve the greatest economic benefit and electrical penetration in the public bus fleet, in line with the sustainability measures promoted in the 'Plan A'. As already explained, this is a plan to combat the city's air pollution and the impacts of climate change.

To achieve its objectives, one of the major lines of action of 'Plan A' is the promotion of sustainable mobility. The expansion and renewal of the public transport fleet is part of this policy, which aims to achieve a zero-emission classification for 100% of all vehicles. To support this measure, the expansion of the electrical charging network is also being promoted, as it is essential to meet the demand for the growing low-emission technology. Therefore, in this sense, the installation of chargers in Plaza de Castilla seems a good starting point for carrying out this policy with a high profitability expected for the whole project life cycle.

6. Future Development

Several paths for a future development have been identified in the project, like further improvements in the modelling or approaches that were out of scope of the case study and that represent an opportunity to the Council of Madrid.

Time Windows, increasing the number of periods or time dimension by using 5-minute time windows, which is the most restrictive frequency for the buses in Plaza de Castilla. The use of 5-minute time windows will reproduce perfectly the schedules of Plaza Castilla station and, therefore, the demand parameter. However, the added complexity translates into increased resolution time, being likely that it will not converge into a solution due to its exponential nature. More efficient formulation will be needed for accomplishing this complexity, where the number of continuous and binary variables increases.

Stochasticity of the Demand, to make a realistic representation of the expected future, where new lines and higher bus frequencies are introduced on current timetables. In order to model this probabilistic approach, different scenarios with certain probability of occurrence will be characterized across the whole electric facility project life cycle. As a result, a "Here and Now" decision will be taken in year 0 and refurbished depending on the evolution of the demand.

Time Shifts between buses, where the operation time of a bus is constrained to get the maximum efficiency and duration of the battery. To model this requirement, the wear of the electric battery throughout its life cycle must be studied to determine the optimum distance and charges to be made in a day of operation to minimize the cost of maintenance.

Including more Bus Stations and Stops, as an opportunity to the Council of Madrid to achieve higher profitability by stablishing more charging points for the buses and the potential private users. This path is subdivided in two approaches, depending on the budget and needs of the city of Madrid.

1. Strategic decision between different bus stations where only one placement can be chosen. Different cash flows are expected for each project and only the most profitable station will be the winner.

2. Network of electric bus stations and stops where charging points are installed, giving the buses the possibility to charge at any of those facilities and to carry out partial charging in the stops where there is a charging point.

Carsharing Alliances, sensitivity analysis of the case study in the event of an alliance between a private carsharing company with the city council. The carsharing company will charge the entire fleet overnight at a set price and will then distribute the cars throughout the city so that they can be used by its customers. This action is an opportunity for the city council to obtain a guaranteed return and not depend on the unpredictability of potential private users.

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