



## Central Station Design Options

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ELECTRIC VEHICLES IN A DISTRIBUTED AND  
INTEGRATED MARKET USING SUSTAINABLE  
ENERGY AND OPEN NETWORKS

## WP4.1 – CENTRAL STATION DESIGN OPTIONS

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## EXECUTIVE SUMMARY

The purpose of EDISON Work Package 4.1 is the evaluation of possible Central (charging) Stations design options for making possible the public charging of Electric Vehicles (EVs). A number of scenarios for EVs are assessed, with special emphasis on the options of Fast Charging and Battery Swapping.

The work identifies the architecture, sizing and siting of prospective Central Stations in Denmark, which can be located at shopping centers, large car parking lots or gas stations. Central Stations are planned to be integrated in the Danish distribution grid. The Danish island of Bornholm, where a high penetration of wind power is present, is considered as special case.

The distribution grid in Denmark is built using larger secondary distribution transformers (e.g. 630 kVA) which in general allows higher flexibility for the installation of Central Stations, compared to Bornholm's distribution grid. With the 3-phase AC quick charging options of 11, 22 kW and 43 kW, (IEC 62196, EN60038, EN 61851) both the Danish and Bornholm environments offer a good chance for EV integration [1]. Dealing with Fast Charging, the study determined that 300kW Fast Charging, which corresponds to 10 minutes charging for a 50 kWh battery-EV is not feasible in Bornholm at the 0.4 kV level, due to predominantly small size secondary distribution transformers, in the range of 100 - 200 kVA. This is possible at the 10kV level (MV level), if the Fast Charging station is equipped with its own dedicated transformer. With DC charging, rated at 50 kW, fast charging would be easier in both Denmark and Bornholm scenarios. For each scenario and charging power level, the possible number of EVs is estimated and finally architectural design options are proposed. Technical assessment is performed for evaluating the benefits of different charging concepts as Fast Charging and Battery Swapping as well as different loading options as DC loading versus AC loading, single phase (230V) versus three phase (400V) loading.

A study on possible siting for Central Stations is performed for the Danish main land, where the average distance covered by EVs is used as input data. A finding of the study is that a reasonable number of fast charging and swapping stations are about 15, assuming that all EVs have a range of 100-120 Km. Furthermore the Bornholm case is not very relevant for fast charging or battery swapping stations, due to the relatively small dimensions of the island.

Several architectures of Central Station are assessed based on different hardware components configuration: in particular we could have a Central Station with dedicated transformer sized ad-hoc for the DC charging equipment. On the other hand, it is possible to have a Central Station connected to an existing distribution transformer; in this case the transformer load management becomes crucial. Furthermore we could have the options of AC versus DC power distribution in a Central Station. In case of DC distribution, we could have multiple fast chargers, implemented as DC/DC converters, operating in parallel and serving different vehicles. Local active harmonics compensation is recommended as a valid option for mitigating the effect on the grid due to fast charging equipment, in compliance to IEC/TS 61000-3-12.

Among power quality issues in distribution grids with EVs, voltage drops and transformer overloading are identified in this work as most critical situations [1]. The mitigation of voltage drops within a Central Station requires the local analysis of the site and eventually the installation of energy storage systems for mitigating the drop during transients or parallel charging, in compliance to EN 50160. Transformer overloading can be prevented, providing real-time access to the local power flow data. The assumption of 50% transformer average loading is used as a single reference point in the current report. For future investigations on transformer overloading, more reference points might be necessary to represent various transformer loading levels.

The subject of safety in Central Station is also addressed. A number of safety rules based on European standards apply to AC charging equipment up to 44 kW. The connection interlock and the automatic de-energization are identified as fundamental requirements for safety in such a charging station. The connection interlock is a solution which ensures that no power is applied to the DC cable when the EV connector is not connected. The automatic de-energization device ensures that whenever a strain on the cable is detected, e.g. due to vandalism, the charge supply circuit is disconnected.

More electrical vehicles on the market are capable today of quick charging up to 50 kW power level. The feasibility of Central Stations with fast charging/swapping option, their capacity, design, costs and grid impact, as well as battery lifetime issues [1]-[2], are actual concerns for their development. At the same time fast charging and battery swapping stations can offer the opportunity of a new concept of electrical mobility, which is somehow similar to the common refueling practice. From a grid perspective, fast charging and battery swapping could be an opportunity for a clean utilization of renewable energies, if this technology is integrated with the excess of power generation from green sources.

## ABBREVIATIONS

The following abbreviations are used in this document:

BMS	Battery Management System
CS	Central Station
DER	Distributed Energy Resources
DSO	Distribution Services Operator
EV	Electric Vehicle
PCC	Point of common coupling
RES	Renewable energy sources
SOC	State of charge
TSO	Transportation Services Operator

## 1 INTRODUCTION

### 1.1 SCENARIOS FOR CENTRAL STATIONS

The definition of scenarios for the design of Central Stations dedicated to Electric Vehicles charging requires considering the following points:

- Number of electric vehicles potentially served
- Grid location aspects
- Fast Charging state-of-the art
- Fast Charging standards and proposals
- Vehicle and battery types
- Siting aspects
- Safety aspects

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#### 1.1.1 NUMBER OF ELECTRIC VEHICLES

The assessment on the number of electric vehicles can be conducted considering some fundamental questions.

**Which is the domain of deployment of an EV Central Station? Is it in urban area, airport area, railway station area, or shopping center parking area? Is it a regional public central station or an individual residential spot?**

Answering the question is fundamental to determine the:

<b>Number of connected EVs (#)</b>
<b>Monitored or forecasted EVs “charging” (#)</b>
<b>Monitored or forecasted EVs “in Vehicle-to-Grid mode” (#)</b>
<b>Monitored or forecasted EVs on IDLE mode (#)</b>

From a grid perspective, requirements dealing with the maximum power flow at the point of connection of a central charging station with the grid need to be addressed.

The assessment needs to take into account the following:

<b>Maximum power flow (W) @ PCC</b>
<b>Maximum current (A) @ PCC</b>

The assessment of the mentioned values permits to determine the maximum allowed number of EVs in “charging” state in a public charging station or in residential charging spots.

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### 1.1.2 GRID LOCATION ASPECTS

Considering a generic electric distribution system, Central Stations could be considered at the Main Substation level (MV level), e.g. tight to a large factory or large commercial building, at a middle size building and factory level, or even smaller, at the secondary distribution substation level (LV level). Depending on the installed capacity needed, Central Stations are planned in one of the aforementioned voltage levels.

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### 1.1.3 FAST CHARGING STATE-OF-THE-ART

Fast Charging of EVs is considered as a way of quickly charging the battery, using a time-window comparable with a fuel station. Battery swapping station could be seen as a fast-charging method from a customer point of view, but it could have different impact on the electrical grid. The battery swapping station has an intrinsic energy storage capability as it contains a number of batteries ready to be swapped. This gives an intrinsic value in terms of renewable energy integration. Fast Charging, on the other hand, is interesting because most electric vehicles (EVs) are equipped with an on-board charger that uses a rectifier to transform alternating current from the electrical grid to direct current, suitable for recharging EV's battery packs with slow charging power mainly. Cost and thermal constraints limit the power sizing of on-board chargers.

With Fast Charging a mechanism for monitoring the batteries status should be set up. Since batteries are composed of many cells connected in series/parallel, the cells behave in different ways during charging/discharging cycles and deteriorate at different times along the project lifetime. In fast-charging stations it is required an automatic mechanism for the identification of the damaged cells. The process of quality control could be available either into the car or at the Central Station level.

A safe charging operation is a major concern for fast-charging EV batteries. Though Battery Swapping stations would result more effective in terms of centralized battery quality control, with this option the EV user does not own the EV battery pack, due to the nature of the charging mechanism. With Fast Charging instead the battery pack is solely dedicated to the vehicle and the EV owner owns the battery as well.

Regarding charging time, the lowest time interval for Fast Charging stations is considered in the range of 10 minutes. Though with after a fast charging cycle, EVs could not reach the maximum SOC, but nearly the 80% of the battery capacity.

Concerning Swapping Stations, it is possible for a swapping process to exchange a battery in about 5 minutes.

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#### 1.1.4 FAST CHARGING STANDARDS AND PROPOSALS

The standardization activity in Europe for EV charging is split in two main technical committees: TC 69, concerning “Electric road vehicles and electric industrial trucks” and SC 23H, dealing with “Industrial plugs and socket outlets”. The activity of TC 69 has focused on the IEC 61851 std. which defines the electric vehicle requirements for conductive charging with AC or DC supply, using AC voltages (according to IEC 60038) up to 690 V and DC voltages up to 1000 V.

The IEC 61851 is composed of 5 parts:

Part 1: general requirements

Part 21: Electric vehicle requirements for conductive connection to an AC/DC supply

Part 22: AC electric vehicle charging station.

Part 23: D.C. electric vehicle charging station

**Part 24: Digital/Data communication of d.c. charging control between off-board d.c. charger and electric vehicle**

The SC 23H committee has formed the IEC62196 Std. which defines plugs, socket-outlets, vehicle couplers and vehicle inlets for conductive charging of electric vehicles. Part 1 of the standard defines the charging of electric vehicles up to 250 A, with AC, and 400 A, with DC.

The actual status for EV fast charging in Europe is mainly defined in IEC 61851 Mode 3 and Mode 4. With Mode 3 there is the option of charging with a power rate of 44 kW, using the on-board inverter as a charger. Mode 4 defines the requirements for DC charging with a stationary off-board charger and DC connection.

The VDE association (Verband der Elektrotechnik) has supplied the National Development Plan for Electric Mobility in Germany with the expectation that charging stations for electric vehicles will be deployed in three phases: the first one involves the 22 kW (400V 32A) Mode 2 (IEC 61851) stations which are introduced in 2010–2013, the second phase involves the 44 kW (400V 63A) Mode 3 stations prospected for 2014–2017 and the third phase, which entails next generation batteries will require at least 60 kW (400Vdc 150A) by 2020 allowing to charge a 20kWh battery pack to 80% in about 15 minutes. Similarly the SAE 1772 DC L2 plan is sketched for charging up to 200A / 90 kW.

Regarding AC plugs, The VDE standard plug for charging stations has a single size and layout for currents from 16A single-phase up to 63A three-phase (3.7 kW to 43.5 kW) but it does not cover the full range of Mode 3 levels of the IEC 62196 specification.

Standard plugs for DC charging are mainly referred to the working group on IEC 62196-3 – DC Charging. A proposal for DC fast charging standard is expected to be published around June 2012 to beginning of 2013. The IEC working group for TC 23/SC 23H/PT 62196-3 (max. 1000Vdc / 400A plugs) has been approved for new work. The IEC expects the functional release in December 2013. Standardization is planned to add DC wires to the existing AC connector types such that there is only one global envelope that fits all DC charging stations, and the new housing is named Combo.

Outside Europe, the Chademo association has proposed a DC Fast Charging solution. The Chademo specification describes a quick charging method for battery electric vehicles, designed to deliver up to 50 kW over a DC cable, using high-voltage (up to 500VDC) high-current (125 Amps). The Chademo DC connector is the current solution utilized in Japan by Nissan, Mitsubishi, Subaru and Tokyo Electric Power. The connector is different from a standard AC charging plug, so two separate sockets are required on the vehicle side.

1.1.5 VEHICLE AND BATTERY TYPES

The vehicle and battery type are two fundamental aspects for the design options of Central Stations. Among different types of plug-in hybrid electric vehicles and battery electric vehicles, a general distinction is based on their plug-in feature and their capability to fast charging. In general, any Li-ion battery could be fast charged, within the current limits stated by the manufacturer. Due to the fact that a battery EV has solely a battery as energy source, it has a greater need for fast charging compared to a PHEV.

This section lists the most common system architectures of plug-in hybrid EVs and battery EV and describes their hardware design. An overview on the different architectures is depicted in Fig. 3:

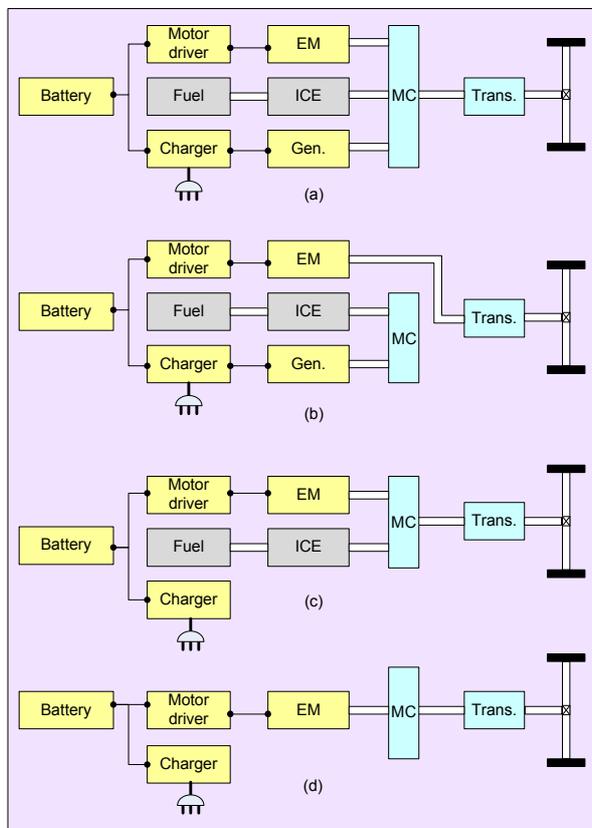


Fig. 3. Plug-in Electric vehicles system architectures. (a) Series-parallel hybrid EV. (b) Series hybrid EV. (c) Parallel hybrid EV. (d) Battery-powered EV

Where:

- EM: electric motor

- ICE: internal combustion engine
- Gen: generator
- MC: mechanical coupler
- Trans: transmission

In the PHEVs class, three variants have been implemented so far:

- Series-parallel hybrid
- Series hybrid
- Parallel hybrid

The main difference among the topologies is the drive system used and the interconnection of its components, before the power is transferred to the wheels.

For the evaluation of Central Stations design, the main vehicle's component is the battery due to its capability to store and provide electric energy and different power rates. Not all EVs are able to be fast charged. Most lithium-ion battery chemistries are able of charging using low or high power rate. Few vehicles models have the capability of 30 minutes charging, or 50 kW charging power, for a 25kWh battery pack. Battery EVs have higher potential of fast charging than PHEVs due to their bigger battery capacity.

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#### 1.1.6 SITING

The geographical location of Central Stations, or Central Station siting, could be addressed country by country or region by region depending on the road maps.

Different scenarios can be derived on Central Stations siting:

- Urban Central Station
- Motorway Central Station

#### **Central Station in urban area**

The evaluation of "How many Fast Charging / Swapping Stations" could be installed in urban area could be addressed considering:

- Town/city geographical extension
- Market penetration of Swapping/Fast Charging capable EVs

In the table below the advantages for having low or high penetration of Fast Charging / Swapping Stations are described. Both types of stations are put in relation to the extension of an urban area and to potential EV penetration levels.

<b>“Low penetration” of Fast Charging/Battery Swapping Stations in towns/cities</b>	
<p>For small urban areas, low penetration of stations means lower capital cost for building one station, one automation infrastructure, advanced meters equipment and a few staff. Low market penetration of EVs could justify a low penetration of stations, in the first years.</p>	<p>In large cities, reaching the station may result very significant for the state-of-charge of the battery. As soon the market penetration of EVs reaches higher levels in big cities, high penetration of stations will be a requirement.</p>

### **Finding a Battery Swapping Station**

The problem of finding a Fast Charging or swapping station in the urban context, when nearly out of energy, will be more acute than that of finding a gas station because of the lower range. Moreover, if the battery runs down, it is impossible to do the equivalent of walking to the nearest gas station and walking back with a can of gas. It is needed a roadside swap from an emergency vehicle. For these reasons it would be worthwhile to have the ability to automatically locate the nearest swap station (using your location as given by your GPS receiver) and give you directions for getting there.

### **IT systems**

In the context of several Fast Charging or swapping stations, a **GPS system** is very important, to be sure to schedule the way in the right way, without risking remaining stopped. The sat-navigator may be implemented with the position of the swap stations, in this way finding a battery-swapping station would result a very user-friendly operation. A **smart IT system** might monitor the state-of-charge of the battery, connecting this information with the distance by the closer swap station on the user route and warn you when you are reaching the non-return point. This would be an important feature for such a system, dealing about optimization of trips, using computer science algorithms.

### **Central Station along highway**

The battery swapping concept in the highway scenario can show the following key factors:

- Which distance there should be between two consecutive swapping stations?

Possible assessment:

- It depends on the range of EVs in the market, type of battery, driving patterns.

In the scenario of motorway/highway, the distance between two consecutive swapping stations could be estimated considering:

- Share of Battery-powered EVs, compared to PHEVs
- average minimum range of EVs
- In a time horizon of 5-10 years, what will be the battery's autonomy for EVs, in the highway scenario?

## 1.2 DANISH SCENARIO FOR CENTRAL FAST CHARGING STATIONS

A scenario was defined for Fast Charging/Swapping Central Stations. A station is planned about every 50 Km, covering the entire Danish territory, Fig. 4. Due to the actual low penetration of EVs, it would be important having a multi-functional Central Station, capable of both fast-charging and battery swapping in order to limit the total costs.



Fig. 4. Proposed siting for Fast Charging Stations

The prospected displacement of 50 km between stations is derived considering the following assumptions:

- average 150.000 new registered cars every year in Denmark
- 5% penetration of EVs in the market, half of them capable of DC charging

Inputs on driving pattern analysis from WP1 - Edison have been taken into account.

### 1.3 BORNHOLM SCENARIO FOR CENTRAL FAST CHARGING STATIONS

The assessment for Central Station scenarios on the Danish island of Bornholm, Fig. 5, has considered:

- Actual range of EVs
- Island dimensions

The study performed on driving pattern analysis [3] determined that the actual range of EVs and PHEVs does not require the installation of Fast Charging or Battery Swapping stations. The overnight charging or day charging should cover the daily need of EV batteries.

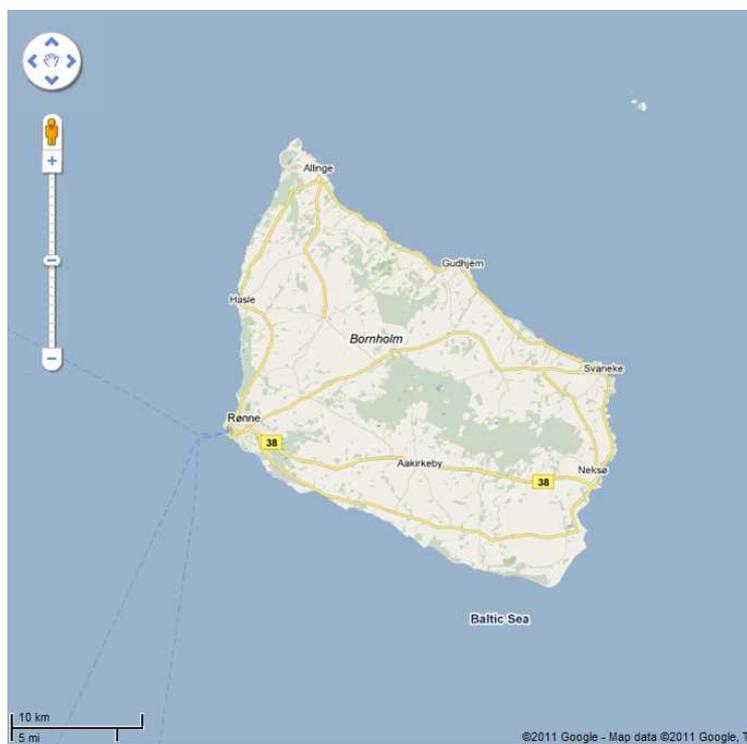


Fig. 5. Road map of Bornholm Island

## 2 TSO REQUIREMENTS FOR CENTRAL STATIONS

### 2.1 REQUIREMENTS FOR REGULATING POWER

The main requirements from the Transmission System Operator which may influence the design options for Fast-charging and Battery Swapping stations are listed below:

- Energinet.dk needs to be informed about reserve of regulating power 15 minutes in advance. In that case they are able to predict the backup energy reserve [4]. EVs can contribute charging or discharging can contribute with a small portion of energy.
- Manual regulating reserves are bought hour-by-hour or daily-by-daily.
- At the moment, the minimum bid for reserve regulating power is 10MW, as indicated by Energinet.dk

The minimum bid for reserve regulating power is being discussed and can be politically changed.

As a consequence of the mentioned requirements there would be a pooling of minimum 10MW under a consumption responsible party. This means that a prospective EV fleet operator could aggregate and coordinate EVs for providing up/down regulation with power steps of at least 10MW. The potential opportunity of regulating power offered by EVs in Denmark is extensively treated in [5].

## 3 DSO REQUIREMENTS FOR CENTRAL STATIONS

DSO refers to std. EN50160 for voltage quality in distribution grid, reported in Annex A. In addition to this DEFU has made two recommendations (only in Danish):

- R16. Voltage quality in low voltage grids (2001)
- R21. Voltage quality in medium voltage grids (1995)

In order to meet the targets, WP4 has to comply with the mentioned power quality standards and recommendations.

### 3.1 DONG ENERGY CASE - DENMARK

Discussion with Dong Energy (WP2) was conducted regarding distribution network planning with large penetration of Wind Power.

Inputs from WP2 (Dong Energy) are:

- power balancing need
- grid constraints

Primary analysis (according to WP2 – Dong Energy) is:

- Load-flow and contingency analysis
- Evaluation of loading limits and voltage limits
- Dynamic response issues are of secondary interest

Constraining elements for Central Station design

It has been derived that constraining elements are load limits on cables, overhead lines, transformers, breakers, etc. with reference to standards in Annex A.

Normal operations	
Max. cable loading	100%
Lowest acceptable MV level	10KV
During disturbances	
Max. cable loading	117%
Lowest acceptable MV level	9.6KV
Voltage variations	According to Std. 50160 – Annex A

Assessment and mitigation of disturbances can lead to:

- **voltage drops analysis**

Voltage drop analysis has as goal the evaluation of the impact by different penetration levels of EVs in distribution grids

- **soft start option vs. stationary storage option**

Soft starters in Fast Charging stations are an option for avoiding dynamic issues such as inrush current at the beginning of the charging process. Soft starters can be useful for mitigating the instantaneous voltage dip on the voltage or cable overloading.

The stationary storage option is another possibility for avoiding the dynamic issues mentioned above. Using a stored amount of energy (battery, flywheel etc.) at the start of a fast charging process, could solve the problem of voltage dips and cable overloading.

- **charge process management at fleet level (software options)**

Software management of parallel loading due to simultaneous fast chargers operation is an option for avoiding dynamic issues on the grid side of a Central Station. The coordination of fast chargers has as goal avoiding the simultaneous “start” charging operation of several chargers which would probably procure voltage dips and cable overloading at the PCC.

**3.2 ØSTKRAFT CASE – BORNHOLM**

With the distribution company of Bornholm, Østkraft, the following topics have been discussed:

<b>Equipment</b>	<ul style="list-style-type: none"> <li>- primary and secondary transformers, feeders (available)</li> <li>- Rønne (North) 10/0.4KV network (available)</li> </ul>
<b>Power flow</b>	<ul style="list-style-type: none"> <li>- Day-by-day</li> <li>- according to Østkraft, it is possible to install meters in some 10/0.4KV transformers</li> <li>- Østkraft has not data regarding power flow at LV level</li> </ul>
<b>Recommendations</b>	<ul style="list-style-type: none"> <li>- for voltage drops, while switching on a big load, which in our case could be a fast-charged vehicle (or more than one)</li> <li>- Østkraft communicated the voltage range: 207-243V</li> </ul>

	<ul style="list-style-type: none"> <li>- for power (or current) limits and quality</li> <li>- Østkraft communicated the limit for start current of load max. 63A</li> <li>- Østkraft informed on the PF that has to be in the interval 0.9-1 inductive in the range over a 15min. period</li> </ul>
	<ul style="list-style-type: none"> <li>- during overloading conditions (for cables and other components)</li> </ul>

#### 4 ASSESSMENT ON POSSIBLE NUMBER OF EVs IN BORNHOLM

The assessment on the possible number of electric vehicles in Bornholm is performed for the main municipality of Bornholm, named Rønne, using as source of data the Bornholm's distribution grid provided by Østkraft, see Annex B, and transformers loading data. Statistical data of cars disposal in Bornholm on statistikbanken.dk, as well as inputs from WP1, Annex C, are also used.

For a rough estimation of the possible number of EVs charging simultaneously, the assumption of 50% transformer loading is used as a single reference point in the current report. For future investigations on transformer overloading, more reference points might be necessary to represent various transformer loading levels. Furthermore, for more details on dynamic grid simulations with EVs considering variable transformer load profiles, please refer to WP2 and WP4.4 reports.

Table3: Family disposal of vehicles in Bornholm by statistikbanken.dk

Area	Family disposal	2009
<b>Province Bornholm</b>		
	Families, total	22161
	Families without cars, total	8194
	Families with cars, total	13967
	Families with 1 car, total	11562
	Families with 1 private car	11237

Families with 1 company car	53
Families with 1 van	272
Families with 2 cars, total	2188
Families with 2 private cars	1912
Families with 2 company cars	1
Families with 2 vans	1
Families with 1 private car and 1 company car	69
Families with 1 private car and 1 van	202
Families with 1 company car and 1 van	3
Families with 3 cars, total	188
Families with more than 3 cars	29

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Correlating data of:

- families with cars
- families with 1 car
- families with 2 cars
- families with 3 cars
- families with more than 3 cars

the total number of cars in Bornholm can be derived:

Number of cars in Bornholm	<b>16618</b>
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Ronne's scenario (main municipality)

Residents in Rønne	Families in Rønne (average)	Cars in Rønne
13879	7266	5410

The number of families in Rønne is derived by considering:

- total residents in Bornholm
- total families in Bornholm

Statistically, each family in Bornholm is composed by 1.91 persons. Considering the assumption performed in Section 1.2 and scaling down for the Bornholm case we have:

- about 1200 new registered cars every year in Bornholm (a scale factor of about 1/100 is applied for comparison between Denmark and Bornholm)
- 5% penetration of new registered electric vehicles with DC charging capability, which leads to about 60 vehicles per year.

Although the island dimensions are such that home charging could be enough to cover the daily demand of an EV battery most of the time, the assessment quantifies the potential number of EVs for any other urban areas with similar social distribution as Rønne in Bornholm. DC charging capability, considering the vehicle available right now in the market, could be available as another portion of the 5%, identified as potential EV penetration level.

## 5 NETWORK CAPACITY

The assessment on the number of electric vehicles is done considering the Edison WP4.2 test-case assumption made for fast-charging:

- actual battery capacity of most of EVs batteries, actually 20-60KWh, is increasing to 50-100KWh in the near future
- charging time up to 10 minutes
- Fast Charging of a 50KWh battery in 10 minutes leads to a 300KW charging station

At the same time a lower power rate for charging is considered, in order to make fast-charging possible using Bornholm secondary distribution transformers.

## 5.1 60/10KV DISTRIBUTION NETWORK

The question of how to connect the EVs into the grid needs to answer which physical medium to choose and which standards and protocols to follow. The two main communication technologies considered for this purpose are conductive and inductive charging.

The assessment on the number of electric vehicles is done considering the Edison WP4.2 test-case assumption made for fast-charging:

- actual battery capacity of most of EVs batteries, actually 20-60KWh, is increasing to 50-100KWh in the near future
- charging time up to 10 minutes
- Fast Charging of a 50KWh battery in 10 minutes leads to a 300KW charging station

At the same time a lower power rate for charging is considered, in order to make fast-charging possible using Bornholm secondary distribution transformers.

## 5.2 FAST CHARGING CASES

The first fast-charging case considers a FC station power of 300kW for and EVs with battery capacity of 50kWh.

1.

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Charging power per EV	
50kWh in 10 minutes	<b>300KW</b>

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Considering the 'Rønne' 60/10 KV distribution network, containing several EVs Fast-Charging stations, we can roughly estimate the number of EVs that could be fast-charged simultaneously. All fast-chargers are assumed to be integrated on the same MV feeder on the main distribution substation. Based on the available consumption data from the DSO in Bornholm, an annual average load of 50% is assumed for the transformers. Data cannot be disclosed or referenced.

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Total substation capacity	<b>10 MVA</b>
Theoretical max. # EVs charging	<b>16</b>

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2.

The second fast-charging case considers a FC station power of 120 kW. In this case, the EVs are assumed with battery capacity of 20 kWh.

Charging power per EV	
20kWh in 10 minutes	<b>120 kW</b>

Considering the 'Rønne' 60/10 KV distribution network, containing several EVs Fast-Charging stations, we can roughly estimate the number of EVs that could be fast-charged simultaneously. A more realistic case will be presented once power flow data are available.

Total substation capacity	<b>10 MVA</b>
Max nr EVs under charge	<b>41</b>

For comparison the standard charge scenario is as follows:

In consideration of the requirements expressed by the standards IEC 61851 and IEC 62196-1 on "Plugs, socket-outlets, vehicle couplers and vehicle inlets – Conductive charging of electric vehicles – Part 1: Charging of electric vehicles up to 250 A a.c. and 400 A d.c.", the following charging options are available in case of standard charging, and the number of EVs is calculated for:

- the 60/10KV Rønne's electrical capacity
- all cars in Rønne are electric
- all cars in Rønne are under charge
- different power options for charging are available
- the base load in the distribution network is assumed 50%

LOADING OPTIONS			# EVs (Rønne)
16A, 230V, 3p	1 Phase	3,70 KW	1351

32A, 230V, 3p	1 Phase	7,40 KW	675
16A, 400V, 5p	3 Phase	11,00 KW	454
32A, 400V, 5p	3 Phase	22,00 KW	227
500V, 125A	DC	50 kW	80
-	DC	120 kW	41
-	DC	300 kW	16

### 5.3 10/0.4KV BORNHOLM DISTRIBUTION NETWORK

As described in Section 2.3, fast charging in Bornholm is not a major requirement for electrical mobility, due to the small dimensions of the island. By the way, an assessment of fast charging is interesting not so much from a siting perspective, as for an electrical constraints point of view. In fact, Bornholm has many distribution transformers with smaller average size than the ones installed in Denmark. More details can be found in Annex B. As assessment on fast charging is therefore interesting in order to investigate how much the transformers size influences the possibility for fast charging.

Different cases are considered regarding the battery pack capacity and the charging power level used.

1.

Power rate assumption:

Charging power per EV	
50kWh in 10 minutes	<b>300 kW</b>

Considering the 'Rønne' 10/0.4 KV distribution transformer, entirely dedicated for EVs Fast-Charging, we would have:

Sec. substations average capacity	<b>273KVA</b>
Max. nr. EVs under charge	<b>0</b>

Fast-charging up to 300KW, on the low voltage network of Bornholm can be immediately discarded because of insufficient capacity.

2.

Power rate assumption:

---

Charging power per EV	
20kWh in 10 minutes	<b>120 kW</b>

---

Considering the 'Rønne' 10/0.4 KV distribution transformer, entirely dedicated for EVs Fast-Charging, we would have:

---

Sec. substations average capacity	<b>273 kVA</b>
Max. nr. EVs under charge	<b>2</b>

---

Fast-charging up to 120KW, on the low voltage network of Bornholm is feasible anywhere, though in 10 minutes only a 20kWh battery can be charged.

3.

Power rate assumption:

---

Charging power per EV	
DC power rating	<b>50 kW</b>

---

Considering the 'Rønne' 10/0.4 KV distribution transformer, entirely dedicated for EVs Fast-Charging, we would have:

Sec. substations average capacity	<b>273 kVA</b>
Max. nr. EVs under charge	<b>4</b>

Fast-charging up to 120KW, on the low voltage network of Bornholm is feasible anywhere, though in 10 minutes only a 20kWh battery can be charged.

#### b) Standard Charge scenario

In consideration of the requirements from the IEC 61581 and IEC 62196-1 the following charging options are available in case of standard charging, and the number of EVs is calculated for the 10/0.4KV Rønne's electrical capacity.

Nr. 10/0.4KV sec. substations in Bornholm	<b>981</b>
Average number of 10/0.4 KV sec. substations in each municipality	<b>65</b>
Number of 10/0.4 KV sec. substations in Rønne (average)	<b>65</b>
Capacity of each 10/0.4 KVA sec. substation in Rønne (average)	<b>273 KVA</b>

In consideration of the requirements expressed by IEC 62196-1 the following charging options are available in case of standard charging, and the number of EVs is calculated for:

- the 10/0.4KV Rønne's distribution network
- all cars in Rønne are electric
- all cars in Rønne are under charge
- different power options for charging are available

LOADING OPTIONS			# EVs (Rønne)
16A, 230V, 3p	1 Phase	3,70 KW	36
32A, 230V, 3p	1 Phase	7,40 KW	18
16A, 400V, 5p	3 Phase	11,00 KW	12
32A, 400V, 5p	3 Phase	22,00 KW	6
500V, 125A	DC	50 kW	2
-	DC	120 kW	0
-	DC	300 kW	0

## Conclusion

In conclusion a 300kW fast-charging station on Bornholm is not recommendable in the LV distribution grid, unless extraordinary provisions are taken, such as stationary storage or a dedicate 10/0.4kV transformers with a larger power rating.

Both DC charging at 50 kW power rate and the 120kW fast-charging cases would be more realistic with the present installation.

In summary, the options for fast-charging are:

- a) DC charging at 50 kW and prospective 120kW fast-charger into the LV network
- b) Installation of dedicated secondary transformers for Fast Charging directly connected to the 10kV feeder
- c) Installation of a stationary storage matching the intended capacity of the fast-charging station

## 6 CENTRAL STATION DESIGN OPTIONS

The following charging infrastructure options have been derived, with inputs by the DSO Dong Energy, see Fig. 6. Grid connection options as well as typical secondary substations capacity are both based on data provided by Dong Energy. The proposed architectures can refer to fast-charging/swapping stations in the Danish system.

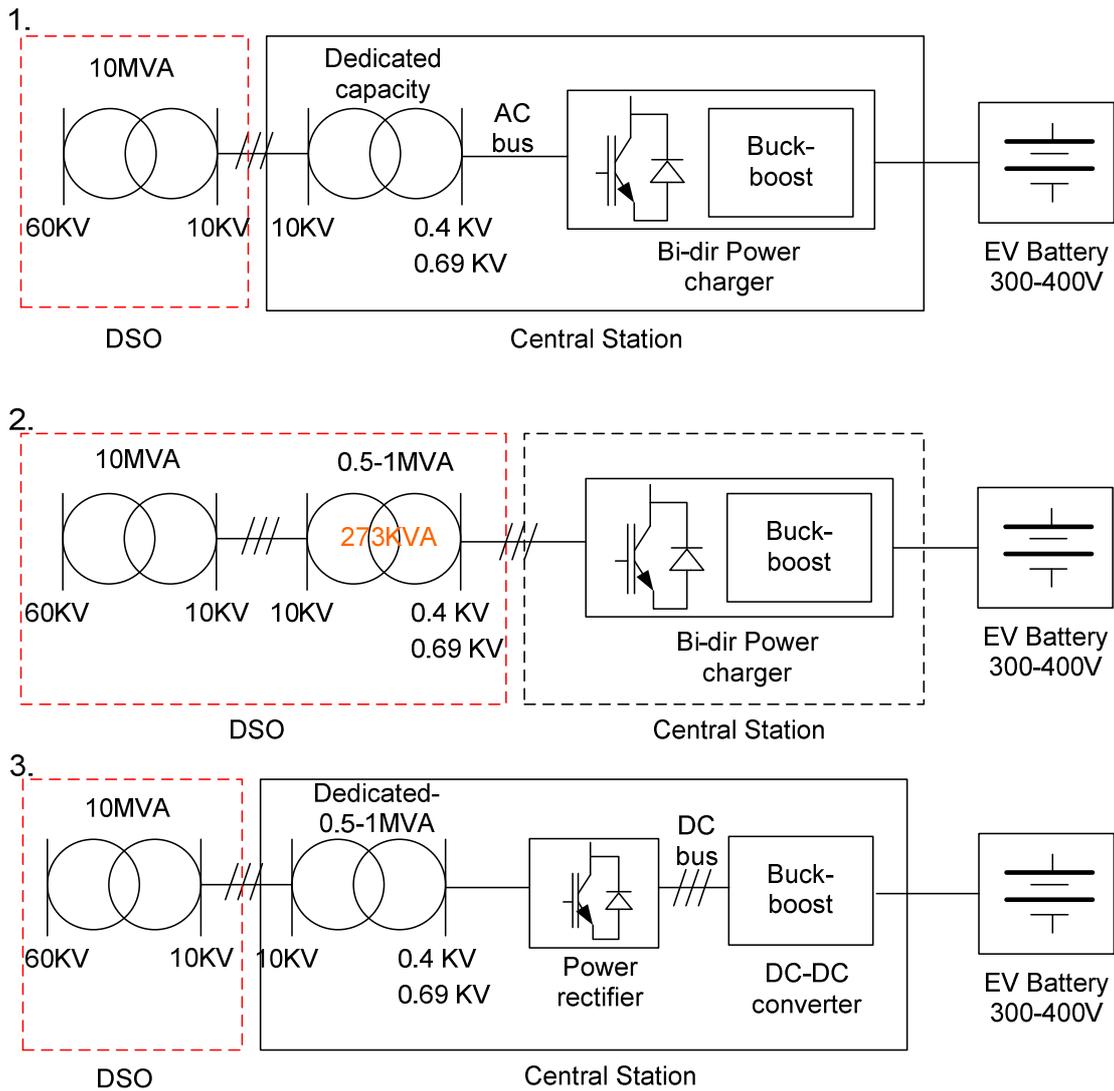


Fig. 6. Central Stations architecture options

## Options descriptions

**Case1** represents the **AC charging - dedicated** option in which the Central Station is equipped with its own dedicated transformer and is directly connected to the 10 kV feeder.

The charger is composed by an AC-DC power converter and a DC-DC converter.

**Case2** represents the **AC charging** option in which the Central Station is supplied by one or more secondary distribution transformers that belong to the DSO. Typical secondary transformers in Denmark are dimensioned for 10/0.4-0.69 kV, 0.5-1 MVA (Dong Energy), while 273KVA is the average capacity for Bornholm case.

The charger is composed by an AC-DC power converter and a DC-DC converter.

**Case3** represents the **DC charging** option. The Central Station is supplied by one or more secondary distribution transformers. In this case a single power converter for the whole Central Station capacity is used to obtain the DC voltage. The charger is composed by a DC-DC converter.

## 6.1 GRID CONNECTION OPTIONS

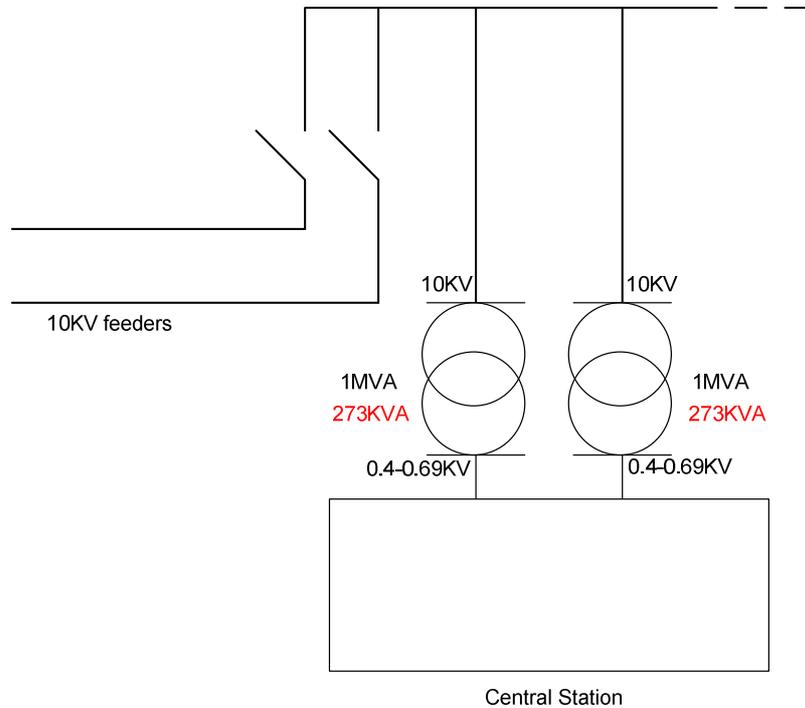


Fig. 7. Grid connection option of Central Station

- A first option of Central Station connection has been derived after discussion with *Dong Energy*. Depending on the power demand required and on the availability of secondary 10/0.4 kV distribution transformers, one or more of them can be used to supply the Central Station, Fig. 7. The option of using more than one secondary transformer is relevant in terms of reliability and flexibility of the Central Station.

- In terms of costs, the tariffs of grid connection options need to be considered. The fixed cost due to the DSO, when connecting the Central Station at 10kV point of common coupling, is lower than at 0.4 kV level. Even if the difference could be negligible for a few EVs, it can come out a considerable advantage in case of massive utilization of EVs.

## 6.2 TOPOLOGIES OPTIONS FOR PARALLEL LOADING

Topologies options for parallel loading are an open issue that needs to be investigated further. The goal is to investigate on the impact of one or more of these chargers on the grid and evaluate pros and cons. For a simulation case, realistic/typical parameters on each of the charger topologies are needed. Several options are listed, to mitigate the transient effect on load switching by parallel loading.

---

### Option 1

6-pulse converters interconnected with zigzag tr.

- + harmonics cancellation
- complex control
- transformer is the most expensive component
- 50% of overall losses are referred to the tr.
- space issues
- saturation issues

---

### Option 2

Diode-clamped

- + high performances
-

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- high numbers of diodes

- cost of diodes

- recommended max. 9 levels

- + high performances

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### **Option 3**

Flying capacitors

- complex control system

- high switching frequency

---

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### **Option 4**

Mixed topology – Clamping diodes and flying capacitors

- + no transformers needed

- + low number of commutations

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Different charger design can be considered when planning a Central Station depending on the cost and on the desired performances. The cost of the different hardware options may vary depending on the power level thus it is not treated in this report.

## 6.3 POWER CONVERTER OPTIONS

The standard charging sequence for an EV battery is Constant Current (CC) – Constant Voltage (CV).

In power electronics, two options of power converter topologies are available for charging an EV battery. The first topology is named Current Source Converter, CSC topology. The second topology is named Voltage Source Converter, VSC topology, and it is the most used for EV on-board chargers.

Although the system configuration is very similar for both topologies, a major difference between a VSC and a CSC is that the first works likewise a voltage source, while the second works as an equivalent current source. A VSC is characterized by a big capacitor bank at its input stage, while a CSC doesn't equip a capacitor bank, but a series of inductors on the output stage instead. A CSC is more immune to grid voltage variations, thus this may be an input for further research.

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### Option 1

Current source converter, CSC

---

### Option 2

Voltage source converter, VSC

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## 7 DISTURBANCES

Inputs from WP2 have been taken for the assessment on disturbances conditions procured by the charge/discharge infrastructure in a CS.

Disturbances inside a Central Station are expected to be:

- a. voltage drops along LV lines
- b. harmonics

In order to evaluate the real effect of disturbances procured by Central Stations, simulations are needed for different charging scenarios, therefore models for components and short-circuit impedance of cables and transformers are required for building up a realistic simulation model.

**Distribution grid requirements (Dong Energy and Østkraft)**

Secondary voltage level	10.4kV (Dong Energy)
Maximum cable loading	117% (Dong Energy)
Lowest acceptable medium voltage level	9.6kV (Dong Energy)
Voltage drop	Standards as listed next paragraph
Harmonics	Standards as listed next paragraph

The first four points deal with voltage quality requirements at medium voltage level, EN50160, IEEE 519. The last one deals with harmonics requirements, IEC 61000-X.

**7.1 COMPLIANCES**

The following standards have to be considered in matter of power quality. In Annex A, a detailed explanation is reported.

Power quality standards	<b>EN 50160</b> (* Annex A) <b>IEEE 519</b>
Harmonics standards	<b>IEC 61000-3-2</b> <b>IEC 61000-3-4</b>

Standards for compatibility between electrical systems and products	<p><b>IEC 61000-2-2</b></p> <p><b>IEC 61000-2-4</b></p>
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## 7.2 VOLTAGE DROPS

<i>Option 1</i>	Energy storage devices
<i>Option 2</i>	Handling with software the situation of simultaneous charging for EVs.
<i>Option 3</i>	Using soft-starters at Charge Power Terminal level, in case of fast-charging station is a possible option.

## 7.3 HARMONICS

### Cases for harmonics generation

#### 1) *Fast-charging*

#### Low-frequency harmonics

One of the potential problems with increased penetration of Central Stations for EVs is the occurrence of new resonances due to the increased amount of capacitance connected to the distribution grid. This capacitance may generate series or parallel resonances that cause amplification of harmonic distortion produced elsewhere. This issue is likely to be evident for VSCs

instead than CSC. This is because all VSCs have a large capacity at the input stage, on the grid side, which the CSC does not require.

**High-frequency harmonics**

Voltage-source converters are known as a source of high-frequency harmonics. The switching frequency and multiples of the switching frequency (1 kHz and up) can be found back in the spectrum of the current. Pulse-width modulation (PWM) leads to groups of frequency components around the integer multiples of the switching frequency.

**7.4 OPTIONS FOR HARMONIC FILTERING**

The methods for harmonics filtering are:

- c. traditional solutions
- d. active solutions

**7.4.1 TRADITIONAL SOLUTIONS**

<p><b>Option 1</b></p>	<p>Coupling transformers</p> <p>For three-phase loading of Central Stations, some harmonics orders can be removed by using coupling transformers, transformers or autotransformers, with a number of displaced secondaries, a solution particularly adopted for powerful rectifiers.</p>
<p><b>Option 2</b></p>	<p>Detuning reactors</p>
<p><b>Option 3</b></p>	<p>Passive harmonic filters</p>

## 7.4.2 ACTIVE HARMONICS CONDITIONING

### Inputs from meeting at Siemens AG

Options for harmonics conditioning have been discussed during the WP4 meeting at Siemens in Munich, on the 10<sup>th</sup> November 2009. In relation to the bi-directional power converters design, it is possible to implement harmonics conditioning system on each power converter.

### General assessment

Simulation studies are needed in order to understand the real impact of harmonics, due to the charge-discharge infrastructure.

With reference to industrial applications which make use of parallel power converters loading, fast-charging can be classified based on the load type as shown in Fig. 7. In the long term, with many EVs and several fast-chargers in the grid, the load type can be represented by several loads.

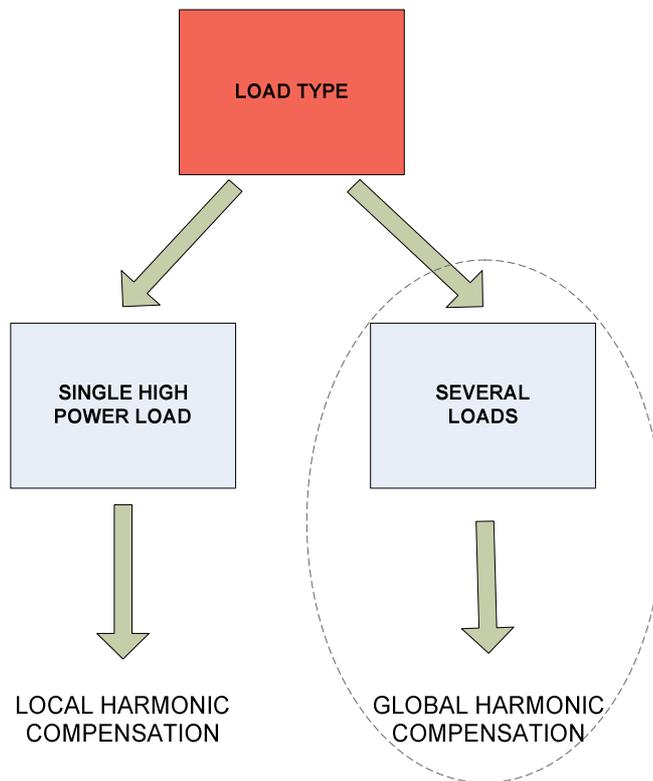


Fig. 7. Harmonic compensation strategies

In a Central Station, we deal with parallel charging when we charge or fast-charge EVs batteries simultaneously. Recommendations from industrial applications suggest the method of global harmonics compensation strategy, but since it is unlikely the case that all fast-chargers will be installed within the same area in the short term, the option of local harmonic compensation for each fast-charger was considered, Fig. 8.

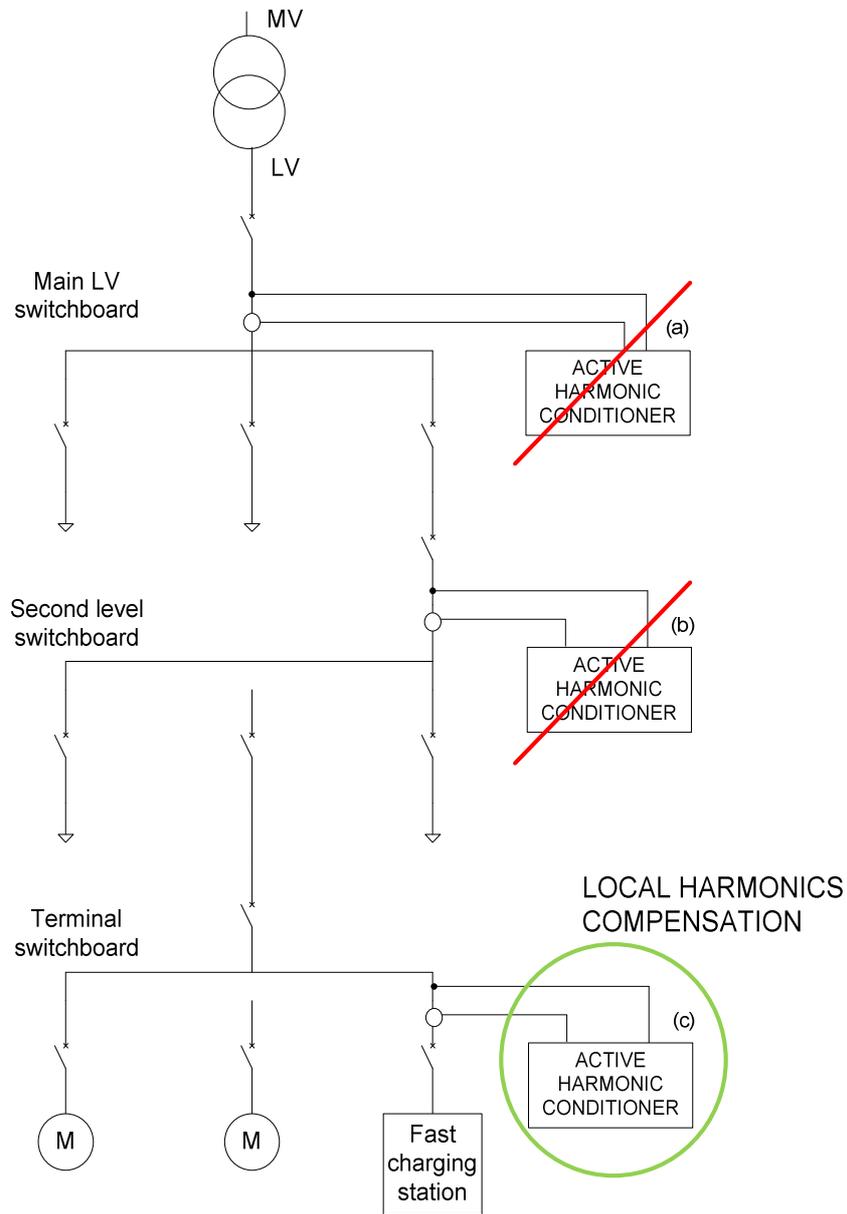


Fig. 8. Local harmonic compensation planning for fast charging station

## 8 STATIONARY STORAGE FOR CENTRAL STATIONS

The option of second life use of batteries for the purpose of stationary storage in Central Stations is an interesting subject for Central Stations.

A research performed by Frost & Sullivan [6] has shown that:

- the majority of EV available in 2015 will be lithium-ion based, which will constitute a challenge for lithium-supply. As shown in the diagram of Fig. 9, the price of lithium will rise. Lithium ion batteries could therefore be used for secondary purposes, at the end of life. EV batteries with reasonable predicted second life can be used in a variety of applications such as grid energy storage, renewable power management, grid balancing and peak price arbitrage.

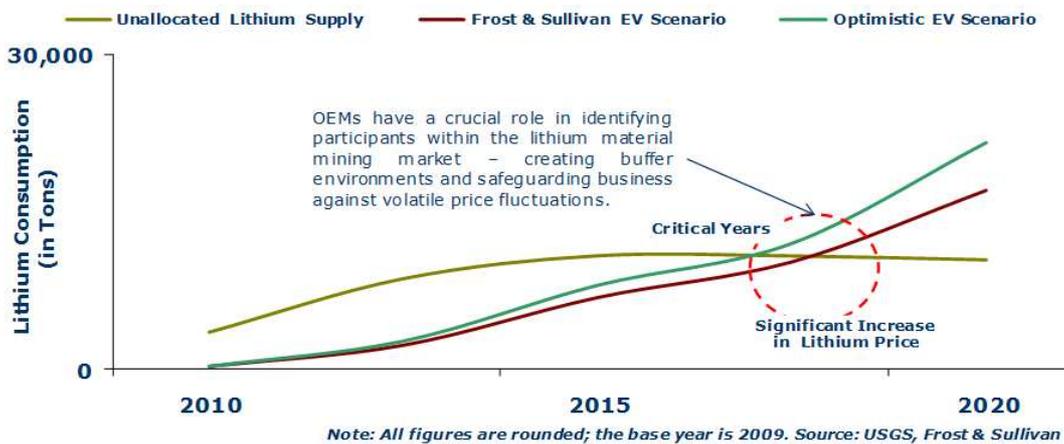


Fig. 9. EV batteries [6]

Normally, an EV battery is ready for its second life when it can no longer provide 80 per cent of the energy or 80 per cent of the peak power of a new battery. A central Station with battery swapping or fast charging concept can utilize second life batteries for the energy storage purposes described in the report. On the other hand, the reliability for using such batteries in a Central Station is still an open issue.

However, Li-ion batteries will have to compete with dedicated batteries used for current second life applications considered. They will have to compete with dedicated batteries designed specifically for those systems in terms of cost, power and energy storage, as most of the characteristics of Li-ion batteries' degradation when reused are still uncertain.

## 9 SAFETY IN CENTRAL STATIONS

Safety standards for Central Station design in Europe are commonly referred to the points summarized as follows:

– EN61851-1

The standard defines the general requirements for electric vehicle conductive charging systems.

Electromechanical locking of the plug is required by the standard that prevents it from being unplugged during charging. This is a fundamental protection against vandalism.

– EN61851-22

The standard defines the requirements for conductive charging for the case of AC electric vehicle charging station.

– EN62186-X

The standard defines the requirements for plugs, outlets, vehicle couplers and vehicle inlets in the case of conductive charging of electric vehicles.

– EN55022

The standard defines the information technology equipment regarding radio disturbance characteristics with limits and methods of measurement.

– EN61439

The standard defines the low-voltage switchgear and control gear assemblies. Part 1 defines the requirements for type-tested and partially type-tested assemblies

A residual current protection device is part of the charging station equipment in order to increase the personal protection.

– EN61000-3-2

The standard defines the electromagnetic compatibility (EMC). Part 3-2 defines the limits for harmonic current emissions with equipment input current of 16 A per phase. For current between 16 and 75A, the Standard EN61000-3-12 applies.

### **The old U.S. codes**

The mentioned IEC requirements for safety in Central Station had similar characteristics to the requirements defined in the '90s by NEC and California Electrical Codes. In order to have a comprehensive picture of all safety requirements available, these requirements are described as follow:

- **Connection Interlock**

The Connection Interlock is a device that creates a dead interface between the EVSE and the vehicle. When the EV connector is not connected to the vehicle, the Connection Interlock prevents power from being applied to the cable or EV Connector.

- **Charge Circuit Interrupt Device**

The charge circuit interrupt device is the solution for the requirement of ground-fault protection. The ground-fault protection is required for all charging levels.

- **Automatic Deenergization Device**

The Automatic De-energization Device is a system that de-energizes the EVSE if a strain occurs to the cable or EV connector and that could result in live parts being exposed. This is a solution to a vandalism event.

- **Ventilation Interlock**

The Ventilation Interlock has been designed as solution against gasification during the charging process. This is referred to old type of batteries, mainly lead-acid technology. For this reason, the Ventilation Interlock is likely to be unnecessary with lithium-ion batteries for EVs.

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## ANNEX A

No	Parameter	Supply voltage characteristics according to EN 50160	Low voltage characteristics according to EMC standard EN 61000	
			EN 61000-2-2	Other parts
1	Power frequency	LV, MV: mean value of fundamental measured over 10 s $\pm 1\%$ (49.5 - 50.5 Hz) for 99.5% of week $-6\%/+4\%$ (47- 52 Hz) for 100% of week	2%	
2	Voltage magnitude variations	LV, MV: $\pm 10\%$ for 95% of week, mean 10 minutes rms values (Figure 1)		$\pm 10\%$ applied for 15 minutes
3	Rapid voltage changes	LV: 5% normal 10% infrequently $P_{It} \leq 1$ for 95% of week  MV: 4% normal 6% infrequently $P_{It} \leq 1$ for 95% of week	3% normal 8% infrequently $P_{st} < 1.0$ $P_g < 0.8$	3% normal 4% maximum $P_{st} < 1.0$ $P_{It} < 0.65$ (EN 61000-3-3) 3% (IEC 61000-2-12)
4	Supply voltage dips	Majority: duration <1s, depth <60%. Locally limited dips caused by load switching on: LV: 10 - 50%, MV: 10 - 15% (Figure 1)	urban: 1 - 4 months	up to 30% for 10 ms up to 60% for 100 ms (EN 61000-6-1, 6-2) up to 60% for 1000 ms (EN 61000-6-2)
5	Short interruptions of supply voltage	LV, MV: (up to 3 minutes) few tens - few hundreds/year Duration 70% of them < 1 s		95% reduction for 5 s (EN 61000-6-1, 6-2)
6	Long interruption of supply voltage	LV, MV: (longer than 3 minutes) <10 - 50/year		
7	Temporary, power frequency overvoltages	LV: <1.5 kV rms  MV: $1.7 U_c$ (solid or impedance earth) $2.0 U_c$ (unearthed or resonant earth)		
8	Transient overvoltages	LV: generally < 6kV, occasionally higher; rise time: ms - $\mu$ s.  MV: not defined		$\pm 2$ kV, line-to-earth $\pm 1$ kV, line-to-line $1.2/50(8/20)$ Tr/Th $\mu$ s (EN 61000-6-1, 6-2)
9	Supply voltage unbalance	LV, MV: up to 2% for 95% of week, mean 10 minutes rms values, up to 3% in some locations	2%	2% (IEC 61000-2-12)
10	Harmonic voltage	LV, MV: see Table 2	6%-5 <sup>th</sup> , 5%-7 <sup>th</sup> , 3.5%-11 <sup>th</sup> , 3%-13 <sup>th</sup> , THD <8%	5% 3 <sup>rd</sup> , 6% 5 <sup>th</sup> , 5% 7 <sup>th</sup> , 1.5% 9 <sup>th</sup> , 3.5% 11 <sup>th</sup> , 3% 13 <sup>th</sup> , 0.3% 15 <sup>th</sup> , 2% 17 <sup>th</sup> (EN 61000-3-2)
11	Interharmonic voltage	LV, MV: under consideration	0.2%	

Table 1 - Comparison of supply voltage requirements according to EN 50160 and the EMC standards EN 61000

## Annex B

### 60/10kV distribution network

Commissioned	Name	Transformers		Feeders
		Nr	kVA	10-kV lines
1959	Olsker	2	8000	6
1959	Bodilsker	1	10000	6
1967	Aakirkeby	2	14000	8
1974	Østerlars	1	6300	4
1977	Snorrebakken	1	10000	6
1980	Hasle	2	20000	7
1981	Nexø	2	20000	6
1983	Rønne Syd	1	10000	4

1984	Allinge	2	20000	4
1988	Svaneke	1	10000	6
1988	Viadukten	1	10000	7
1989	Rønne Nord	1	10000	6
1990	Poulsker	1	10000	5
1994	Vesthavnen	1	10000	3
1998	Gudhjem	1	4000	4
<b>Tot</b>	<b>15 substations</b>	<b>20</b>	<b>172300</b>	<b>82</b>
10 kV high voltage power plants				9
Total 10kV-feeders				91

### 10/0.4kV distribution network

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	Substations	Transformers			Average consumers pr. station
		Tot.	Tot. kVA	Average kVA	
31.12.2005	960	988	249004	252	29
31.12.2006	972	998	265464	273	29
31.12.2007	978	1004	268294	274	29
31.12.2008	981	1006	268294	273	29