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Perspective in the European Union

Aymen Chaouachi,
Catalin Felix Covrig, Gianluca Fulli

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Abstract

Historically road transport has been exclusively dominated by petrol and diesel engines. Both alternatives are proved to be unsustainable due to their environmental impacts and the limited nature of their primary resources. Today's transportation sector in the European Union (EU) accounts for 23% of CO2 emissions, 72% of which is being emitted by road transport [1, 2]. The European Union's CO2 emission regulation for new cars [3], has come as a response to set emission performance limits for new passenger cars with the goal of establishing a road map change for automotive sector. Furthermore, the EU has set challenging targets to reduce greenhouse gas emissions by 40% in 2030 (relative to emissions in 1990) and for energy consumed to be generated at least with 27% from renewable sources in 2030. As regards energy efficiency, the 2030 framework also indicated that the cost-effective delivery of the greenhouse gas emissions reduction target for 2030 would require increased energy savings of the order of 27% [4].

The renewable energy directive [5] particularly identified: technological innovation, energy efficiency and contribution of renewable energy sources in transport sector as one of the most effective tools in reaching the expected targets in terms of sustainability and security of the supply. In such context it is obvious that reaching these challenges will be certainly depending on the rollout of Electric Vehicles (EV) as a mean of sustainable transport, higher penetration of distributed renewable energy sources. One consequential challenge will consist in accommodating such paradigm in the most cost-efficient fashion through active involvement of customer and better flexibility of the demand.

This report highlights the current trends and expected evolution in the EU in term of electromobility, Photovoltaic (PV) systems and smart grids, with the aim of identifying mutual synergies aiming at enabling: energy efficiency, sustainable transport and higher share of renewable energy sources in the final energy mix. A technical conceptual architecture for integration of EV facilities and distributed generation sources in the context of smart grid is proposed to identify the predictable penetration limits of PV systems and EV users.

1. Introduction

The EU member states are jointly working on addressing the future energy challenges, both in terms of security of supply as well as sustainability, in that perspective achieving a sustainable transportation system will be critical component. Electrification of the transportation sector seems to be one of the most promising alternatives in terms of increasing the security of supply as well as promoting a sustainable mobility through limitation of pollutant resulting from conventional transportation. However, great care should be taken to the primary electricity energy source, in fact the GHG emissions originally generated by petrol/diesel engines could be offset by emissions generated from polluting power plants used to provide EV's electricity source. Furthermore, centralized power sources supply would result in higher electricity transport losses and inefficiency of the whole cycle. In that optic, EVs deployment can be considered as a sustainable emission alleviating solution only when powered by electricity systems with considerable share of Renewable Energy Sources (RES) that are reasonably close the demand sinks.

Conversely, the deployment of EV should not come at the expense of the consumer ability to satisfy his mobility needs, this would mainly depend on the autonomy level of the car translated as the charging availability whenever and wherever needed. From electricity supply point of view, a physical limitation is expected while trying to accommodate an increasing level of RES sources under considerable load demand from EV users both at off peak and peak time. On the other hand, an efficient penetration of intermittent RES depends on the ability of injecting the maximum available power within the boundary stability of the electricity networks. It is clear that the flexibility of EVs load can be of great advantage when addressing the issues mentioned before: in fact, from operational point of view the synergy between EVs and distributed RES could be a major advantage for implementing Demand Side Management (DSM) within the smart grid. Various studies had already acknowledged and investigated the EVs potential in DSM enhancement as flexible/controllable loads for taking part in load shifting and in reshaping the demand duration profile. In fact, the rolled recharging could involve off-peak valley filling, consequently resulting in a significant improvement of the load volatility.

In the first part of this report, we start by introducing the outlook of EV in terms of sales figures and potential trends in the forthcoming years within the EU. The goal is to assess whether a tangible impact would be expected on the electric networks in the short-term that could justify further investment on the network assets to mitigate such impact, or to lever incentives for more cost-efficient integration. Similarly we take a look at the PV grid-connected systems integration status in the EU and expected trends with respect to reaching the EU targets for renewable sources. In the light of the current slowdown in terms of penetration, it is clear that both electromobility and distributed energy resources integration have a great potential in terms of synergies that could help accommodate both entities taking consideration of the fast evolving trends in distribution system. In the last subsection, we identify the actual and future trends of key solutions in terms of Energy Management System (EMS) in the context of smart grids and how such investments could help fostering load control and mechanisms for energy balancing aiming to accommodate higher penetration of PV distributed resources and electromobility.

The second section is dedicated to present a conceptual smart grid architecture aiming to enable decentralized operational synergy between intermittent RES and EVs based on a coordinated EVs charging. The conceptual framework is in line with the common available and foreseen standards in terms of interoperability prospective and functionalities. Finally the last section is dedicated to introduce an assessment framework to identify the combined thresholds of increasing EV and PV penetration levels - taking into account the prosumers' mobility and electricity production patterns - in the context of the earlier proposed conceptual architecture. Such assessment framework is needed to identify the electricity network limits in terms of PV and EV penetration for both business as usual situation or for an advanced control strategy enabled through the proposed conceptual smart grid architecture framework.

2. Electric Vehicles and PV generation outlook in Europe

2.1 Electric Vehicles penetration outlook

Electric cars have been considered as an alternative of transportation since the beginning of the 18th century, conversely EV had already achieved the top-selling road vehicle in the United States, (28% of the market shares) in 1900 [6]. Nonetheless, ultimately the electrification of transport system, has been mainly deployed in railway based transport and limited public based road transports (trolleybus, tramcars). The electric supply was relying on track-based direct connection to dedicated electrical networks (either DC or AC based supply) resulting in geographical limitation of such transportation means. Recent development on electricity storage, triggered by the usage of telecommunication mobile devices and mobile computers, have resulted in major innovation in term of batteries portability (size, weight) and autonomy. More compact, light and efficient batteries has provided a good leverage for the development and the consideration of EVs as potential private or public mean of transport.

Recently, in Europe, increasing political dedication to promote alternative transport means is being observed, such measures are aiming at less environmental impact comparing to actual internal combustion engines, in fact, the European Commission particularly backed the adoption of electric mobility through the directive of the European Council and parliament on the deployment of alternative fuels infrastructure [3] that explicitly supports clean fuel transport and proposes explicit models for the expected infrastructure deployments.

Comparing to newly registered conventional engine cars, EVs are still exhibiting limited growth in the EU. Evolution of such figures would mainly depend on the extend of governmental support and the consumer willingness to shift towards a new type of transport. In this subsection, we present the primary data collected from the EU member states with respect EV sales and deployments. The goal is to assess the forthcoming market trends, the progress in EV deployment and gauge their potential impact with respect to the electricity supply and the readiness on the very short term and the mid-term to accommodate the penetration of subsequent shares of EVs.

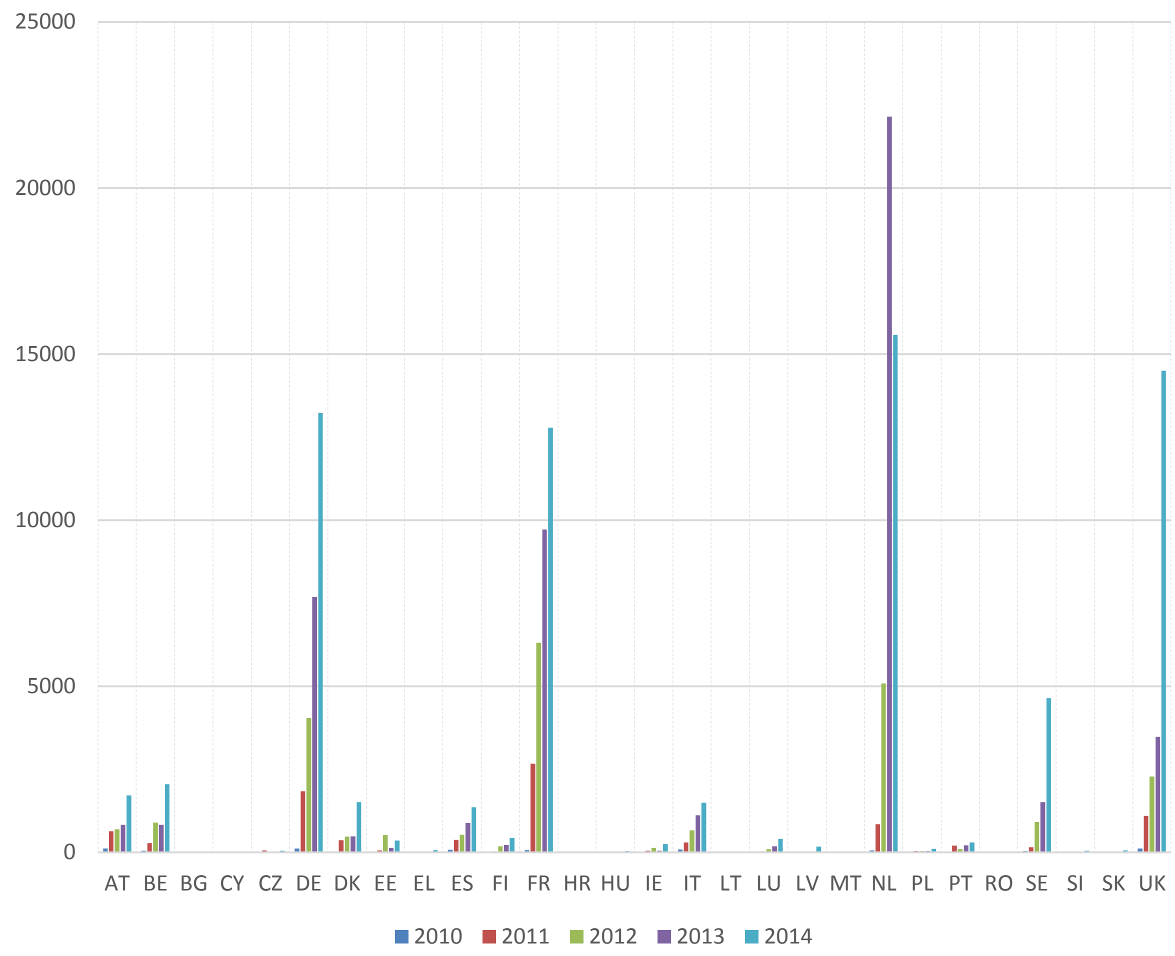

Figure 1 Electric Vehicles sales in Europe years (2010~2014) [7] [8]

Figure 1 illustrates EV sales figure in the EU 28, it is clear that all the member states have registered – growth in sales figures (except for the Netherlands decrease in 2014 comparing to 2013). In total for all the EU 28 states the sales figures doubled 10 times between 2010 and 2014. The Netherlands, France, Germany and UK are the frontrunners in terms of deployment, totaling 80 % of the sales up to 2014.

Projections estimates that we are entering an early phase of EV acceptance and sustained rollout, as major milestones have been already achieved since the year 2013, with major sales figures achieved by two fully electric models ranging from small urban model as the Nissan leaf to more luxury sector limousines with the Tesla S. In fact todays' new market already offers rich portfolio and alternatives to meet the diverse needs and preferences of customers in term of vehicles power, size or even luxury segment. It is expected in the near future that the market will include further alternative of high end fully electrical vehicles as prototype models are already being developed by Ferrari, Bentley and Porsche.

Likewise currently the electric vehicles on the market are relying on several technological solutions: as fully electrically supplied vehicles referred as Battery Electric Vehicles (BEV), to Hybrid Electric Vehicles (HEV) based on a combined powertrain of and electric motor and an internal combustion motor, Fuel Cell Electric Vehicle relying on a full electric motor and storing energy excess in form of hydrogen.

Whiles sales figures in the EU member states shows variances in term of EV rollout with most of the new sales being registered in four member states, it is important to adjust the EV sales with respect to the total new registered cars per country. Figure 2 depicts the share in percentage of EV sales among the newly registered vehicles from 2010 to 2014 (data for Cyprus and Malta non-available). This reflects that EV's sales figures are quite limited well below 1% of newly registered cars in most of the EU. Shares of EV sales among newly registered cars provide better insights due to the size difference in terms of fleets among the EU states. This clearly demonstrates that other member states had indeed achieved relatively positive rollout figures as Estonia, Sweden and Denmark. Likely the United Kingdom, Germany and France are leading in terms of total EV sales behind The Netherlands; whereas their respective shares among the total newly registered cars are well below 1%. On the other hand, it remains clear that, both in terms of total sold EV and their shares among all new registered cars, The Netherlands has achieved the highest rollout figures averaging 2 % of EV shares up to 2014, while the highest share has been registered in 2013 as one vehicle sold among twenty has been an EV.

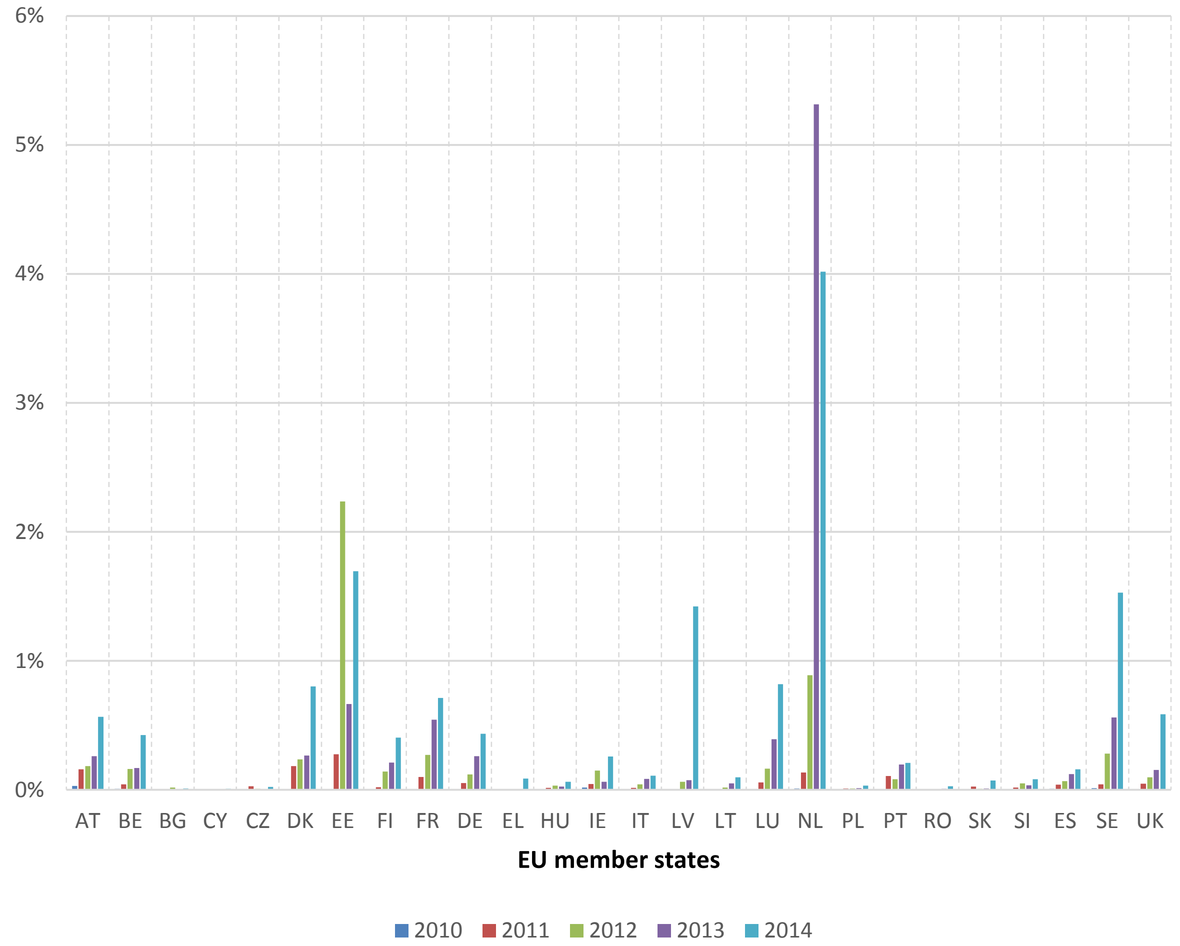

Figure 2 EV shares per total registered cars in Europe years (2010~2014) [7]

Figure 3 illustrates the evolution of EV yearly sales growth, where high Compound Annual Growth Rate (CAGR) have been registered for most of the countries in the year 2011 (effective start of EV commercialization), followed by a sustained decrease in subsequent years that could be explained by the lack of incentives as well as investments in relevant infrastructures as public charging stations and lack of market alternatives offered by EV automotive industries.

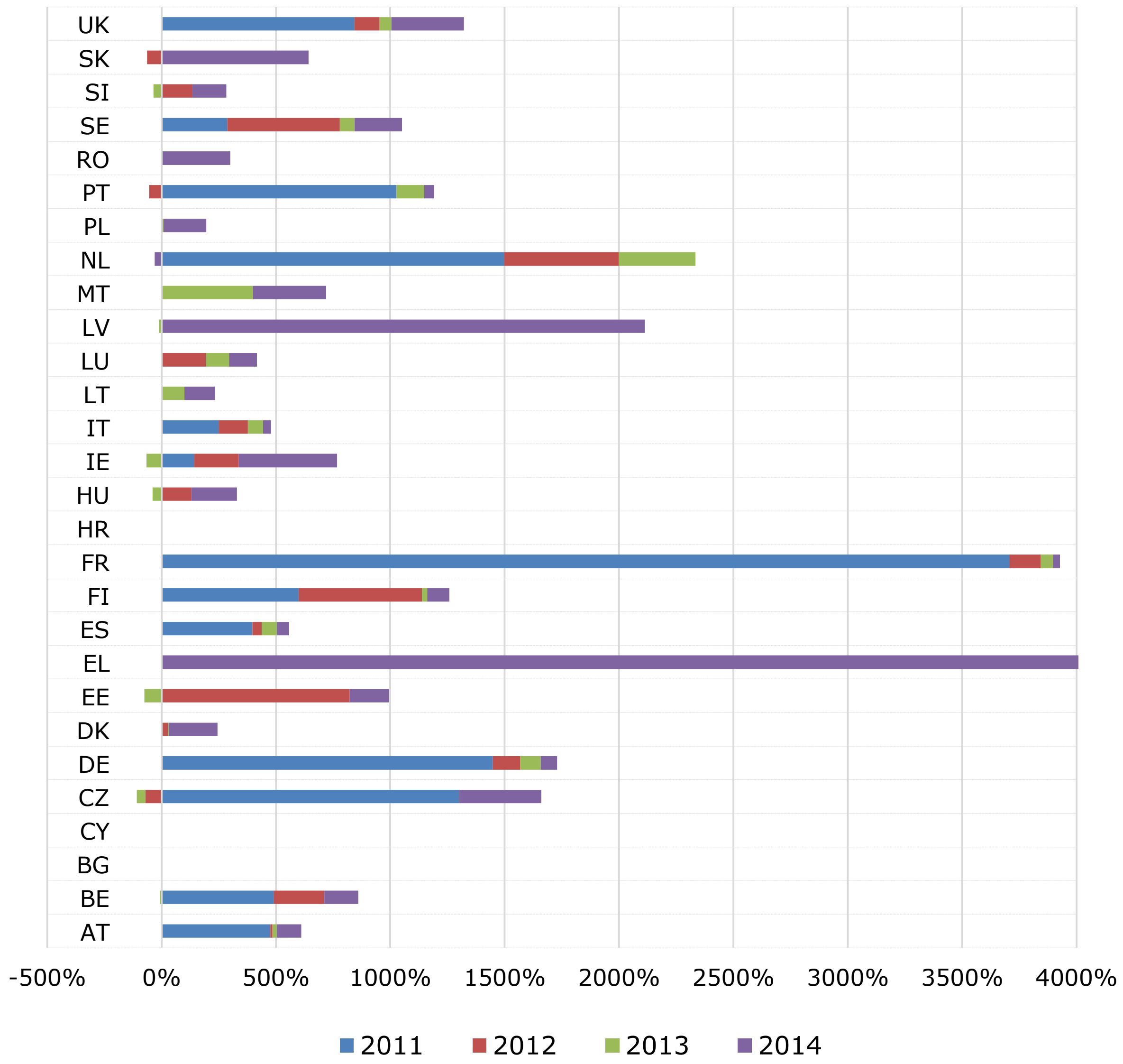

Figure 3 Sales growth rate evolution for years (2011~2014)

Figure 4 illustrates within the EU (28) level the sales figures evolution and the annual compound growth rates, it is clear that despite a continuous increase in number of registered EV per years the compound growth rate is rather being limited and steadily decreasing over the years. In fact this is showing the limitation of the opportunities and governmental stimulus provided to encourage the transition to electromobilty. In fact, the primary wave of EV adopters consisted mainly in high-income consumers class mainly driven by environmental consciousness. It is clear that in order to have a full access for lower class incomes (cost consciousness decision driver), further efforts are needed in terms of stimulus as well as the deployment of EV-enabling infrastructures (charging substations, attractive battery leasing plans).

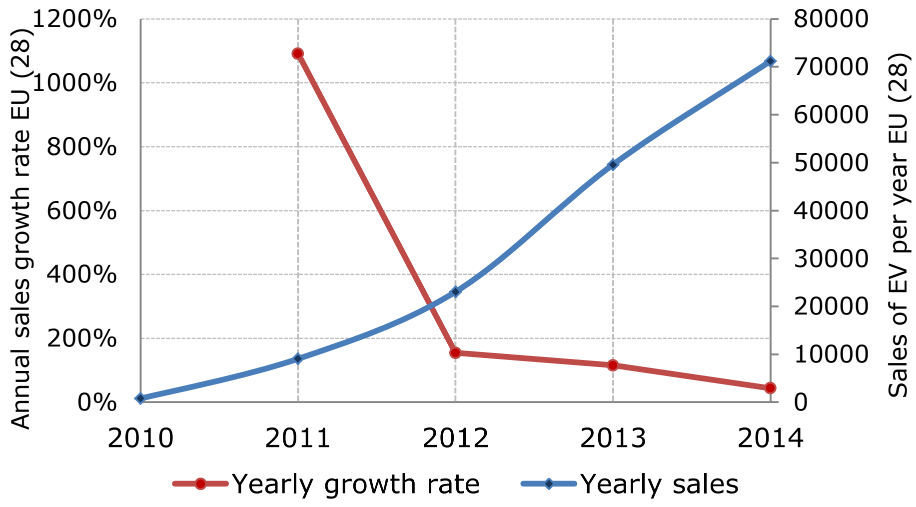

Figure 4 Yearly EV sales and compound growth rates

It is critical in this context, to demonstrate proactive investment rather than a reactive strategy by passively following the subsequent demand. A high increase of EV shares shall be well accommodated from several perspectives, as tax incentives without a rollout of sufficient charging stations or dedicated EV parking spots could result in consumer dissatisfaction that would be difficult to restore on the long term.

While on the short-term, the current low penetration trends of EVs does not present a sizeable impact on the electricity networks operational aspects (reliability, power quality). Nevertheless, to anticipate an accelerated roll out of EV, necessary measures have to be adopted to accommodate the resulting impact on the electricity demand from power and energy perspective both in geographic and temporal aspects. In fact, in a business as usual scenario EV users will be rather concentrated mostly in dense urban areas and soliciting the network coincidently during peak hour demand. Furthermore, paradigm changes need to be proactively addressed with respect to electricity infrastructure, so that such changes could not result in negative impact on the security of supply or even for the overall CO_2 emission levels (electromobilty should solicit more renewable generation on the energy mix rather than conventional polluting power plants).

In fact, the newly emerging trends of electromobility are to be considered within the context of other coincident major trends as higher penetration of RES, efficiency improvement and increasing complexity of electricity systems (unbundling, multiple market actors, consumer involvement). All these trends are undoubtedly resulting in major mutual impact with the electricity networks operation and energy management. The challenge here is to consider the mutual interaction and leverage the potential synergies in proactive fashion at business, functional and infrastructural levels.

This could be reached by enabling harmonized standards of charging couplers and communication protocols to reduce manufacturing costs and efficient integration within utilities and distribution system regardless of the car manufacturer, utilities or billing systems. Such concept has been referred to as roaming services [9], consisting in providing the EV's user with the ability to solicit the same service provided by his own contractor, independently from his location through bilateral or multilateral agreements, pretty much in analogy to services offered by telecommunication service providers.

2.2 PV sources penetration outlook

Figure **5** illustrates the cumulative installed capacity of grid-connected PV distributed generation reaching 80 GW for the year 2013. A sustained increase in installed capacity is observed, with mainly Germany and Italy as clear front runners, with an almost doubled capacity between from 2009 to 2010.

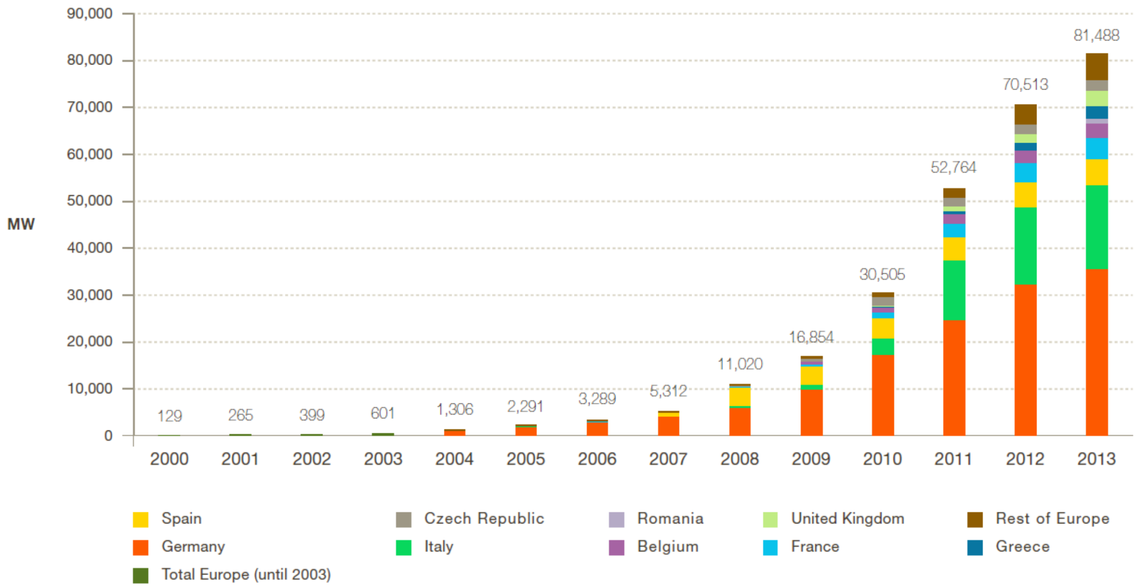

Figure 5 Evolution of PV cumulative installed capacities in Europe (2000-2013)[10]

Figure 6 illustrates the yearly installed capacity of grid-connected PV, it is clear that the growth has been decreasing starting from 2012, this is mainly visible for Germany and Italy. Besides the financial burden of renewable generation incentives, there has been an increasing stress on the electricity networks mainly due to the volatility effect as well as the excess of generation in some operational scenarios. In fact, more than 80 % of the PV capacity is connected to low voltage level, resulting in considerable stress in assets (transformer, feeders) and more needs of flexibility to manage the generation volatility and peaks. Concretely the registered increasing penetration rates of PV generation, has already resulted in several issues that includes reverse power flows, generation curtailment and rising voltage levels during coincident high RES generation and low demand.

The EU's 20-20 targets of reaching 20% of energy consumption provided by RES [5] is being on track with respect to the Nation Renewable Energy Action Plan with 14.07% of overall shares in 2012 against the estimated 12.87% target [11]. On the other hand, objectives for 2030 [4] in reaching 27 % share of renewable energy consumption – specifically to 45% in the electricity sector- and an overall reduction of 40% cut in greenhouse gas emissions could be challenging as saturation of the penetration levels is already tangible. In fact, this has resulted in speculations to consider limiting the capacity expansion of PV in Europe and particularly in Germany until further storage capacity and more intelligent demand mechanisms are in place [12].

In fact, as it can be seen in the Figure 6 Germany had experienced a substantial decrease in PV system installation: from 7.6 GW installed capacity in 2012 to 3.3 GW in 2013 and up to 1.89 GW in 2014. Such decrease has been associated to the amendment of the Renewable Energy Sources Act (Erneuerbare Energien Gesetz). Concretely the 2012 amendment limited the increase of total feed-in-payments for PV facilities (effective 1 April 2012), by 1% monthly reductions in tariffs as well as the limitation of the total power of a facility to 10 Megawatt. As result, the actual tariffs (October 2014: EUR 0.1265/kWh) for residential systems less than 10 kWp are below end-user electricity rates (EUR 0.289/kWh), providing a clear investment signal for limiting injection and rather opting for more local consumption either by more flexibility in the demand or investing in local storage [13].

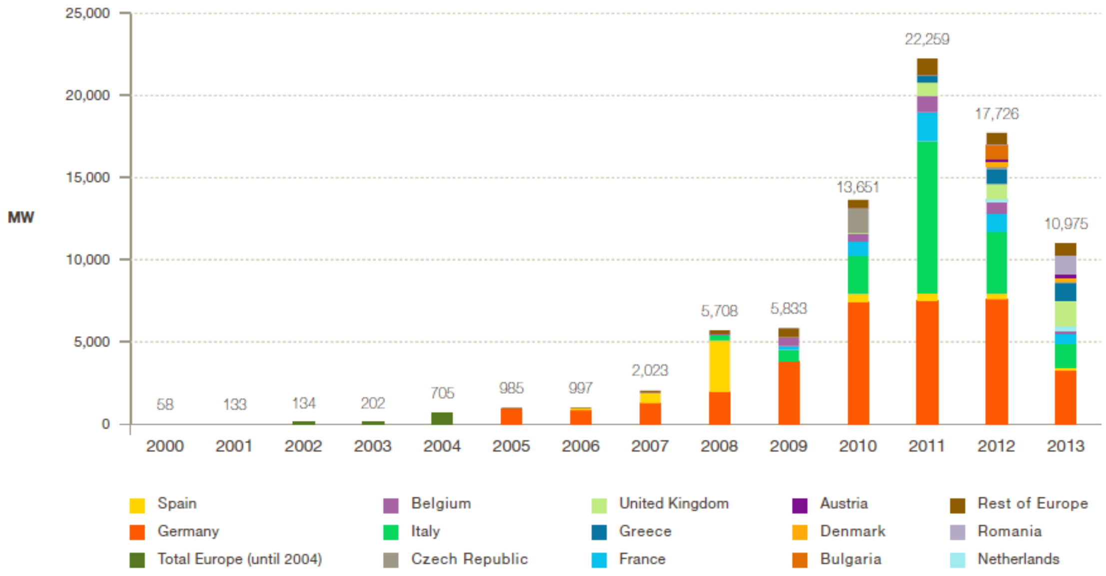

Figure 6 Evolution of European new grid-connected PV installed capacities (2000-2013)

Figure 7 combine both the total sales growth figures for EV sales and new PV installation in the EU, visibly demand growth for both entities remain relatively constant. EV sales while still registering positive growth rates, slight reduction is observed from 2012, on the other hand, PV installed capacities are registering negative growth rates since 2012 which is mainly due to the slowdown observed in Germany and Italy.

In the context of the recent drops of oil prices reaching 68% decrease between June 2014 and January 2016 [14], reluctance toward investing on renewable energy sources or EV is expected. Even though, no clear fundamental linkage between oil prices and renewable energy growth could be established, as slowdowns in PV penetration rates since 2014 are also due to other factors mainly the decrease of subsidies. As for the EVs market, while oil prices could affect to some extend new segment of affordable vehicles taking into consideration the correlation between electricity and oil prices and continuous batteries cost decrease. On the other hand, first waves of EV and high end models owners (Tesla, BMW i3…) are rather insensitive to gasoline prices and are more driven by environmental consciousness or social status.

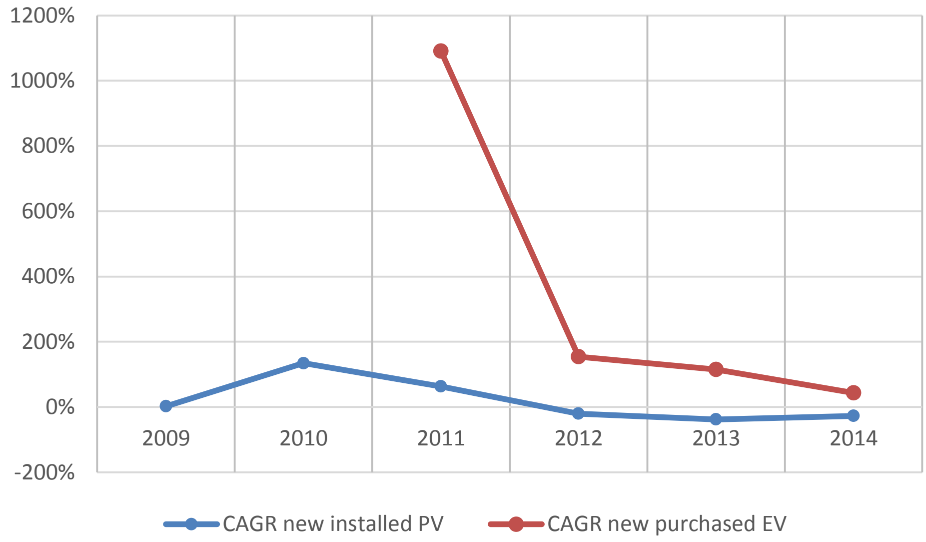

Figure 7 Sales growth rate evolution for PV and EV in EU (28)

2.3 Synergies between EV needs and PV distributed generation

In this subsection, we introduce the concept of synergies between undispatchable generation sources and controllable loads, using specifically PV distributed generation and EV batteries. In the context of smart grids, further increase of PV generation would require storage means to modulate power injections, in such context clearly EVs (i.e vehicle2grid) do have clear advantage comparing to conventional storage means (i.e. fully dedicated batteries).

Penetration of renewable energies and specifically PV generation comes at the expense of higher electricity retail prices (cost socialization) and ultimately on the security of supply. On the other hand sustainability targets are still ahead: further RES capacity is expected (share of renewable energy of 45% in the electricity sector by 2030 actually 21% only) and more sustainable transport has to be achieved, therefore the need to integrate both entities in the most cost-efficient way. Fig. 8 illustrates per unit (p.u.) based outlines of the load demand profile and PV generation versus vehicles mobility patterns profile; corresponding respectively to the maximum peak load demand, Watt-peak installed PV capacity and the maximum shares of vehicles in motion. As long as the EV vehicles are charged in unrestricted fashion, it is clear that no interdependence can be drawn between the penetration impact of both EV and PV. In fact, the peak in EV generated load is expected to happen subsequently to the daily commuters returning trips during the evening peak electricity demand. Furthermore, the EV demand peak coincides with no electricity being generated from PV sources or in best case to a minimal extent during the summer when the days are longer.

Enabling more flexibility in the EV demand could substantially facilitate a greater penetration level of DER, while mitigating the intermittency effects of high penetration of PV generation. Such synergy implies the shifting of the EV demand peak not only in an effort to avoid congestion and high electricity tariffs during peak demand but also to mitigate the excess of PV power generation. It is important to underline that the pursued goal is mainly oriented toward risk mitigation rather than rather than minimizing operational costs, that's being said, failing to mitigate risk could be monetized as well (e.g. penalty from regulator, energy not supplied or degrading the reputation of the utility).

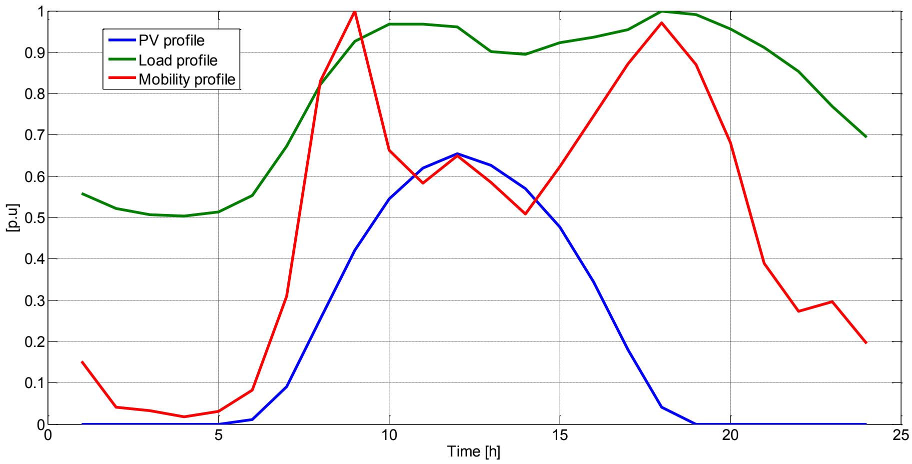

Fig. 8 Distribution load demand versus typical EV load profile and PV generation profile.

Taking into account the complexity of the future electricity distribution systems, a more decentralized operation could simplify the tasks of grid operation by seamless prosumers involvement. In fact, the emerging distribution systems are planned to integrate plug-and-play devices, enabling a set of new functionalities related to the various actors (retailers, DSO, aggregator, prosumers,..) and implemented through various technologies (generation devices, loads, communication,…) [15] in which will be possible to efficiently exchange information and commands. The end users specifically have to incorporate smart appliances capable of communicating their status and auto-adjusting their operation based on their requirement and/or the DSO/retailers provided set-points (when relevant).

2.4 Infrastructure investments outlook

In this report infrastructure investment covering the integration of intermittent RES and electromobility –either in the form of independent or concerted projects enabling jointly the two entities– are analyzed for the EU(28) states.

The data has been mainly collected from the annual Smart Grid Project Outlook [16], the considered investment are composed of Smart Network Management (Demand side response) covering several technical aspects: (i) Distributed Energy Sources integration (DER), (ii) Smart Customer and Smart Home, (iii) Smart network management, (iv) Virtual Power Plants and (v) Electric Vehicles and vehicles2Grid applications.

The integration of DER is mainly related to projects introducing novel control schemes and hardware solutions for the integration of distributed generation while improving the system security of supply and reliability. Such solutions include reactive power/voltage support, storage for power flow modulation, aggregation of DER into Virtual Power Plants and microgrids. This category of projects aims generally to facilitate the integration of distributed generation within the existing distribution network by providing more flexibility for power modulation (through aggregation or storage integration).

Smart customer and Smart Home is covering investments dedicated to establish the necessary interfaces and functions for prosumers interactions with the relevant entities (i.e utilities, energy aggregators, DSOs…). This mainly involves direct investments in terms of white goods, smart meters as well as the assessment of prosumers engagement and sensitivity to different incentives (prices mainly).

Smart network management is more generic category covering mainly the observability and the controllability over the distribution network. The increasing complexity of electricity networks does requires a more developed observability and controllability of the system equipment and states ranging from a single prosumer, distribution feeder up to MV/HV substations. In fact, in order to guaranty a stable operation of the network while allowing active involvement of customer (prosumer) and accommodating a high share of non-dispatchable generation sources, better granularity of the system's observable states is needed (real-time monitoring up to the feeder/home level). Likewise, better observability would result into more efficient controllability allowing real time remedial actions and implementation of stability means that were historically reserved for the transmission level (power frequency control, voltage / reactive power control, controllable loads….). This category will be addressed in the section 3, where we introduce a conceptual architecture enabling such concept in emerging distribution systems.

Virtual Power Plants aggregation is perhaps the most appealing category with respect to the synergies between EV and PV, needless to mention that its implementation is closely depending on other categories. Such investment focus on physical as well as market aggregation between distributed generation as well as controllable loads forming together a virtual power plan. A virtual power plant comparing to a more conventional RES present several advantages mainly: bigger inertia (aggregated sources), controllability (via storage or demand side management) allowing the possibility to interact as a market player either by providing ancillary services or bidding in energy market.

Finally the last category considered in the investments outlook is the Electric Vehicles charging stations and Vehicle2Grid initiatives, such category of investment represents the "front-end" needed investments (assets mainly) that would be necessary for the deployments of EV and guarantying the physical interaction with the existing distribution networks as AC public charging station or aggregated fast charging infrastructure.

Figure 9 illustrates the total investments per the defined categories within all the member states EU (28), clearly throughout the past decade most of the EU states have been extensively investing in infrastructure assets mainly targeting integration of distributed RES and electromobility. Although it is clear that most of the investment are rather driven by market opportunities related to better prospects to more integrated distributed resources rather than electric vehicles penetration as it could be reflected from the sales figures depicted in the subsection 0.

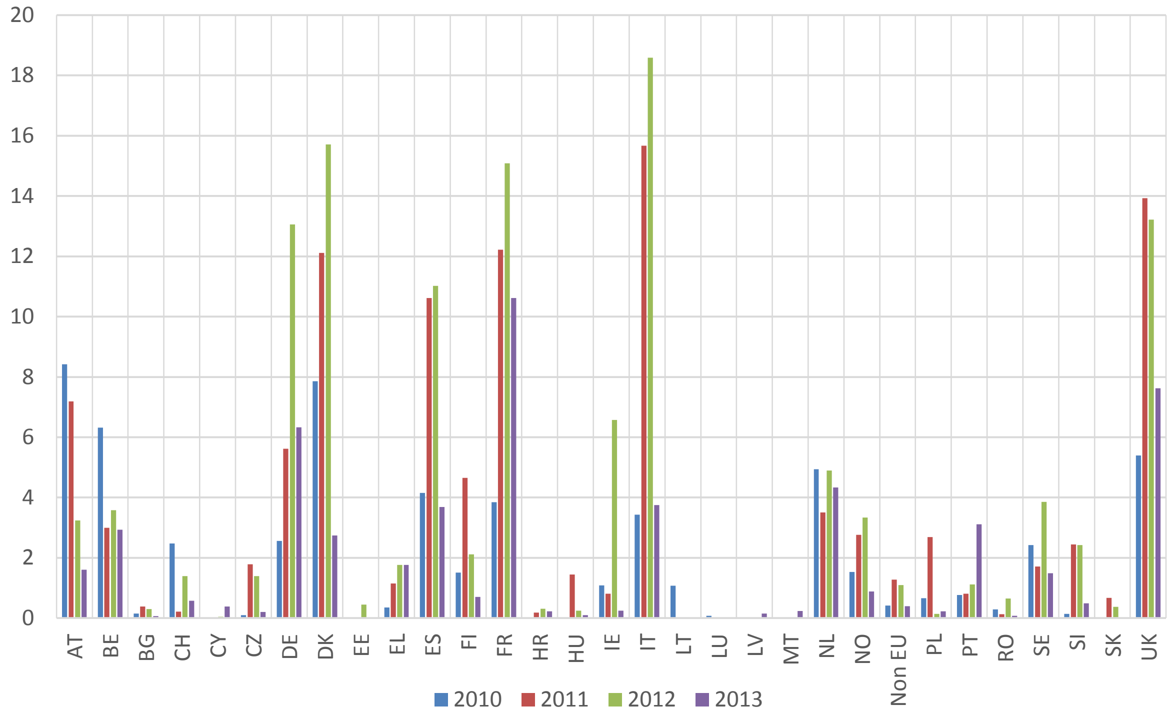

Figure 9 Infrastructure related investment years (2010~2013)

Figure 10 depicts the investment evolution for all the EU member states from 2002 up to 2012, figuring a substantial increase in investments starting from 2010, where Italy, the Uk, Germany and France are positioned as front runners.

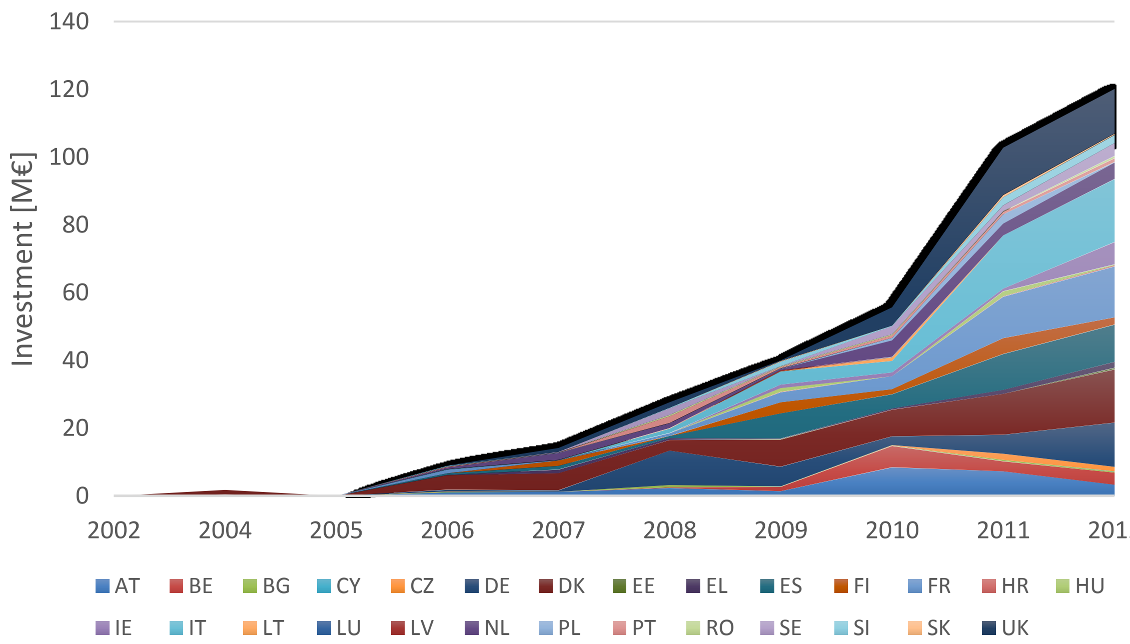

Figure 10 Evolution of infrastructure related investment years (2002~2012)

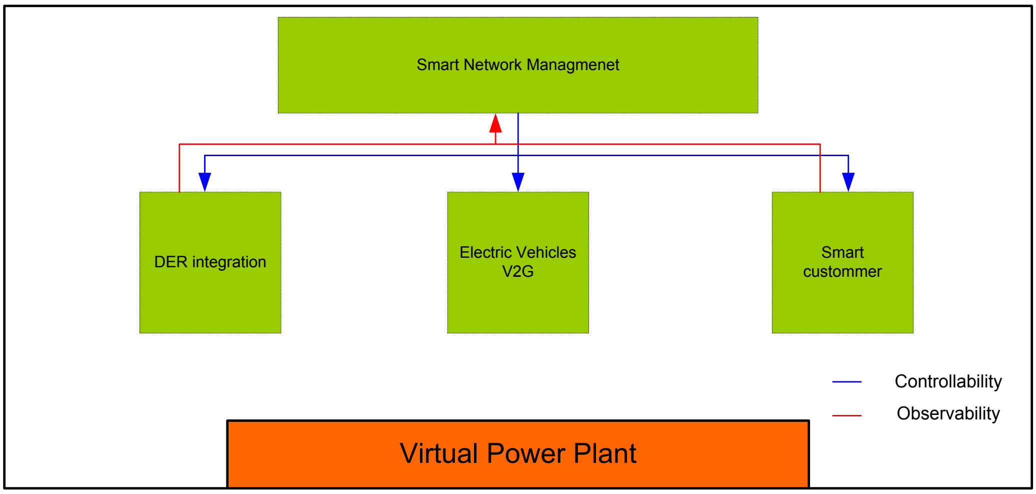

Figure 11 Investment categories mapping and interactions

Figure 11 illustrates a high-level mapping and interactions between the different elements considered as part of infrastructure investment. In order to enable synergies between distributed non-dispatchable generation (integration of DER category) and electric vehicles, other investments are necessary to accommodate and enable operational and functional interactions between the main involved actors (including prosumers, DSO, utilities and VPP). Depending on the inertia of prosumer, he can be directly interacting with the smart network management –as an element of a VPP- or via an energy management aggregation. It is clear that for such complex model to be fully integrated and operating within existing electricity network, efficient and reliable communication between the different actors across the Distributed Energy Management System (DEMS) domains is critical. Within the smart grid physical components and the deregulated energy markets, it is expected to have diverse operating actors using diverse equipment providers. These actors have to efficiently communicate and coordinate with interoperable solutions, this is expected to result in a substantial implementations costs due to the sheer number of processes and required equipment and applications to be integrated. In this context, several international initiatives on applicable standards[1] are under course, including among others: the IEC 61850 for communication networks and systems in power industry automation, and the IEC 61970/61968 for Common Information Model (CIM). Standards deployment will clearly enable the integration of DEMS applications developed independently by different vendors. This will result in the fulfillment of interoperability requirements in an all-inclusive architecture supporting decentralized decision making via bidirectional communication channels at the distribution level.

[1] A prominent example is the European mandate M/490 aiming to perform continuous standard enhancement and development in the field of Smart Grids, while maintaining transverse consistency and promoting continuous innovation.

The next section of the report will be dedicated to assess the interoperation needs and to define conceptual smart grid distribution architecture to enable decentralized operational synergy between intermittent RES and EVs based on coordinated EVs charging. The developed architecture and the energy management methodology is aimed to be in line with the common available and foreseen standards in terms of interoperability prospective and functionalities.

3. Smart grid conceptual architecture: technical and market outlines

The CEN CENELEC focus group on European Electromobility , recommended in their standardization and associated infrastructure report (response to the Mandate M/468 concerning the charging of electric vehicles) a set of endorsement to tackle smart charging issues, with aim to achieve optimal electromobility , energy usage and efficiency [9]. With respect to communication and controllability, the report recommended end-to-end scenarios between all the involved European Standard Organizations in order integrate harmonized and interoperable links between the different communication standards for electromobility , smart grids, energy management systems and utilities. In that sense "interoperability hubs" are introduced as generic and neutral concept for mediation between two or several parties (service providers, utilities, energy management aggregator..) for validation services, exchange of technical information and coordination [9].

In this section we propose a conceptual smart grid distribution architecture to enable decentralized operational synergy between intermittent RES and EVs based on coordinated EVs charging. The developed architecture and the energy management methodology are in line with the common available and foreseen standards in terms of interoperability prospective and functionalities. The assessed EV charging consists in uncontrolled and coordinated charging strategies. The proposed framework aims to enable efficient and reliable communication between the different actors across the DEMS domains. For the smart grid and the deregulated energy markets, it is expected to have diverse actors using diverse equipment providers. These actors have to efficiently communicate and coordinate with interoperable solutions, leading to substantial implementations costs due to the sheer number of processes and required equipment, applications to be integrated.

Fig. 12 illustrates a conceptual architecture that is derived from the EU smart grid reference architecture [15]. This conceptual model is originally based on an extended NIST model with provisions to fulfill the EU specific requirements in terms of DER penetration and interoperability mechanisms. The foreseen methodology in this report aims to capture a direct control feature involving both DER and EVs aggregations within the local (decentralized) energy management systems.

The proposed conceptual architecture consists of several domains and zones, each of which contains several applications and actors that are connected through logical connections and interfaces [17]. The domain dimension expand the electric distribution conversion chain that includes the distribution operation, DER and prosumers; while the zone dimension refer to the hierarchical system aspects spanning the whole smart grid plane.

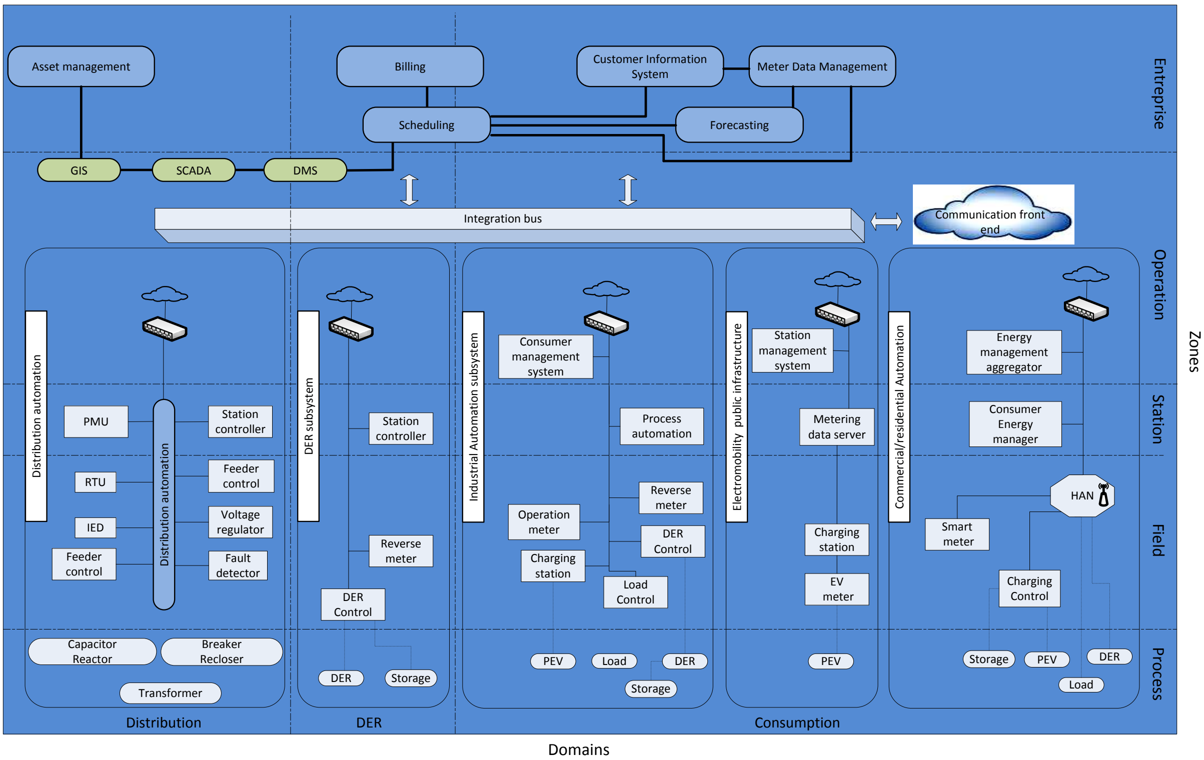

Fig. 12. Smart grid distribution conceptual architecture.

The process zone includes the primary set of equipment associated to the physical layer of the electricity network, such equipment includes: DERs, transformers, overhead lines, cables, electrical loads and smart appliances. Where a smart appliance is considered as a white good capable to act as response to an external signal while the ultimate control is reserved to the user. The field zone is dedicated to auxiliary equipment committed to the control and the monitoring of the electricity networks as the smart metering devices, charging controllers and the Home Automation Network (HAN). Specifically the HAN plays the role of a functional entity that allows the access to metering devices and message transfers with the home display devices. The station zone main functionalities are assumed by station controllers and Customer Energy Manager (CEM), the CEM optimize its clients energy consumption and/or production based on signals received from the grid, consumers settings, HAN and contracts. At higher hierarchical level the operation zone includes the Energy Management Aggregators (EMAs) offering services to aggregate energy production and controllable loads, such actors interact toward the grid as one entity that is coordinating the operation and commands of the CEMs. The enterprise zone covers higher hierarchical level, including the commercial and organizational processes, as utilities power scheduling, service providers and energy traders. Although some overlapping between the operational and the enterprise zone might exist, it is clear that effective model exchange platforms have to comply with the interoperability requirements in highly decentralized distribution schemes. While not depicted in the Fig. 12, a higher Market zone exists beyond the enterprise level reflecting the retail operations, encompassing bulk wholesale energy market figures that are not considered in this distribution oriented conceptual architecture.

All the equipment, with the exception of those defined under the enterprise and the operation zones, can interact using mature existent technology that are compliant with the relevant communication standards [18-20]. On the other hand, the local sub-networks defined in the field and station zones, therefore directly interlinked with the EV, DER, smart appliance and controllable loads, require decentralized bidirectional communication and more interfacing flexibility to coordinate with other entities of the smart grid via high-level communication protocols. Such communication architecture would have the potential to convey and relay data through intermediate devices, creating a meshed network without requirement for centralized control [21].

The penetration of EV and specifically intermittent utility-grade PV generation is expected to further increase, making it difficult to balance further the volatile demand and supply. This might result in lines congestion, overload, reverse power flow, voltage-VAR deviations and excessive phase unbalances. To mitigate such conditions and guarantee system integrity within its technical limits, clear monitoring structure and management protocols have to be defined and implemented. In fact, as illustrated in the Fig. 12, as EV and DER can belong to different domains and subdomains (DER, consumption, industrial, commercial and residential), it is clear that the domain affiliation implies different EMS strategies and communications support. To describe the mutual interaction between the smart grid mapping zones and fields, we will classify the distribution automation operation in two functioning modes: standard operational mode and abnormal operational mode.

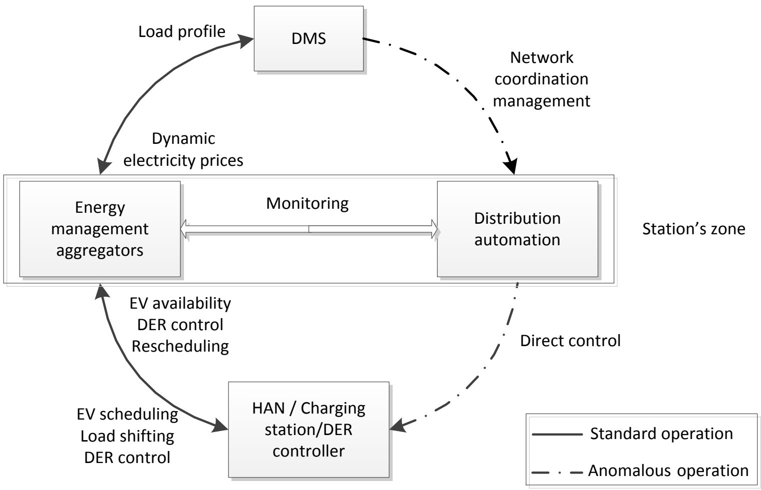

Fig. 13. Distribution automation under standard and abnormal modes.

Fig. 13 shows the implication of the two main operation modes at the level of the field zone along the overall distribution domains. Devices in the field zone exclusively interact with the EMAs during normal operation via coordination with the relevant CEMs to optimize the plant/building performance with concern to energy cost. On the other hand, during abnormal operation, the field zone is subject to direct control set points defined by the DSO's Distribution Management System (DMS).

3.1 Standard operational mode

The interaction between the DER and the EVs within the electricity market during normal operation is locally managed in a decentralized fashion via the EMAs at the level of operation zone. In fact, in order to manage a large amount of EVs and distributed generation sources in a large and evolving geographical area, the presence of decentralized automation operation is of capital importance. The EMA will offer the capability of grouping EVs to represent a controllable load device with the adequate size to participate efficiently in electricity markets operation. Similarly, the DER subsystems and prosumer owned grid-connected DER could be aggregated to allow easier integration and automated controllability within low hierarchical zonal level comparing to DSO's enterprise level. Fig. 12 shows the disposition of the energy management aggregation units that exists across the distribution domains within the station zone. These units bilaterally communicate downstream (field and process zones) with their respective CEM to process the information related to EVs charging status, charging schedules, storage/charging levels and DSM actions. The EMA can, in coordination with the distribution automation domain, implement decentralized feeder monitoring to operate within the stability limits for optimized network capacity by increasing injections at the level of the distributed generation or limiting the electricity losses through Conservation Voltage Reduction (CVR) [22].

From the cost minimization perspective, the CEM monitors the energy consumption of different locations (within industrial or residential domains) and their relevant costs, aiming to identify potential peak demand surcharges that can be avoided. During the normal operation mode, the EMA can potentially take role in the market negotiation at the DSO level, as they are sensitive to the electricity prices variance and therefore can proceed to DER-storage adjustment or controllable load shifting (mainly EVs and smart appliances). In fact, energy management aggregators can perform single/multi-site load profiles, as a support to stimulate the DSM through consumption costs in concordance with the enterprise zone and the station zone. This would result in different rate structures and shifting scenarios of energy usage proposal, from on-peak to off-peak hours in accordance to the previous day market settlement.

Considering the most low domain level (commercial/residential subsystem), each prosumer interfaces with its relevant CEM via the local HAN while he is guaranteed to have the choice to accept the optimal set points proposed by the CEM or request a rescheduling of either the controllable load profile, the usage of storage or EVs charging cycle. The CEM and eventually the EMA in such case are obliged to mend their plans to address the prosumers right to deviate from the optimal load profile (i.e. minimum electricity cost) in order to fulfill either emergent needs or more relaxed constraints.

3.2 Anomalous operational mode

Under limited operational risk within the distribution network, first remedial actions can be initiated by the EMA, such actions consist in load shifting trough economic incentives and rescheduling of the DER/PEVs control set points at the level of the CEM actors. In coordination with the distribution automation domain, the EMA takes part in feeder monitoring to assure outage detection and identification of potential electric distribution problems. Moreover, given the very fast time response EV batteries/converters (i.e. vehicle2grid concept [23, 24]) or local DER-storage, the EMAs can potentially provide ancillary services while being compensated for the capacity they can provide. In such structure, the system would be able to address frequency and voltage support needs and limit the start-up cost of cycling and peaking units. Moreover, at advanced domains (i.e. electromobility infrastructure subsystem, industrial subsystem) located on the MV level and characterized by higher inertia impact, the EMAs can sell significant storage capacity to address potential unserved load or congestion problems.

More severe threats to the network integrity involve higher hierarchical management, at the level of the DMS. In such case, the control set points are directly relayed by the EMA through the process zone overriding the initial CEM plans (Fig. 13) via load shedding, direct control on the DER/PEVs or power curtailment. In the case of high impact of simultaneous charging events, occuring during peak demand, under-voltage and/or congestion issues are to be expected. In order to address such operational violation, coordinated remediation actions should be centrally decided (DMS) and yet implemented via the EMA. On the other hand, in the case of high DER generation level (due to favorable weather conditions mainly) occurring at low peak demand, price incentive actions can be initiated to mitigate the unbalance between the demand and the non-dispatchable supply. Failing to address the imbalance due to low elasticity of the demand, will lead to severe market concerns[2] [25]. In such scenarios the DSO can intervene to exploit the elasticity and controllability of electric vehicle loads in order to fill the valleys in the demand profile via requesting fast charging set points that are enforced at the CEM's charging control systems level. Such corrective actions should be elaborated in coordination with the distribution automation subsystem that monitors the feeder's regulation limits mainly in terms of voltage and frequency stability. In the most extreme situation, DSOs have to appeal to power curtailments measures at the level of the distribution domain [26-28], usually such measures concern large wind farms or grid-connected PV systems, but recently are enforceable on individually owned PV systems[3].

4. Assessment framework of EV and PV generation synergies

The proposed assessment framework aims to identify the combined thresholds of increasing EV and PV penetration levels - taking into account the prosumers' mobility and electricity production patterns - in the context of the earlier proposed conceptual architecture. In the suggested assessment framework, the uncontrolled charging constitutes the simplest charging conduct whereby EV users plug in their vehicles upon arrival to obtain a full battery State Of Charge (SOC) at a fixed charging rate. Such scenario occurs in off-line conditions, with neither decentralized management nor active demand engagement in place. On the other hand, the coordinated charging requires real-time communication (observability and controllability means) within the grid while taking into consideration the infeed of distributed non-dispatchable generations (i.e. RES).

Whilst the direct goal of this assessment is to maximize the combined EV and PV penetration levels (as well as maximizing power injections), without compromising the

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[2] A combined share of wind and solar assured more than 60% of power generation shares in Germany that resulted in several hours of negative power prices (falling below -100 €/MWh in Germany and Belgium, -200 €/MWh in France).

[3] The 2012 German PV amendment stipulates that PV system owner should be able to curtail power output and must contribute with 50 % of curtailment equipment costs with partial compensation on the curtailed energy (95% of feed in tariff rate) in a conservative effort to limit the penetration of DER in congested areas.

security of supply, other strategic sustainability objectives are implicitly pursued. In fact, the efficient correlation and integration of EVs and PV will contribute to an ultimate target of net CO_2 reduction amid the transportation and electricity sectors. In this sense, higher penetration of distributed PV will foster emission reductions by displacing fossil fuel-based generation sources supplying "traditional" electricity demand and electromobility charging demand.

3.1 Uncoordinated EV charging approach

The assessment of EV and PV optimal penetration levels begins with the most conservative approach of uncontrolled EV charging, implemented without any enhancement of the distribution systems in terms functionalities. In such scenario the EV users are free to connect and charge their vehicle batteries as soon as they park foreseeing a minimum duration, without any charging control or coordination performed via the CEM and/or the EMAs as previously introduced in the conceptual architecture (Fig. 12).

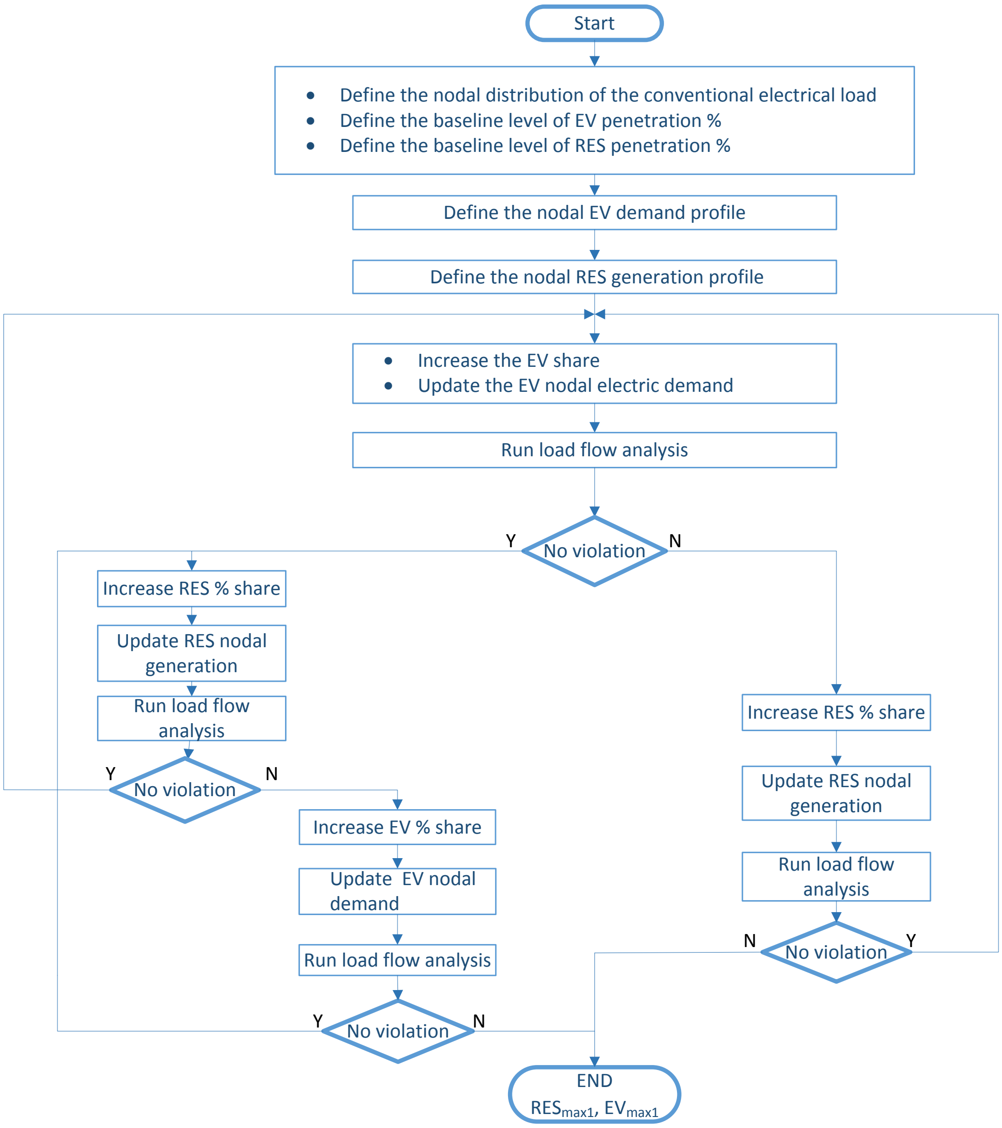

Fig. 14. Uncontrolled EV and PV sources penetration assessment.

The absence of coordination at the end-user level, will result in unstructured charging events, eventually leading, beyond a certain EV penetration level to violation of the distribution network operational constraints. In this assessment framework (baseline uncoordinated scenario), the electricity system performances are tested against 1% step-wise sequential increases of PV and EV levels, up to when a voltage or line limit violation occurs (PVm1 and EVm1 respectively designating the maximum penetration of PV and EVs). Since there is no possibility for coordinated EV charging, the developed assessment algorithm will tend to mitigate the effects of uncoordinated charging through higher PV penetration. However, it is clear that such measures, in the absence of coordination, have limited effect as the peak demand generated by EVs occurs while the PV generation is mostly not available, subsequently resulting in generation surplus under different operating conditions.

Fig. 14 illustrates in detail the penetration assessment flowchart, where RES_{max1} and EV_{max1} respectively designate the maximum penetration of the PV distributed generation and the EV. The voltage violation threshold in the load flow analysis (Fig. 14) is fixed to ± 5 % of voltage deviation [29] for each iteration[4]. These iterations represent hourly based combinations of load flow analyses. Once the voltage level or the line congestion limits are exceeded, it is established that the maximum penetration of PV and EV is reached under that specific penetration level (RES_i and EV_i). In the case of a voltage violation, the loop is restarted with adjustments in the PV or the EV penetration level until no improvement can be obtained.

3.2 Coordinated charging approach

The proposed coordinated charging assessment takes into account the functions that have been proposed at the operation zone through the energy management systems, in coordination with the distribution automation domain. In this assessment, the intended coordination approach does not aim only to assess the EV penetration level but to enable functional synergy between the EVs and the PV distributed generation; this is achieved while taking into account the features of the road traffic patterns, the distribution network lines and equipment physical constraints. The proposed framework could be adapted to integrate other type of undispatchable generation sources as wind power which could be more attractive in some aspects due to its lower levelized cost of electricity. Nevertheless, PV distributed generation can present considerable advantages mainly with respect to flexibility (lower rated capacity and possibility of connection on the LV levels) as well as better forecasting accuracy which is important for the efficiency of the DSM scheduling.

In the following, two possible implementations of the coordinate charging are considered: 1) Technical Coordination charging: consisting in a purely technical coordination taking advantage of the enhanced communication and decentralized control capabilities within the distribution network 2) Enhanced coordination: with further market control signals in form of incentives practically resulting in more flexibility in

[4] The EU directive 89/336 on the voltage characteristics of electricity supplied by public distribution systems, states that the compliance limit is ± 10% during 95 % of the time in one week period. In this study the limit has been restricted to ± 5% due to the potential high recurrence and periodic nature of such violation events.

shifting the EV's charging events (with the goal to achieve further relaxation of the charging patterns constraints).

It is worth mentioning that the second coordination approach is meant to assess the potential benefits of the market control signals in terms DSM, while no further penetration level is considered. In fact, the outcome of such methodology will significantly depend on the assumptions considered in terms of consumer behaviour and sensitivity to the price signals adjusted to real traffic patterns and social interactions tools [30-32]. Such approach could provide insights and quantitative analysis of EVs user's response to price signals and willingness to change their driving and charging patterns behaviour accordingly.

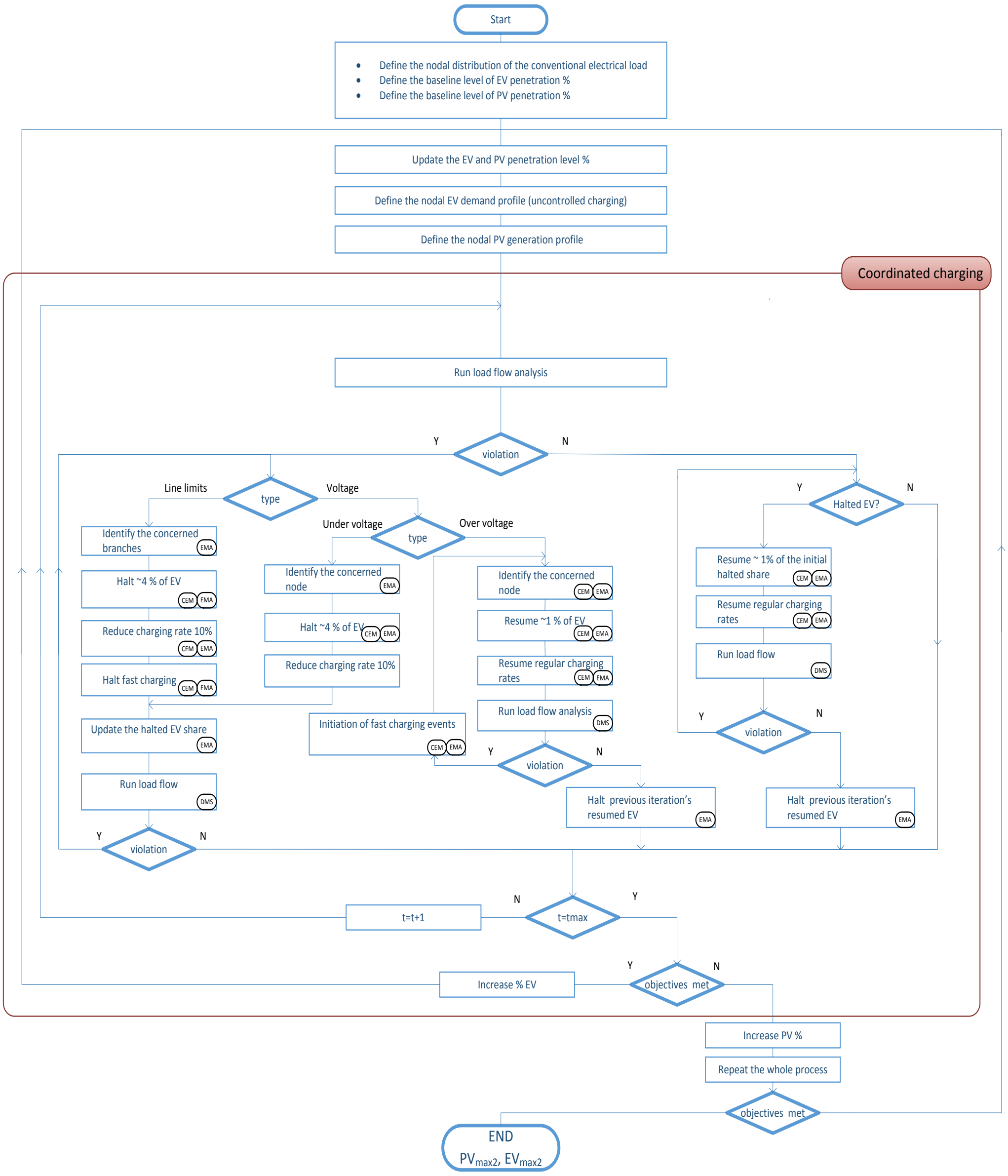

Fig. 15 Flow-chart for the coordinated PV and EV penetration assessment

In the proposed assessment framework, the main criteria to be satisfied while incrementing the EV share, is the ability to meet all the EV charging schedules without any ensuing violation of the network constraints (**Error! Reference source not found.**). In this sense, the baseline nodal EV demand profiles shall be derived from the requirements of the EV users and therefore reflecting their needs in terms of trips, battery charging state and availability. This will confer a realistic approach vis-à-vis to the assessment of the expected mobility traffic behavior, therefore reflecting the effects on the electricity network deriving from high penetration of EVs. The first step of the assessment consists of establishing the nodal distribution of the conventional electricity demand across the MV/LV substations. The results of the first assessment approach (based on uncoordinated charging) could be used as a baseline scenario penetration's level (PV_{m1} and EV_{m1}).

In the penetration assessment, overloaded lines and under/over voltage nodes are addressed by limiting the charging rates or by postponing charging events to keep the system feasible. Failing to address the issues through the EV load shifting, the second step would imply an increase of the PV penetration level to the level of the buses downstream the congestion lines and/or the buses with undervoltage violation. On the other hand, the overvoltage issues -frequently noticeable during the midday intervals due to excess PV generation- are addressed by resuming any remaining halted EVs charging schedules, recommencing usual charging rates or initiating fast charging events. Fast charging events are actually limited to 5 % of the actual parked EVs that are available for fast charging at the level of the nodes experiencing the constraint violation.

The EV charging profile implemented in the market based enhanced coordinated charging could be adjusted on the assumption that a certain proportion of the EVs users are willing to fully reschedule their charging plans based on price signals provided by the CEM (e.g. 20% of the users).

The price signals in this context, seeks to shift the EV charging demand to off-peak and/or high PV generation periods, according to the RES forecasted generation availability. In practice, the remediation of network constraint violations presents more flexibility, with similarly higher tolerance for halting charging events with for instance a 20 % rate comparing to 4% for the basic technical coordinated charging (**Error! Reference source not found.**). It is clear that such approach can induce considerable change in the EV driving behavior, offering higher demand responsiveness. However, it should be highlighted that the shift in the driving behavior of EV users cannot be mapped using historic traffic patterns datasets. In such case, real-time mobility data are needed to gauge the responsiveness of users with respect to different sensitivities of incentives and derogation from their original charging plans.

5. Conclusions

This report highlights the current trends and expected evolution in the EU in terms of electromobility, PV grid-connected systems and smart grids. It is clear from the identified trends that the EU sustainability targets are well on track, however, necessary investment in terms of demand side management and electromobility infrastructures are needed to accommodate the necessary shares of DER RES and leverage eventual higher shares of EVs. Against this background, a conceptual architecture for integration of EV facilities and distributed generation sources in the context of smart grid was proposed in with the aim to identifying mutual synergies enabling energy efficiency, sustainable transport and higher share of renewable energy sources in the final energy mix. The conceptual architecture allows a direct control feature involving DER, EVs and smart appliances during standard and anomalous operation modes. The described conceptual architecture, will enable the interoperability and operational flexibility needs. The ultimate goal is to allow decentralized assets managements to address the increasing complexity of the evolving distribution network and the active role of electricity consumers (prosumers). The merits of the conceptual architecture are corroborated with an assessment framework aiming to identify the combined thresholds of increasing EV and PV penetration levels for either uncontrolled charging patterns or coordinated charging based on the proposed conceptual smart grid architecture. Further work is needed to gauge the prosumers responsiveness and sensitivity to incentives based on real-time mobility data and social interaction tools.

References

[1] European Commission, "EU ENERGY IN FIGURES 2010 CO2 Emissions by Sector," Directorate-General for Energy and Transport, Brussels2010.

[2] European Environment Agency, "Climate for a transport change: TERM 2007: indicators tracking transport and environment in the European Union," Luxembourg2008.

[3] "Setting emission performance standards for new passenger cars as part of the Community's integrated approach to reduce CO2 emissions from light-duty vehicles," ed: Official Journal of the European Union, 2009.

[4] *A policy framework for climate and energy in the period from 2020 up to 2030*, 2014.

[5] "Renewable Energy Directive 2009–28-EC Annex 1 " *European Commission,* 2012.

[6] K. Kahen. *Electric vehicles: From the 1800s to today*. Available: http://www.bankrate.com/finance/auto/timeline-electric-vehicles.aspx

[7] ACEA, " New electric vehicle registrations in the European Union."

[8] T. Christian, K. Jette, and D. Panagiota, "Electric vehicles in the EU from 2010 to 2014 - is full scale commercialisation near?," European Commission, DG Joint Research Centre2015.

[9] CEN CENELEC, "Standardization for road vehicles and associated infrastructure," 2011.

[10] E. P. I. Association, "Global Market Outlook for Photovoltaics 2014–2018," 2014.

[11] Keeping on track 2020, "Keeping Track of Renewable Energy Targets towards 2020," 2014.

[12] H. Wirth and K. Schneider, "Recent facts about photovoltaics in Germany," *Report from Fraunhofer Institute for Solar Energy Systems, Germany,* 2013.

[13] A. Jäger-Waldau, "PV Status Report 2014," European Commission, DG Joint Research Centre2014.

[14] Crude Oil Price History , [Online]. Available: http://www.macrotrends.net/1369/crude-oil-price-history-chart

[15] CEN-CENELEC-ETSI, "Technical Report Reference Architecture for the Smart Grid," Smart Grids Coordination Group2012.

[16] Joint Research Centre, "Smart Grid Projects Outlook 2014," 2014.

[17] NIST, "NIST Framework and Roadmap for Smart Grid Interoperability, Interoperability Standards, Release 3.0," 2014.

[18] IEC, "Application integration at electric utilities – System interfaces for distribution management Part 11: Common information model (CIM) extensions for distribution," 2013.

[19] IEC, "Energy management system application program interface (EMS-API) 61970-301 Part 301: Common information model (CIM) base," 2011.

[20] IEC, "Power Utility Automation," in *Communication networks and systems in substations: 61850 1-10*, ed. Geneva, 2005.

[21] B. Ritter, "Making Smart Grids 'Participatory' through End-to-End Communication," in *2nd Annual Smart Grid China Summit*, Beijing, 2011.

[22] R. Singh, F. Tuffner, J. Fuller, and K. Schneider, "Effects of distributed energy resources on conservation voltage reduction (CVR)," in *Power and Energy Society General Meeting*, 2011, pp. 1-7.

[23] W. Kempton and J. Tomić, "Vehicle-to-grid power fundamentals: Calculating capacity and net revenue," *Journal of Power Sources,* vol. 144, pp. 268-279, 2005.

[24] K. Clement-Nyns, E. Haesen, and J. Driesen, "The impact of vehicle-to-grid on the distribution grid," *Electric Power Systems Research,* vol. 81, pp. 185-192, 2011.

[25] D. Energy, "Quarterly Report on European Electricity Markets," European Commission.

[26] S. Hussain, N. Honeth, R. Gustavsson, C. Sandels, and A. Saleem, "Trustworthy injection/curtailment of DER in distribution network maintaining quality of service," in *Intelligent System Application to Power Systems (ISAP), 2011 16th International Conference on*, 2011, pp. 1-6.

[27] H. Klinge Jacobsen and S. T. Schröder, "Curtailment of renewable generation: Economic optimality and incentives," *Energy Policy,* vol. 49, pp. 663-675, 2012.

[28] M. Fulton and R. Capalino, "The German Feed-in Tariff: Recent Policy Changes," Deutsche Bank2012.

[29] CENELEC, "Voltage characteristics of electricity supplied by public distribution systems.," vol. EN 50160, ed.

[30] P. H. Nguyen, W. L. Kling, and P. F. Ribeiro, "A Game Theory Strategy to Integrate Distributed Agent-Based Functions in Smart Grids," *IEEE Transactions on Smart Grid,* vol. 4, pp. 568-576, 2013.

[31] O. Egbue and S. Long, "Barriers to widespread adoption of electric vehicles: An analysis of consumer attitudes and perceptions," *Energy Policy,* vol. 48, pp. 717-729, 2012.

[32] F. Gangale, A. Mengolini, and I. Onyeji, "Consumer engagement: An insight from smart grid projects in Europe," *Energy Policy,* vol. 60, pp. 621-628, 2013.

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