Optimal sizing of microgrids: a fast charging station case

C. Corchero, M. Cruz-Zambrano, F.-J. Heredia, J.-I. Cairo, L. Igualada-Gonzalez, A. Romero-Ortega

Abstract—**In this work we focus on the optimal design of electric vehicle charging stations. We consider investment, operational costs, physical constraints and different electricity pricing strategies. The size of the various components in the microgrid architecture and the suitability of the storage system are analysed. The electric vehicle charging demand is modelled through a queuing system.**

Index Terms—**charging station, electric vehicle, microgrid components optimal size, queuing system, energy storage system.**

I. Introduction

Electric vehicles have become a strategic technology investment for the automotive sector over the past few years. Currently a significant share of automobile manufacturers produce plug−in electric vehicles (PEV), both battery electric vehicles (BEV) or plug−in hybrid electric vehicles (PHEV). Furthermore, during the next few years almost the major of manufacturers are planning to introduce PEV models. This maybe attributed to: first, the increase of cost−effectiveness of the technology , mainly driven by the reduction of storage cost and rising fossil fuel prices; second, the environmental and energy policies set up at an international level, supported both by geo−strategic reasons as well public awareness and desire for sustainability.

Market penetration scenarios for PEV put expectations between 1% and 4% for BEV and 2% to 35% for PHEV in the European market by 2020 [1]. This scenario diversity is due to many factors that could affect final figures, including technology evolution and macroeconomic scenarios. Recent market penetration scenarios regarding PEV are reducing expectations taking because of financial crisis during the last years. One thing is clear however: initially PEV will have limited autonomy compared with conventional vehicles. The availability of the public recharging infrastructure plays an important role in the deployment of PEV, and fast charging is the best option for the mobility needs of the users.

The Japanese Utility TEPCO made a study in 2008 to quantify the effects of the introduction of fast charging systems on PEV usage [2]. Changes in the mobility pattern of its own fleet were analysed. This fleet provided service to an area of 8 x 15 km before and after the installation of a fast charging point.

After the installation of the second fast charging point, the mobility area of the operators extended to cover the entire service area. Despite the increase in mobility, the second fast charging point was hardly used. Therefore, the second recharging point was purely functional, providing a psychological benefit by having a place to do a fast charge if necessary [3].

To quantify the increase in mobility, some data from the state of the charge of the battery (SOC) were taken before and after the installation of the fast charging point (see Figure 1). The average discharge of the battery changed from 30% to 70% after the fast charging point installation.

Considering a battery capacity of 20kWh and an energy consumption of 15kWh every 100km, the average daily path rose from 39.5km to 93.3km, experimenting 133% of increase in the daily mobility of the fleet.

The results obtained by TEPCO in 2008 are confirmed in the study that BMW carried out recently on 500 units of its electric model "Mini E" [4]. This Project took place in the cities of Los Angeles, Berlin and London and it included a set of surveys for new users including the recharging infrastructure and various other aspects.

Specifically, in Berlin (where there was a fast charging public point available to users), 85% of users expressed their wish to have a second additional charging point available where they usually park. 80% considered public charging infrastructure absolutely necessary [5], however, as in the TEPCO experiment, the use of public charging stations was very small, again highlighting the psychological benefit. Public infrastructure and, more precisely, the fast charge, play a key role in the development of the electromobilty. We can extract the following conclusions:

- The public charging infrastructure plays two roles: one functional and one psychological. In the studies presented so far, low utilization of the public infrastructure shows how the psychological benefit plays a very important role, especially during the initial stages of electrical vehicles adoption.
- The public charging infrastructure alleviates range anxiety, increasing user acceptance of PEV and opening up its market niche.

Therefore, during the early stages of introduction of electric vehicles, low usage of recharging infrastructure can be expected; however, the psychological function of these systems cannot be ignored.

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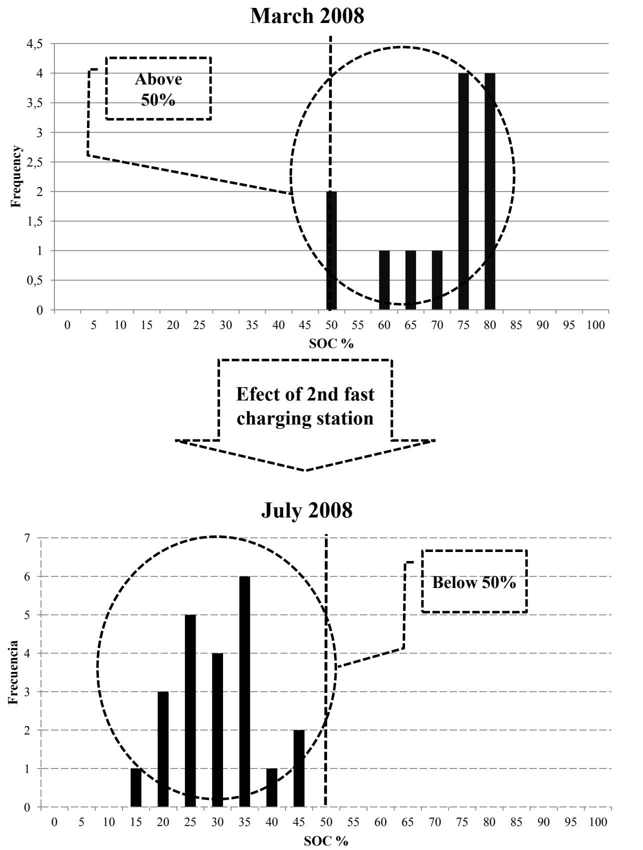

Figure 1. Effect in the energy consumption of the EVs after the installation of the fast charging point. Source: IREC using data from TEPCO, 2011.

In line with the promotional initiatives carried out by some regions around the world, the installation of fast charging infrastructures must be considered as viable for the creation of development strategies by regional governments. A network of fast charging stations is needed, however it is still an open problem where these charging stations should be placed and how they would be designed and sized.

Currently there is much debate regarding the technology to be applied to fast charging stations. Two major technological streams are fighting to become the standard: AC fast charging, also known as IEC 61851 Mode 3; and DC fast charging, included at IEC 61851 Mode 4 standard. In this paper we focus on the DC alternative, which currently is the most common in Spain and the rest of Europe.

The most popular approach of DC fast charging station is the use of an AC/DC converter per charging point and without any storage capacity. In this study we show that by changing some aspects of the classical architecture, the profitability of the fast charging stations can be increased, and their negative impact in the power network can be also reduced.

The first change made was the introduction of an energy storage system with two possible advantages: *(i)* the station would be able to charge more power than allowed by the grid tie and, *(ii)* operational costs and grid impact would be reduced by storing energy during off−peak hours. This approach was previously used in other works like Zhenpo2010a, were a storage power and charging station to solve the main conflict between the future demand of electricity due to the electric vehicle and infrastructure construction is presented. The second proposed change was the use of a single AC/DC converter for multiple charging slots leading to a common DC bus architecture as described in Figure 2. Using an AC/DC converter per charging slot is the most common practice since each slot has access to an AC connection. However, in new facilities where new infrastructures have to be implemented, it can be proposed to locate a DC power bus that feeds the common access points of the slots. In that case, the complexity of the power converters, and also the cost can be minimized using the proposed practice. Each DC/DC converter has much lower complexity that an AC/DC converter, and also the power transfer could be done by high voltage DC minimizing the losses. A central controller would be required to deal with the new energy management profiles.

The main objective of this work is to find the optimal dimension of the grid tie and the AC/DC converter and the optimal capacity of the storage system taking into account investment, operational costs and PEV demand. Other secondary objectives of this work are: to optimally size the charging station components, to model the PEV demand and its implications in the charging station specifications and to model the uncertainties that will define the operational costs.

Few previous studies address these issues. In [7] the design of a charging station is done by means of simulation and the possibility of a DC or a AC bus based architecture is modelled. Also by means of simulation the optimal allocation between the power supply capacity and the power storage capacity under a certain scale of charging station is found in [8]. However, none of them are using optimization techniques, which can be identified as the main contribution of this work.

II. Microgrid description

Microgrids can be defined as a power system composed of Distributed Energy Resources (DER) that can operate as an electrical or thermal generator, a storage system or as a load, to provide maximum electrical efficiency with minimum incidence to loads in the local power grid [9]. Since the elements that compose the system described can be considered as DER, the whole system can be considered as a specific case of a microgrid with controllable loads (electric vehicles), storage devices and grid interconnection. Generation assets like renewable resources are not included in this work. DC bus based systems however provide a convenient way to integrate microgenerators. In further research the integration of microgenerations will be considered.

A. Charging station architecture

The fast charging station considered in this work is described in Figure 2. While current fast charging stations are composed of both AC/DC and DC/DC converters per charging slot, in this case a single AC/DC converter is proposed to be installed. Thus, a DC bus is used for power distribution along the different charging slots as well as the storage device.

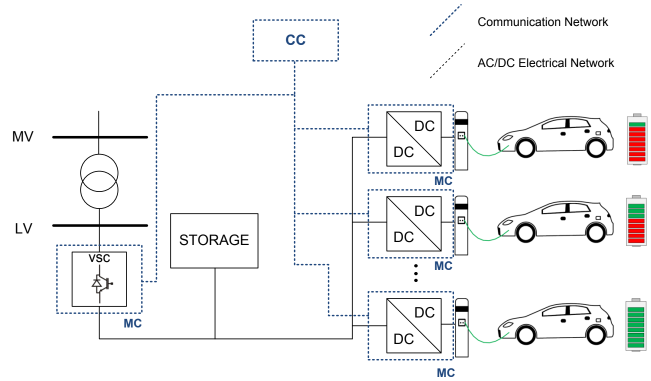

Figure 2. Fast charging station using a single AC/DC converter.

The operation and management of the fast charging station microgrid in different modes is controlled and coordinated through local microsource controllers (MCs) and the central controller (CC) executes the overall control of microgrid operation and protection through the MCs.

B. PEV Demand

A controlled load at a charging station depends when the majority of electric vehicles start charging. This demand will depend on vehicle flow which, in its turn, depend on location and time interval, among other aspects. With data from the Movilia project [10] we have made some assumptions to model the electric vehicles arrivals, which has been modelled by means of queuing theory like it was proposed previously in [11] and [12]. Supposing that the charging station is located in a residential area in a specific city of Spain, we have estimated PEV penetration by 2020 and we use the percentage of commutes during a working day to estimate the charging processes that will take place. The distribution of arrivals is estimated obtaining the hours in which the number of expected charging processes are the highest.

The goal of this paper is not to introduce in detail this scenario but to present the procedure of obtaining the estimations. Based on this data we propose some hypothesis and assumptions that focus on the scope of possibilities without eliminating the thoroughness of the methodology.

1) Description of observed area: The assumptions for the PEV penetration are taken from a study in the same project context, with the aim of estimating the power requested for charging PEV′s from 2010−2020. For this study we have just considered the case of residential areas. Using the assumptions made from conventional combustion cars mobility data as this what is currently available, we can extrapolate mobility with PEV′s as described in the following paragraph.

2) Assumptions on mobility: An average consumption for an PEV is 200 Wh/km. A mean travelling distance of 15 km, and the average speed for an electric vehicle is approximately 30 km/h, mainly in urban areas. The capacity of the battery will depend on the type of vehicle. Here we suppose an average BEV with 25 kWh of capacity. From these considerations the daily request of charge (RoC) will be on the order of 1/8 of the battery capacity:

$$RoC = 0.2\frac{kWh}{km}15km = 3kWh \tag{1}$$

From the work [10], the number of commutes by auto and motorcycle either on a work day or a non−work day in the specific city of Spain is shown:

- Number of Commutes on average work day: 41,151
- Number of Commutes on average non−work day: 38,022

The number of commutes done by the different types of PEV is according to the following distribution:

- PHEV: 36.83%
- BEV: 45.02%
- Electric motorcycle: 18.15%

In Figure 3 we can see the distribution versus time of percentage of commutes returning home on a work day [10].

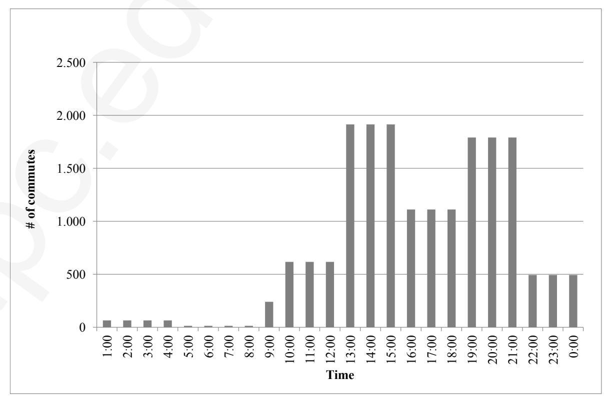

Figure 3. Percentage of commutes returning home for a labor day

3) Charging Request is a Poisson Distribution: One of the most common statistics for arrivals modeling and RoC due to its simplicity and properties, is the Poisson process. An important property of this distribution is a *non memory system*, since every arrival of the units is independent from the previous arrival; *infinite source*, makes it independent from the time window of observability to take averages values. Also the probability of having an arrival into the system is proportional to the time Δt, i.e. the $\lambda\Delta t + O(\Delta t)$, where $O(\Delta t)$ is a Landau O.

With the previous hypothesis the probability of having n arrivals of PEVs at time T (or Δt) the following law follows:

$$P_n(t) = \frac{(\lambda T)^n}{n!}e^{-\lambda T} \tag{2}$$

From figure 3, we make the assumption that our window time of interest is from 8 hours until 16 hours in the morning. In that window, we can obtain a distribution rate of λ = 4.2 ev/h, with f_i as the relative frequency of observations:

$$\lambda = \bar{X} = \frac{1}{n}\sum_{i=0}^{k} x_i f_i \qquad f_1 + f_2 + \cdots + f_k = n \tag{3}$$

In figure 4 the Poisson distribution of arrival probabilities is plotted comparing the measured data [10] and the estimated data. The lower use of fast charging stations compared to household charging has been considered for modelling the number of arrivals.

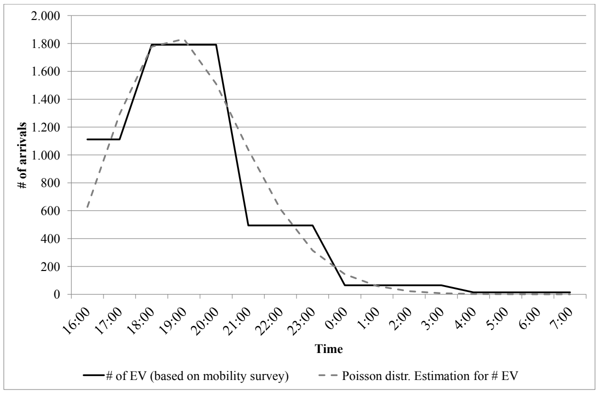

Figure 4. Poisson distribution of arrival probabilities for a work day.

C. Electricity Market

The charging station is connected through the grid tie to the electricity distribution network and indirectly to the electricity market (usually buying the energy through a retailer). As the PEV demand approach is based on a Spanish city, we will focus on the Iberian Electric Market. The system will receive a price signal for each hour. Based on this signal the system will optimally control the power demand from the grid and the storage system to reduce operating costs. In order to estimate these costs we have forecasted this price signal by means of time series factor analysis [13].

The calculation of the price signal for the energy considered for each time period T is shown in (4). For each pricing period, the efficient price is a load−weighted average of the hourly wholesale competitive prices for that time period, where the weights are the hourly loads [14].

$$P_T^* = \frac{\sum_{h \in T} Q_h FMP_h}{\sum_{h \in T} Q_h} \tag{4}$$

The variables are as follows:

T	Time period	
P_T^*	Efficient price in period T	€/MWh
Q_h	Load in hour h	MWh
FMP_h	Final market price in hour h	€/MWh

Spain and Portugal final market prices, obtained from OMEL database for 2010 [15], include wholesale prices of energy as well as ancillary services for the system. The periods T are chosen to be the same as the typical industrial tariffs, including 3 periods: peak, off−peak and shoulder.

III. Mathematical model

A. PEV Demand Modeling

The charging service described is naturally modelled through a queuing system. The elements that define the system are the following:

- Arrival process: PEVs with some necessities of the battery to be charged.
- Service process: time to charge the PEVs battery.
- Queue discipline: first come, fires served.

Supposing a charging station with 4 charging points, the appropriate model is M/M/4, where the arrival times are exponential with rate λ, the service times are exponential with rate μ and there are 4 parallel systems. We have built successive identical queueing systems with different λ and μ depending on the hour of the day and the seasonal moment, we consider only work days. The rate of the arrival times, λ, is calculated based on the data from the previous section. The service time is calculated as a function of the available power in the charge station, i.e., the time that the charge slot will need to charge a battery will depend on the available power in the charge station as well as the state of charge (SOC) of the vehicles to be charged.

This dependence is modeled through a linear function and it is explicitly introduced into the optimization model through the corresponding constraints. In this way, we assure that the optimal sizing of the charging station is taking into account both the physical constraints and the behaviour of the service system regarding the available power.

B. Microgrid physical constraints

The microgrid, as it has been defined in the previous section, consists of a grid tie connected to an AC/DC converter with a DC bus which distributes the power along the 4 charging points and the storage device. We have considered the following constraints:

- The physical limits of the grid tie.
- The physical limits of the AC/DC converter.
- The physical limits of the storage device.
- The power served by the charging slots must be obtained from the grid (observing the grid tie limits) and from the storage device.

C. Decision variables and objective function

The decision variables are directly related to the objectives of the problem:

- $\bar{E}^s$: Storage device capacity (kWh).
- P^a: Grid tie capacity (kW).
- E_t^s: Energy taken from the grid to the storage at each time interval (kWh).
- $E_t^{s,c}$: Energy taken from the storage to the converter at each time interval (kWh).
- E_t^c: Energy taken from converter for each time interval (kWh).
- SOC_t^s: Energy stored each time interval (kWh).

The objective function takes into account the investment and the operational costs of the fast charging station, specifically:

- C: Investment costs of grid tie, main power converter, storage device (€).
- C^m: Operational and maintenance costs of distribution network (€/kWh), main power converter (€/h), storage device (€/kWh).
- M_t: Supply cost (energy market price), (€/kWh).
- n: Annuity factor for investment cost.

where the superscripts used are:

- a: grid tie
- c: converter
- s: storage

D. *Formulation*

$$Min \quad \frac{C^a + C^c}{n^c} P^a + \frac{C^s}{n^s} \bar{E}^s + C^{m,s} \sum_{t=1}^{T} E_t^s + \\ + C^{m,c} \sum_{t=1}^{T} (E_t^s + E_t^c) + \sum_{t=1}^{T} M_t (E_t^s + E_t^c) \qquad (5)$$

$$s.t. \quad E_t^c + e_{ff} E_t^{s,c} = d_t L_t \qquad \forall t \in T \qquad (6)$$

$$SOC_t^s = SOC_{t-1}^s + e_{ff} E_t^s - E_t^{s,c} \qquad \forall t \in T \backslash \{1\} \qquad (7)$$

$$SOC_1^s = SOC_i^s \bar{E}^s + E_1^s - E_1^{s,c} \qquad (8)$$

$$0 \le E_t^s + E_t^c \le d_t P^a \qquad \forall t \in T \qquad (9)$$

$$e^- \bar{E}^s \le SOC_t^s \le e^+ \bar{E}^s \qquad \forall t \in T \qquad (10)$$

$$E_t^{s,c} \le r^s d_t \bar{E}^s \qquad \forall t \in T \qquad (11)$$

where:

L_t	Demand in each $t \epsilon T$	kWh
d_t :	Duration of each interval $t \epsilon T$	hours
e^-, e^+	Levels max. and min. for SOC	%
r_s	Relationship between power and energy in storage	
e_{ff}	Efficiency factor to storage	%
SOC_i^s	Initial SOC of the storage	kWh

IV. Results and conclusions

In this section the main results obtained from the optimization process are explained.

Main input data used for the model are shown in Table I. Three different daily periods have been defined based on the mobility patterns as well as on electricity market prices. Regarding the arrivals rate λ, the year has been also divided in three groups taking into account available mobility analyses: September−March; April−June and July−August. The used service rate μ has been estimated as 5.5 taking into account the average time needed for the fast charging of electric vehicles in 50kW charging spots.

TABLE I
MAIN DATA INPUTS FOR THE MODEL

Period	Hours	Price (€/kWh)	λ
			4.4
p_1	13-24	0.133355	4.2
			4
			4.2
p_2	7-13	0.050174	4
			3.8
			0.6
p_3	0-7	0.032802	0.6
			0.6

In Figure 5 the total yearly costs of the fast charging stations are shown. It can be seen from the figure that storage prices lower than 430 €/kWh can make the integration of storage systems in the fast charging station profitable. Since current prices of storage systems are expected to be reduced in the next years, this price will not be difficult to reach in the future. Also, the second life of PEV batteries, can play an important role in these types of applications. A linear decrease of overall costs is obtained: 10% for 300€/kWh, a 20% for 200€/kWh and a 30% for 100€/kWh. Higher savings could be expected if energy prices are increased, making the difference between peak and off−peak periods higher.

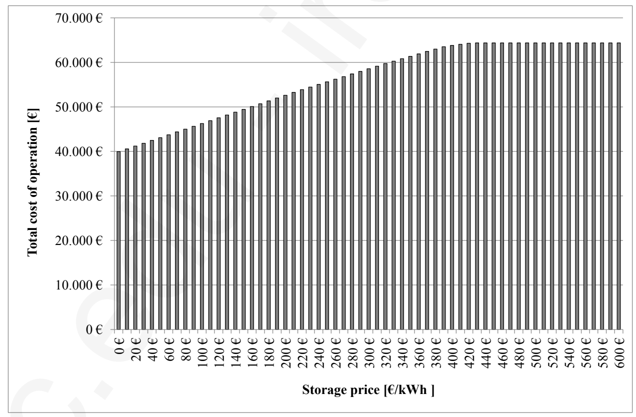

Figure 5. Total yearly cost versus storage costs.

In Figure 6, the optimized values for storage capacity and grid tie capacity are shown. In this figure, three different parts can be identified. For the higher prices of storage systems *(i)*, no storage capacity is installed. Then, grid tie is dimensioned to be equal to the maximum power demand caused by the electric vehicles. For 430€/kWh *(ii)*, the break−even point is achieved, so storage capacity is installed for reducing the electricity consumption during peak hours. At this point the reduction on variable costs (energy costs, maintainance, etc.) offsets the increase on initial investment for the storage installation. As a consequence, the grid tie capacity is reduced and is optimally dimensioned as the shoulder period maximum power demand. For prices lower than 380€/kWh *(iii)*, the grid tie capacity is increased instead of reduced, together with the storage size. The reason for such an increase of the optimal values for both parameters is the possibility of carrying out large charging processes during off−peak periods (overnight), for reducing power consumption during peak and shoulder periods.

Table II shows the results for daily energy costs of the fast charging station. It can be appreciated how the introduction of storage devices produces a reduction in the daily energy costs. The reason for such an effect is the higher consumption during low prices periods. The cost savings are increased up to 60% in case of the larger storage device. However, the efficiency of the charging and discharging processes causes a higher energy consumption when the fast charging station is including storage devices.

TABLE II
FAST CHARGING STATION DAILY VARIABLE COSTS

Storage cost (€/kWh)	Storage size (kWh)	Daily energy consumption (kWh)	Daily energy cost (€)
600	0	1327.63	137.02
400	550	1513.85	115.16
200	1250	1523.51	57.49

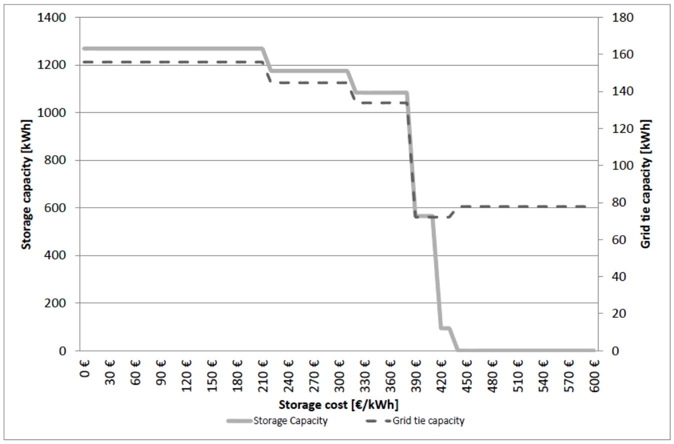

Figure 6. Optimal grid tie and storage capacity versus storage costs

Unexpected results are obtained for low prices of storage systems: the grid tie, far from being reduced, is increased for maximizing the amount of energy that can be consumed over energy low prices periods. At first glance these results may appear negative from the utility company point of view. Investment for installing higher capacity grid ties would be needed.

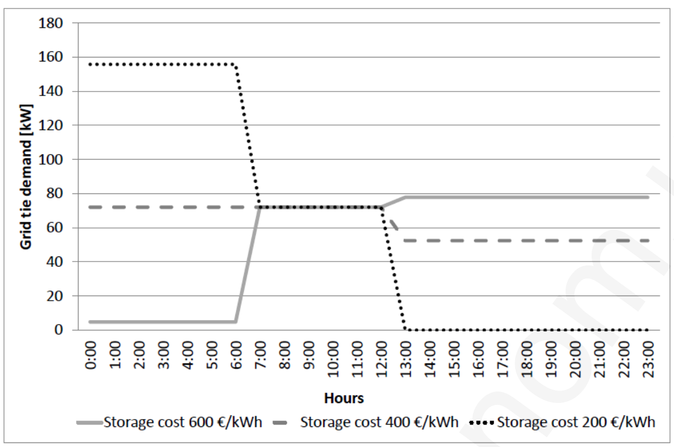

Figure 7. Daily demand profile per storage cost

However, if the results are analysed from a global point of view taking into account the overall distribution system instead of the individual consumer (the fast charging station), the results obtained are positive. As it can be seen in Figure 7, the fast charging station demand profile obtained after the introduction of the larger storage system (when storage price is 200€/kWh) is the optimal one: power consumption over peak periods is almost zero, while the demand overnight is increased. In that case medium voltage distribution networks will not be needed for being reinforced and only local investments in the grid tie will have to be done.

In this paper a new methodology based on optimization techniques has been introduced for fast charging microgrids sizing. The results obtained show how the overall costs can be highly decreased if storage systems prices are reduced. Distribution network costs can also be lowered, providing a demand profile much more efficient from the point of view of utility investments.

However, the results shown in this paper have to be considered only as a preliminary approach to these kind of fast charging facilities. Further research has to be done in this field, including a wider variety of installations and electric vehicle demand profiles. Also, the inclusion of on−site generation technologies will be also tested, increasing the sustainability of this kind of facilities (if renewable resources are considered), and enhancing energy self−sufficiency.

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