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Economic Impact of Distribution Grid Operation Scenarios for the Integration of Electric Vehicles

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Abstract

Electric Vehicles (EVs) will become an important part of the transport system in Europe and can thus create a number of benefits in term of oil dependence reduction, air quality improvement and trade balance enhancement. However, they can also become a burden for distribution system operator (DSOs) if they charge in an uncontrolled way. In addition, the increasing deployment of renewable energy sources (RES) and other distributed energy resources (DER) are making the distribution grid planning more complicated than in the past, when consumers were considered to be passive elements and grid was dimensioned to meet peak demand.

PlanGridEV project proposes new planning procedures, which take into account the possibility to manage consumers' electricity demand, including the charging process of EVs, both to better integrate DER and to more efficiently plan the investments in the distribution grid. The planning rules will be validated by carrying out four test beds, which will serve as an input for assessing the economic performance of four scenarios, representing four theoretical alternatives for distribution grid planning. Different services that EVs can provide to DSOs and other actors in the e-mobility ecosystem will be analysed in each scenario. Then, a grid planning tool will be developed to help DSOs consider EVs and demand and other demand response (DR) capabilities when planning distribution grid extension.

Keywords: smart grid, load management, optimization, cost, demonstration

1 Introduction

Electric Vehicles (EVs) are expected to play an important role in the future of European mobility, especially in the city environment, with the aim of decreasing the big dependence on fossil fuels (oil accounted for 94% of the energy consumed for transport across Europe in 2010 [1]) and, hence, reduce pollution and improve the European Union (EU) trade balance (oil imports totalled up to €1 billion a day in 2011, around 2.5% of Gross Domestic Product (GDP) [1]).

Fig. 1 shows the dependency on oil imports in the EU and other countries.

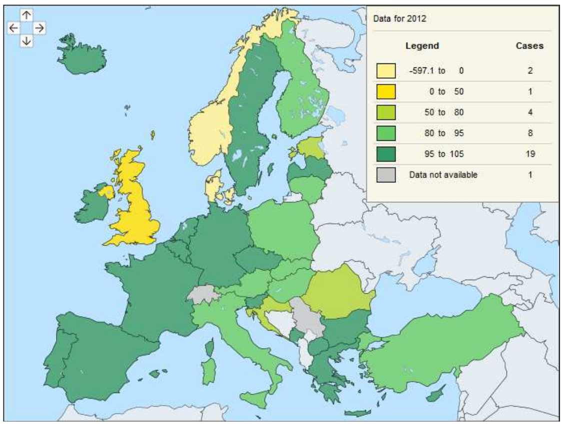

Figure1: Oil imports vs consumption (%). Source: Eurostat [2]

In order for EVs to become a reality, potential buyers of an EV must be confident that it is a good idea to do so. From the customers' perspective, the main barriers seem to be the high purchase cost of the EV and the range anxiety (including both the fear of not having enough electricity in the battery to reach destination and the uncertainty about available charging infrastructure) [3], [4], [5], see Fig. 2.

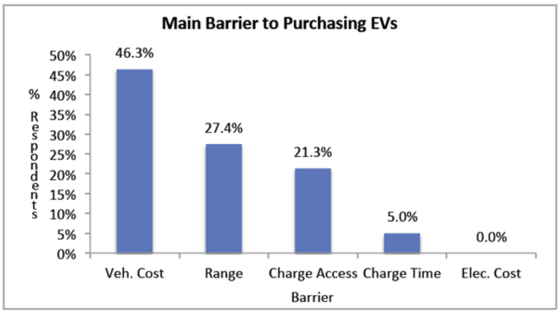

Figure2: Main barriers to purchasing EVs. Source: [5]

The European Commission (EC) has recently taken steps towards helping reduce range anxiety, by setting requirements on Member States to, on the one hand, ensure that the right information is available for potential EV buyers and, on the other, establish 2020 targets for publicly accessible recharging points and make it mandatory that a common plug is used across the EU [6].

Although these steps go in the right direction to facilitate the adoption of EVs, customers still need to make sure that they will be able to use any type of recharging infrastructure, both regarding the technical aspects of the Electric Vehicle Supply Equipment (EVSE) and the contract handling process of the Electric Vehicle Service Provider (EVSP). The first point requires the development of interoperable solutions and the second one the use of roaming agreements between different parties, which are topics being addressed by different research & development projects [7], [8].

In addition, a viable financial approach needs to be found for the deployment of the publicly accessible charging infrastructure, as demonstrated by [9], and the impact of EVs on the electricity distribution grid must also be taken care of [10].

2 E-mobility Ecosystem

The e-mobility ecosystem is the whole value chain from Original Equipment Manufacturers (OEMs, i.e. auto-makers), Information and Communications Technology (ICT) infrastructure providers and users, Transmission System Operators (TSOs), Distribution System Operators (DSOs), EVSE operators and EVSPs to EV users. This ecosystem is a good example of a network where coordination and interoperability are required for an efficient and economically sustainable operation.

Different participants may have different roles under different market models ([11]), so it is advisable to focus on roles, rather than in actors, as shown in Fig. 3.

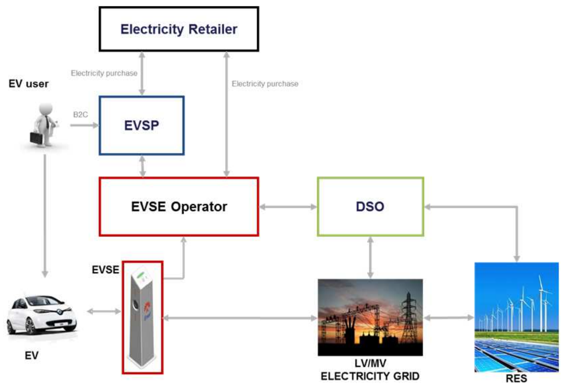

Figure3: E-mobility role model. Sources: [8], [10]

The main activities of the different roles presented in Fig. 3 are summarised below:

- DSO: Its main role is to build and operate the distribution grid, to ensure the electrical system capacity to meet future demand, while maintaining service quality levels consistent with regulatory requirements and also minimizing the environmental impact of the assets.

- EVSE Operator: It is responsible for building and operating the EVSE. In other words, it deploys EV charging infrastructure.
- EVSP (also known as e-mobility provider or e-mobility service provider): It is the party who has the contract with the user and provides e-mobility services (including the charging of the EV) to EV users.
- Electricity Retailer: It sells electricity for final use.
- EV user: He or she uses the EV and, hence, recharges the battery.

3 EVs and distribution grid

3.1 Impact of EVs

In principle, EVs could be considered as any other load in the electricity system, but being usually connected at low voltage (LV), their relatively big size (which can be almost as much as the whole household load) deserves special attention from the grid impact point of view.

For example, it is planned that Spain will have 2.5 million EVs in 2020 [12]. The EC defines slow charging as the one which takes up to 22 kW [13], but even if the charge is assumed to be made at 3.7 kW (230 V, 16 A, single-phase), the worst-case scenario, where all the EVs charge at the same time, results in an electricity demand increase of 9.25 GW. Such amount is about 23% of current Spanish power system peak (40 277 MW in 2013, excluding non-peninsular systems [14]).

It is therefore important that both the TSO and the DSO consider the possibility to control the charging process of EVs. Different studies ([15], [16], [17], [18], [19]) show that the impact of EVs in distribution grids strongly depends on the grid itself (topology, consumption profile of non-EV related electric loads…) and that EV integration can be made more efficiently with some kind of control over the charging process.

Moreover, the control over the EV charging process can also be seen as an opportunity for DSOs and the power system in general. Indeed, EVs have some characteristics (especially, the possibilities to store energy and to be placed at different points of the grid) which make them especially appealing as flexibility providers.

As a result, EVs can provide value-added services for the electricity system, including:

- Participation in demand response (DR) programmes.
- Provision of ancillary services to system operators (e.g. frequency control).
- Balancing of generation and/or consumption forecast errors, which can be used, for example to avoid curtailing production from renewable energy sources (RES) and other distributed energy resources (DER).
- Improvement of power quality and security of supply.

3.2 Traditional planning criteria

The choice of appropriate planning criteria is important to ensure a progressive improvement of safety standards and quality of electricity energy distribution under criteria of technical and economic efficiency, along with risk analysis and environmental concerns. Traditionally, the DSO has solved the planning problem in a stepwise process that includes some simplifications, such as considering consumers as passive elements and dimensioning always for the most severe operation scenario. The main goal is to meet the highest peak load demand, within the required reliability standards and for the smallest possible cost.

The first distribution planning methodologies followed a deterministic process, since the existing computational power and availability was limited. In time, parts of the process were automatized, but the main rationale remained unchanged. Recently, increasing levels of DER plus the expected rollout of EVs have been introducing uncertainties. The worst case scenario to be evaluated is no longer necessarily peak load, as DER could cause voltage and reactive power problems in off-peak conditions. At the same time, there is a greater concern in developing long-term (LT) plans with the prospect of achieving better overall solutions.

3.3 New planning alternatives

Advances in smart grids and Demand Side Management (DSM) have been made as a response to these challenges. The planning assumptions must be revised to effectively integrate and consider the potential benefits of these concepts. Major advances have been made in terms of new operation scenarios including DER and/or DR, but their integration into planning lags behind.

Additionally, the new distribution paradigm of smart grids with active participation of DER and load in network operation deeply relies on an adequate communication infrastructure. Thus, the challenges of communication must be understood and incorporated into the planning problem as alternatives to conventional reinforcements.

Future distribution planning tools should include better representations of the uncertainties posed by DER. DER units based on intermittent energy sources such as wind and solar require complex modelling for grid planning, where the energy availability also needs to be represented.

In order to contribute to the development of new and revised planning rules and operational principles of DSOs, the EC funded the PlanGridEV project [10].

The overall objective of the project is to develop new network planning tools and methods for European DSOs for an optimized large-scale roll-out of electric mobility in Europe, whilst at the same time maximizing the potential of DER integration. The project will also identify gaps in current network operation procedures and update tools and methods to address local load and congestion issues, leveraging on the possibilities of managing EV as controllable loads. For the validation activities the project will rely on existing infrastructures of the four involved DSOs.

3.4 Scenarios

The transformation from present distribution grid planning procedures to the envisaged future criteria will be an evolutionary process, where DSOs are expected to have an increasing control over the EV charging process over time.

Such different degrees of control are represented by the four scenarios defined in the project, as shown in Table 1 [10].

- **Conventional** (Co): EVs are accommodated by reinforcing the grid to widen existing hosting capacity, without any load management.
- **Safe** (Sf): some soft, fleet-focused load management (by means of ToU tariffs) is made in order to avoid or postpone the constraints that may appear in the LT, and thus reduce grid reinforcements.
- **Proactive** (PA): massive EV penetration and management is considered, hence strongly reducing the needs for grid reinforcements. There are DR programmes, where the DSO and EV customers (or demand aggregators, on their behalf) sign regulated, bilateral contracts for the provision of DR to avoid both ST and LT constraints in the grid.

Smart grid (SG): granular control of EV load management is made, so that the hosting capacity (of both EVs and DER) is optimised and grid reinforcements are avoided or reduced as much as possible. Different DR markets are created, where participants compete with each other to provide different services (ST and LT constraint management for the DSO, ancillary services for the TSO, energy trade optimisation for retailers, DER integration for DER producers…). In order to provide some of these services, EVs might even return part of the electricity they store to the grid when feasible.

The selection of one or another scenario will depend on the economic performance of each of them. Proactive and smart grid scenarios are likely to have higher operational costs, mostly because communication requirements will be higher but, on the other hand, they will lead to lower investment costs by reducing the need for reinforcements. Intermediate scenarios, sharing the characteristics of some of them, will also be possible in real life.

Table1: Characteristics of distribution grid operation scenarios

	Conventional	**Safe**	**Proactive**	**Smart Grid**
Charge management	None	Soft, fleet-focused	Massive	Massive, local
Energy flow	Grid →EV	Grid →EV	Grid →EV	Grid ↔EV
Remuneration	None	ToU	Bilateral contract	Market
Grid reinforcements	High	Some	Reduced	Minimal or none

3.5 Services to be provided by EVs

The different services that EVs are expected to be able to provide are listed below:

- **Frequency regulation**: In most EU power systems, the TSO requests frequency regulation services to guarantee frequency stability at system scale. Technical conditions to provide the service (minimum power rate, response time…) depend on whether primary, secondary or tertiary level frequency regulation is provided [20]. From the characteristics of EVs, it can be expected that they will be able to provide secondary or tertiary level frequency regulation, by aggregating enough EVs to sum up at least 200 MW within a geographically constrained group of primary High Voltage (HV)/Medium Voltage (MV) substation, and controlling their charging process to provide the service within a time frame of 10 seconds to 5 minutes and maintain it for up to 2 hours.
- **Voltage regulation**: In LV and MV electricity grids, voltage is regulated by either controlling reactive power devices (including capacitor batteries) within primary and secondary substations, or by modulating active and reactive power generation or consumption of DER (both independent and linked to a consumption point) and consumers' appliances and loads. EVs ability to provide the service will depend on both the design of the LV/MV grid, the depth of regulation and the typical power factor, which has high sensitivity on the charging technology and the EV model. In order for EVs to have a significant impact on providing the service, their penetration under a primary substation serving more than 10 000 customers should be 10%, and they should be working at low power rate, so that the sensitivity against the ratio between active and reactive power allows for using them to control the voltage.
- **Planned DR – Load management according to LT minimisation of electricity grid investment**: As demonstrated above, EV adoption results in an electricity demand increase which may require investing in upgrading existing distribution grid. With this service, the DSO aims at lowering the impact of EV penetration by postponing or avoiding the investments in power assets and wires. A typical example of this service would be that EV users send their preferences (initial and final state of charge, and time of departure) to the EVSE Operator (through the EVSP), who then considers them, together with power availability at LV level (DER) and target load curve in the area provided by the DSO, to obtain the charging process curves for each EVSE. The service can be planned few hours in advance, especially where charging behaviour does not vary much (home or fleet charging).
- **Planned DR – Load management for fleets**: Although the application principle is the same as in the case above, this service aims at reducing the electricity bill of the fleet manager, by either charging more electricity in cheaper periods, flattening the demand curve to reduce the capacity or power-related term (€/kW) of the electricity bill, increasing the use of local DER installed at the premises of the fleet manager or a combination of them.
- **Planned DR – Load management due to electricity market price**: Similar to the case of fleets, individual EV users can also manage the charging process of their EVs to charge in cheaper periods or reduce the capacity term. However, in this case, the most likely situation is that EV users have a ToU tariff and only manage their charging process by activating it in the lowest price period.
- **Planned DR – Enhanced RES integration**: The purpose of this service is to plan EV charging processes within MV/LV domain in accordance with the forecasted availability of DER (in particular, RES). Both the DSO and DER operators can be the requesters of this service. The DSO would request it to enhance DER hosting capacity without necessarily designing the grid for the worst case scenario, which is the business-as-usual approach, while DER operators aim at increasing their electricity output to maximise their income. This service would need to have about 10% penetration rate of controllable EVs below a HV/MV transformer [21].
- **Quasi-real-time DR – Enhanced RES integration**: This service is used by EV users who have RES generation units in their homes and adapt the charging of their EV to maximise the use of RES output. It is planned with a few minutes or seconds in advance.
- **Quasi-real-time DR – Load balancing**: This service is used to solve the same issues as the rest of planned DR services, but with an activation time of few minutes or seconds.

Table2: Mapping of services to scenarios

	Service requester	Co	Sf	PA	SG
Frequency regulation	TSO	No	No	No	Yes
Voltage regulation	DSO	No	No	No	Yes
Planned DR – Load management to minimise grid investments	DSO/TSO	No	No	Yes	Yes
Planned DR – Load management for fleets	Fleet operator	No	Yes	Yes	Yes
Planned DR – Load management due to electricity prices	EV user	No	Yes	Yes	Yes
Planned DR – Load mgt. for RES integration	DSO/DER producer	No	No	No	Yes
Quasi real time DR – Load management for RES integration	DSO/DER producer	No	No	No	Yes
Quasi real time DR – Load balancing	DSO/TSO/User/fleet op.	No	No	Yes	Yes
V2H	End user	No	No	No	Yes

- **V2H**: V2H is a complex service belonging to the quasi-real time demand response domain, with the additional feature of possibly including the reverse flow of energy from the EV. The purpose of this service is a composition of most of the above, depending on the amount of assets installed at household/building location: minimization of power back-up from the electricity grid, maximization of production coming from household/building DER installation, exploitation of ToU tariffs if available to perform off-peak charging of EV and on-peak discharging of EV, using the EV as hydro pump storage plant.

The mapping of these services to the scenarios described above is presented in Table 2.

Other services like phase balancing, harmonic distortion reduction, flicker reduction or voltage dip compensation could also be provided by EVs to DSOs (via the EVSP and, potentially, the EVSE Operator) in the smart grid scenario, but they will not be considered here.

3.6 Communication requirements

The DSO needs to build up a communication architecture which is able to fulfil the speed, reliability and cost requirements of the services considered in each scenario, with communication patterns of varying complexity.

The conventional scenario mainly relies on non-EV and EV related grid reinforcements and therefore comprises just a limited scale of operations controlled by ICT.

In contrast, the Smart Grid scenario tries to avoid all kind of grid reinforcements by centralised and decentralised power flow control through added-value ICT operations.

The communication within future energy grids is mainly covered by machine-to-machine (M2M) communication. This refers to technologies that enable wireless and wired technical units (systems) to communicate with other interoperable devices. There are three stages for possible applications within automation processes of smart grid systems:

- **Within building**: This covers metering and improved in-house energy management, including optimisation of DER production. The ICT infrastructure needs to cope with a huge amount of devices (tens), within a small area (meters), so wireless technologies such as ZigBee, Bluetooth or wireless M-Bus are well suited for it.
- **District**: This refers to e.g. residential areas of the distribution grid. Several technical units are linked to each other within different aggregation levels and communicate a huge amount of data. The amount of devices increases rapidly (thousands) for wider areas (district, kilometres). Wireless LAN or even cellular radio systems are commonly used, as well as wired technologies, such as broadband PLC, Ethernet and DSL.
- **Region**: This includes the communications within a region, where the amount of devices increases from about 1000 devices per km to of an order of several million devices per 1000 km. In this context, the most promising ICT technologies are cellular radio systems, such as UMTS or LTE.

Fig. 4 presents a summary of the coverage and data rate for different technologies [22].

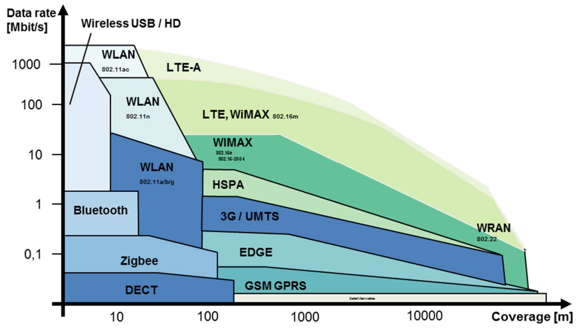

Figure4: Coverage and data rate of different ICT technologies

In order to support the continued growth of M2M technology in future energy grids, a global adoption and deployment of the Internet Protocol Version 6 (IPv6) is required to identify and address each technical unit individually.

3.7 Economic impact

The economic performance of the different scenarios will depend on the value created by the services provided by EVs, but also on the costs that DSOs will face, which mostly depend on communications, equipment costs and on remuneration for EV users.

As an example of the potential benefits that DSO may have, a very rough assessment of the economic performance of the conventional and the smart grid scenarios in Spain has been performed [23].

According to it, the investments required in the distribution grid until 2020 are 600 million euro lower in the smart grid compared to the conventional scenario (10% saving).

4 Next steps

The new planning rules proposed in PlanGridEV will be assessed and demonstrated by means of three different actions: Test beds, economic assessment and creation of a grid planning tool.

4.1 Test beds

Each of the DSOs involved in the project will test different services and grid operation procedures in a demonstration project.

The four test beds (TB) are described below:

- **TB1**: The DSO will try to demonstrate that, in some locations, it is possible to postpone grid investments by operating switches remotely. Both the business as usual (optimal configuration of the network) and a DSM (network configuration considering EV and DER control) approach will be tested in Portugal.
- **TB2**: The effect of introducing EVs in a typical single-phase rural network will be monitored and studied in Ireland.
- **TB3**: Smart charging of EVs will be evaluated in Italy, based on constraints by the end user and the DSO. Local DER generation, controllable loads and stationary storage will also be considered.
- **TB4**: Smart grid components will be used by the DSO in order to demonstrate network operation and planning optimisation in Germany. Controllable assets include transformers' tap changers, battery storage, LV switches, public and home EVSE and home appliances (by using a Home Energy Management System).

The test beds take the scenarios as a basis, but do not completely stick to them, as they are aimed at testing real-life conditions, rather than theoretical "ideal" conditions. Table 3 maps test beds to scenarios.

Table3: Scenarios of the TB

TB	Scenario
1	Conventional-Safe
2	Conventional
3	Smart Grid
4	Safe-Proactive

4.2 Economic assessment

Based on the data gathered during the test beds, the different scenarios will be assessed from an economic point of view. This work will also be built upon the results of the economic assessment of Green eMotion [9], where the publicly accessible charging infrastructure was analysed. Indeed, the charging service analysed in Green eMotion was defined there as a basic service [24], whereas the services analysed in PlanGridEV will be value-added services. In order to keep consistency between both analyses, the e^{3}value methodology will be used [25], which gives the advantage of evaluating the impact that the provision of the different services has on all the participants in the e-mobility ecosystem.

As a starting point, the services of Planned DR – Load management to minimise grid investments, Planned and Quasi real time DR – Load management for RES integration and V2H will be assessed, which, more or less, are the ones to be tested in TB3.

In later steps, the scope of the analysis will be extended to more services and countries.

4.3 Grid planning tool

The grid planning tool aims at aiding the DSO in the development of grid expansion plans. The scope of the tool will not simply be to help DSOs develop their networks, but also that they become able to evaluate and/or integrate other stakeholders' perspectives in this activity. Moreover, the tool will embrace the current and future challenges and paradigm of distribution grid architecture and operation. Hence, it will allow to:

- Develop a concrete set of projects to expand the grid (new lines, transformers or smart equipment, such as smart meters, sensoring, control gear and communications).
- Schedule the set of projects to be implemented in the planning period.
- Recreate grid operational environment for proper simulation of demand response, including EV, DER control and other advanced control actions.
- Include the essential ICT characteristics in the planning process as an alternative to investment in copper, while enabling advanced system controllability.
- Perform robust analyses of a system facing increasing uncertainties. In the past, analysing the yearly peak load conditions would satisfactorily address the distribution planning problem. Nowadays, there are many changing elements besides loads and so the definition of a worst case scenario for which the system must be prepared is more and more unsatisfactory.
- Describe a multi-objective problem that can be adapted to the planners' needs and sensitivities. The planner may also activate multiple technical and economic restrictions. It will be possible to address the perspectives of different actors: DSOs, consumers, EV aggregators, regulators, or others.

5 Conclusions

EVs can create a number of benefits in term of oil dependence reduction, air quality improvement and trade balance enhancement, but they can also become a burden for DSOs if they charge in an uncontrolled way. Grid planning rules need to be revisited to evolve from present distribution grids to the smart grids of the future.

PlanGridEV project proposes an adaptation of present rules to better accommodate both RES and other DER and EVs. The innovation of the project lies in the fact that it does not only assess the distribution planning problem from a technical point of view, but that it also takes into account economic considerations when dealing with the potential alternatives.

Moreover, the project will perform a number of test beds to check the technical performance of the proposed alternatives, and will develop a grid planning tool which can guide DSOs to better plan the extensions of their grids.

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