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Analysis of the impact of charging of Plug-in Hybrid and Electric Vehicles in Spain

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Abstract. This paper studies the effect of different penetration rates of plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EV) in the Spanish electrical system. A stochastic model for the average trip evaluation and for the arriving and departure times is used to determine the availability of the vehicles for charging. A novel advanced charging algorithm is proposed, which avoids any communication among all agents. Its performance is determined through different charging scenarios.

Key words

Electric vehicle integration, grid impact

1. Introduction

One of the main objectives of European Commission related to climate and energy is the well-known '20-20-20' targets to be achieved in 2020: Europe has to reduce greenhouse gas emissions of at least 20% below 1990 levels, 20% of EU energy consumption has to come from renewable resources and, finally, a 20% reduction in primary energy use compared with projected levels, has to be achieved by improving energy efficiency [1].

In order to reach these objectives, it is necessary to reduce the overall emissions, mainly in transport (reducing CO_2, NOx and other pollutants) [2], [3], and to increase the penetration of the intermittent renewable energy (wind and photovoltaics). A high deployment of battery electric (BEVs) and plug-in hybrid electric vehicles (PHEVs), with a low-cost source of energy storage, could help to achieve both targets.

In 2008, Spain developed an action plan under Spain's Energy and Efficiency Strategy. This plan consisted of a set of specific and different measures which specifically target seven disaggregated sectors: Industry, Transport, Construction, Public Services, Household and office automation equipment, Agriculture, and Energy transformation [4]. In the transport and mobility area, the Ministry of Industry and the Institute for Diversifying and Saving Energy (IDAE) implanted an electric mobility plan called Proyecto Movele 2009-2010 [5]. Under this project, the government has installed an electric car infrastructure in several cities (Madrid, Barcelona and Seville) and has subsidized private purchase of a small fleet of electric cars, trying to reach 2000 PHEV-EV before the end of 2010 and 250000 vehicles before the end of 2014. A new action plan (Movele 2010-2012) has been recently approved [6].

In 2011, Nissan and Citroen-Mitsubishi-Peugeot have launched BEVs and General Motors-Opel, Toyota and others, have announced the introduction of PHEVs-BEVs in the Spanish market in 2012.

Hybrid electric vehicles (HEVs) use a combination of a conventional internal combustion engine (ICE) with one (or more) electric motor. There are different grades of hybridation from micro-hybrids with start-stop capability, mild hybrids (with kinetic energy recovery), medium hybrids (mild hybrids plus energy assist) and full hybrids (medium hybrids plus electric launch capability). These last types of vehicles use a typical battery capacity around 1-2 kWh [7].

Plug in hybrid electric vehicles (PHEVs) use larger battery capacities to achieve limited electric-only driving range. These vehicles are charged by on-board electricity generation or either plugging into electric outlets. Typical battery capacity is around 10 kWh.

Battery Electric Vehicles (BEVs) are only driven by electric power and their typical battery capacity is around 15-20 kWh [8]. One type of PHEV, the Extended Range Electric Vehicle (EREV), operates as a BEV until its plug-in battery capacity is depleted; at which point its gasoline engine powers an electric generator to extend the vehicle's range [9].

The charging of PHEVs (including EREVs) and BEVs will have different impacts to the electric grid, depending on the number of vehicles and the start time for charging.

This paper analyses the electrical power requirements for charging a high penetration of PHEVs-BEVs in Spain through the study of different charging scenarios (and different penetration rates of the PHEV-EVs).

2. Defining main assumptions of the study

A. Specifications of PHEVs-BEVs

In this section, a reference PHEV-EV is defined based on real data. Chevrolet Volt, and its European equivalent, Opel Ampera, are an Extended Range PHEV. Both vehicles have a battery with a storage capacity of 16 kWh [10]. Citroen C-zero (and its equivalent models, Peugeot iOn and Mitsubishi i-MiEV) are BEVs and they have also the same battery storage capacity than the Volt [8], thus the battery size chosen for this study will be the same.

In order to increase the battery life time, a maximum of 81.25% depth of discharge (DoD) will be allowed, reducing the effective capacity to only 13 kWh. Charging efficiency will be 90%, similar to the values reported in previous papers [11], [12], so this value will be assumed in this work.

Finally, the driving efficiency is fixed to 4 km/kWh. This value is very conservative, because a Chevrolet Volt has a full electric driving efficiency of 5 km/kWh [8] and Citroen C-zero has a driving efficiency of 9.37 km/kWh [10]. Table I summarizes this information.

Table I. – PHEV-EV model specifications

Battery size	16	kWh
Depth of Discharge	81.25	%
Effective battery size	13	kWh
Charging efficiency	90	%
Driving efficiency	4	km/kWh

B. Power system assumptions

Spanish household has, at least, a single phase 230 V, 5750 W, 25 A connection [13-15]. Assuming a charging current of 16 A, the charging power will be limited to 3.68 kW.

A summer load profile has been selected from Spanish System Operator, *Red Eléctrica de España* [16]. This load profile is the highest in the summer of the 2011 and covers 24 hours. The power consumption is measured on a 1-hour time base and then it is interpolated on 1-min time base as shown in Fig. 1. In this study, no correction for the rise in the load demand will be made, thus it is assumed that load demand (apart from that due to EV charging) will be kept constant for the evaluation period.

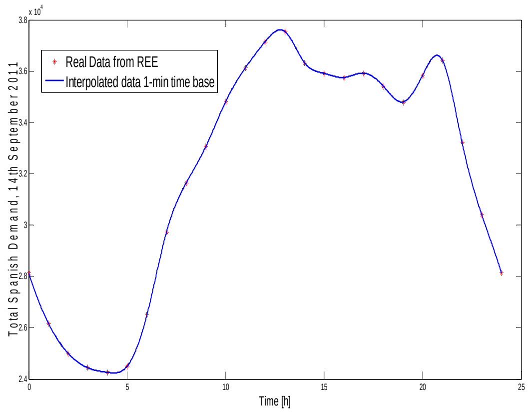

Fig. 1. Summer load profile for the mainland Spanish system

C. Mobility assumptions

The average trip number in Spain is 3 trips per day and the average trip length is 13.3 km [17], thus the average distance travelled per day is close to 40 km. A probability density function, based in a gamma function given in Ec.1, is used to select the distance trip for an individual traveller, as shown in Fig. 2.

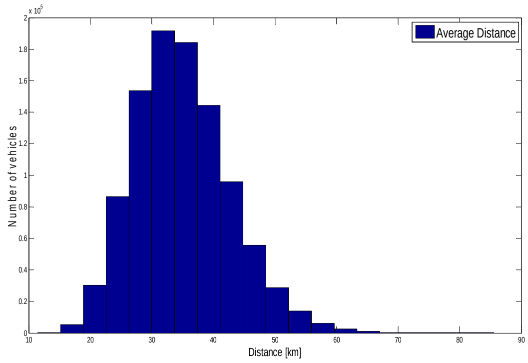

Fig. 2. Distribution for average travel distance per day

$$y = f(x|a,b) = \frac{1}{b^a \Gamma(a)} x^{a-1} e^{-\frac{x}{b}} \quad (1)$$

Given the average daily travel distance and the driving efficiency (defined in Table I), the required electrical energy is evaluated for each vehicle. From this information, the time needed for recharging can be determined.

Arriving and departure time to/from home is modelled by Rayleigh probability functions modelled by equation (2), similar to the distribution probability functions proposed in [11], [18].

$$y = f(x|b) = \frac{x}{b^2} e^{-\left(\frac{x^2}{2b^2}\right)} \quad (2)$$

Fig. 3 shows the distribution for arriving and departure times.

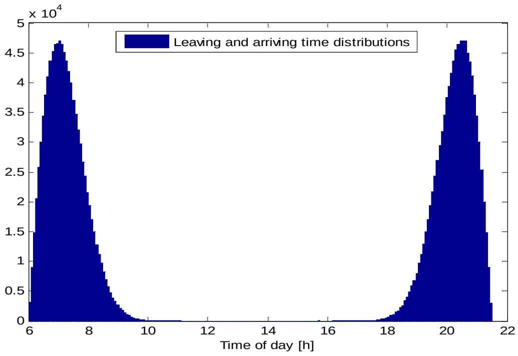

Fig.3 . Departure and arriving times distributions

C. EV penetration assumption

The deployment of electric vehicles will depend on a large variety of factors, so it is very difficult to make any market projection and impossible to define one single scenario about the penetration of electric vehicles [19], [20]. In this work, it is assumed that, according to Spanish electric mobility plan MOVELE [5], there will be around 250,000 electric vehicles in the fleet before the end of 2014. Based on this plan, a prospective growth study has been performed in [21] and a proposed Spanish market penetration rates have been obtained. The result of this study is summarized in Fig. 4. The Spanish total automotive fleet in 2011 is 22,325,847 [22].

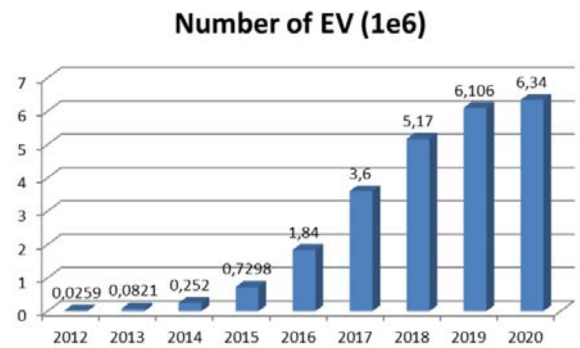

Fig.4 . EV market penetration prospective [17]

3. Proposed scenarios

This section describes an analysis of automotive EV charging at residential location only. The analysis considered six EV charging scenarios to help to understand the aggregate effects of EV charging. The proposed scenarios are arranged in order of negative impacts in the grid (from the worst impact to the best one) and three different penetration rates are simulated for each scenario: 2014 (252,000 EV), 2017 (3,600,000 EV) and 2019 (6,100,000 EV). It is assumed that all the batteries must be fully charged at the end of the charging period.

A. Empty double tariff uncontrolled scheme (ES1)

Starting with the worst scenario, all EV will be discharged (81.25% DoD) and, assuming that all users have a dual tariff, the vehicles will be charged only during the off-peak hours. Double tariff in Spain has different off-peak hours in summer or in winter. In this paper, the peak load time in summer is defined as from 13:00 to 23:00, and the off-peak load time is defined as from 23:00 to 23:59 and from 00:00 to 14:59. Thus, in this case, all vehicles will start to charge at the same time (at 23:00).

B. Empty single tariff uncontrolled scheme (ES2)

In the second scenario, all EV will be discharged and users have a single tariff scheme (most of people have this residential tariff in Spain). In this case, the vehicle will be charged when drivers arrive home in the evening following the arriving distribution pattern presented in Fig. 3.

C. Empty single tariff charging with end by departure uncontrolled scheme (ES3)

In the second scenario (ES2), vehicles start to charge their batteries during the evening peak demand in the load profile (see Fig. 1), thus it is expected that a higher peak demand will be obtained.

In this third scenario (ES3), all empty vehicles will be charged just before the morning departure, taking the advantage of charging during the low electric demand period. In this scenario, it is assumed that the fleet of vehicles is configured to complete charging by differing times ranging between 6:00 and 11:00 (depending on their individual departure times in the morning).

D. Empty single tariff charging with advanced scheme (ES4)

It is very important, from the system operator (SO) point of view, to manage the recharging times to contribute to flattening the demand curve. Some controlled schemes have been proposed in the literature [2], [22], [23]. Most of them required a new agent, called aggregator. The SO will communicate its restrictions and its needs to the aggregator and this agent will communicate to each EV individually, giving the control recharging signals. In this case, it is mandatory to develop a bidirectional communication infrastructure, based on smart meters, to allow the data communication among all involved parts.

In this paper, a simpler novel proposal is presented (and called herein ‘advanced scheme’). The charging time of an individual vehicle will be chosen randomly from a standard uniform distribution on the open interval between the arriving time for and its departure time minus the time needed to fully recharge its battery. Assuming that all vehicles under these previous scenarios are completely discharged, the charging time will be around 191 minutes (3 hours and 11 minutes).

E. Partially single tariff charging with advanced scheme 1 (ES5)

In this scenario, each electric vehicle travels a distance with a probability density distribution shown in Fig. 2, thus the initial state of charge (SoC) of each battery is different from zero at the beginning of the charging period.

The charging time is chosen randomly as in ES4. In this case, a penetration rate of 27% (6,106,000 electric vehicles) is assumed.

F. Partially single tariff charging with advanced scheme 2 (ES6)

This scenario is similar to the ES5, but the charging time of an individual vehicle is chosen randomly between the start of the off-peak tariff (23:00) and the departure time (minus the time needed to fully recharge the battery), not between the arriving time and the departure time minus the time needed to recharge the battery (ES4 and ES5).

In this case, two penetration rates are evaluated, 27% (6,106,000 electric vehicles) and 100% (22,325,847 electric vehicles) – which corresponds to the total number of the automotive fleet in Spain.

In Fig. 5 the set-time for charging for scenarios ES1-ES4 are presented.

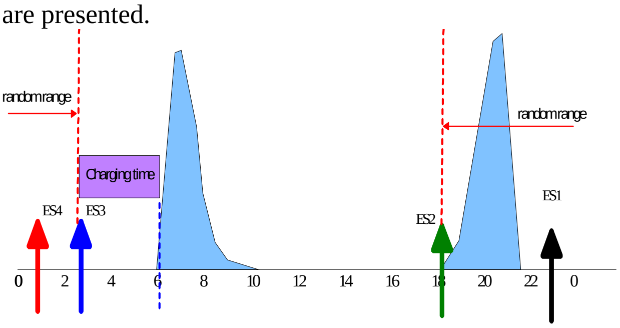

Fig.5. Starting charging time (ES1-ES4)

4. Results

A. 2014 year penetration

Fig. 6 shows the estimated power demanded by the electric vehicles in 2014 (with 250,000 EV) for the ES1-ES4 scenarios. In ES1 scenario (black line), the set-time for charging is 23:00 and all electric vehicles (with their batteries completely empty) start to charge at the same time. In ES2 scenario (green line) the charging time is distributed following the arriving pattern. Electric vehicles will be charged when drivers arrive home in the evening following the arriving distribution pattern presented in Fig. 3. In ES3 scenario (blue line) all electric vehicles have the same charging time (around 3.2 hours), because it is assumed that their batteries are depleted, and start to charge 3.2 hours before departure during the morning, following the leaving time pattern presented in Fig. 3. Finally, during ES4 scenario the starting time is randomly chosen between the arriving time and the departure time minus the required charging time.

The total load demand is shown in Fig. 7. In ES1 scenario (black line) all electric vehicles start to charge at 23:00, thus a significant high peak demand is observed in this particular moment. With this low penetration rate, no significant impact in the generation is observed.

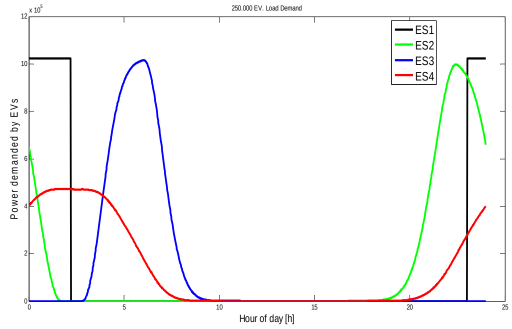

Fig.6. Power demanded by electric vehicles (ES1-ES4)

In ES2, vehicles start to charge in a peak of the demand curve. The effect over the total load demand is to slightly increase this peak (around 20:00 hour) without exceeding the highest peak of the day (around 13:00). ES3 and ES4 scenarios (blue and red lines) allow charging the vehicle during the lowest demand period. ES4 scenario has the lowest effect on the demand curve, because its set-time for charging is randomly chosen from a standard uniform distribution on the interval between the user arriving time and their departure time (minus the time needed to fully recharge its battery, purple block in Fig. 5).

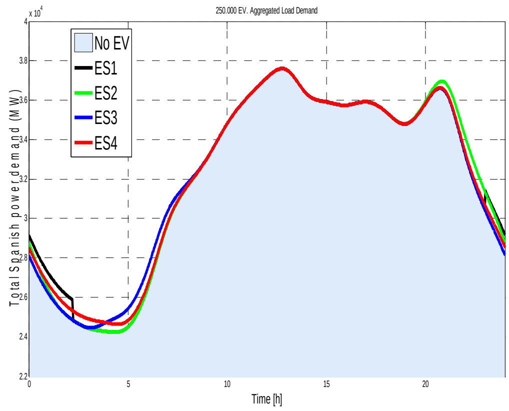

Fig.7. Total load demand NoEV-ES1-ES2-ES3-ES4 (2014)

Fig. 8 shows the aggregated load demand (MW) for the above scenarios. Only a slightly increase in the medium range (from 50% to 85%) is observed.

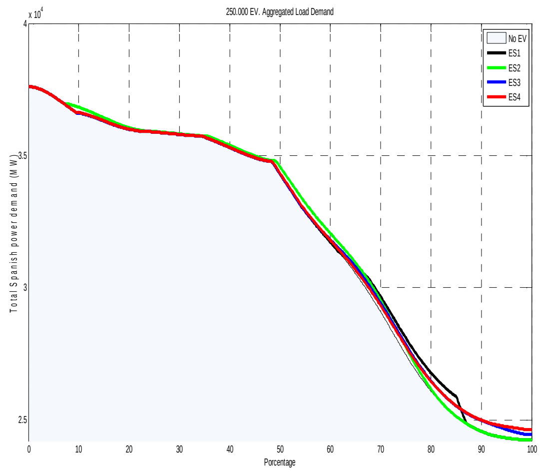

Fig.8. Aggregated Load demand NoEV-ES1-ES2-ES3-ES4 (2014)

B. 2017 year penetration

The estimated power demanded by the electric vehicles in 2017 (with 3,600,000 EV) for the ES1-ES4 is a scaled version of the estimated power demanded in 2014 (Fig. 6).

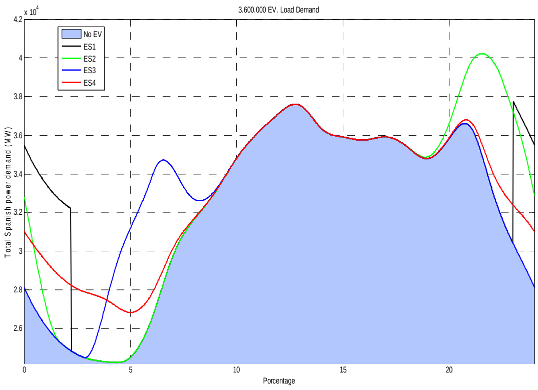

Fig.9. Total load demand NoEV-ES1-ES2-ES3-ES4 (2017)

In Fig. 9, the total load demand for each scenario is shown. In ES1 scenario the daily peak is shifted from 13:00 (highest peak with no EV) to 23:00 and it is increased from 37600 MW (no EV) to 37720 MW. In ES 2 scenario, there is also a shift in the peak time and the peak demand is increased in 2600 MW (from 37600 MW to 40200 MW). ES3 and ES4 are still acceptable without exceeding the maximum peak value of the no EV demand curve.

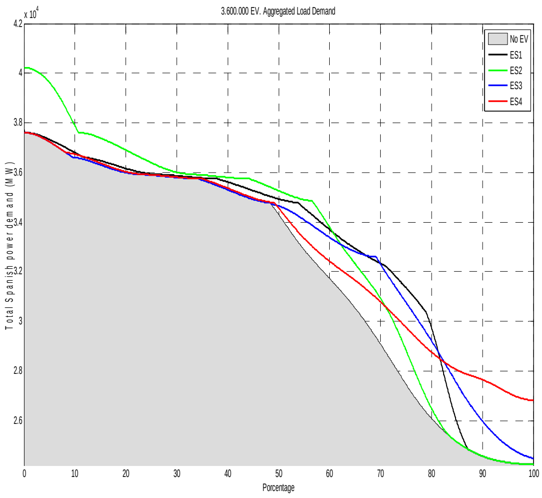

Fig.10. Aggregated Load demand NoEV-ES1-ES2-ES3-ES4 (2017)

Fig. 10 shows the aggregated load demand (MW) for the above scenarios (in 2017 penetration rate). ES2 scenario creates the worst peaks in demand, and new peak power plants (with the largest marginal costs) should be connected. For ES4 scenario, the peak power is not increased but the minimum power is increased in 2600 MW, allowing connecting load power plants (lowest marginal costs).

C. 2019 year penetration with partial load

Fig. 11 shows the estimated power demanded by the electric vehicles in 2019 (with 6,100,000 EV) for the ES5-ES6 scenarios. In both scenarios, the charging starting time is chosen randomly from a predefined margin. ES5 margin is between the arrival time and the departure time (minus the time required to recharge the battery). ES6 margin is between the start of the off-peak tariff (23:00) and the departure time (minus the time needed to fully recharge the battery). The peak value is lower in ES5 than in ES6 scenario, but it is observed from the figure that the starting time to charge in ES5 scenario is at 18:00, during the on-peak period of the load demand.

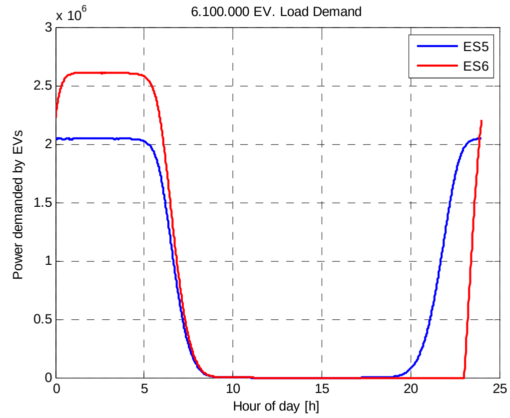

Fig.11. Power demanded by electric vehicles (ES5-ES6)

Figure 12 shows that, even with this great penetration rate (around 27%), the additional load due to PHEV-EV charging is absorbed by the system without increasing the peak demand and filling up the off-peak valley.

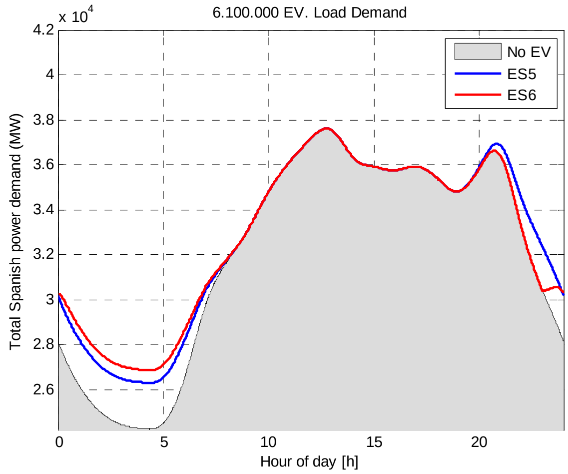

Fig.12. Total load demand NoEV-ES5-ES6 (2019)

D. Maximum penetration with partial load

Fig. 13 shows the expected total load demand if all cars in Spain [18] are changed from internal combustion engines to electric motors. It is observed that despite of charging all vehicles during the off-peak period; the peak load demand is increased substantially (from 00:00 to 5:30).

Anyway, the annual peak power demand in 2010 was 44,122 MW (January, 11th, 2010), thus even with a 100% integration of electric vehicles in the Spanish fleet, the actual electric generation capacity could cover the expected load demand.

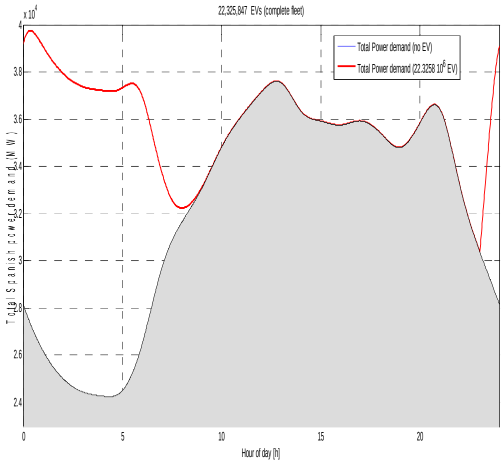

Fig.13. Total load demand NoEV- ES6 MAX

4. Conclusion

This paper presents an analysis of the impact of the charging of a fleet of PHEV-EVs in Spain for different penetration rates scenarios (expected in 2014, 2017 and 2019). If the charging is performed without any coordination, peak power will increase substantially with the increasing penetration rates.

A novel charging method is proposed in this work. Using this methodology allows reducing the peak power and fill up the off-peak valleys without implementing any bidirectional communication among all involved agents.

Acknowledgement

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