COUPLING BETWEEN DISTRIBUTED BATTERY SYSTEMS AND PHOTOVOLTAIC GENERATION: A TECHNO-SOCIO-ECONOMIC REVIEW

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Abstract:

In the energy transition scenario, the need to decarbonize the power and mobility sectors are the two main goals established during international environmental summits. The rising sales of electric vehicles as well as the great increase in photovoltaic battery systems deployed around the world are clear consequences of policies established to push the deployment of these technologies to reach climate agreement targets. Distributed battery storage (electric vehicles batteries and stationaries ones) and photovoltaic (PV) systems are disruptive technologies not only because they can individually contribute to CO_2 emissions reduction but also due to the positive synergy between them. Batteries can store electricity surplus produced by PVs during the day, avoiding curtailment, and restore it to the grid to shave peak load or when external grid constraints are identified. This article provides a techno-socio-economic review of the coupling between electric vehicles equipped with bidirectional chargers, stationary batteries and PVs. The aim is to provide a framework for academics, stakeholders and policymakers willing to acquire further knowledge of the under-explored PV–EV–battery relationships. Firstly, the viability of the coupling is deeply impacted by the techno-economic scenario and its future perspectives. Inappropriate regulation of the electricity sector and outdated strategies formulated by the automotive one could jeopardize all the potential benefits brought by adoption of new technologies. Secondly, the emerging social aspects are found to be decisive variables in whether people are aware of the existing possibilities and willing to change their behavior or invest in distributed energy systems.

Keywords: Electric vehicle, photovoltaic energy, stationary battery

1. Introduction

In the energy transition scenario, the need to decarbonize the power and mobility sectors are the two main goals established during important international environmental meetings such as COP21 in Paris. Those two sectors contribute together with more than half of all greenhouse gases emissions on the planet due to the use of fossil fuels to produce electricity in power plants accounting for 42% of the total CO2 emissions and to set internal combustion vehicles in motion accounting for more 24% [1]. The coordination between agents in both sectors is necessary to accelerate the development and integration of recent technologies which substitute fossil fuel applications in the market [2]. The worldwide increase of electric vehicle (EV) units sold, crossing the threshold of one million units sold in 2017 (an increase of 54% on a year-on-year basis) [3], as well as the great augmentation of photovoltaic battery systems (PVB), also known as Solar plus systems deployed around the world are clear consequences of policies established to drive the deployment of these technologies to reach climate agreement targets [4]. Solar PV accounted for only 2% of the global generation in 2017 with almost 400 GW installed, but with its massive deployment due to continuously falling cell costs, the share could reach almost 10% of worldwide generation in 2040 [5]. Distributed battery storage, notably the electric vehicle batteries and the stationary ones, and photovoltaic (PV) systems are disruptive technologies not only because they can individually contribute to CO_2 emissions reduction but also due to the positive synergies between them. Electric vehicles are well suitable candidates to help the decarbonation of the mobility sector worldwide since its propulsion battery will avoid the direct oil utilization during internal combustion. However, if the electricity from which they are charged come from fossil fuels, all the avoided CO2 emission in the mobility sector would be jeopardized by the increase of emission in the power sector, threatening the global reduction of greenhouse-emission gases. EVs charged from non-renewable energy could even worsen the actual situation and increase the global emission. This is the reason why solar PV could benefit both sectors at once, where an intermittent power generation could match an intermittent demand of EV with smart charging.

Battery high cost, including cell and pack costs, is usually known to be the greatest barrier to the massive adoption of battery storage systems in the last few years. However, since 2008, lithium-ion battery costs have been reduced by a factor of four and its costs are projected to be around 100 $/kWh by 2030 benefiting from a large economy of scale driven by the growth in the electro-mobility sector [1]. They can be used to increase self-consumption by storing electricity surplus produced by PV during the day to avoid curtailment [6-8]. Restoring energy for load peak shaving to reduce maximum demand charges [9] or restoring it to the external grid when constraints are identified [10] are important drivers to the technology adoption. Several other services behind and in front of the meter can be provided by battery systems and electrical vehicle fleet, such as: frequency regulation [11,12], voltage regulation [13,14], demand response [15] and congestion management [16].

The need to be in compliance with climate agreements, the falling costs of both PV and battery pack and the large quantities of services battery storage can provide, all those facts stimulates further studies about the high potential benefits from the synergy between those two technologies. The technical and economic issues related to EV/PV systems are well studied separately in the literature [17], nevertheless, a general panorama including social and joint aspects between these three fields is lacking. There is an ongoing social acceptance trend shift concerning the coupling of these technologies, where passive consumers are becoming more independent from the electrical grid due to the installation of their own microgeneration sources; i.e., consumers are increasingly becoming prosumers [18]. Furthermore, the creation of a solid market of distributed battery storage coupled with photovoltaic generation needs not only the mastery of technologies involved and its accessible costs but it also depends mainly on the final consumer acceptance to pay for it. Willingness-to-pay (WTP) is commonly known as maximum price range a consumer will spend on a product or a service in a specific location. For the case of distributed energy resources, this variable is suitable to frame how ready people are to invest in batteries, EVs or renewable generation at a specific period, so policymakers could know better how to guide those technologies development comparing the WTP results with its market prices [19].

This paper provides up-to-date techno-socio-economic information on the coupling between electric vehicles equipped with bidirectional chargers, stationary batteries and PV. We provide a framework to academics, stakeholders and policymakers involved in an energy transition scenario willing to gain further knowledge of the under-explored relationship between these three entities. Aiming to provide a complete analysis, we split the coupling in three aspects (technological, economic and social) with intersections (techno-economic, socio-economic and socio-technical). The most important information in each area is highlighted with the support of literature on each aspect studied as well as the relations between them which allow the identification of the impacts, feedbacks that one field has over the other and the literature gaps that warrant further investigation.

2. Framework description

The paper will be presented accordingly to the analytical framework as follows: First, the technical aspects will be reviewed aiming to confirm the feasibility of the coupling involving both well-known technologies and innovative ones. The technoeconomic intersection will be dedicated to review the most pertinent models and strategies proposed in literature to optimize energy flows with an objective to reduce costs or CO2 using batteries, EV and PV. The last technical intersection which is socio-technical, will be devoted to the development analysis of energy community systems which are groups of different households investing together in renewable generation and distributed storage to supply their own needs for electricity as a heterogenous community. It can be a very good platform for regulators and policymakers to test, on a small-scale, new policies for local electricity markets and to analyze different social behaviors among communities. The following section will be devoted to the economic assessment of support mechanisms and barriers to implement a system with these distributed resources. We will also shed light on the third and last field of this framework: the social aspects. With respect to the pure social aspects, willingness-to-pay is going to be the main subject reviewed to capture the societal general goodwill and awareness towards distributed energy resources adoption. Finally, the last intersection will be dedicated to the socioeconomic analysis of successful local actions using coupled distributed energy resources.

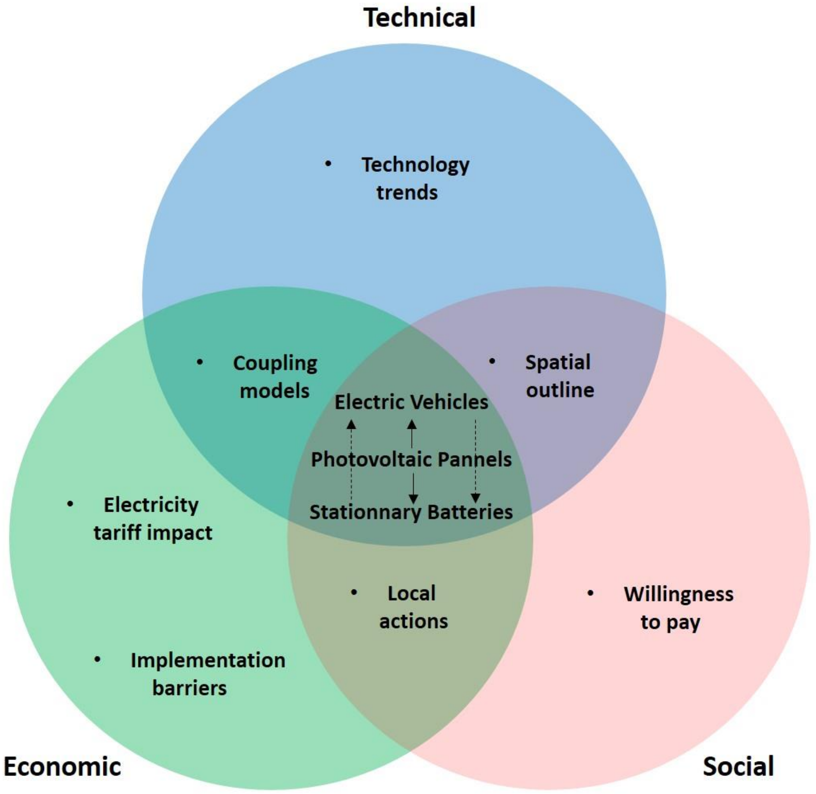

Fig. 1. Analytical framework for distributed battery storage and photovoltaic panel techno-socio-economic analysis.

3. Technical aspects

3.1. Technological Trends

The core energy resources going to be studied in this paper are batteries and photovoltaic panels, nevertheless, these are not the only technologies involved to achieve an efficient coupling able to provide socioeconomic benefits for those who install it. Innovative technology trends, e.g., microgrids, vehicle-to-grid can contribute to energy loss reduction, energy and financial flows optimization, thus enhancing economic gains. We are going to focus mainly on discussions concerning these technology trends, notwithstanding, batteries and photovoltaic panels latest technological breakthroughs will be briefly discussed as well.

3.1.1.Photovoltaic Panels

The main carbon-free distributed generation technology easily installed in residential and rural areas undoubtfully is solar PV. It is a noiseless, renewable, environmentally friend and reliable source that converts solar light into electricity, but with a relatively high initial cost. [20]. According to Subtil et al. [21], we have three generations of photovoltaic technology: the first is crystalline silicon based on silicon wafers; the second is the thin film technology and the third generation which refers mostly to disruptive changes in the way the technology works refers to organic cells and advanced inorganic thin films.

The Silicon based wafer technology accounted for about 95% of the total production of PV technology in 2017, while the 5% left was the contribution of thin film technology production [22]. Silicon cells have excellent conversion efficiency ranging from 22.3% for multicrystaline cells to 27.6% for single crystal cell. Controversially, the second generation was the first photovoltaic cell to be developed in 1976 in RCA Laboratories with the amorphous silicon [23]. The researches on thin-cells increased so fast to lower costs and reduce the required material to fabrication comparing to crystalline silicon cells which use 99% more material to absorb the same amount of sunlight [24]. Thin film panels are easy to install, flexible, durable (25 years of lifetime) and have an efficiency from 14% for the newest amorphous silicon cell until 23.3% for copper, indium and gallium-selenide (CIGS) cells.

Finally, the last generation of PV technology stands mostly for organic photovoltaic cells aiming massive applications on future power generation field. The motivation for research relies on the use of low cost and abundant materials like organic polymers and the less expensive manufacturing process. Although its maximum efficiency until now is 15.6%, the technology has been in continuously progress since 2005 when the efficiency was five times lower [25].

3.1.2. Batteries

When coupled with photovoltaic panels, batteries performe many different services behind-the-meter and in front-of-the-meter in the form of ancillary services. The most used technologies for stationary battery applications are Lead acid batteries and Li-ion batteries, as for electric vehicles applications, the NiCd and NiMh batteries were initially used, but due to their limited energy density and low autonomy, they have been substituted by Li-ion batteries since 2009. [26,27].

Lead acid batteries is in use since late 1800s, being the oldest technology among the others referred in this section. Obviously, it had many improvements since the first use, however, since the first appearance of sealed batteries (valve regulated lead-acid) in 1957 the technology did not have much evolution as expected [28]. This type of battery has limited usable capacity which varies between 30-50%, very low lifetime of 3-5 years (if compared to the average of 25 years of the photovoltaic panels), limited number of cycles during lifetime (between 300-500) and are highly sensitive to Peukert's loss meaning that when the power output required is higher than the specified one by the manufacturer, the delivered capacity is less. [29]. Regardless of its limitations, VRLA batteries still dominate the market for photovoltaics off-grid applications due to its affordable costs for great installed capacities, but they are the overall weakness of the system and tend to be substituted by more promising technologies like Li-ion batteries [30].

Li-ion batteries are nowadays the major technology applied in electrical vehicle main battery and a very good candidate to stationary applications. They can be use with a depth-of-discharge up to 80% of its total capacity, great number of cycles varying between 2000 and 5000 and greater efficiency with great loads as power inverters having almost no Peukert's loss. In terms of chemistry, four different cathodes cells technology can be highlighted: Lithium Nickle-Cobalt-Aluminum (NCA), Lithium Iron Phosphate (LFP), Lithium Nicke-Manganese-Cobalt (NMC) and Lithium Manganese Oxide + Nickle Manganese Cobalt (LMO-NMC). Due to the great prevalence of carbon-based anode materials in Li-ion batteries, all the referenced cell technologies normally omit the names of the anode material and just mention which cathode material is been used.

NCA presents the superior behavior concerning calendar life and the highest specific capacity vs Cell Potential ratio. In other words, its degradation due to changes in temperature and state of charge (SOC) results in the least amount of capacity fade. However, it comes with the highest cost to manage the temperature rise to be operated without any problems. LFP degradation is more temperature-driven than SOC-driven causing a pronounced power loss and capacity fade at high temperatures. LFP does not require high investments to manage its operating temperature because the technology is the safest concerning possible thermal runaways, however this comes with a tradeoff of reducing specific energy and specific capacity vs Cell Potential ratio [31].

The predominant characteristics of NMC and LMO-NMC come from the NMC technology, while the addition of LMO is done to improve safety and increase specific capacity vs Cell Potential ratio in the overall system. They show similar behaviors in capacity loss degradation and power loss being highly affected by high SOCs and high temperatures (above 50 °C), although the influence of the SOC tends to be less present in the pure NCM technology. Comparing with NCA and LFP, the NMC and LMO-NCM have the second-best specific capacity vs Cell Potential ratio and the second worst thermal characteristics, speaking differently, they are the technology right between the other two regarding these technical aspects [32]. EVs manufacturers are investing highly in thermal management battery systems to maintain cells temperature at an acceptable level enabling the use of the technology with the highest specific energy and lowest degradation ratio [33].

The promising metal-air battery technology started to raise attention especially from the automotive sector due to the high energy density and the facility to obtain oxygen from air which is responsible for the reduction reaction in the cathode electrode. Among all the candidate metals to compose the battery anode, the lithium as it is the lightest metal, holds the highest theoretical capacity and energy density (several times higher than that of all lithium-ion batteries) being the most suitable one for electric vehicle application [34]. Nevertheless, several barriers like poor cycling life, low peak power and low practical capacity still need to be overcome with further researches in this field [35].

3.1.3. Vehicle-to-grid (V2G)

The mainly purpose of electrical vehicles is to fulfil mobility needs of its owners by providing a reliable, efficient and convenient way of transportation. Whereas fully battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) have a battery inside and at some point, they need to be connected to the grid, they could also return the stored energy back to it. The ability to restore electricity to the grid by plug-in vehicles is referred in the literature as vehicle-to-grid (V2G) and this concept was first introduced in 1997 [36]. However, it was just ten years later, in 2007, that the first experiment using V2G-equipped electrical vehicle took place [37], starting a new development for the technology with many project demonstrations since then. There are around 50 V2G projects going on around the world where half of them are in Europe [38].

Turning an ordinary EV into a V2G capable EV is not a simple task due to the high technical complexity of the ecosystem and the number of agents involved. First, it must have a bidirectional charger whether located in the vehicle (on-board) or in the charging station (off-board) to enable the power flow between the battery and the grid [39]. The rated power of the charger varies along the type of charge the user wants, for example, slow charging is commonly called Level 1, typically using low power levels from 1 to 2 kW located at home. Level 2 charging ranges from 4kW until 20kW that is mostly found in commercial and workplaces. The last level 3, known as fast charge, occurs with power rates above 20 kW such as: 50 kW, 150 kW and even 350 kW that can be as fast as filling up at a gas station [40]. Then, the communication between the EV, charging station and aggregators must be assured by different protocols so the aggregator who aims to optimize the aggregated capacity of EV fleet can participate among the grid services. The protocols dealing with the communication between the vehicle and the electric vehicle supply equipment (EVSE) have as main objective to assure the interoperability between cars and EVSEs so that the whole infrastructure can be shared by the users. The SAE J2847 and CHAdeMO are currently being used in V2G projects [41], while the European ISO 15118 is a partially published standard which is still under development [42]. The Open Charge Point Protocol (OCPP) and ISO 61850 complete the communication network linking the EVSE and aggregator.

EVs can provide a good number of services to both transmission and distribution electricity grid increasing the economic gain opportunity for the user. As pointed out in [16] concerning the short-term market, EVs can provide frequency containments reserves (FCR) and secondary reserves according to the local market rules. Additionally, it can also participate in system balancing, congestion management, and voltage regulation in the distribution grid level. Behind-the-meter services could be also very profitable depending on the market and tariffs applied. Vehicle-to-anything (V2X) appliances are exhaustively reviewed in [43], however all the economic gains will be discussed in details in section 4 . Besides the participation in those markets, the vehicle-grid integration is a promising concept to integrate more easily the intermittent renewable generation like wind power [44] and solar PV [45] whereas the vehicle stays almost 95% of its lifetime parked thus connected to the grid [46].

The majority of V2G pilots are using plug-in based connections with the grid, however, the wireless charging concept also appears in several V2G prototypes [47]. The wireless charging introduces more complexities than the plug-in charges due to lack of actualized standards and relatively low efficiency caused by the great air gap and misalignments of magnetic coils in the primary and secondary. Introducing a bidirectional wireless charger would add up the difficulties of the V2G implementation with the induction power transfer constraints. Nevertheless, the opportunity to reduce battery installed capacity, thus EV costs, and the massive adoption of autonomous driverless vehicles are clear with the development of this technology [48].

3.1.4. Microgrid

The advances of the technologies discussed until now (PV, Batteries and V2G) opened the path to the development of microgrids. A microgrid is not characterized by just a combination of distributed energy resources and loads interconnected, it is a necessary condition, yet it is not a sufficient one. Several technical requirements must be met to quality a cluster of interconnected loads and DERs as a microgrid, such as: the capacity to operate in grid-connected mode and islanded mode, the ability to ensure smooth transition between them, reliable protection against unexpected events and great power quality [49]. They can be classified according to the power type (AC or DC), supervisory control (centralized or decentralized), operation mode (islanded or grid-connected), phase (single phase or three phase) and the application (residential, industrial; utility, etc).

Starting with the power type classification, AC power has dominated the appliances of network since the 19th century due to the capability of transmission over long distances with easily protection scheme, the ability to power rotating machines in factories and the facility to change the voltage level with transformers, not surprisingly, AC loads have dominated the market over the century. With the development of power electronic converters, the connexion of small DC loads to de AC main grid was possible, however, nowadays DC loads like stationary batteries and EVs and photovoltaic generators are getting greater in number and capacity; reviving the debate about the efficacity of AC versus DC power network. DC microgrid can avoid multiple power electronic interfaces, using a single stage with easier design, control and reducing energy conversion losses [50]. For example, the inverters present in photovoltaic panels systems, batteries systems and in V2G-capable charging stations must operate first with the stage DC-DC and then DC-AC to be compatible with the grid, in DC microgrids, the second stage would disappear, reducing losses and costs for these DERs. According to Wunder et al. [51] 50% of energy losses and 70% of volume necessary for the rectifier (AC-DC) of a small DC load would be avoided in the case of a DC grid connection. For higher DC-loads and with onsite generation literature suggests an overall energy savings up to 15% depending on the microgrid configuration, converters efficiency and the buildings distribution system [52]. DC microgrids are perfectly applied to offices, data centres and residential areas, although they deserve more research efforts in standardisation, bus selection, islanding control techniques [53] and economic evaluations using not only PV and Batteries [52], but electric vehicles equipped with bidirectional-chargers as well.

The energy management of a microgrid is done basically by a joint operation of the central controller (CC) and local controllers (LC) to increase system energy efficiency, reduce energy consumption, increase reliability and avoid energy losses [54]. In a centralized control strategy, all the requirements and resources available of each prosumer or consumer composing the microgrid is sent from the LCs to the CC, so the latter can determine the optimal energy schedule for the microgrid. On the other hand, in the decentralized control strategy, there is a real-time negotiation between LC and CC to optimize the schedule according to local and the microgrid global objectives. Regarding the operation mode, it is worth to point out the difference time period a microgrid can stay in islanded mode, for example, a microgrid which can stay indefinitely in islanded mode can be considered an off grid microgrid. Usually, self-sufficiency will lead to an overinvestment in DERs to fulfil all the load needs of the microgrid, whereas using the grid as a support for the periods with low power generation could be an economic sensible decision [55]. Finally, the microgrid framework can evolve into energy community systems and storage community systems where houses, commercial buildings, factories can all manage their own microgrid together and communicate with the external world as one virtual power plant (VPP), being able to sell and buy electricity from the main grid available or from other community systems [56]. This last topic will be further discussed in section 5 with a socio-technical approach.

3.2. Techno-Economic Coupling Models

Techno-economic models are often used to assess the financial, environmental, or both gains of different distributed energy resources (DER) in residential, commercial or industrial sites and optimize it compared to the base scenario without any DER installed. Those models are well explored in the literature, however, due to the high number of parameters included, their complexity and the different optimization methods, a lot of different models are proposed each one with its own particularity. We focus mainly on models with distributed battery resources and photovoltaic power generation, nevertheless, those which occasionally add other distributed resources such as heat pump, hydrogen storage or cogeneration can also be considered in this section if they show interesting results and optimization methods. These models can be exogenous, where the values of DER installed is already fixed before simulation, so the model results in the optimized batteries charging and discharging strategies according to the load profile, the electricity tariffs proposed by the utility, the cost of each DER unit and externalities like insolation degree to reduce home electricity costs, reduce CO2 emissions, both at the same time using multi-objective strategies or increase self-consumption, in these cases they are used to simulate the home energy management system (EMS). On the other hand, if the model is endogenous, it will decide both the optimum values of DER installed having the same objectives as the exogeneous models plus the possibility to achieve self-sufficiency.

The models containing distributed battery resources and PV can get very complex depending on physical detailing adopted, the method used to optimize it and the number of decision variables selected which can easily go up to millions of variables during the simulation. The literature explores a great variety of mathematical methods used to model and find an optimal solution for those problems.

Author	**PV**	**ESS**	**EV+V2G**	**Objective**	**Number of profiles**	**Load Profile**	**Model type**	**Mathematical modelling**
Schopfer et al. [57]	Yes	Yes	No	Profitability	4190	R30	Endogenous	Stochastic Programming
Doroudchi et al. [58]	Yes	Yes	Yes	Self-sufficiency	1	S60	Exogenous	MILP
Ancillotti et al. [59]	Yes	Yes	Yes	Self-sufficiency	251	S1	Exogenous	Finite state machine
Hoppmann et al. [60]	Yes	Yes	No	Profitability	1	R15	Endogenous	Grid search algorithm
Laurischkat et al. []	Yes	Yes	Yes	Profitability	3	?15	Endogenous	System dynamics

Table 1. Techno-economic models' description.

Schopfer et al. [57] use a Monte-Carlo optimization coupled with machine learning algorithms to predict, based in few input variables, the profitability of a PV-Battery (PVB) systems. They asses the maximum net-present value for 4190 households in Zurich, Switzerland to show how the heterogeneity of load profile among dwellings can completely change the optimum investment (if there is one) in PV and batteries. According to them, battery costs should decrease towards the range of 250-500€/kWh to become profitable in a populational scale.

Doroudchi et al. [58] develop a MILP model to approach as much as possible net zero energy housing in Finland, i.e., the summation of exported and imported energy should be minimized and the use of on-site energy should be maximized. PV, stationary battery and EV equipped with V2G functionalities are used to achieve this goal. Net zero energy buildings (NZEB) are not yet economically viable due to the large gap between annual savings and high system costs, mainly in countries where electricity is not expensive like Finland. Ancillotti et al. [59] study plug-in EVs integration to NZEBs using their mobility and building load models. In first scenario where PEVs are the only energy storage resource, self-sustainability is not guaranteed due to the mobility needs, however, it can avoid 40% of energy import over the year with a 75% of battery capacity available for discharging. When stationary battery is added it can contribute with more 5% to 18 % of energy import reduction depending on the PV size installed.

Hoppmann et al. [60] uses a techno-economic model to investigate the conditions which battery storage will be economically viable in residential PV systems in Germany under eight different electricity prices scenario from 2013 until 2022. They found PVB systems to be already profitable in 2013 for small households, showing an optimum system size rising at a point that they become net electricity producers over time when retail prices tend to increase whereas wholesale prices and initial investment costs tend to decrease.

4. Economic aspects

The following section will be dedicated to the economic impacts and constraints linked to DERs implementation. First, the impact on electricity tariffs will be explored aiming to uncover the issues that arise for the electricity providers when distributed photovoltaic power generation and batteries are present as well as possible solutions. Then, the barriers for the coupling implementation will be pointed out considering the great but not enough decrease of prices in all technologies discussed. Ultimately, a socio-economic analysis of the most important local actions and policies examples taken worldwide to promote the development of these technologies alone or concomitant with the coupling itself will be conducted.

4.1. Electricity tariff impact

The electric power system has been under an important transformation since the past few years due to the strong development of renewable energy resources which are becoming more affordable and cost-competitive with the traditional ways of producing electricity using fossil fuels, for example. The generation part of the system is undergoing a bottom-up transformation since a growing number of consumers are becoming prosumers, i.e. they are producing their own electricity and are not highly dependent on electricity from the grid like before [2]. The current network tariffs, however, are not adapted to recovering all the costs of the utility in a scenario with a high penetration of photovoltaic systems and decentralized electricity production for self-consumption [62]. Furthermore, the addition of a battery storage systems would increase the self-consumption rate, avoiding curtailment of the photovoltaic systems and saving even more money than before [60]. In fact, this is likely to happen due to the tremendous decrease in the costs of battery packs, cells and managements systems. The "spiral of death" is a classic problem inflicted on the network operator by the penetration of photovoltaic battery systems [63]. When prosumers are consuming less electricity than before, the energy volume sold in kWh by the utility decreases and so does its revenue, making a full cost recovery unlikely. Consequently, the tariff increases, giving even more incentive to install photovoltaic panels and become less dependent on the power grid. To illustrate this effect with a real case, Gautier and Jacqmin [64] studied the impacts of tariff increase on the adoption of PVs in the region of Wallonia in Belgium, they founded that for each eurocent per kWh of tariff increase leads to, all else equal, an increase of around 5% of new PV installations. This is a case in which those who do not have PV panels will end up subsidizing those who have, raising an equity issue between consumers and an efficacity issue due to the high electricity prices if more panels are installed. Many researchers have suggested different tariff designs to break the spiral using a capacity-based tariff [65]; however, this type of tariff also has issues if badly formulated as it could overstate the value of the facility peak load and give even more the incentive for battery storage [66].

Electric vehicles are becoming a trend in the mobility sector, which is aiming to reduce CO_2 emissions generated by conventional vehicles by increasing the penetration of battery-powered vehicles in the market. In addition to their environmental contribution, electric vehicles could also play an important role in providing services to the electric power grid (if equipped with a bidirectional charger) and in attenuating the negative effect of increasing tariffs caused by photovoltaic panels. As the general electricity consumption would increase, the utility could recover its fixed and variable costs more easily and the tariff would tend to decrease for all customers [67,68]; however, knowing the quantity of vehicles needed to counterbalance, in the case of grid sunk costs for example, the tariff increase caused by solar energy is very important and not obvious to determine. This question is still open to discussion among the researchers and network operators willing to know the most efficient, from the system point of view, and equal, from the consumers perspective, tariff structure under different DERs like batteries, EVs, PV or heat pumps.

4.2. Implementation barriers

The first and most evident barrier to the massive adoption of the discussed distributed energy resources is the cost of technology. Starting with PV panels, according to one benchmark study done by NREL [69], from 2010 to 2017 the price of the kW installed in residential PV dropped 61%, which in the beginning was around 7240 $/kW going down until 2800 $/kW. The fast decrease in price is explained by several reasons: the increase in technology fabrication efficiency, like decrease in raw silicon material, reduced in almost 25% the cost of PV modules from 1980 until 2012; Private and public funded R&D, economies of scale and learning effects also played an important role [70]. Pillai [71] adds that from 2005 until 2012 the most important factors leading price reduction of solar panels were also the increasing market penetration of lower costs firms in China and increases in industry investments, however, economies of scale and learning effect are insignificant when efficiency considered, suggesting that policies should be aligned with technological advancements more than subsidies. The projection made by IRENA [72] is that PV systems will cost around 1000 $/kW already in 2022.

The high cost of batteries is not only a barrier for photovoltaic-battery systems worldwide adoption but also for electric vehicles sales increase. The prices in lithium-ion battery have decreased 73% from 2010 until 2016, achieving the mark of 273$/kWh [73], in a so-called realistic prediction of 2030 prices, they are expected to be around 124 kWh/kWh [74], that could be economically viable for PVB systems adoption [75] but not for EVs compared to internal combustion engines vehicles if no subsidy is given for the purchase. The factors discussed for the PV technology reduction have an important effect for batteries cost reduction, however, the prices of lithium and cobalt can reach a price floor when the scarcity of active materials leads to a cost increase overtime outperforming the gains due to efficacity increase, economies of scale and learning effect.

EVs adoption would be enhanced if a solid and widespread charging infrastructure with different power levels according to user's needs was in place. There's always the question of whom is supposed to invest first in infrastructure to unlock all other investments, some automakers delegate this task to the public administration and electricity companies, so they can manufacture cars, the latter tends to think that automakers with public support should first fabricate electric cars that will increase the need for infrastructure planning and development. The "chicken and egg" dilemma of which one should come first, infrastructure or vehicles, to incentive investment on the other is still an issue warranting further investigation. Without EVs in the market, the coupling with PV through V2G technology would not be possible, knowing that V2G will add value to EVs by providing remunerated services behind and in front of the meter, policies and market rules adapted to V2G services will directly support EV adoption as well. If those services are provided, mainly the frequency containment reserve has the higher revenue potential among them [12], they can drastically reduce the total cost of ownership of an electric vehicle [76].

The V2G technology is ready from a pure technological point of view, however, the barriers to FCR procurement are mostly market rules-based in many countries. The actual rules and a new market design to allow EVs participation in France is discussed in [77], highlighting the importance to increase the temporal granularity of products from one week long to four hours long and to decrease at least the bid increment if it is not technically possible to enhance volume granularity. As FCR deals with interconnected TSOs, it is possible to establish a common platform for cross-border procurement reserve across countries like in Europe, nevertheless, regarding the services provided for the distribution grid, due to the great heterogeneity of distribution systems and the diversity of regulatory frameworks, policies should be recommended almost individually very carefully following one roadmap, like discussed and proposed in [78].

4.3. Local actions and solutions

Feed-in tariffs (FiT) is a supporting scheme used to accelerate the development of renewable energies productions, notably solar PV and wind power, by offering a remuneration, either valued at retail price of higher, for each kWh of energy produced from a green source and exported to the grid. Countries like Spain and Germany experienced successful PV development since 2008. The United States, mainly in California, and Australia also presented a boom in PV installations after FiT implementation. However, the high penetration of PV, leading to the duck curve problem in electrical system, raised doubts about the continuation of FiT tariffs and which methods should be used to deal with this problem. Nelson et al. [79] alert the regressive form of taxation almost three times higher for low income households that could appear under some FiT schemes in Australia, Gao et al. [80] evaluates many FiT schemes over the world and propose solutions to countries which experienced a PV proliferation under these conditions. They propose a FiT based tendering scheme which will allow a competition between consumers to benefit from financial support, controlling booms and contributing even more for the development of the technology. Net-Metering schemes could also be combined with FiT to balance the development in adoption of PV according to [81], being more or less profitable depending on the location, the kind of system and level of tariffs. Although FiT for storage systems is also discussed as a possible solution to improve storage in coupled PVB systems in [82], the continuity of the strategy is still a debate depending on the location and the PV penetration, now the focus should be on how elaborate innovative strategies to stimulate battery adoption to increase self-consumption and offer flexibility to the grid using the produced electricity.

As discussed in section 4.2, regardless of prices decrease in future, li-ion batteries will face a minimum price limit caused by the scarcity of cobalt and lithium available. The recycling of those batteries is important to avoid pollution caused by the disposal of the metals inside and to reuse directly or indirectly the remaining materials in the manufacturing process of new batteries, lowering the price of them. To date, the existing recycling methods require sophisticated techniques and costly material to recover several components from a li-ion battery due to the great variety of materials inside [83]. The absence of recycling regulation makes even more difficult the recycling of end-of-life li-ion batteries [84], whereas adapted policies to standardize the recycling processes regardless the battery composition could be a solution. The second way is reutilization, where batteries coming from EVs can be reused as stationary battery, once it still has 80% of its initial capacity, providing support to EV charging stations for over 30 years, self-consumption and grid-oriented services for 12 years [85].

Finally, to have more electric vehicle battery to recycle and reuse as stationary, more EVs are need on the streets. Springel [86] uses data from the Norway automotive market between 2010 and 2015 to verify if EV purchases were more affected by station subsidies or consumer price subsidies. It is found that every dollar spent on station subsidies resulted in more than two times additional EVs purchases compared with one dollar spent on price subsidies, but then the relation inverts as spending increases. At the beginning of EVs development, more subsidies on infrastructure means more EVs on the market, consequently, more possibilities to provide V2G services.

5. Social aspects

5.1. Willingness to pay

The emerging social aspects are found to be decisive variables in whether people are receptive and willing to change their behavior or invest in distributed energy systems. Willingness-to-pay is a trustful parameter used to quantify, in a monetary way, how much people in a determined area are ready to pay to green energy coming from PV, electric vehicles or participation in V2G services. Nevertheless, different valuation methods, controlling for knowledge about technologies, households' characteristics, income and education might result in biased results of WTP [87]. Although the quantitative results among studiers vary a lot, a qualitative analysis is possible to be done between countries to frame which factors are decisive in a higher WTP. In Germany, Denmark and Japan the WPT for green energy tends to be higher due to the massive information campaigns about RES [88]. Countries with high electricity consumption and low prices like the United States and Finland also states a high WTP per households, but low per kilo-watt hour [87]. This kind study helps policymakers to have an idea of which direction follow to help developing distributed energy resources in their cities, states and countries. For example, regarding specifically solar electricity, in 2010 British people are willing to pay GBP 2831 [89] and Irish people EUR 6207 for PVB systems [89] At that time, the market price was much higher than the WTP, today with supporting policies to enhance WTP and the technology costs decrease, they may rich parity soon, meaning that people are completely ready to install PVs.

Concerning the electric mobility, variables like income level, mobility patterns, environmental concerns and attitude towards technology are found to the decisive in WTP for EVs [91]. Regarding participation in V2G (vehicle-to-grid) markets, people are becoming less worried about remuneration and mainly seeing it as a service provided to the community via the electricity power grid [92]. This last find could be applied to the whole coupling viability; information campaigns and commitment to achieve energy transition towards renewable energies (e.g. solar PV) could work very well in many countries around the world.

5.2. Spatial outline

The fundamental unit is formed by individual dwellings, which may be aggregated in residential or commercial buildings, so all of them can constitute a single community. Community energy systems and community energy storage are found to be a promising socio-technical trend in the field of distributed energy resources. The objective of these communities is to group different households to invest together in renewable generation, storage and electric vehicles to supply their own needs for electricity as a heterogenous community and to be an example to be followed [93]. An aggregation of communities is often called integrated community energy systems (ICES) in the literature and defined by Mendes et al [94] as a “multi-faceted approach for supplying a local community with its energy requirements from high-efficiency cogeneration or trigeneration energy sources and from renewable energy technologies coupled with innovative energy storage solutions including the EV and energy efficiency demand-side measures”. The contribution from these communities is twofold, first they make a great contribution to the direct decarbonation of electricity once only investments in renewable distributed generation are done avoiding buying electricity from fossil fuels and they also play an important role as flexibility providers, allowing higher penetration of intermittent energy in the electricity mix. It can be a very good platform for regulators and policymakers to test, on a small-scale, new policies for local electricity markets and to analyze different social behaviors among communities.

The barriers for ICES development have distinguished natures due to its high socio-technical complexity. First the purpose of the community will define how many different actors will be involved and then its complexity [56]. Shared residential energy are often distributed energy resources installed behind-the-meter of a household to attend its own need and those from the community. Shared local energy have resources owned by the community installed in from of the meter and behind the transformer to supply local needs and shared with the outsider distribution grid. Finally, shared virtual energy are aggregated resources located in different communities able to share energy in a national or international level depending on market design. The number of actors increases as we go from shared residential to virtual shared energy where the figure of the aggregator clearly appears alongside with international regulators. Germany is a pioneer country regarding the development of energy community systems, an example of local shared energy is Feldheim energy community where 10 MW of li-ion batteries were jointly constructed with 2.25 MWp of solar PV and other kinds of renewables [95]. A second example also in Germany, but of virtual energy communities, is the project sonnenCommunity where the surplus of PV which is not stored in the sonnenBattery is fed into a virtual energy pool to serve other members [96].

6. Conclusion

The synergies of the coupling between distributed battery resources and photovoltaic power generation will help to decarbonize the electric power and mobility sectors while being profitable, if well managed, to all the agents involved: systems operators, regulators, ordinary consumers, etc. In the energy transition context, the urgency to change outdated electricity production methods that contribute to greenhouse emissions is driving the development of “cleaner” new technologies and new synergies; however, important policies and regulations are still struggling to follow this evolution and provide a perfect framework for them to be integrated without major inconveniences. In this article, the technological trends were discussed along with economic issues as well as socio impacts of the DER coupling.

Technological progress regarding PV, batteries and EVs were often a step ahead polices and regulations derived from its implementation, causing strategies to be outdated and imposing barriers to extract the maximum benefit from each resource. It is time to change the behavior towards innovation and assure that the other way around, where policies are always ahead the technical progress, is true. They can prepare the field to accommodate DERs and accelerate the adoption of them based on results from techno-economic models and socio-technical analysis mentioned.

Solutions that aggregate more than one resource to promote its adoption can be a shortcut to increase customer acceptance. If PVB systems are proposed as a “package”, customers would understand faster the benefits of the coupling, costs and could increase their willingness to pay in both resources rather than separated PV and battery systems which have its own benefits, constraints and costs. The same framework can be applied to the automotive industry regarding EVs selling and infrastructure. Automakers should sell the “package” EV plus charging infrastructure, due to the intrinsic relation between them, car industries could expand their business models exploring the gains from EVSEs, and consequently, from EV sells. The V2G capability could also be part of the package, however, the relation between car manufacturer and aggregator should be simplified for potential clients.

Finally, regarding the electricity system evolution, energy community systems are a future consequence of the bottom-up transformation of the electricity system with accessible DERs, however, if this development is completely uncoordinated, the system could end up centralized again with the aggregation of many communities. The control of the distribution electricity system could be partially, if not fully, transferred to private aggregators rather than distribution network operators where the public government would have less over them, risking the optimum societal welfare.

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