D1.6 IMPACT ASSESSMENT RESULTS

VOLUME 2: MADRID, SPAIN

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SOLUTIONSplus Impact Assessment Results

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EXECUTIVE SUMMARY

This report presents the work performed by the SOLUTIONSplus consortium for the impact assessment task of the Madrid demonstration project. It starts with some background and context of the city of Madrid, describing the location and geography, the climate as well as the population and urbanisation. Then the urban transport system is described including the different operating companies. Further, the sustainability strategy “Madrid360” which frames a favourable environment for electric mobility, setting ambitious goals for electrification is shortly described. An identification of the main problems shows that the road transport sector is one of the main responsible for GHG emissions. Regarding passenger transport, since the early 2000s, Madrid has been testing different types of electric and hybrid buses. Thus, it has made great progress in improving the environmental performance of its fleet.

The SOL+ Madrid pilot is led by EMT, Empresa Municipal de Transportes de Madrid, a public company owned by the Madrid City Council that was created in 1947. EMT operates and manages the whole network of urban public buses in the city and is also responsible for additional mobility services such parking, tow trucks, public bike sharing system –BiciMAD-, cable car. The living lab in Madrid focuses on smart charging systems including inverted pantographs for the e-buses in the city. Therefore, the relevant stakeholders and user needs have been identified by means of a user needs assessment (UNA). The UNA was to be performed via 2 activities: (i) an on-line survey and (ii) a set of stakeholder and expert interviews. Both are designed to grasp the perspective of local decision makers, operators and relevant stakeholders with respect to e-mobility and therefore investigate the suitability of the e-mobility solutions to be tested in Madrid vis-à-vis their needs and requirements as well as local barriers and opportunities.

The next step was to identify a set of priorities of the stakeholders relevant for the Madrid pilot regarding electrification of urban mobility. Priorities are formally determined through the weights assigned to a list of selected attributes (KPIs) which apply to all Sol+ pilots. The attribute weighting activity in Madrid took place in conjunction with the stakeholder interviews organized within the UNA task. For the investigation of the conceptual impact assessment questions and the calculation of related KPIs the needed data has been defined. Further, a baseline scenario considering existing trends in passenger and freight transport was defined in order to define and calculate the baseline KPI values. Within the baseline KPI values trends as the increasing population, energy supply data as well as the bus fleet composition per drivetrain technology (Diesel, CNG, hybrid and electric) have been considered.

In the ex-ante assessment for the demonstration action in Madrid the focus related to the charging technologies of e-buses and the expected effects have been described. Therefore, detailed specification of the inverted pantograph chargers from ABB have been given and innovative charging concepts as smart charging and vehicle-to-grid have been explained. Afterwards, the impact of the inverted pantograph charging in combination with smart charging have been described including potential saving for energy costs by means of peak shaving.

In the ex-post assessment measurement data from EMT Madrid regarding energy consumption and power measurements recorded in the Bus depot Carabanchel in Madrid have been analysed. In there, the max. power has been assessed depending on the month, day of the week as well as the fluctuations during the day. These data have been compared with potential costs savings and grid impact from literature. Also, an analysis of electricity prices in the EU in 2022 has been conducted and potential cost savings and grid impact for different charging strategies (e.g. peak shaving, day-ahead trading, provision of grid services as FCR). It could be concluded that peak-shaving algorithm reduces costs by 22,8 % to 31,9 % compared to conventional charging, but more advanced charging strategies like DAM (forecasting electricity prices) trading and V2G (vehicle-to-grid) result in only marginal further savings. Based on that the impact of smart charging strategies and the related hardware have been analysed by means of technical KPIs (e.g. max. Power) as well as financial KPIs (e.g. payback period, net present values). It was shown that the payback period for the smart charging hardware and software was very short with 1.15 years and a net present value of 280.998€ resulted in a calculation for 15 years. Finally, the impact of a second-life battery storage for self-consumption optimization has been investigated. Therefore, photovoltaic systems with 300 kWp and 750 kWp have been considered in combination with the battery storage. The amount of excess energy has been calculated for both variants and the impact of higher self-consumption and less feed-in energy to the grid. It could be concluded that the energy storage only makes sense for a very high amount of energy surpluses, which is currently not the case with the assumed 300 and 750 kWp systems.

The second component involved piloting of a MaaS-application that allowed users to plan multimodal trips, access information regarding timetables, public transport routes, schedules, stations and stops as well as purchase tickets for public transport. The pilot took place during one month between November-December 2022, during which 45 students used the developed application prototype. Several usability issues hindered application usage and realizing its potential in terms of impacts. However, given such issues would be resolved in the future, MaaS-approaches could have a positive impact in terms of public transport accessibility and different reaching destinations, thus contributing to shift away from private cars towards sustainable modes of mobility.

CONTENTS

1 CITY: MADRID

1.1. BACKGROUND AND CONTEXT

Madrid is the capital and most-populous city of Spain. With more than 3.3 million inhabitants (see details in Table 1), Madrid is the second-largest city in the European Union by population within city limits and its metropolitan area is the second-largest in the EU, surpassed only by Paris.

Madrid's energy consumption amounts to approximately 5.5% of Spain's total consumption. In 2018, renewable energy sources accounted for about 40% of electricity generation, mainly through wind energy and hydropower. Nuclear energy is still the most important source of electricity. The share of coal was 13.5% (Red Eléctrica de España, 2019b). The Autonomous Community of Madrid is highly dependent on the national electricity network as it has an installed power capacity of only 458 MW, one of the lowest in the country, and an electricity demand of 28,624 GWh. Madrid consumes 10% of the national electricity (Red Eléctrica de España, 2019b).

The city's Greenhouse Gas (GHG) emissions comprise 5% of national totals. Madrid's transport sector is responsible for 53% of direct emissions and 36% of total emissions. In the past 4 years, the Municipality of Madrid implemented a series of measures that aimed at reducing the intensity of private motor vehicle traffic by promoting public transport and encouraging pedestrian and bicycle transport. Madrid aimed to reduce the use of conventional cars by introducing tax incentives for clean-energy vehicles and by gradually restricting access and parking for high-polluting vehicles, including the creation of a low emission zone (Madrid Central) in the city centre (launched in November 2018). These were some of the measures included in the former Air Quality and Climate Change Plan, known as Plan A, approved in 2017 with a scope up to 2020. The city has recently launched a new plan, so-called "Madrid 360", to replace Plan A, targeting even more ambitious goals in terms of air pollution reduction.

Table 1 - Details for the city of Madrid (elaboration from various sources)

Population	3.334.730 (2020)*
GDP per capita	20.612 € (2016)*
City Area	60,445.52 Ha*
Density	55 ab/Ha* (2020)
CO_2 emissions (total)	10,706 ktCO_2-eq (2016)

(*) source: Portal web del Ayuntamiento de Madrid, http://portalestadistico.com/

1.1.1. Geography and the social/urban context

Location and topography:

Madrid Region has about 6.5 million inhabitants (and thus it is the third more populated region in the country) in an area of 8,028 km2 and counts 179 municipalities. The region is split into three zones, or "rings" (Figure 1).

- Madrid City (Ring A), the main municipality of the region which concentrates the economic activities.
- Metropolitan Ring (Ring B), which consists of several large and medium size

entities around the municipality of Madrid, with significant mobility flows to and from the central area.

• Rest of the Region (Ring C), with small and medium size municipalities.

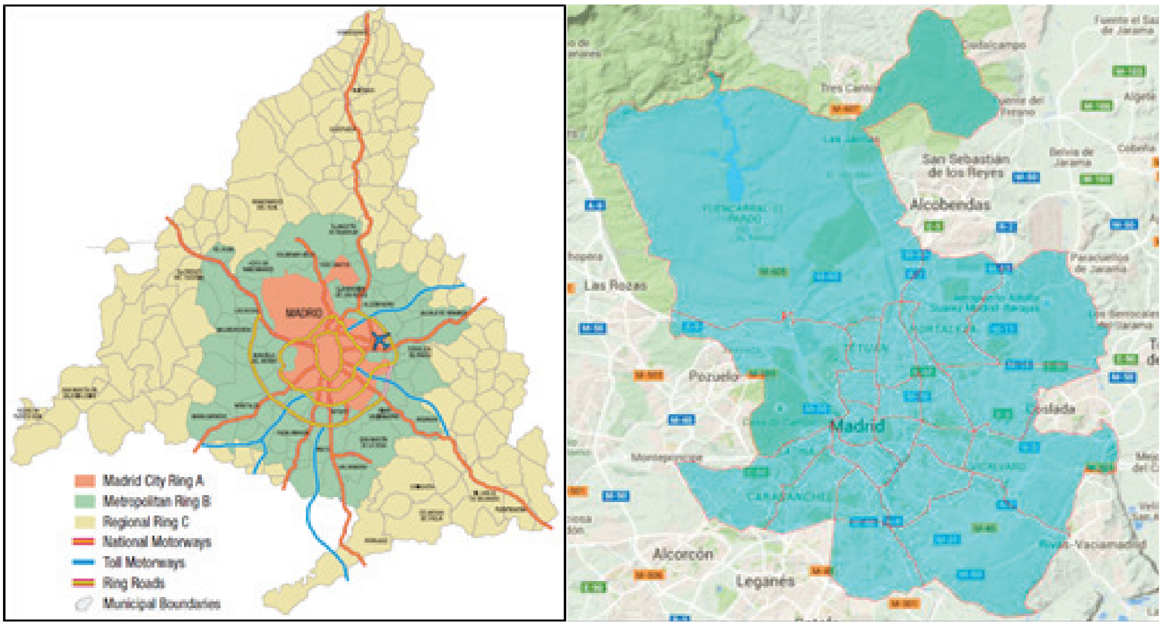

Figure 1: Territorial Structure of Madrid Region and Madrid City (Ring A)

Madrid lies right at the heart of the Iberian Peninsula. It is situated on a plateau (Meseta) at an elevation of about 650 metres above sea level, thus making it one of the highest capitals in Europe. To the northwest of Madrid is the Sistema Central mountain chain that forms the "dorsal spine" of the Meseta and divides it into northern and southern subregions.

Most of Madrid city lies in the southern region, which is comparatively flatter than West region, which rises steeply into the Sierra of the Sistema Central.

Climate:

Madrid has an inland Mediterranean climate (transitioning to a semi-arid climate in the eastern half), characterized by dry summers and cool, wet winters. Winters are cool due to its altitude and include sporadic snowfalls and frequent frosts in the period December to February. Summers are hot, in the warmest month, July, average temperatures during the day range from 32 to 34 °C depending on location. Due to Madrid's altitude and dry climate, diurnal ranges are often significant during the summer.

Population/Urbanisation:

The population of the city of Madrid has stabilised at approximately 3 million since the 1970s. Like many large urban areas in Europe, most of the growth of the last few decades has taken place outside the historic urban centre. Since the 1970s, the suburbs have captured nearly 98 percent of the population growth. While in 1970, nearly 90 percent of the urban area population was in the city of Madrid, by 2016, the city share of the population had declined to 51%.

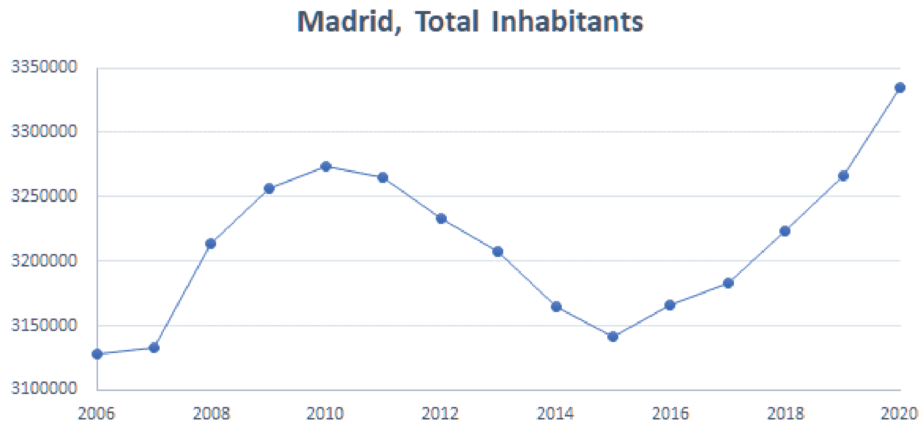

Figure 2 – Population in Madrid (2006-2020), source: Instituto Nacional de Estadística

The Madrid metropolitan area comprises Madrid and the surrounding municipalities. According to Eurostat, the "metropolitan region" of Madrid has a population of slightly more than 6.271 million people covering an area of 4,609.7 square kilometres.

1.1.2. Urban transport

744,000 of the jobs in the city are held by residents of other municipalities, while 242,000 residents in the capital have jobs outside. Thus, passenger flows are predominantly into and out of the city centre, although further decentralisation of economic activity to the outskirts is altering this pattern. From the point of view of sustainable transport, Madrid has performed well from the compactness of the city centre and middle-to-high-density peripheral nuclei, favouring public transport and pedestrian movement .

The public transport's offer of the Madrid Region is an extensive and complex intermodal system. More than 1600 million people used the public transport network in 2019, which represents a 3.4% increase compared to 2018 and confirms an increasing trend since 2014 (Figure 3).

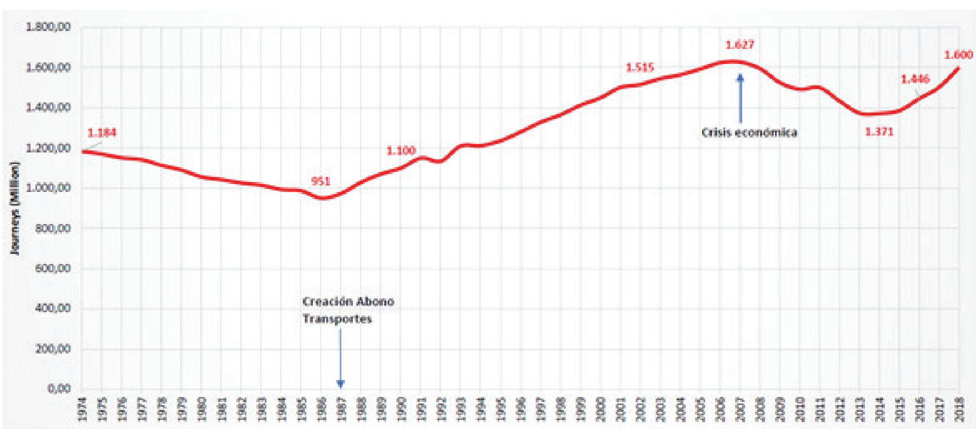

Figure 3 – Territorial Structure of Madrid Region and Madrid City (Ring A)

1 Estructura Económica de le Ciudad de Madrid, Ayuntamiento de Madrid (Madrid City Council), August 2013

The system consists of various modes of transport which are operated by different companies, both public and privately-owned:

- EMT, Madrid Municipal Company of Transport (Empresa Municipal de Transportes) is a public limited company owned by Madrid municipality, operating buses in Madrid city. In 2019 EMT operated 212 lines with 2,049 buses and transported more than 420 million of passengers.
- Metro de Madrid S.A. is a public company under the Regional Government. It operates 12 lines, for a total length of 287 km in 2014
- Renfe Cercanías is a public company owned by Spanish Government. It operates 9 lines, with a total network length of 391km and transported 184.3 million of passengers in 2014.
- 3 railway concessionaires operate 4 lines of light rails. They have a total network length of 35 km and 56 stations. Around 14 million of passengers were transported in light rails in 2014.

Interurban buses and urban buses of other municipalities are operated by 30 private companies. They operate 109 urban bus lines and 328 interurban bus lines with a total network length of 9,050 km and transported more than 202 million of passengers in 2014.

Regarding the modal share, the Madrid Regional Transport Authority has published the results of the mobility household survey with data from 2018 . Overall, data shows an increase in daily trips in the region (15.8 million vs 13 million in 2014) and an overall increase in the use of private car vs public transport (depending on areas), as shown in Figure 4. In the Madrid city centre (Madrid Almendra) there is the highest share of all public transport modes (ca. 40%), followed by public transport (35%), and private vehicles (20%) and their modes (5%).

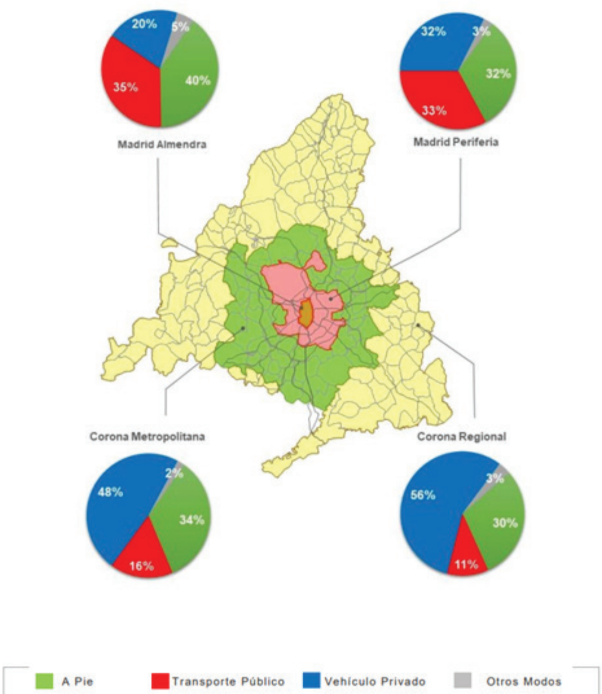

Figure 4 – Regional mobility survey, Source: EDM 2018, Consorcio Regional de Transportes de Madrid

2 https://www.crtm.es/conocenos/planificacion-estudios-y-proyectos/encuesta-domiciliaria/edm2018.aspx

The focus of the SOL+ pilot in Madrid is on electric mobility which is currently considered a priority for the city and a pillar of several strategic plans at national, regional and municipal level, as a measure to reduce air pollution in the city, which sets ambitious sustainable goals for the coming years. Madrid City Council is committed to extend electric mobility as an ally to reduce the negative impacts of urban mobility, being aware also about the potential coming from the strong position of Spain as a vehicle manufacturer in Europe.

At National level, the Spanish Government has recently drafted (May 2020) the first Climate Change and Energy Transition Law to achieve emissions neutrality by 2050, aligned with the EU Green Deal, which may include the implementation of measures by city governments. At Regional Level, Madrid Regional Government (Comunidad de Madrid) has the Air Quality and Climate Change Strategy, so-called “Plan Azul +”, in line with the Sustainable Development Goals set by the European Union, providing funding for fleet renewal, among others. The aim is to help the decarbonization of transport to achieve zero emissions, thus complying with the international agenda set by the Paris Agreements and the European Commission for 2050, including for this purpose also the setting of the Regional Board for the Promotion of Electric Mobility, which includes an active participation of many different stakeholders (industry, politics, media, institutions, etc.).

Finally, Madrid City Council launched its new Sustainability Strategy “Madrid360” last September 2019, which frames a favourable environment for electric mobility, setting ambitious goals for electrification (which includes public companies owned by the municipality, as it is the case of EMT). For example, reaching a network of 150 fast charging points by 2023 (today there are 45) or reaching a full electric bus fleet of 1/3rd (668 buses out of 2076) by 2027, among others (today there are 85 electric buses).

1.1.3. Identification of main problems

One of the main drivers behind the SOL+ Madrid pilot is the need to support the deployment of zero-emission mobility in the city and therefore reduce the climate and environmental impact of the transport sector. Investigating and testing in real-life the feasibility of smart charging solutions for electric vehicles is a key step in this process.

Currently Madrid’s transport sector is responsible for 53% of direct emissions and 36% of total emissions. Notably, the city of Madrid since 2010 has been exceeding the EU-permitted levels of NO_2, with an annual average value of 44.54 µg/m3. (2018 data, Figure 5) As a consequence, in 2015 the European Commission filed a case against Spain and in July 2019, decided to lodge an official complaint with the European Court of Justice that could lead to sanctions for Spain (Miguel & Planelles, 2019). Moreover, despite being within the EU standards for PM_{10} (40 µg/m3/year) and $PM_{2.5}$ (25 µg/m3/year), Madrid does not comply with the WHO standards in these 2 pollutants (20 µg/m3/year and 10 µg/m3/year respectively) (Kodukula et al., 2018).

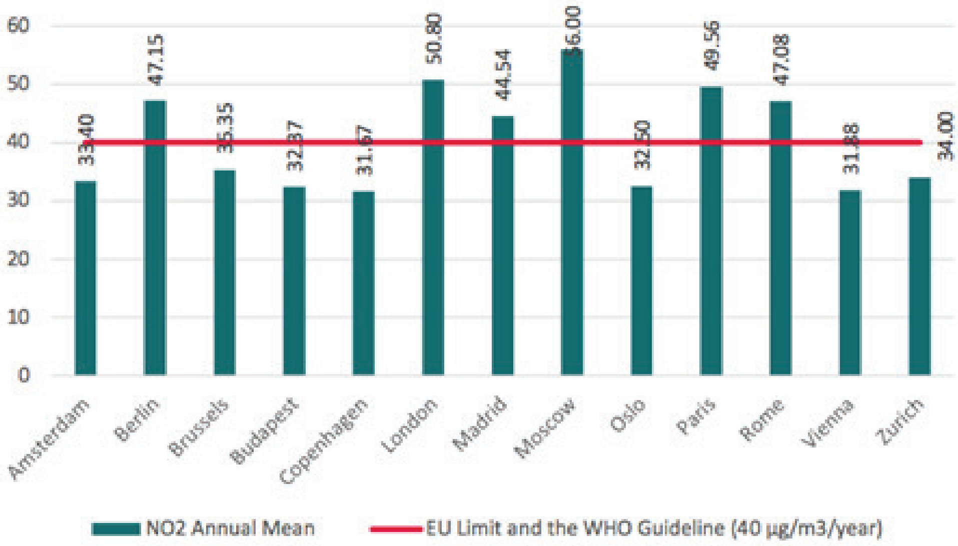

Figure 5 - NO2 annual mean values in European Cities,
Source:(Kodukula, Rudolph, Jansen, & Amon, 2018)

Regarding GHG emission, the total direct and indirect GHG emissions of the city of Madrid in 2016 reached 10,706 kt CO2eq, a figure that confirms the decrease that has occurred since 2005 (16,182 kt CO2eq). In fact, in the period between 1990 (12,953 kt CO2eq) and 2016, the reduction has been 17.35%. Per capita GHG emissions in the municipality of Madrid decreased by 36% and emissions per unit of GDP by 49% in the period 2000-2016

The Road Transport sector is one of the main responsible for GHG emission, accounting for about 22.9% of the total (2016 data). A downward trend can be noticed in its total emissions -29%) in the period 1999-2016 (Ayuntamiento de Madrid, 2016).
It is worth mentioning that in 2020, several European cities have experienced a drop in air pollution during the COVID19 virus outbreak. Data from the Copernicus Atmosphere Monitoring Service (Cams), which tracks pollution in 50 European cities, show that 42 of them measured below-average NO2 levels in March, including Madrid, and so has happened with CO2 emissions.

Passenger transport services

Regarding passenger transport, since the early 2000s, Madrid, led by the Municipal Transport Company (EMT), has been testing different types of electric and hybrid buses. Thus, it has made great progress in improving the environmental performance of its fleet: 83% of its bus fleet is now clean or low-emitting, i.e., 65% GNC, 16% Diesel Euro V and hybrid, and 2% electric.
In 2007, Madrid launched the city's first entirely electric bus lines, the M1 and M2, using fully electric microbuses. These bus lines had very specific characteristics as they run in two areas of the city centre where streets are very narrow (cobblestone type).
Then, in 2018 the city launched the first fully electric bus line with "conventional" characteristics (typology of itinerary and bus size), bus line 76, which currently runs with 5 fully electric buses charged by induction on a 14km route with 42 stops. The 5 buses that run on this line were retrofitted from hybrid CNG-buses into fully electric.

More lately, EMT added fully electric 12-meter buses in several lines, and the most recent launch has been the so called "00" bus lines, which are two lines using fully electric buses that are also free of charge for passengers that allow getting to and cross the Low Emission Zone of the city.
At present, there are 55 e-buses 12 meters long and 30 mini e-buses running in the city with the goal of having 105 by the end of 2020. This is complemented by a fleet of over 2,400 pedelecs distributed across the 207 stations of BICIMAD, Madrid's bike sharing system operated by EMT.

1.1.4. Demo description

The SOL+ Madrid pilot is led by EMT, Empresa Municipal de Transportes de Madrid, a public company owned by the Madrid City Council that was created in 1947. EMT operates and manages the whole network of urban public buses in the city and is also responsible for additional mobility services such parking, tow trucks, public bike sharing system –BiciMAD-, cable car. Figure 6 shows the main figures of the company.

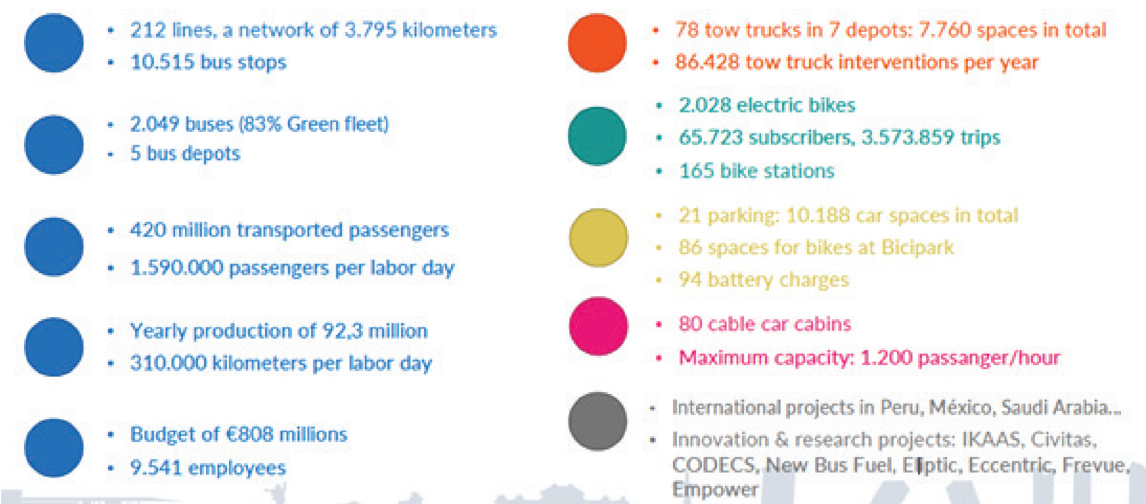

Figure 6 – EMT in figures, Source: (Fernández Balaguer, 2019)

The living lab in Madrid focuses on smart charging systems for the e-buses the city is currently testing and will be increasingly adopting in the upcoming years as part of a strategy aimed at raising the share of e-buses operated by the EMT – the Municipal Transport Company– with about 80 e-buses by 2020. Fast opportunity charging via new inverted pantographs will be tested and allow updating the fleet charging and operational strategy as well as investigating on charging interoperability for multi-brand bus fleets. The charging infrastructure will be installed in one of the EMT bus depots. Currently, the location is under definition. More specifically, the demonstration will focus on the following measures:

- Testing a software to monitor and control the power network for charging stations and e-buses, maximizing bus availability and operational efficiency.
- Installation of inverted pantographs for opportunity charging with a modular design offering charging power of 90kW, 180kW, 270kW and 360kW, enabling charging times of 3-6 minutes using a low-cost and low-weight interface on the roof of the bus. Besides increasing the power and thus the speed of each charge, the smart and wireless characteristics of this equipment, will increase the efficiency and safety of the charging process.

Overall, it is expected to reduce the human-interfaced charging tasks, thus make it possible to significantly increase the share of e-buses to be charged in one depot.

Additionally, the pilot will relate to the promotion of e-mobility in the taxi, car-sharing and – potentially – last-mile delivery sector, by promoting easy access to charging infrastructure managed by EMT, especially in the city centre, and support the development of profitable business models. In this regard, the effects of the COVID-19 pandemic need to be considered. In Madrid, for instance, the car sharing segment has already experienced a significant decrease in the demand.

If the smart charging solutions under test in Madrid will prove to be successful, their scale-up potential is significant as they will play a key role in supporting the achievement of the goals set-up by the City Council in its Sustainability Strategy "Madrid360", among them reaching a network of 150 fast charging points by 2023 and reaching an electric bus fleet of 668 buses (out of 2003) by 2027. Recently, the City Council has announced the goal to have a bus fleet diesel-free in 2023. A tender for more than 100 fully electric buses has been already published.

1.1.5. Relevant stakeholders and user needs

This section summarises the key findings of the User Needs Assessment (UNA) task. For a comprehensive report refer to D1.3 (User needs assessments) and the Madrid User Needs Assessment – City Report. The UNA task was kicked off in November 2020 with the identification of stakeholders active in the city/region of Madrid and relevant for the topic the city demo is addressing, i.e. smart charging for e-buses and support of e-mobility by promoting easy access to new charging infrastructure. 9 stakeholders were identified as relevant and invited to contribute to the task according to their expertise and knowledge.

The UNA was to be performed via 2 activities: (i) an on-line survey and (ii) a set of stakeholder and expert interviews. Both are designed to grasp the perspective of local decision makers, operators and relevant stakeholders with respect to e-mobility and therefore investigate the suitability of the e-mobility solutions to be tested in Madrid vis-à-vis their needs and requirements as well as local barriers and opportunities. The online survey has been considered suitable only for the stakeholders fully informed about the design and implementation of the S+ Madrid demo. Overall, 3 responses have been totalised.

On the contrary, all the stakeholders listed in Table 2 have been invited to take part in the expert interviews. Overall, 7 interviews have been conducted, totalising 10 experts.

Table 2 - Relevant stakeholders and UNA engagement

Stakeholder Group	Organisation	UNA activities	
		Online survey	Interview and KPI weights
Public Transport Operators	EMPRESA MUNICIPAL DE TRANSPORTES DE MADRID SA - EMT	√	√
Regional / Local Authorities	CONSORCIO REGIONAL DE TRANSPORTES DE MADRID - CRTM		√

Regional / Local Authorities	Madrid City Council		√
E-Vehicle OEMs	BYD Europe		√
	Irizar e-mobility		√
	ABB		√
Electricity and charging infrastructure companies	Iberdrola		√

Aims of the city to transform urban mobility

In the Madrid region different fleets (buses, scooters, taxis, bikes, trucks for last-mile delivery or waste collection) are currently experimenting or looking at e-mobility. This is also the result of the ambitious goals set-up by the City Council in its Sustainability Strategy "Madrid360", among them reaching a network of 150 fast charging points by 2023 and reaching an electric bus fleet of 668 buses (out of 2003) by 2027. Recently, the City has also announced the goal to have a bus fleet diesel-free in 2023. A tender for more than 100 fully electric buses has been already published.

To reach these goals, local decision makers need to gain knowledge from real-life tests on the technical and financial feasibility of smart charging solutions when applied to several fleets of different vehicles with different operational needs. This knowledge will guide, for instance, the future tenders for the renewal of the bus fleets in the whole Madrid region. By the end of 2024, new tenders will be published with higher requirement in terms of clean vehicles, being today 20% of the fleet the target to meet.

Providing an efficient charging system and charging strategy to a continuously growing e-fleet is one of the main challenges the local bus operator is facing. S+ demo is a key opportunity for testing new charging solutions and infrastructures, improve their expertise for the upscaling of the electric fleet from an operational perspective (e.g. upgrading of facilities) as well as for the definition of requirements for future tenders.

Regulations

Regulations on e-mobility in Spain have been improving significantly in the last years and, overall, the current national and regional regulations address several aspects related to the implementation of e-mobility. Aspects that seem to need further deployment are:

- Administrative barriers for the legalisation of charging solutions. Current processes, often very long and time consuming, need to be reviewed and discussed with local, regional and central authorities.

- Role of private and public actors in e-mobility. Public administrations have a key active role in the promotion of e-mobility. EU regulations establish that charging services are to be provided by private operators. Public Administrations should facilitate the access of private operators in the market and allow the private sector developing business models to facilitate efficiency and increase competitiveness.

- New solutions, such as so me fast-charging technologies, still lack appropriate regulations on safety and security which are normally addressed at national level. This seems to be due to the novelty of the solutions and the lack of information on the field: it is not yet clear what needs to be covered by the regulations in such a multidisciplinary environment.

- Guidelines and instructions for the installation of fast charging solutions, such as pantographs, in public spaces. Currently, the installation of charging infrastructure might require licenses released by different authorities at municipal, regional or national level. A simpler regulative framework is needed to integrate all different stakeholders and reduce the barriers for the implementation.

- From an operational perspective, there is the need to adapt regulations dealing with taxi (existing regulation seems to not respond anymore to the changing urban mobility ecosystem) and micromobility. Also, in a scenario of continuously growing e-fleets there is the need to investigate the access to charging infrastructure for fleets of private vehicles.

Obstacles, limitations and barriers for EVs

The main challenge to face for the electrification of the Madrid city bus fleet is the availability of power supply, since in the areas where the facilities (bus depots) are located the power that can be supplied by the electricity company has been almost reached, as well as in other areas across the city centre. For an upscale of the SOL+ demonstration, beyond the project lifetime and scope, there is the need to investigate the quality and the capacity of the electricity distribution network and assure the possibility to supply enough energy in key locations across the city.

Buses are not the only electric fleet to address. Taxi, last-mile delivery trucks, motorbikes, bikes, private cars, car sharing, etc. represent a growing and diversified electric fleet with specific charging requirements. An accurate planning of the electricity power is needed in order to optimize the power availability. Optimization might include a time-based strategy, where some vehicles are charged over-night (e.g. buses at the depots) and others are charged at daytime.

Apart from improving charging power technology, if charging stations can be built as many as gas stations, more and more customers would choose electric vehicles, also thanks to the support of big data and cloud service to provide smart charging management.

Additionally, as of today there is an absence of charging infrastructure dedicated to electric trucks in the EU. So far, the European Commission has set infrastructure deployment targets, but these only apply to filling stations / charging points for cars and vans – not those for heav-duty vehicles. This sets a really big setback in rolling out trucks since customers will not want to invest in a transport solution without the right infrastructure.

E-mobility is a multidisciplinary environment and requires the involvement of several expertise (e.g. energy provider, energy distribution company, public transport and mobility operator, OEMs, ITS providers) as well as multiple levels of public administrations. The commitment and the involvement from early stage of all the actors involved in the electrification of mobility in cities is critical. Such cooperation should lead to the definition of a roadmap, where potential obstacles, like compliance of the e-components to existing regulations as well as upfront costs, are timely addressed.

Sustainability of the e-Mobility solutions to be implemented

Electric mobility is a pillar of several strategic plans at national, regional and municipal level which set ambitious sustainable goals for the coming years. Among them:

- the first Climate Change and Energy Transition Law to achieve emissions neutrality by 2050, aligned with the EU Green Deal, recently drafted (May 2020) by the Spanish Government.

- the Air Quality and Climate Change Strategy of Madrid Region, so-called "Plan Azul +", in line with the Sustainable Development Goals set by the European Union, provides funding for fleet renewal, among others, with the goal to help the decarbonization of transport.

- the new sustainability strategy "Madrid360" of Madrid City, launched in September 2019, which sets specific target for electric mobility and air quality (e.g. reducing the nitrogen oxide emissions by 20% until 2023).

The findings of the S+ demo can influence and guide the renewal of the bus fleets in operation not only in the city of Madrid but also in the suburbs and the surroundings, where a significant mobility demand can be met within a relatively small distance, with a potential target of 1M people living in an area up to 10km far from the city. In fact, to achieve environmental goals, it is important to have electric vehicles implemented in the whole Madrid region and - at the same time - focus on green energy and therefore work on the energy sources. The less noise associated with e-buses in comparison with traditional buses is seen as a positive factor not only as a benefit for the city, due to its impact on the noise pollution, but also to improve the working conditions of bus drivers.

Business model

Overall, supporting to deployment of electric technology and e-mobility services is seen as an opportunity to boost the economy, by developing new business opportunities based on emerging technologies. However, successful business models are possible only if public administrations recognize the role of the private sector in the process of electrifying mobility in cities and allow private partners to step in.

Technology is advancing very fast and electro-mobility is a sector of on-going and future growth, therefore the OEMs that are betting and investing in electro-mobility solutions are already adapting their business model to this new scenario. There is need for vehicle manufacturers to control the full production process, from the raw materials to the final product, and understand the entire electric motor and technology, from the drive aisle, the electric motor, the design of the electric systems to the charging strategy. This approach simplifies the life of the customers, as the OEM serves as a one-stop shop.

Finally, it was pointed out that the deployment of e-mobility on a large scale asks for employees with the needed expertise for both operators and industries. Trainings and new curricula are needed to re-train the current employees and form the future workforce. This can certainly have an impact on academia and the research business.

Implications for Planning and Urban Development

In the deployment of the Madrid e-mobility solutions urban planning goes hand-in-hand with the planning of the transport and the energy network. It is well-known that the deployment of e-buses requires adaptions to the urban spatial planning. Key factors are, among others, the location and distribution of bus hubs, availability of space at bus stops for opportunity charging facilities, bus stop and bus bays design (position of the bus vs the charging technology), re-design of the bus depot to house the necessary charging infrastructure.

The designing of the whole transport system is affected, from the vehicle to the operational dimension (network and route design, fleet management, maintenance and depot operations, workforce skills and training, investment and tendering). In fact, any change derived from the introduction of e-buses must be able to ensure safe and reliable operation, offering service excellence without compromising the versatility and flexibility of bus operations.

E-mobility is one of the tools to reduce the use of private cars in the coming years by offering a wider offer of mobility services. Madrid is already a demo city for e-sharing services, such as electric car and motorbike sharing, and the local authorities are willing to further support the deployment of such services as a complement to traditional public transport. This implies policies to supply parking and charging facilities both in dedicated areas (e.g. public transport operator parking facilities) and on-street. For the time being the charging points are not enough and are mainly located in the city centre. Actions are needed to supply specific charging points for sharing services and deploy them in a bigger area to extend the services outside the city centre. Plans exist to offer electric solutions and infrastructure also for the logistic and last-mile delivery sector. These initiatives are already part of the overall urban transformation and are complementary to solutions to further support sustainable mobility behaviours such as increasing pedestrian areas and bike lanes.

1.2. KEY PERFORMANCE INDICATORS (KPIS)

1.2.1. Prioritization of KPIs addressing the specific city needs

The purpose of this task is to identify a set of priorities of the stakeholders relevant for the Madrid pilot regarding electrification of urban mobility. Priorities are formally determined through the weights assigned to a list of selected attributes (KPIs) which apply to all S+ pilots, as extensively described in Section 2.1.4.

The attribute weighting activity in Madrid took place in conjunction with the stakeholder interviews organized within the UNA task (section 1.1.5). Overall 6 stakeholders took part in this activity representing 4 stakeholder groups, namely: (i) Public Transport Operators, (ii) Regional / Local Authorities, (iii) E-Vehicle OEMs, (iv)Electricity and charging infrastructure companies.

However, the aggregation procedure described in Section 2.1.5 has not been completed yet. The feedback collected so far pertains only to the first round of the Delphi method (Step 1 of Section 2.1.5). In this sense, the results presented here should be seen as tentative, pending completion of the Delphi application during the coming months.

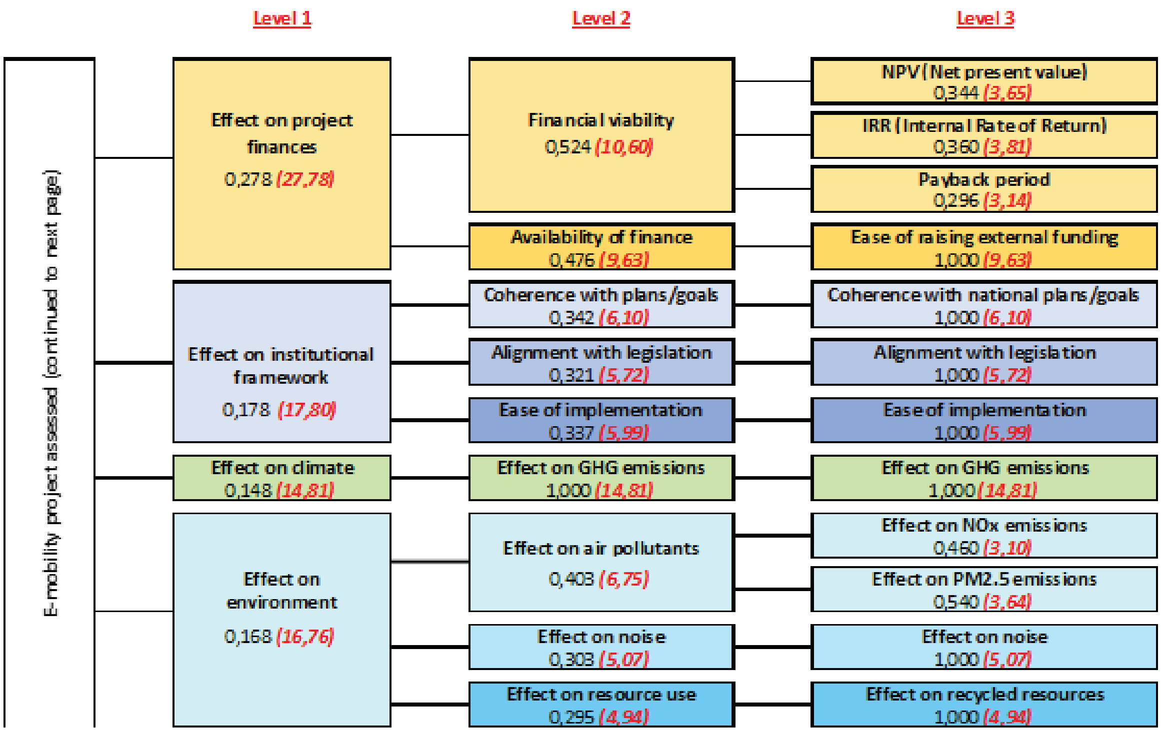

Figure 7 – Results of the attribute weighting activity in Madrid

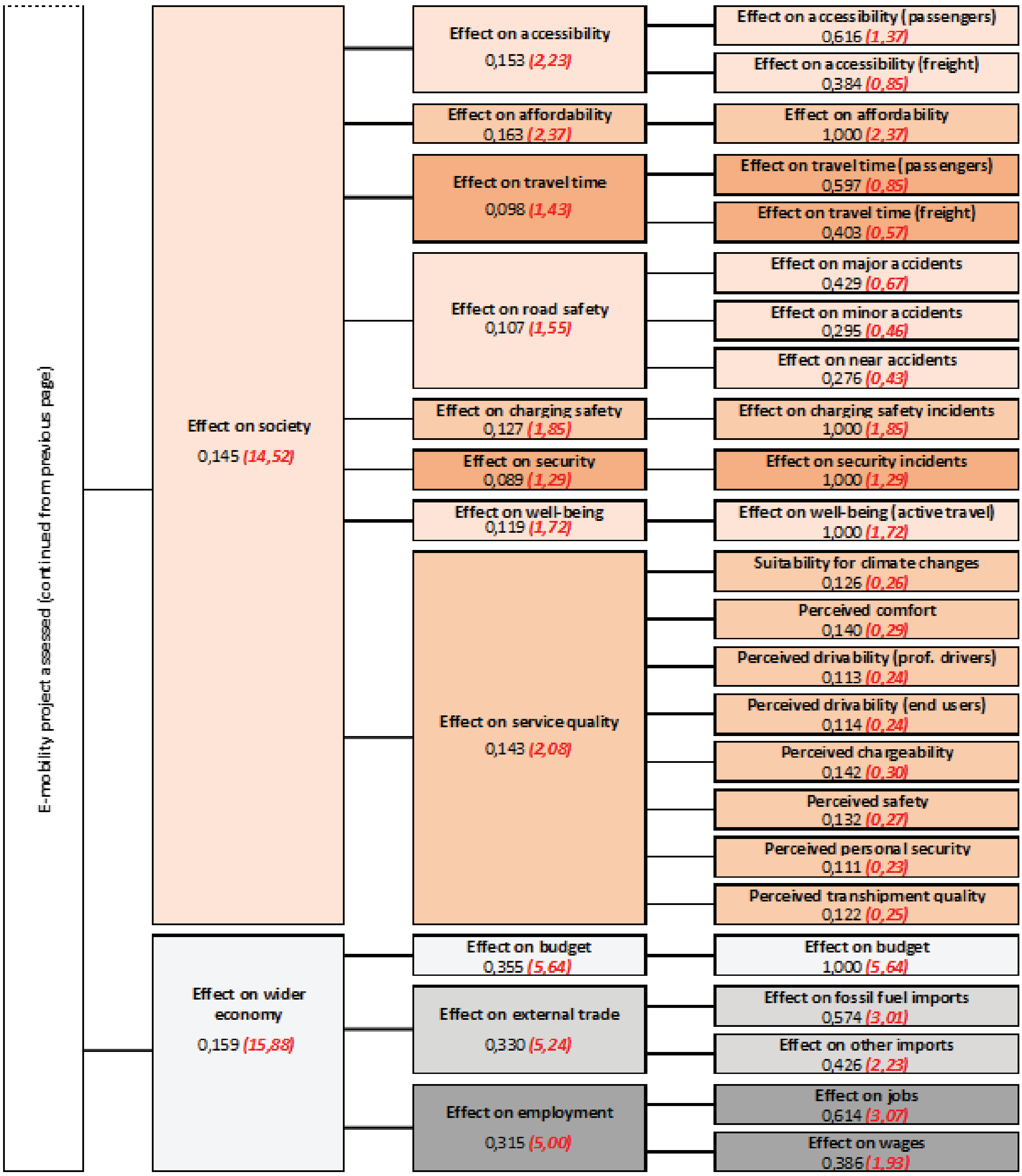

Figure 8 - Results of the attribute weighting activity in Madrid

1.2.2. KPI estimation methods and data needs

For the investigation of the conceptual impact assessment questions and the calculation of related KPIs data from the charging process with the inverted pantograph and the related vehicles is needed. Table 3 gives an overview of the needed data including their category, a short description and its source. More details can be found in the related deliverable D1.4 "data collection plan".

Table 3 - Data category, description and data source for the city of Madrid

Category	Description	Source
Vehicle data	Data about the e-Buses that will be charged with the inverted pantograph technology (e.g. battery capacity, driving range etc.) will be collected.	EMT
Data from the charging process	Details regarding the inverted pantograph technology (max. charging power etc.) has been obtained from the manufacturer ABB and will be obtained from the assessment of the charging process during the demonstration action. Further, also the feedback of the operators (bus drivers, maintenance personnel) shall be collected via surveys.	ABB, EMT
Data from the bus depot	In order to assess possible improvements in terms of the charging process for the bus depot the current situation has to be monitored and the boundary conditions in terms of the depot collected.	EMT
Grid data	Also boundary conditions from the power supply side (e.g. max. connection power) shall be collected.	EMT

1.3. BASELINE SCENARIO

1.3.1. Existing trends in passenger/freight transport

The following section desribes the general mobility trends as well as the expected consequences of this mobility in a qualitative way.

- Institutional Political:

At National level, the Spanish Government has recently drafted (May 2020) the first **Climate Change and Energy Transition Law** to achieve emissions neutrality by 2050, aligned with the EU Green Deal. The Law underlines the role of cities in achieving the Climate objectives, thereby favouring the creation of more liveable and healthy spaces, with improved air quality. In this sense, it establishes that the municipalities with more than 50,000 inhabitants and the island territories will introduce, in urban planning, mitigation measures that allow reducing emissions from mobility, including the implementation of low-emission zones no later than from 2023; it includes also the request of implementing actions to facilitate travel on foot, by bicycle or other means of active transport; and the improvement and promotion of the use of the public transport network. Shared electric mobility and the use of private electric means of transport should also be promoted.

At Regional Level, Madrid Regional Government (Comunidad de Madrid) has the **Air Quality and Climate Change Strategy**, so-called **"Plan Azul +"**, in line with the Sustainable Development Goals set by the European Union, providing funding for fleet renewal, among others. The aim is to help the decarbonization of transport to achieve zero emissions, thus complying with the international agenda set by the Paris

Agreements and the European Commission for 2050. Also at Regional level, the main strategic mobility framework is the one set by the **Sustainable Mobility Strategic Plan of the Madrid Region** which contains more than 200 programs comprised by 12 measures, fed by the latest Mobility Household survey with data from 2018.

At City Level there are three main strategic frameworks for mobility:

1. The first one is the new sustainability strategy "Madrid360", launched in September 2019 (which also includes objectives for EMT, the public transport operator owned by the city). This strategy will substitute the former Air Quality and Climate Change plan (so called "plan A") and aims to be the tool with which the Madrid City Council will comply with the air quality limits established in Directive 2008/50 / EC of the European Parliament and of the Council of May 21, 2008. Madrid360 addresses air quality through three axes: transforming the city, mobility and administration, and focusing on six strategic lines: a sustainable Madrid; an efficient Madrid; an intelligent Madrid; a global Madrid; a healthy Madrid, and an accessible Madrid. Among some of the targets we could point out those specific to electric mobility, such as reaching a network of 150 fast charging points by 2023 (today there are 45) or reaching a full electric bus fleet of 1/3rd (668 buses out of 2076) by 2027 (today, there are 85). One target regarding the air quality is to reduce the nitrogen oxide emissions by 20% until 2023.

2. Currently, the Madrid City Council is also working on the New Madrid 360 Sustainable Urban Mobility Plan. This plan will develop the strategic mobility lines set out in Madrid 360 strategy. Madrid 360 SUMP will set ambitious Safety, Health and Sustainability targets for 2030 promoting the use of smart and emerging technologies.

3. Last but not least, Madrid City Council is also working on the new Road Safety Plan (the current one has the horizon up to 2020), and it will include also measures regarding mobility.

1.3.2. Baseline KPI values

Socio-economic data

Population

The population data for the city of Madrid was taken from the portal of the Municipality of Madraid (http://portalestadistico.com/) . Available data are shown in Table 4 and Figure 9. The last available data is for 2020, with an increase of 2,1% in comparison with 2019.

Table 4 - Total population, city of Madrid

	1987	**1992**	**1997**	**2002**	**2007**	**2012**	**2017**	**2020**
Total Population	3.100.507	3.017.439	2.882.971	3.043.535	3.187.062	3.237.937	3.182.175	3.334.730

Figure 9 – City of Madrid, evolution of the population 1987-2020
(source: Ayuntamiento de Madrid, 2020).

Gross domestic product

The evolution of the GDP in the city of Madrid from 2001 to 2019 is taken from the data of the Ayuntamiento de Madrid. Data is provided as the GDP index per quarter (Figure 10). The last available data is for the IV quarter of 2019, with an index value of 115 and an annual increase of 1,8%.

Figure 10 – City of Madird, GDP index 2001-2029
(source: Ayuntamiento de Madrid, 2020).

In addition the Gross Disposable Income per capita is available as an annual value for the period 2000-2016 (Figure 11).

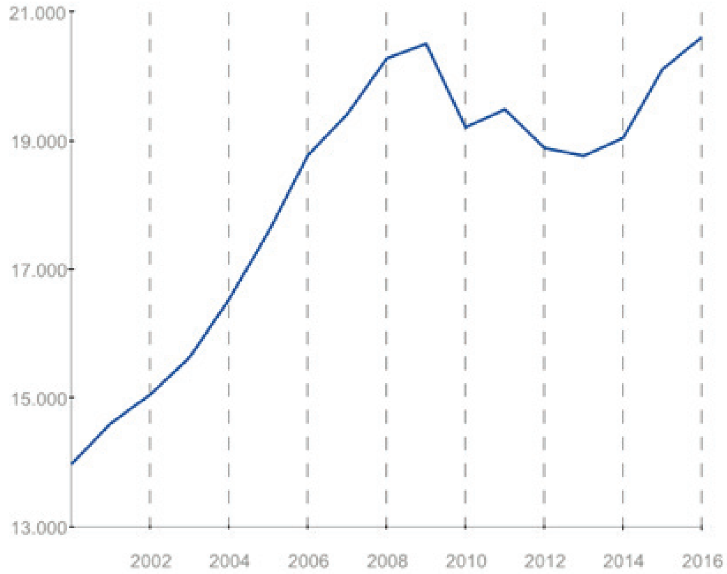

Figure 11 – City of Madrid, Gross Disposable Income per capita, 2000-2016
(source: Instituto de Estadística de la Comunidad de Madrid. Base 2010).

Energy supply data

Key data to elaborate on the Spanish energy mix is taken from the World Energy Balances 2020 of the International Energy Agency,. (https://www.iea.org/data-and-statistics). Data related to the Spanish Total Energy Supply (TES) by source is available for the period 1990 – 2019 (Table 5). The last available data is for the year 2019. TES excludes electricity and heat trade. Coal also includes peat and oil shale where relevant.

Table 5 - Total Energy Supply by source, ktoe
(source: World Energy Balances 2020, IEA)

	1990	1995	2000	2005	2010	2015	2019
Coal	19267	18996	20940	20566	7763	13353	4913
Natural gas	4970	7722	15219	29844	31129	24538	30897
Nuclear	14140	14449	16208	14992	16152	14903	15229
Hydro	2190	1985	2430	1582	3637	2420	2104
Wind, solar, etc.	26	52	444	1894	4857	7444	8183
Biofuels and waste	4067	3684	4131	5115	6744	7030	7941
Oil	45469	53508	61606	67548	57701	48693	51863

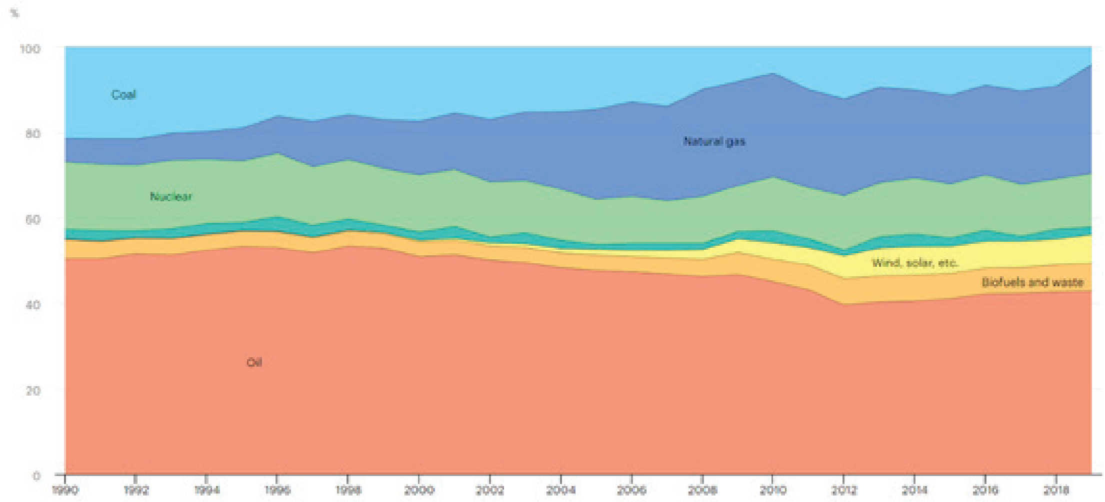

Figure 12 – Total Energy Supply (TES) by source, percentage
(World Energy Balances 2020, IEA)

Bus fleet composition per technology and evolution

Currently EMT operates a fleet of 2.100 buses. The technology share of the fleet is as follows:

- Diesel: 21%
- CNG: 75%
- Electric and hybrid: 4%

According to the strategy of EMT, the ambitious goal is to reach 0% of diesel buses by January 2023, even though some units will remain as an emergency back up, but possibly not providing daily services. In the longer term, the share of electric buses is expected to increase and reach about 32% of the total (667 over 2100 buses). This goal is also stated in the Madrid 360 sustainability strategy.

Techno-economic bus parameters

Annual mileage: 50.000km (average km travelled per bus per year). If we consider the technology, on average each bus runs for 200-250 km, while the same value is normally lower (about 200km) for electric buses which are in operation in shorter lines.

Load Factor: 25 (average number of passengers per bus).

Technical lifetime: On average buses are in service till they reach a mileage of 20.000 km.

Fuel economy (FE) diesel ICE: 50l/100km, 50kg/100km.

Emission standards: the current bus fleet is made of Euro 4, 5, and 6.

1.4. EX-ANTE ASSESSMENT OF THE SOL+ DEMONSTRATION PROJECT

The focus in the demonstration project of Madrid is on the charging technology of e-buses. EMT has analysed the charging technologies available on the market for their electric bus fleet and the following solutions have been studied and weighted:

- Opportunity charge: Carrying out charging on public roads, using fast charging solutions using a pantograph, or other skid-type systems or induction charging systems. EMT has carried out tests on this system (specifically, the induction system has been implemented), reaching the conclusion that this solution is not adapted to the needs of EMT, preferring the option of loading the buses in the Operations Center except on certain lines or occasions but not as a scalable solution for the entire fleet.

- Plug charger in Operations Center: This system has also been tested by EMT and although for a limited number of electric buses it could work adequately, in order to find a solution for an operations center with more than 300 electric buses a "universal charging" system is required in which each bus can park in any parking space and that also allows fast charging (the pantograph allows charging at higher powers than the plug charger). It should be noted that in plug-in charger systems, each type of bus is associated with its specific charger. EMT makes its purchases of buses in different tenders and in each purchase the brand of the bus may change, depending on who is the winner of the contract. The time to plug in each bus is important, in addition to having to locate each brand in its place and not on other chargers.

- Pantograph type charger in Operations Center: Based on the above, it was concluded that the most appropriate system was the pantograph type charger, charging in the Operations Center for time optimization (parking and charging without plugging in) as well as to allow intelligent charging. According to available power, schedule, and service of that bus, etc. In this sense, two alternatives were studied:

  › Pantograph on the bus. This solution is technically considered adequate, although it was observed that it had two drawbacks:

    - It implies that all buses are transporting the pantograph throughout its entire route, so it entails, on the one hand, greater weight for the bus and, on the other hand, it implies a risk of damage during the journey.

    - Additionally, as each bus is connected to its pantograph, in the event of a pantograph breakdown, said bus could not go out onto the street (whereas if the pantograph is in the operations center, if a pantograph is damaged the bus can go to load to another point).

  › Inverted pantograph:
  Based on everything previously described, it was considered that the inverted pantograph solution is the one that best adapted to the needs of EMT since:

- Loading is done in the Operations Centre.
- The pantograph is in the Centre, so it is not overweight for the buses and is safe from inclement weather, accidental blows, etc.
- Allows charging at different powers (both slow charging and fast charging)
- It allows to have a "universal charger" in which each bus can charge in any parking space.

Currently all electric buses recently acquired by EMT come with the pre-installation for inverted pantograph charging.

1.4.1. Expected output

In the demonstration project of Madrid the inverted pantograph from ABB (see Figure 13), that enables charging times of 3-6 minutes using a low-cost and low-weight interface on the roof of the buses, will be tested. This charging solution can be integrated in existing operations by installing them at endpoints, terminals or intermediate stops.

Figure 13: e-Bus charged with inverted pantograph technology
(source: new.abb.com)

Figure 14 and Figure 15 show the specifications for the ABB pantograph for opportunity charging and overnight charging.

Pantograph Up specification – Opportunity charging

Technical specifications	
Power	150 kW, 300 kW, 450 kW, 600 kW
Input AC connection	3P + PE
Rated input current & power (per 150 kW power cabinet)	3x 250 A, 173 kVA
Input voltage range	400 V AC +/- 10 % (50 Hz or 60 Hz)
Maximum output current (per 150 kW power cabinet)	250 A Max is 600 A (limite d by contact hood)
Output voltage range	150-850 V DC
DC connection standard	IEC 61851-23 / DIN 70121/ ISO 15118
Connection method between charger and bus	4-pole contact dome
Environment	Indoor / Outdoor
Operating temperature	Standard:-10 °C to +50 °C Optional: -35 °C to + 50 °C
Dimensions (W,D,H)	Power cabinet: 1170 x 770 x 2030 mm Pole: 3250 x 406 x 5007 mm
Network connection	GSM / 3G modern 10/100 base-T Ethernet
Protection	IP54- IK10
Cable length between power cabinet and pole	Up to 100 m

Figure 14: Pantograph specification for opportunity charging

Pantograph Up specification – Overnight charging

Technical specifications	
Power	50 kW, 100 kW, 150 kW
Input AC connection	3P + PE
Rated input current & power	50 kW: 3x 80 A, 55 kVA 100 kW: 3x 170 A, 117 kVA 150 kW: 3x 250 A, 173 kVA
Input voltage range	400 V AC +/-10 % (50 Hz or 60 Hz)
Maximum output current	50 kW: 125 A 100 kW: 166 A 150 kW: 250 A
Output voltage range	150- 850 V DC
DC connection standard	IEC 61851-23 / DIN 70121/ ISO 15118
Connection method between charger and bus	4-pole contact dome
Environment	Indoor / Outdoor
Operating temperature	Standard:-10 °C to +50 °C Opt ional: -35 °C to + 50 °C
Dimensions (W,D,H)	50 kW power cabinet: 325 mm x 770 mm x 1300 mm 100-150 kW power cabinet: 1170 x 770 x 2030 mm Control box: 600 x 600 x 250 mm
Network connection	GSM / 3G modern 10/100 base-T Ethernet
Protection	Charge cabinet: IP54-IK10 Control box: IP65-IK10
Sequential charging	Yes, up to 3 outlets per charger
Cable length between power cabinet and contact dome	Up to 150 m
Cable length between 2 contact domes	Up to 30 m

Figure 15: Pantograph specification for overnight charging

In the demonstration project in Madrid the charging behavior of an e-Bus using the inverted pantograph shall be investigated regarding the following parameters:

- Charging time
- Charging power
- Battery state of charge over time

- How many buses can be charged per night
- What is the impact on the bus depot design
- Comparison of cable charging and pantograph charging in terms of depot design, needed area for charging, resources, investment and operating costs, personnel etc.

1.4.2. Planned input

The required input for the investigation of the pantograph charging is:

- Installation of the inverted pantographs in a bus depot of EMT
- Personnel for the operation of the pantograph and the installation of the required on-board equipment on the bus enabling the usage of the inverted pantograph

1.4.3. Expected effects

The expected impact of charging e-buses with the inverted pantograph technology is to facilitate the charging process. It requires no personnel (in contrast to the plugging process) and offers further advantages regarding safety & security, which enable the usage of a higher voltage and thus higher charging power.

In total, this technology enables a faster introduction of an electric bus fleet (target for the city of Madrid: multiply the number of electric vehicles by ten in the next 8 years) due to a facilitated and faster charging process. The use of the inverted pantographs facilitates the charging process (no cables, less personnel needed) and can help – together with a smart charging software - to reduce the peak power and therefore lower the variable energy costs.

Before the details are discussed, the following terms describing innovative charging concepts are explained:

Smart Charging (V1G):
Smart charging (also called V1G) refers to the ability to modify the charging power and the charging time. This can help to reduce the peak power and to decrease the cost of charging.

Vehicle-to-Grid (V2G):
Vehicle-to-grid (also called V2G) refers to bidirectional energy flow between an electric vehicle and the grid. Thus, the owner of an electric vehicle becomes a “Prosumer” (consumer who also produces) of energy and can for instance help to stabilize the grid during peak hours.

Vehicle-to-X (V2X):
Vehicle-to-X (also called V2X) includes V2G, as well as V2C (Vehicle-to-customer). The latter includes vehicle-to-building (V2B), where the energy is transferred to non-residential buildings and vehicle-to-home (V2H), where the electric vehicle provides energy to a residential building.

For the depot “Carabanchel” in Madrid with 50 charging stations a Smart Charging concept has been elaborated. The precondition was that the charging scheme must not influence the operation of the bus fleet.

The following changes in the charging scheme were suggested:

- The charging starts at midnight, whereas before charging started at 23:30 and also the peak load occurred before midnight.
- The charging ends at 04:00 in the morning, with a constant total charging power for the whole duration. Before, the charging power reached a peak before midnight and was decreasing step by step until 02:45 in the morning.

With these changes and the constant total charging power managed by the smart charging software, the peak load can be reduced significantly from 3000 kW (3 MW) to 1500 kW (1.5 MW). Further, the biggest part of the energy is consumed outside of the peak hours.

Due to this smart charging strategy, which can be applied for up to 50 charging points, saving of 50.000 €/Year could be achieved without changing the current power tariff.

1.5. EX-POST ASSESSMENT OF THE SOL+ DEMONSTRATION PROJECT

This chapter summarizes the findings of the ex-post assessment of the Sol+ demonstration project in Madrid with focus on smart charging technologies for the bus depots.

1.5.1. Smart charging

Using a conventional charging method, the charging of electric vehicles (EVs) would proceed at maximum power until the batteries reach the desired state of charge (SOC). For instance, if several vehicles start to charge at the same time there would be a peak in power consumption as a result. Hence, the demands for the local infrastructure are higher than necessary and electricity costs could be increased if the energy tariff is linked to the power output.

Figure 16 shows the power consumption of a bus fleet of 100 buses during charging with a conventional strategy. You can see that the power is not distributed evenly which results in a peak of nearly 10 MW. The complete fleet is fully charged at about 3 a.m., which is possibly long before the buses must leave the depot.

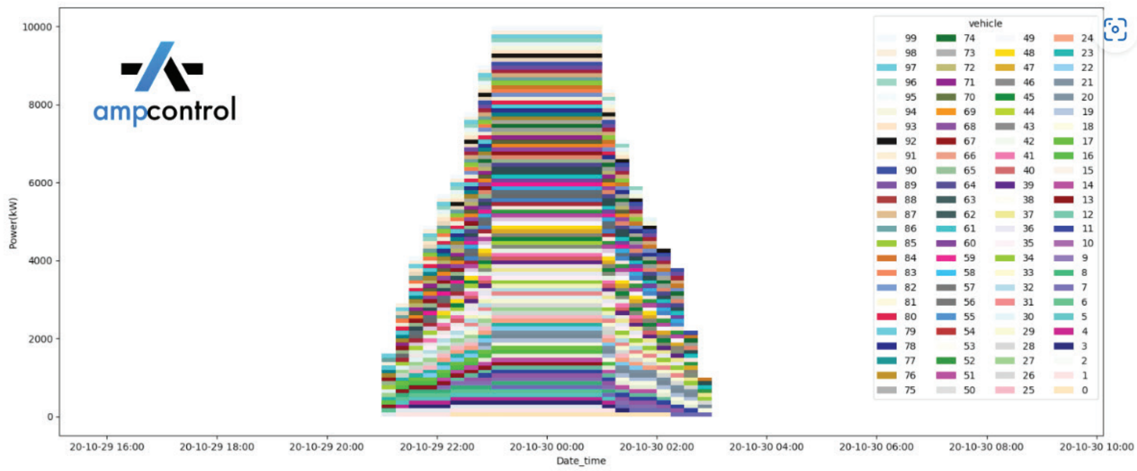

Figure 16: Power consumption of a bus fleet with non-optimized charging
(Source: Ampcontrol)

In contrast, smart charging can automatically reduce the power output from the grid. As a consequence, peak loads can be reduced significantly (peak-shaving). With smart charging there is also a possibility to shift the charging to off-peak times where the demand for electricity is lower or to times when a photovoltaic system produces more energy (self-consumption optimization).

In Figure 17 you can see the power output of the same bus fleet as shown in figure 1, but this time a smart charging strategy is applied. This causes a drastic reduction of peak power to about 4MW. The charging duration is considerably longer, but the time schedule of the buses should not be affected.

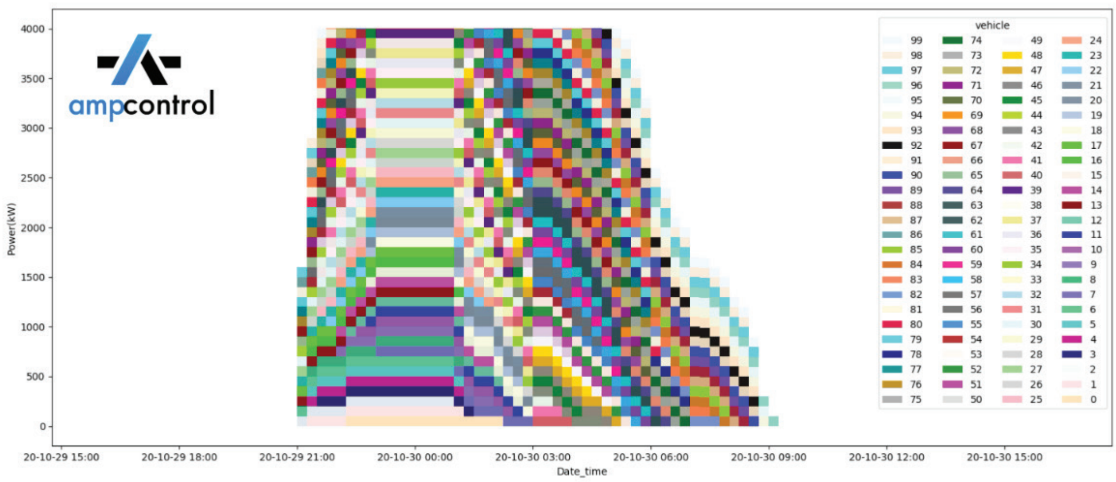

Figure 17: Power consumption of a bus fleet using smart charging
(Source: Ampcontrol)

Using smart charging instead of a conventional charging method has several benefits:

- **Reduced costs**
  Energy costs can be reduced substantially by smoothening the power consumption or by shifting the charging to times when electricity prices are cheaper. When using smart charging in combination with a photovoltaic system the self-consumption rate can be increased.

- **Lower demands for the infrastructure**
  Due to the reduction in peak power the requirements for the infrastructure are decreased noticeably. So, possible adaptions may not be necessary when moving to a smart charging method.

- **Increased grid stability**
  Smart charging can help cutting off peaks of the grid demand. This helps energy providers with the energy distribution and improves the overall efficiency of the energy system.

- **Environmental benefits**
  When using smart charging there is a possibility to shift the charging to times when more renewable energy is available on the market.

1.5.2. VEHICLE-TO-GRID (2G)

V2G is an extension of the smart charging technology that enables bi-directional power flow between the vehicle and the power grid. This means that EVs can not only draw electricity from the grid to charge their batteries, but also inject electricity back to the grid when needed (typically in periods of higher demand and cost).

For instance, the batteries of the EVs can be used to store energy produced at a PV system during the day and feed the energy into the grid when the overall demands are higher or less renewable energy is produced.

Using vehicle-to-grid functions in combination with a smart charging method leads to additional benefits:

- **Grid load balancing**
  V2G helps to stabilize the grid by discharging the EVs battery when needed. Especially with an increasing production of renewable energy that has a very unsteady power output this is getting more and more important.

- **Further cost savings**
  With V2G further savings in costs can be achieved by feeding energy back into the grid when overall electricity demands and therefore feed-in prices are high.

- **Emergency backup**
  In case of a power outage the batteries of the EVs can supply energy for the nearby infrastructure.

Although there are several benefits, there are also some drawbacks of V2G:

- **Increased battery wear**
  Due to the constant charging and discharging the life of the battery is slightly decreased. However, this effect is only marginal, because the amount of energy that is fed into the grid is small relative to the battery capacity.

- **Lack of standardization**
  Currently there is no standard protocol for vehicle-to-grid communication making it difficult for different systems working together.

1.5.3. Potential cost savings and grid impact according to research

The article of Brinkel et.al deals with the comparison of costs and grid impact of different charging strategies for electric buses.
Three depots of the bus operator Qbuzz in the Netherlands serve as case study.

- Location A: 101 buses used in rural area (longer distances, higher energy demand)
- Location B: 39 buses used in urban area
- Location C: 13 buses used in urban area

Following charging strategies were investigated:

1. Charging on arrival
All buses start charging as soon as they enter the depot with the nominal power of the charging system (conventional charging).

2. Peak-shaving
Smart charging strategy where the charging schedules are optimized to limit the peak demand from the grid by spreading the load over time.

3. Day-ahead market trade (excluding V2G functions)
Electricity prices are forecasted with high accuracy. The charging of the buses is shifted to times with low prices.

4. Day-ahead market trade (including V2G functions)
Extension of the previous charging strategy where extra benefits are gained by using V2G functions.

5. Provision of FCR and aFRR
The battery-electric-busses are used to restore the grid frequency when imbalances of supply and demand occur.

Costs using different charging strategies:
The results of this study regarding costs of each charging strategy are shown in Figure 18. Brinkel et. al reported that there is a reduction in charging costs ranging from 22,8% to 31,9% when changing from a conventional charging strategy to a peak shaving strategy.

Forecasting the market price (DAM trading) can lead to a further cost reduction of 6,3% to 11,1%. Using V2G functions in addition results in only marginal further savings (0,8% to 1,4%). Reasons for that are costs for the increased wear of the battery and that the complementarity between typical bus schedules and beneficial moments for discharging battery-electric-buses is low.

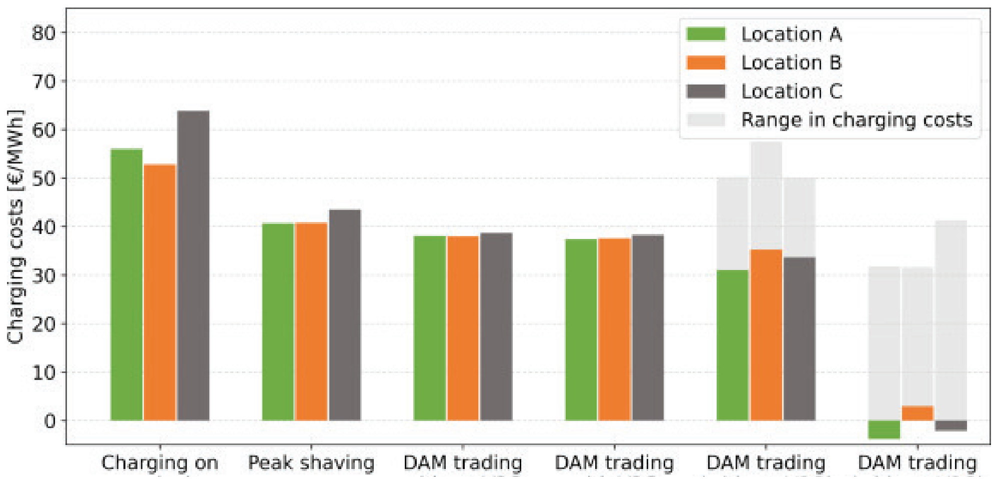

Figure 18: Costs with different charging strategies
(Brinkel et. al)

Power demand using different charging strategies:
In Figure 19 the power consumption of each combination of charging strategy and location investigated is shown.

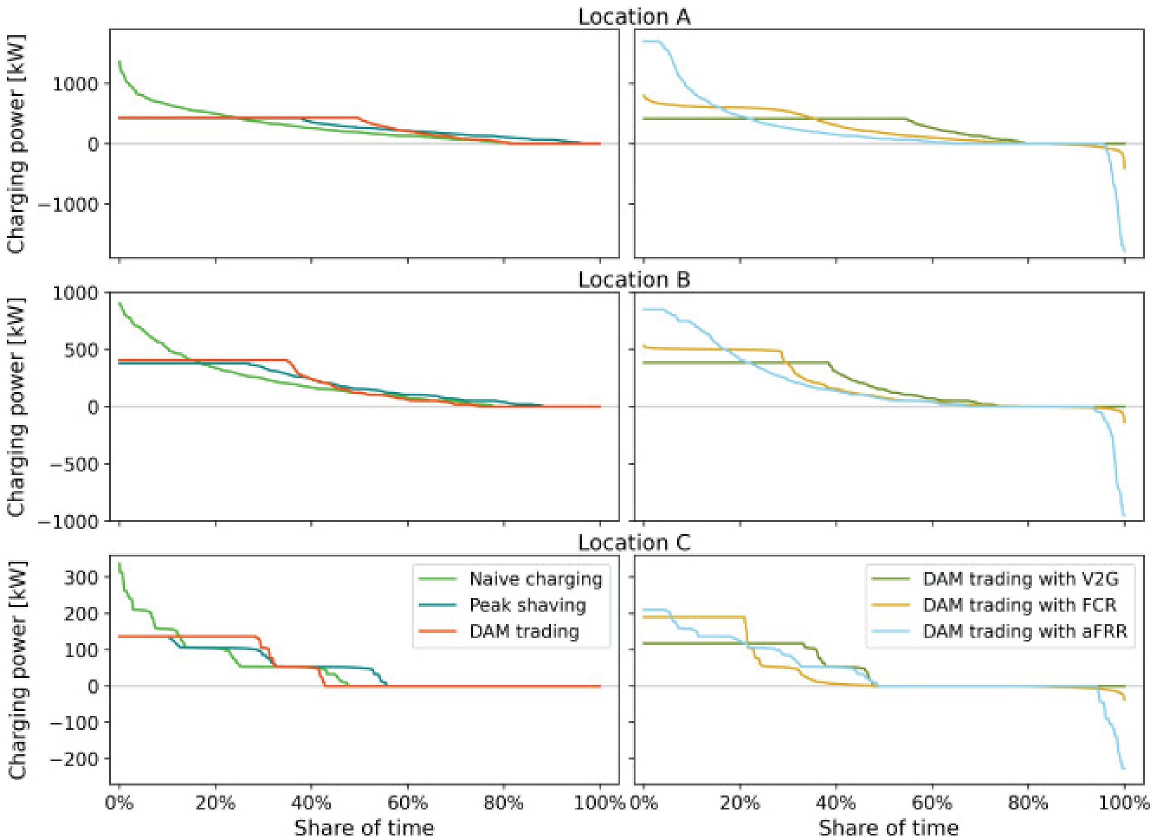

Figure 18: Costs with different charging strategies
(Brinkel et. al)

According to the study, applying a peak-shaving algorithm reduces the peak load by 58% to 69% compared to the "naive charging strategy" (charging on arrival). When using a DAM trading strategy (with and without V2G) the maximum power consumption is similar to the peak-shaving strategy.

Conclusions from this study:

- Using a peak-shaving algorithm reduces costs by 22,8 % to 31,9 % compared to conventional charging.
- More advanced charging strategies like DAM (forecasting electricity prices) trading and V2G (vehicle-to-grid) result in only marginal further savings.
- Peak-shaving, DAM trading and V2G strategies reduce grid load equally (reduction of 58% to 69% compared to the charging on arrival strategy).

Energy prices in Europe:
Figure 20 shows how electricity prices for non-household consumers differed in the European Union in 2022.

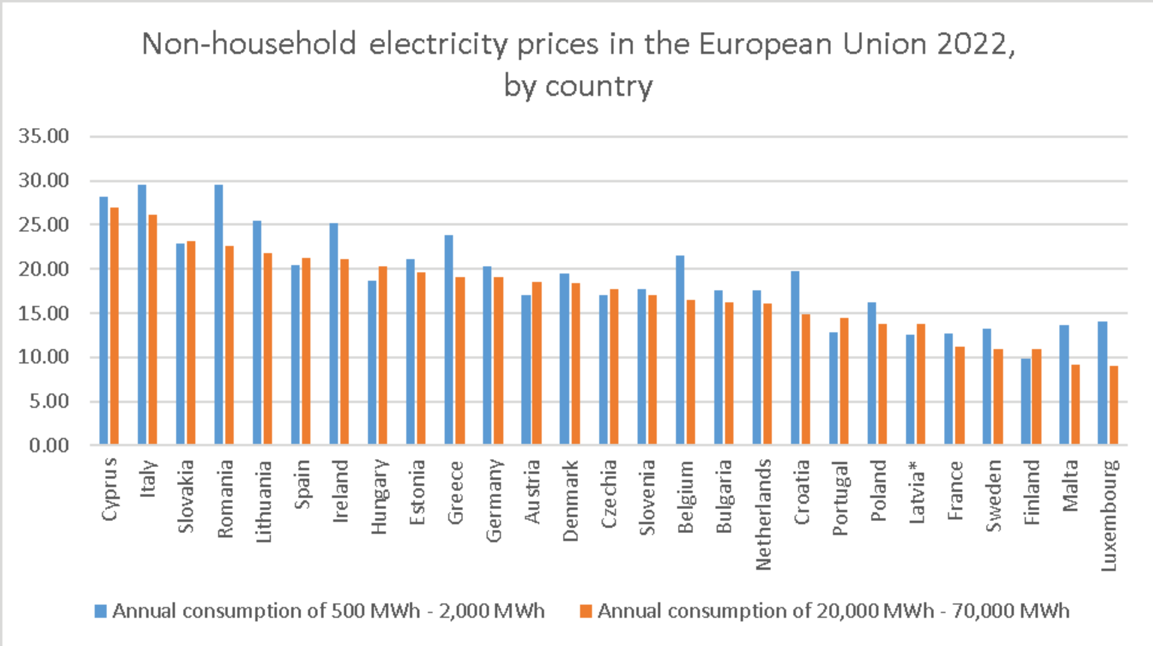

Figure 20: Non-household electricity prices in the European Union 2022, by country (Statista, 2023)

For consumers with an annual consumption between 20.000 and 70.000 MWh Cyprus recorded the highest prices at 27,03 cents/kWh. Overall energy prices in the EU differed quite a lot. At 8,99 cents/kWh prices in this category were lowest in Luxembourg. Consumers with less annual energy consumption (500 MWh to 2.000 MWh) had to pay most in Romania (29,60 cents/kWh) and least in Finland (9,79 cents/kWh). In Spain energy prices in 2022 were rather high with 21,21 cents/kWh in the upper class and 20,41 cents/kWh in the lower class, respectively. A progression of the energy prices for industrial consumers in Germany is shown in figure 6. Between 2001 and 2021 prices remained relatively steady. They fluctuated between 6,69 cents/kWh (2001) and 9,75 cents/kWh (2009). In 2022 prices rose dramatically to 15,12 cents/kWh (see Figure 21).

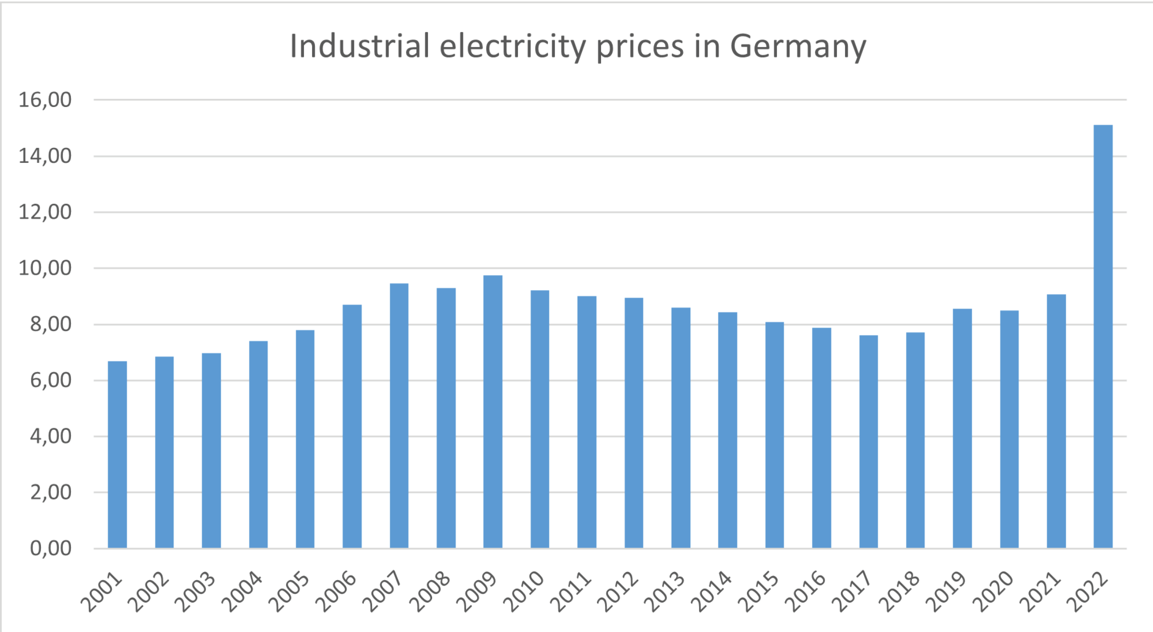

Figure 21: Electricity prices in Germany for industrial consumers (Statista, 2023)

1.5.4. Assessment of measurement data from EMT

The following chapter deals with the assessment of energy consumption and power measurements recorded in the Bus depot Carabanchel in Madrid. Data of 52 inverted pantographs used by 30 buses was collected.

Power consumption:
Figure 22 shows the average maximum power consumption of the pantographs over a day. The data was measured every 15 minutes from 8th May to 15th June 2023.
In average, at 01:00 the power reaches a peak of 3.029 kW. Then it drops steadily to about 500 kW at 04:00 before levelling out. During the day there are two slight increases at 10:30 and 16:30, respectively.

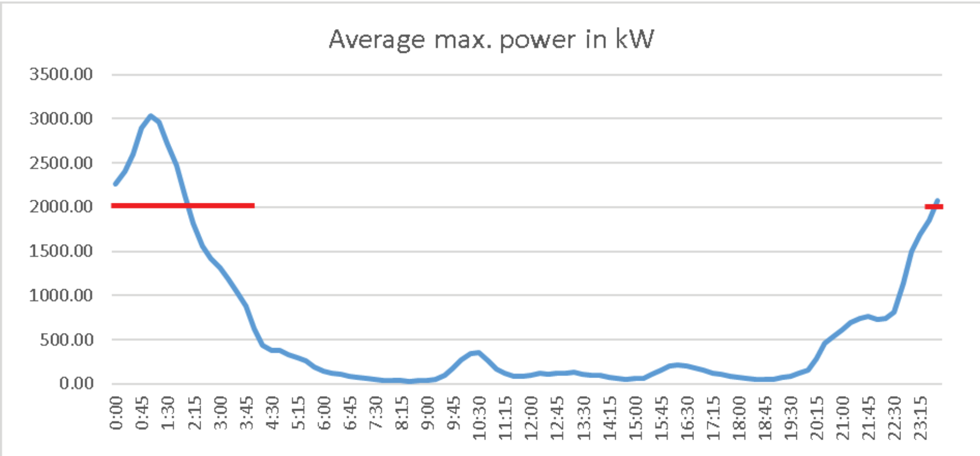

Figure 22: Average max. power consumption over a day – EMT Madrid

Between 23:30 and 04:00 the average maximum power is about 2.000 kW. So, assuming that during this time all buses are in the depot the peak power could be reduced by roughly one third when distributing the load evenly. Note that for this calculation the maximum power values every 15 minutes were used, which makes it slightly inaccurate. So, the actual possible reduction is even higher.

Figure 23 shows the maximum power output recorded on each day from 8th May to 12th June. The lowest maximum power was measured on 22nd May at 2248 kW. The maximum power measured on June 6th was nearly double that amount at 4432 kW.

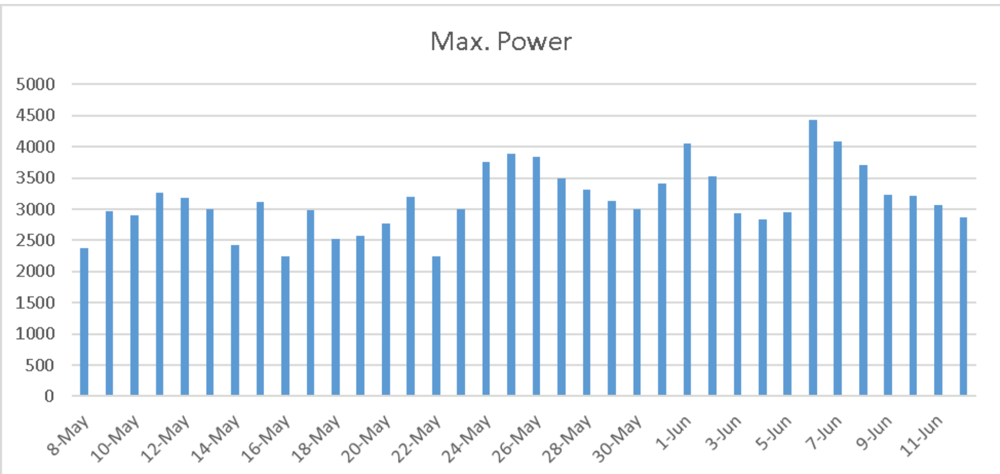

Figure 23: Max power consumption from 8th May to 12th June – EMT Madrid

From CW 19 to CW 23 the average maximum power consumption increased slightly (Figure 24). The lowest value was measured in CW 20 (2.772,57 kW), while the highest average peak power occurred in CW 23 (3528,00 kW).

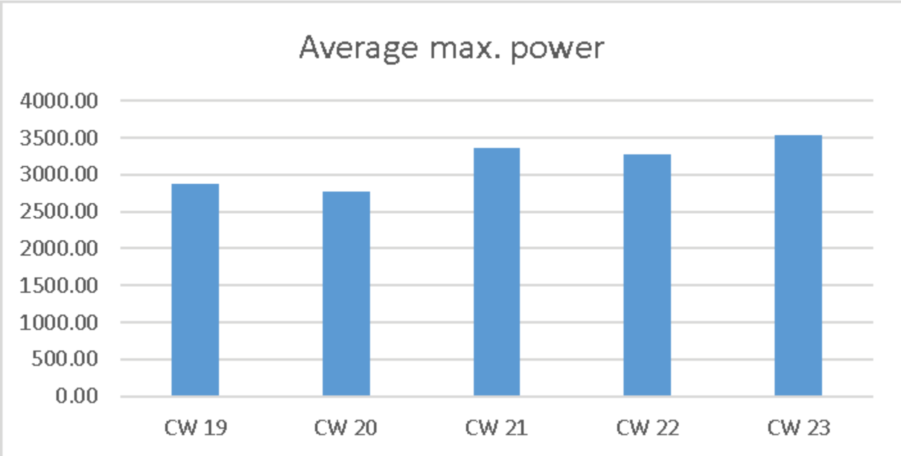

Figure 24: Average max. power consumption per calendar week – EMT Madrid

As shown in Figure 25, in average the highest peak powers were recorded on Wednesday and Thursday with 3.428,8 kW and 3484,8 kW, respectively. The lowest values were recorded on Mondays with 2782 kW in average.

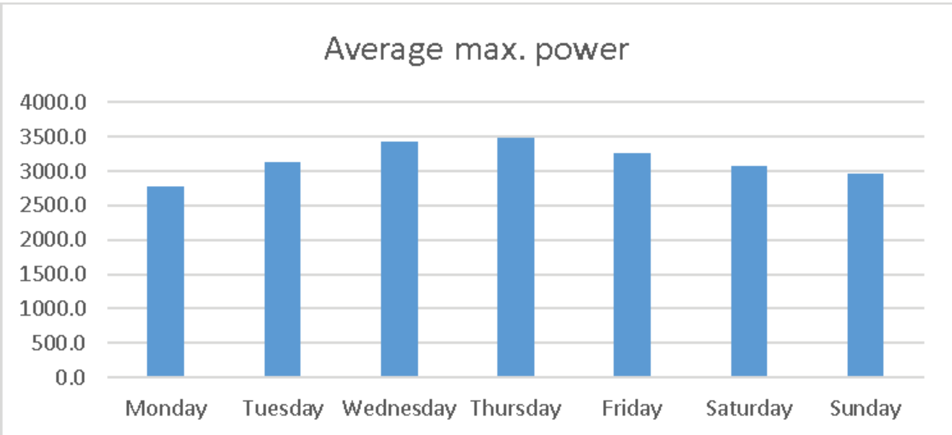

Figure 25: Average max. power consumption per weekday – EMT Madrid

Energy consumption:

The energy consumption of the investigated pantographs from 8th May to 22nd June is shown in Figure 26. The orange line represents the energy that came from a PV-system, the grey line stands for the energy received from the power grid. The total energy consumption is shown with the blue line and is the sum of the other two values. The energy recorded on 8th May was an outlier compared to the other data. On this day the total energy consumption was only 2238 kWh. A reason for that could be that the measurement started later during that day because it was the first day recorded. The most energy was consumed on 7th June (7200 kWh). In the last two weeks you can see a trend that the energy consumption was high from Wednesday to Friday and relatively low on weekends. 92,01 % of the consumed energy came from the grid. Energy from the PV-system accounted for only 7,99 % of the total energy consumed (Figure 27).

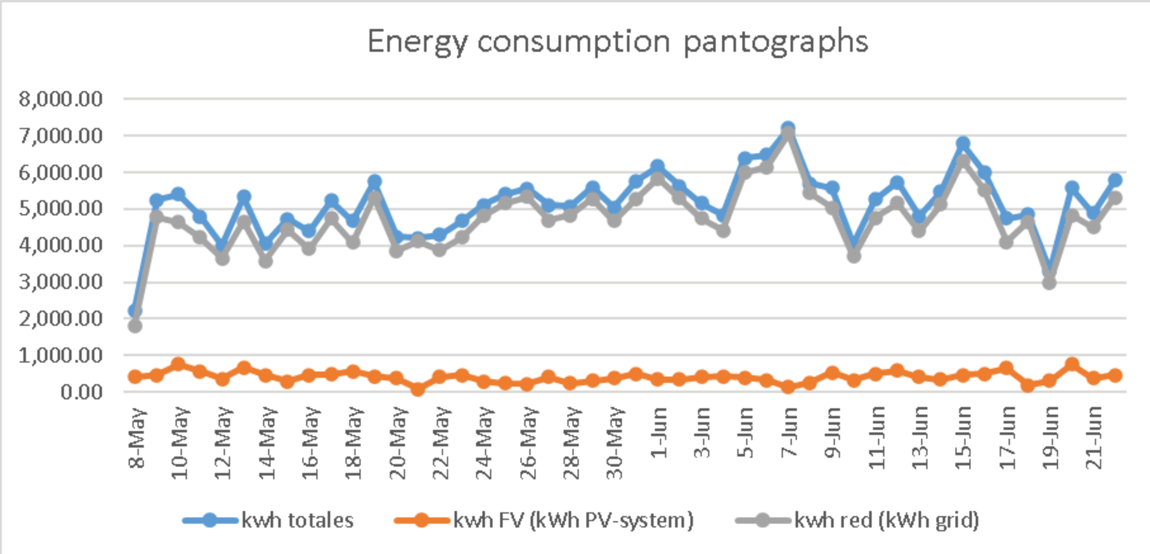

Figure 26: Energy consumption pantographs per day - EMT Madrid

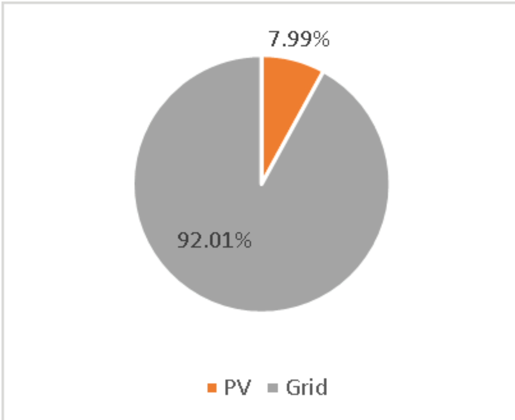

Figure 27: Energy sources – EMT Madrid

Figure 28 shows the energy consumption of the pantographs in each week from CW 19 to CW 24. The consumption in CW 19 was the lowest recorded (31.060 kWh), also conducted by the outlier on 8th May. Therefore, in this week the relative consumption from the PV-system was higher compared to the other weeks (11,94 %). The most energy was consumed in CW 23 (40.617 kWh).

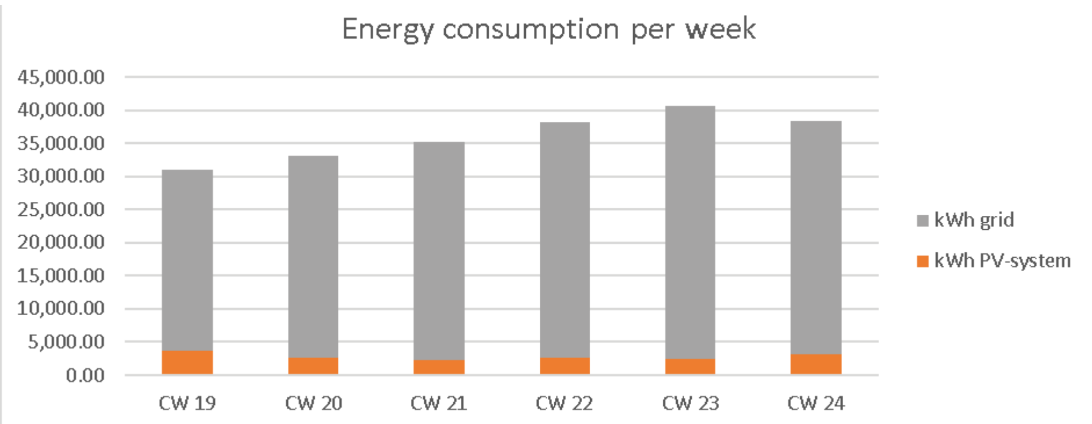

Figure 28: Energy consumption per week – EMT Madrid

The average energy consumption of each weekday is shown in Figure 29. The outlier on 8th May was not accounted in this diagram. You can clearly see that the highest consumption occurs from Wednesday to Friday. The consumed energy on weekends is significantly lower.

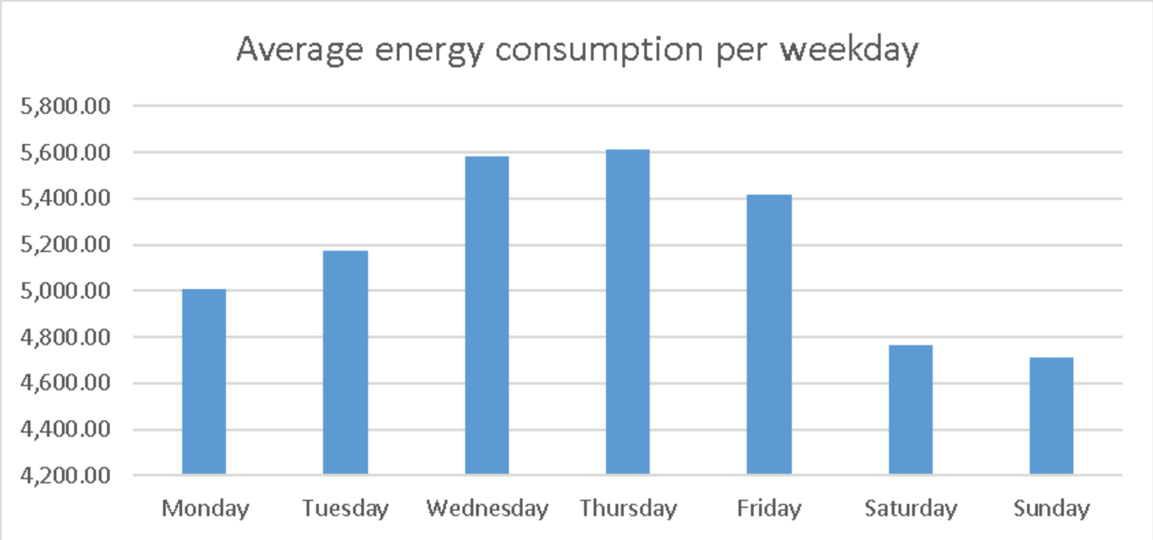

Figure 29: Average energy consumption per weekday - EMT Madrid

1.5.5. Calculation of key performance indicators (KPI)

Calculation of financial indicators:

Definition of chargers and charging points:

- Current status: 50 Chargers (4 models)
- Planned: 413 Charging points (8 models)
- Per charger: 1-3 charging points for pantographs or 1 for cable-based chargers
- Assumed number of charging points per charger: 2 → Number of chargers: 207

Savings:

- 80.000 €/year for 413 charging points

Costs for Smart Charging Hardware and Software:

Investment costs:

- Hardware needed for smart charging (local PLC): 15.000 € for 413 charging points
- Costs for integration: 2.500 € per model → 20.000 € for 8 models
- → Total investment cost for 413 charging points: 35.000 €

Running costs:

- 19,95 per month per charger = 49.556 €/year for 207 chargers (equivalent to 413 charging points)

Payback Period:
The payback period is defined as the time that it takes to refund the costs of an investment (time to reach the breakeven point). An investment is unprofitable when the payback period is longer than the depreciation life of the investment. The depreciation life was estimated at 15 years.

$$Payback\ period = \frac{Initial\ investment}{Cash\ flow\ per\ year} = \frac{35.000€}{80.000 - 49.556€} = 1{,}15\ years$$

Net present value:
The Net Present Value (NPV) is a financial metric used to evaluate the profitability of an investment or project. It represents the difference between the present value of cash inflows and the present value of cash outflows over a specified period of time.

A positive NPV indicates a profitable investment, whereas a negative NPV indicates a that a project or an investment is unprofitable. NPV can be calculated according to the following equation, where "t" stands for the depreciation time of the investment, "r" for the required annual discount rate, which was assumed to be 5%:

$$NPV = \sum_{n=0}^{T} \frac{Cashflow_t}{(1+r)^t} - Investment$$

This leads to the following calculation of NPV for 15 years shown in Figure 30. Figure 31 shows the net present value as a function of time. After 15 years a net present value of 280.998 € is reached, which indicates a clearly positive investment.

Time in years	Investment	Savings	Yearly costs	Rev/(1+r)i	NPV
0	35.000 €	0 €	0 €	0 €	-35.000 €
1	0 €	80.000 €	49.556 €	28.994 €	-6.006 €
2	0 €	80.000 €	49.556 €	27.614 €	21.608 €
3	0 €	80.000 €	49.556 €	26.299 €	47.907 €
4	0 €	80.000 €	49.556 €	25.046 €	72.953 €
5	0 €	80.000 €	49.556 €	23.854 €	96.807 €
6	0 €	80.000 €	49.556 €	22.718 €	119.524 €
7	0 €	80.000 €	49.556 €	21.636 €	141.160 €
8	0 €	80.000 €	49.556 €	20.606 €	161.766 €
9	0 €	80.000 €	49.556 €	19.624 €	181.391 €
10	0 €	80.000 €	49.556 €	18.690 €	200.080 €
11	0 €	80.000 €	49.556 €	17.800 €	217.880 €
12	0 €	80.000 €	49.556 €	16.952 €	234.833 €
13	0 €	80.000 €	49.556 €	16.145 €	250.978 €
14	0 €	80.000 €	49.556 €	15.376 €	266.354 €
15	0 €	80.000 €	49.556 €	14.644 €	280.998 €

Figure 30: Net present value calculation table for 15 years

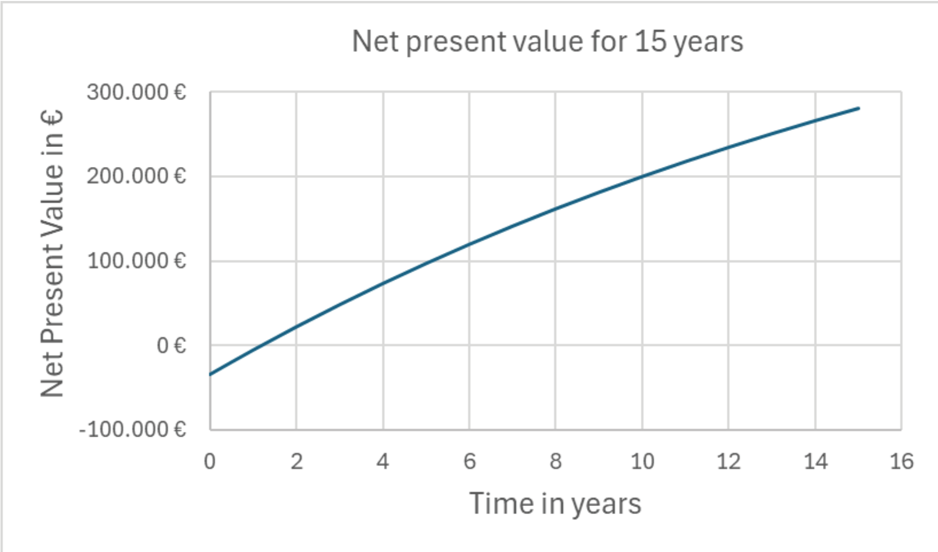

Figure 31: Net present value as a function of time

Calculation of technical indicators:

Reduction of peak power/grid load:

As mentioned above a smart charging strategy can reduce the peak power consumption from 3 MW to 2MW, which is a reduction of 33%.

1.5.6. Second-life battery storage for self-consumption optimization

When the battery capacity of an electric bus falls below 70% to 80% of the nominal capacity the batteries are too weak to be used for transportation purposes any longer. These batteries could be repurposed in stationary applications, for instance to increase the self-consumption rate of a solar power system.

Especially with the currently unstable energy prices giving the batteries a second-live as stationary storage could be profitable. Extending the operating life of a lithium-ion battery would also bring environmental benefits.

Second-life battery storage for bus depot Carabanchel:

Figure 32 shows the energy output of a 300 kWp PV-system in each month calculated with the JCR Photovoltaic tool of the European Commission. The calculation was made for the exact location of the bus depot Carabanchel. A system efficiency of 84% was assumed. The produced energy is highest in July at 73.955,4 kWh, which is 2385,66 kWh per day and lowest in November at 38.706,2 kWh (1.280,21 kWh per day). In June the PV system produces 2.238,39 kWh per day in average.

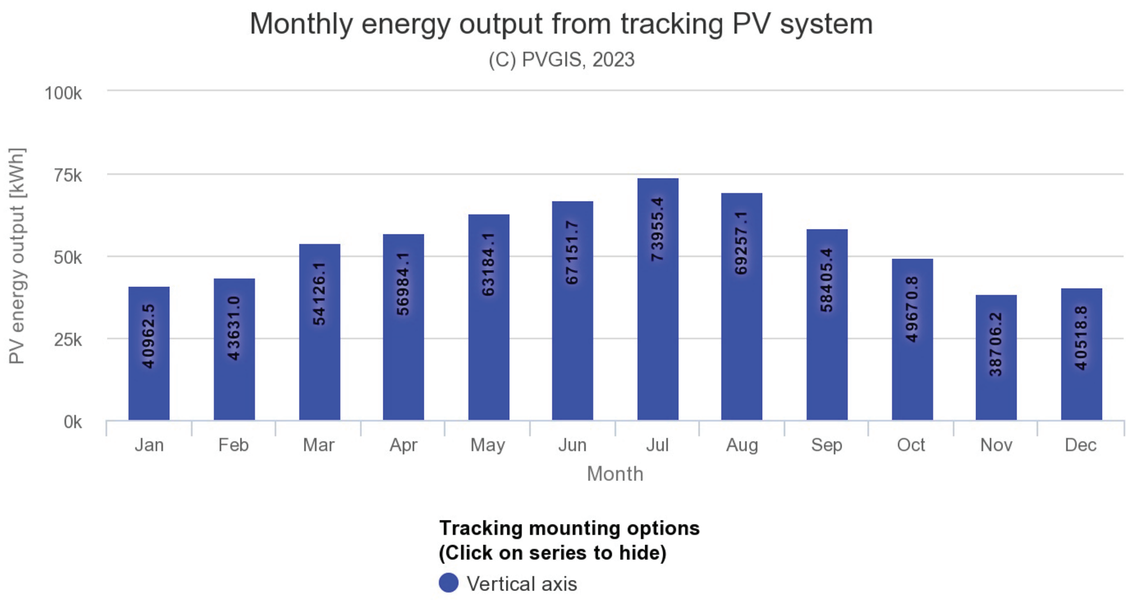

Figure 32: Energy production of a 300kWp PV-system in Madrid
(JRC PHOTOVOLTAIC GEOGRAPHICAL INFORMATION SYSTEM)

In Figure 33 the irradiance profile of Madrid in July was generated (figure 17). Perfect conditions were assumed (sunny day). The maximum irradiance occurs at 11:30 UTC.

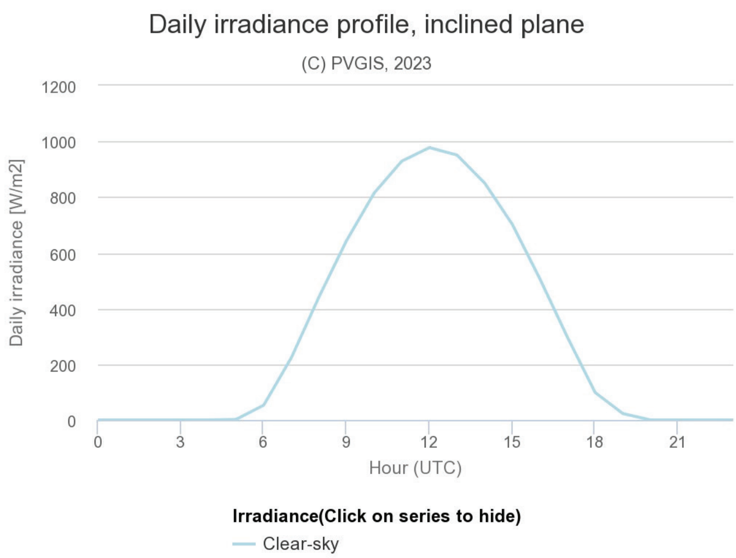

Figure 33: Irradiance profile for Madrid in July
(JRC PHOTOVOLTAIC GEOGRAPHICAL INFORMATION SYSTEM)

In figure 18 the estimated power output of a 300 kWp solar power system on a sunny day is fitted into the power curve of the pantographs from chapter 3.1.

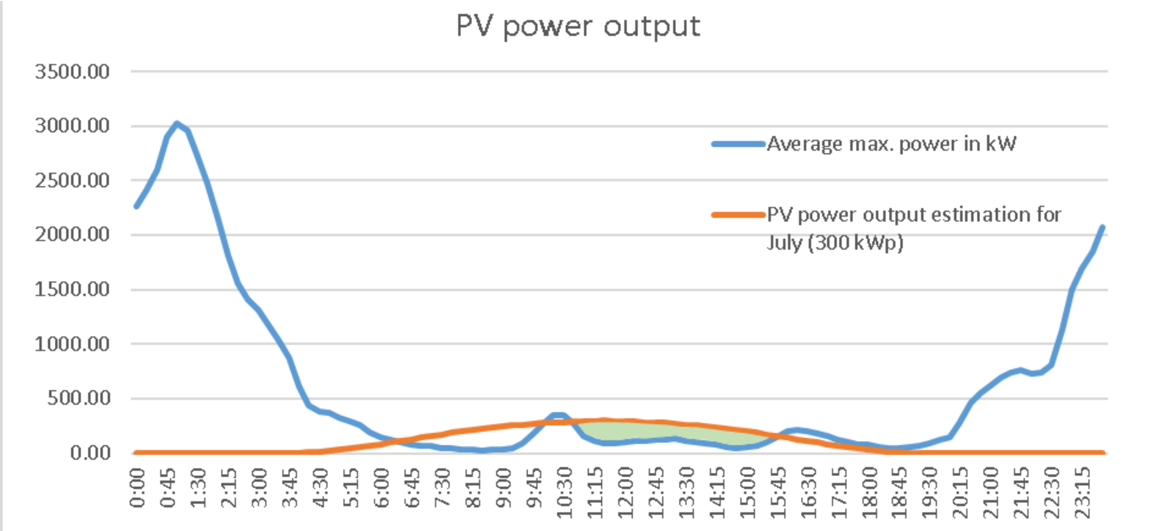

Figure 34: PV power curve on a sunny day for Madrid (300 kWp PV-system)

This graph shows that a 300 kWp PV-system does not produce much excess energy that can be stored in a second-life battery storage (green area). However, looking at the values for the total energy consumption in June a 300 kWp solar-power system would produce roughly half of the total energy needed. In the graph above the energy from the PV system is far less than that. This suggests that the number of busses measured to collect energy and power data were not the same. From the data provided by EMT it can be concluded that approximately 2,5 times more buses were used for the power output data.
As shown in Figure 35 a 750 kWp PV system would produce much more excess energy using the same power consumption curve. Without a battery storage only the energy of the red area can be used directly. The rest must be fed into the grid (green area). By using a storage, the energy in the green area is stored into the battery and discharged during the night when the majority of charging takes place.

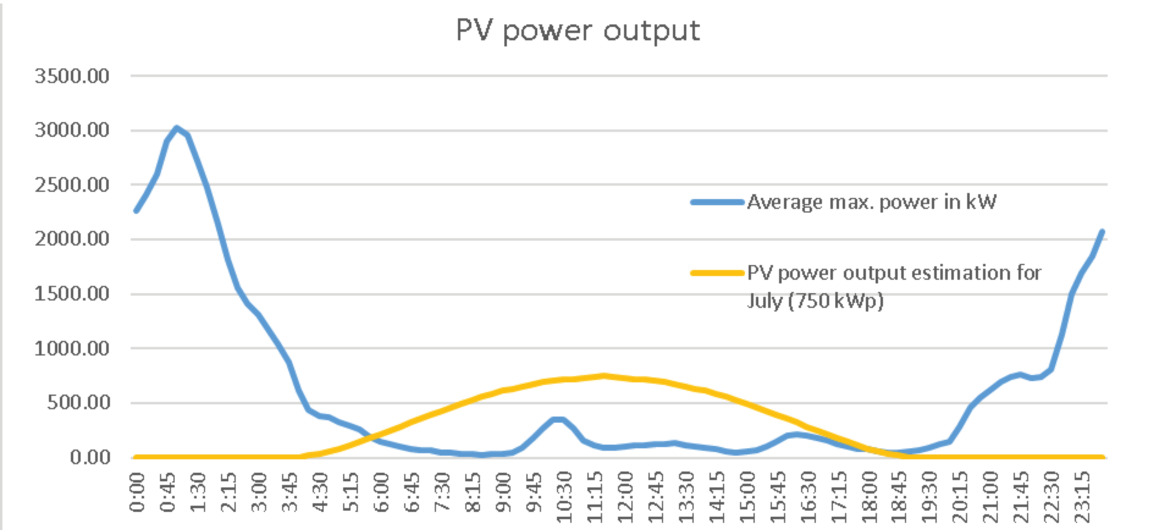

Figure 35: PV power curve on a sunny day (750 kWp PV-system)

Overall, the overlap between energy consumption of the pantographs and energy production of the solar power system is relatively small. So, especially for large PV-systems a battery storage makes sense.

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