Self-consumption of electricity produced with photovoltaic systems in apartment buildings - Update of the situation in various IEA PVPS countries

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***Abstract* — Over the last two decades, grid-connected solar photovoltaic systems have increased from a niche market to one of the leading power generation capacity additions annually. In 2019 the total worldwide installed photovoltaic electricity generation capacity exceeded 630 GW. It is forecasted that 1 TW will be reached by 2022. This further development is coupled with the question at what prices solar photovoltaic electricity can be provided and delivered to the customers. The installation of PV systems for self-consumption is already now an interesting option for many people but in general limited to those who have access to a rooftop they own or can use. Enabling residents of multi apartment buildings to commonly use electricity generated by a PV system (collective self-consumption) is a relatively new development and is still facing a lot of administrative and regulatory challenges. This paper provides an overview of existing regulatory schemes in IEA PVPS countries and presents and analysis of two self-consumption case studies.**

Keywords— photovoltaic systems, solar power generation, self-consumption, collective self-consumption

I. INTRODUCTION

The costs of electricity at the PV module level have dropped to less than 0.02 USD/kWh, making it the technology with the lowest cost for electricity generation in most countries. Nevertheless, there is an additional cost component to provide the electricity to the customer where and when it is needed.

Since 2012, when cumulative installations of solar photovoltaic systems passed the threshold of 100 GW, the total PV capacity has increased more than sixfold to exceed 630 GW at the end of 2019 (Fig.1) [1].

During this time, annual installations have more than tripled from about 31 GW in 2012 to over 100 GW in 2019. However, the main growth came from large utility scale PV systems, whereas the new installed capacity of grid connected decentralised PV systems has stayed more or less within the same order of magnitude, i.e. 16 – 17.6 GW annually between 2011 and 2016 increased in 2017 and 2018 and decreased in 2019 again [2, 3].

The urgent need for a de-carbonisation of the power sector was again stressed during the COP25 meeting in Madrid, Spain in December 2018. The special advisor to the UN General Secretary, Jeffry Sachs, outlined during COP25 that time is running out to stay on the 1.5°C pathway. The only chance is that all signatory countries to the Paris Agreement come forward with realistic decarbonisation strategies by 2050 for their respective countries before COP26, which due to COPID19 is now postponed to 2021.

Various scenarios with a 100% renewable power sector or even energy sector on a regional or world-wide scale have been published [4, 5, 6, 7]. All these scenarios have highlighted the importance of solar photovoltaics to achieve this goal in a cost-effective manner. The next decade will be crucial and an annual growth rate of new PV installations of at least 25% over the next decade has to be maintained to stay on the decarbonisation pathway [8].

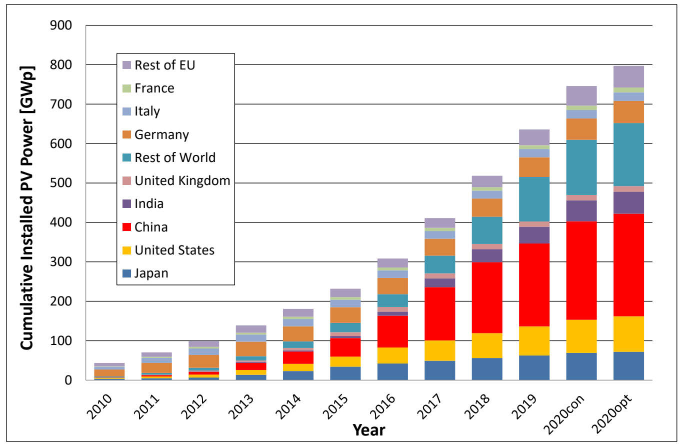

Fig. 1. Cumulative photovoltaic installations from 2010 to 2020 [1]

In order to achieve the necessary growth of PV installations over the coming decades in a sustainable and economic way, the number of residential and commercial roof-top PV installations has to start growing more consistently. The conservative IEA predictions in the Energy technology Perspectives 2016 show a worldwide technical potential of 4 350 GW of PV system capacity on rooftops in cities by 2030 and over 9 TW by 2050 [9]. Studies by NREL for the USA and the Joint Research Centre for the EU have revealed that with current technology more than 2 100 TWh of electricity could be generated by PV systems on rooftops in EU(28) and the USA [10,11].

Amidst these predictions, the electricity network operators in some countries give allowance for the connection of PV systems only at the high and medium voltage level, which is a strong barrier for self-consumption schemes. They hesitate to introduce distributed PV systems at the low voltage network due to lack of insight and control as to its effect on the distribution system. Additionally, in areas of the low-voltage network with high penetration of existing rooftop PV, some operators are restricting the connection of new PV capacity, to address issues of overvoltage or reverse power flows, while prosumers are seeing increasing curtailment of their generation as their inverters respond to voltage excursions. This creates equity and cross subsidisation issues between households. The IEA PVPS Task14 reviews experiences from different countries in several reports regarding how these challenges have been resolved [12]

II. ANALYSIS

PV generation is now the most cost-effective solution to provide electricity for many people around the globe. If electricity is generated locally for costs below grid-provided electricity, self-consumption of this electricity offers the largest economic benefit as guaranteed feed-in tariffs are no longer widely available.

In general, the share of self-generated electricity that can be self-consumed in a residential or commercial system without local storage is limited and a portion of the electricity has to be sold via the grid. The question is: what kind of pricing to apply for this part – contract, wholesale or day-ahead prices or what are the acceptable costs for storage?

There is a wide range of prices for PV systems as well as electricity for customers in different countries, which defines the attractiveness of self-consumption. The level of overall PV production affects the level of self-consumption and hence the cost of the self-consumed electricity. Other parameters like the base to peak load ratio, or the composition of the electricity portfolio have big impact on the amount of renewable energy operating, and network costs. Best practices will be shown in the full paper.

So far, self-consumption in most countries has been limited to the owners or tenants of single-family homes or small PV systems in apartment buildings.

Over the last few years, the concept of PV system use in apartment buildings has gained momentum and new economic concepts have been developed to use the electricity from a common PV system for all tenants in such a building: now referred to as "collective self-consumption".

Different concepts, administrative provisions as well as technical regulations end electricity codes from various IEA PVPS countries will be presented and compared.

Australia

Although more than 7.5GW of distributed PV is installed on one in four Australian houses [13], the estimated potential 2.9GW–4.0GW of rooftop capacity on the country's apartment buildings [14] is largely unused. The low penetration of PV on these multi-occupancy residential buildings is due, in part, to characteristics of the Australian regulatory environment including governance of apartment buildings (under 'Strata Title') and regulation of the energy market [15].

Median per-occupant residential energy use is lower for apartments than for houses [16], but common loads (comprising lighting, heating, cooling and ventilation of carparks, stairwells and other common area, as well as lifts and other shared facilities) are highly variable and may comprise more than half of total building load. For high-rise buildings, with high common loads and relatively low roof area, installation of a single PV system to serve the common load may achieve 100% self-consumption, with the benefits (reduced bills for common electricity loads) flowing to all owners.

In contrast, many of the 61% of Australian apartments that are in buildings with three floors or less [17] have low common loads and rooftop potential to install PV systems sized, on average, at 3kW for each apartment [14]. However, retrofitting of shared PV applied to apartment loads is still rare. Installation in new developments is often simpler, as the property developer does not face same the decision-making challenges as a strata body (the organisation of apartment owners responsible for managing shared ownership of the building structure) and because potentially high additional costs to upgrade outdated wiring and switchboards can be avoided.

Due to high penetrations of distributed PV, parts of the low voltage network are seeing increasing frequency of high voltage excursions and midday reverse power flows, and some distribution network service providers (DNSPs) are addressing this by imposing connection constraints on PV system size or export potential. Shared PV systems applied to aggregated building loads, with reduced export and greater self-consumption (due to highly diverse apartment load profiles [16]), may have less detrimental grid impact than individual household systems.

Installation of shared PV, distributed behind-the-meter and sold through a PPA with households retaining a separate retail contract for grid-imported electricity, is being trialled in some commercial developments and on social housing, supported by some state governments.

If PV is distributed to consumers through an embedded network (EN), the financial benefits of self-consumption can be combined with benefits from accessing lower commercial tariffs for grid-imported energy to create significant savings for consumers [18]. Embedded networks involve multiple customers sharing a single point of connection to the main grid (the 'parent' or 'gateway' meter). In some jurisdictions they are called micro-grids, but do not have the ability to disconnect from the main grid. Addition of shared battery storage can further increase self-consumption, but the economic case is not compelling without subsidy at current capital prices [19].

Meanwhile, there are some signs of increasing partnerships between developers, retailers and embedded network operators to install ENs with renewable generation in new developments. Rule changes relating to governance of embedded networks (ENs) and sale of electricity [20], designed to reduce the barriers for large electricity retailers participating in the EN market, may help normalise ENs as a means for distributing PV generation in new buildings. However, there are continued concerns that these regulatory changes are also increasing barriers to new market entrants and, in particular, make it extremely challenging for a strata body to install and manage an EN in an existing building with benefits flowing to apartment owners and tenants.

Austria

Since the amendment to the Green Electricity Act [21] and the associated amendment to the ElWOG in 2017 [22], photovoltaic systems can now be used efficiently on buildings with more than one user. For example, tenants or owners of apartments can join together in multi-party buildings, but also in office buildings or shopping centres in order to jointly operate a PV system.

The new investment funding and feed in tariff scheme for PV systems [21] makes self-consumption of PV electricity much more attractive and together with the regulation for multi-party buildings makes such solutions very attractive. Some procedures for the planning and installation as well as for the operation must be considered.

First of all, the participation of potential participants has to be clarified. At least two or more parties must participate in the PV system. The planning and construction of the PV community system must also be clarified with the owner of the property and the owner of the house or the owner of the property, as well as, if necessary, with the property management. The PV system must be connected to the shared line (main line) of the building.

The optimum operating model for the community plant must be clarified and an operator / plant supervisor determined, who is also referred to the grid operator as the contact person. It can be selected from several implementation variants (operating models) [23]:

- MODEL 0: Standard power supply without any PV system.
- MODEL 1: PV-system as infrastructure and „free electricity“: the property owner invests in the PV system and provides electricity to the residents (e.g. bicycle storage, laundry room)
- MODEL 2: Establishment and use by residents' association: Residents / property owners invest in the PV system and regulate the operation and the usage shares themselves (for example as association).
- MODEL 3: An external company invests and operates the PV system and residents lease a right of use for self-consumption.
- MODEL 4: Contracting: Contractor builds and operates the PV system and delivers PV self-consumption power to the residents
- MODEL 5: Energy supplier builds PV system as 'full-service supplier', he operates the PV system and supplies PV self-consumption electricity and grid electricity to the residents.

For all participating residents a distribution key must be defined: this is either a static allocation (according to fixed shares) or dynamic allocation (after consumption) of the generated PV electricity.

For the measurement of the 1/4-hour values, on the one hand the current power consumption of the participants, on the other hand the current PV power production, a smart meter or load profile counter is necessary and to be installed at each participant.

The PV system itself must have its own metering point, for the injected energy. The billing of the operator with the participants takes place independently of the network operator on the basis of contractual agreements between the operator and the participants. The operator receives from the network operator the data for billing.

Denmark

Apartments buildings in Denmark are allowed to use one of two national net metering programs (group 2 and 3) administrated by the Danish Energy Agency. The net metering program allow PV owners to install PV systems on the building and allows self-consumption from the PV plans as a substitute for purchasing electricity from the grid.

Net metering group 2 allows net metering on an hourly basis and Net metering group 3 is a net metering program on an instant basis. The value of the self-consumed electricity is app. 0.3 EUR/kWh.

Depending on the choice of net metering program the PV owner has the options to send the excess electricity from the plant to the grid (small administrative cost) for free or enter a commercial agreement for selling the electricity to an electrical trading company at net price at app. 0.02 – 0.03 EUR/kWh. The low price for the produced energy is a motivating factor and a small market driver for installing battery systems in connection with the PV system.

Most apartment buildings have a challenge in using net metering. Often each apartment has their own meter and there is one meter in the building for the common electricity use (light, ventilation, escalator etc.). The PV system has to be installed to one of these meters. The common electrical meter often has a low consumption and are not really usable for consuming the amount of energy produced by the PV plant.

The other option connecting the PV plant to the tenant’s meters will effectively mean that each tenant need to have a part of the PV system directly connected via a dedicated inverter for each tenant.

Both solutions described are not optimal in terms of high self-consumption level or financial.

If the apartment building has only one DSO Utility meter measuring the whole consumption in the building and the building owner measures and charges the consumption at each apartment, a PV system can be installed and used for self-consumption in the whole building.

A few years ago, there was an attempt to introduce a virtually net metering scheme where a PV plant installed on an apartment building could produce directly to the grid and then be deducted in each tenant’s electricity bill. The schema was newer implemented due to large challenges in the DSO´s and electricity sales companies to handle this in their billing systems.

For PV systems above 50 kW it is required to have a production meter (M2) installed and pay a production fee of less than 0.01 EUR/kWh.

In the last year several utilities have beginning charging grid access fees to PV systems owners, for smaller systems there is an annual fee and for larger system above 50 kW the fee is based on the M” meter reading and could be as high as 0.025 EUR/kWh.

France

In France, self-consumption of solar electricity has been recognised in the French law for more than 4 years. From this temporal viewpoint, France can be considered an EU pioneer on this topic. But there are two realities. Whereas individual self-consumption is well established with 70 000 households equipped in 2019, collective self-consumption progresses far more slowly with only around 20 projects operational to date. Within the framework of the national multi-annual energy programming (PPE) being discussed, French Government plans between 65 000 and 100 000 self-consumption installations by 2023, which is not a lot. According to RTE estimations, the number of self-consumers could double each year and amount to 4 million by 2035 representing 9 to 20 TWh (maximum 4% of the total French electricity consumption) [24]

Collective self-consumption was first defined with ordonnance n°2016-1019 of July 27th, 2016 after which a structuring application decree was published in 2017. New legal rules have been implemented in May 2019 and then in November 2019. In particular, the perimeter of one operation has been extended. Initially, participants needed to be located below one same substation. Now, they have to be on the low-voltage grid and respect a geographical criteria; French Government officialised in end of 2019 the possibility of 2 km maximum separating the farest points in the project. The DSO (Enedis covering 95% of the territory) calculates the electricity attributed to each consumer on a time step of 30 minutes and according to rules defined by a specific legal entity organising the operation and clustering each participant. [25] This requires communicating meters set up on all generation and consumption sites.

Among the first collective self-consumption projects led in France, one can flag “DIGISOL”, an ambitious collaborative innovation project carried by a solar engineering company, TECSOL, a start-up focused on energy & blockchain, Sunchain, and a public local land developer, Roussillon Aménagement, and supported by the French funding system called Investment of the Future, managed by the French Environment and Energy Management Agency ADEME (https://www.ademe.fr/digisol) [26] This consortium aims at implementing a blockchain solution in order to optimise the sharing of energy in collective self-consumption operations. It is targeted to deploy the solution in up to 500 multi-family buildings and eco-districts by mid-2020. Within this framework, a municipality in Southern France (Prémian) has recently become a producer with nearly 30 kWp decentralised PV installed on the local culture and art center providing cheap solar electricity to other public buildings in the village (school, post office...) as well as to several other users (bakery, inhabitants...). Thanks to Sunchain’s service, the municipality can count on a reliable and certified energy management system and value this digitally enabled system towards all local citizens in order to trigger energy transition beyond this first step. Another project using the same technology has been installed in a social housing building in Onet le Chateau (Aveyron) and belonging to SOLIHA, one of the major social housing actors in South of France. Equipped with 9 kWp PV on its roof (+20 kWp in individual self-consumption for the commons of the building). This system is working since 07/2019 with 20 tenants. A socio analysis is ongoing in 2020. Thanks to public funding, the PV system payback is less than 12 years with a CAPEX of 51 500 € with annual savings of 4 521 €. On the energy flux level, this system is permitting to achieve nearly 90% of self consumption rate.

Germany

General requirements: Self-consumption of electricity generated with a PV system (up to 100kWp) in multi-family houses is possible, if the PV electricity is used directly by the tenants. The additional direct supply for self-consumption in multi-family houses is granted through the ”Mieterstromnovelle” [27], if inter alia the following criteria are met:

- At least 40% of building area is living area.
- Delivery from PV owner to a third party (tenant).
- Close proximity to the area.
- No use of the public grid.
- Tenants are not obliged to participate in the scheme.
- Locally generated electricity (PV) and electricity from the grid are bundled in one delivery contract and managed by a local distributor.

Locally generated electricity, which is consumed without entering the public grid has no grid fees, but the EEG levy has to be paid. In addition, there is the subsidy "Mieterstromzuschlag" in form of a tariff for self-consumed energy from the local PV systems (up to 100 kW) and a feed-in tariff for the surplus energy fed into the public grid. Further self-consumption schemes can be in place, i.e. for CHP plants.

Technical requirements: The distribution of the locally generated electricity is managed by a local distributor. The multi-family building is connected to the grid by a two-way counter and the PV system feeds directly in the building grid. Each customer has his own counter and depending whether or not the tenant participates or not in the local generation scheme, the tenant receives a mix of locally generated electricity and grid electricity or grid electricity only.

The concept of the electricity counting has to be compliant with § 20 Abs. 1d EnWG and can be realised with load profile counters (SLP), with registering load measurement (RLM) or a combination of both.

Since 2017 18,5 MWp have been installed within the German self-consumption scheme for multi-family houses [28] which is far below the expectation of 500 MW/year. The discussed and announced possible adaptations and improvements of the funding scheme are not yet in place.

Greece

In Greece for the self-consumption of electricity produced from PV systems there is a net-metering legislative framework. Under this scheme the excess electricity injected into the grid can be used at a later time to offset (compensate) consumption during times when PV generation is absent or not sufficient, meaning that the grid is used as a backup system for the excess power productions. The compensation covers a three-year period and any excess energy after the compensation within this period is not remunerated. So practically the size of the PV system should be restricted to a size such that its' annual production does not exceed the annual consumption.

The prosumer avoids the charges for the electricity that he self-consumes. The excess energy injected into the grid is compensated with consumed energy. However, the regulated charges (e.g. charges for the use of the network) for this part of energy are not avoided. This favours the self-consumption of the generated PV energy and forms a motivation for the increase of self-consumption instead of injection into the grid.

In the classical net-metering scheme each PV system is corresponded to one consumption meter, and the output of the PV system is connected physically behind the meter. The same person, physical or legal, should be the owner of the PV system and the consumption meter.

It is possible also for some legal persons to use virtual net-metering (different location for production and consumption), but with the same restriction, the owner of the PV system and of the consumption meter(s) should be the same. It is noted that in the virtual net-metering scheme the energy that is virtually compensated with distant consumptions does not avoid the regulated charges.

The case of multiple ownership of a single PV system to use the energy at the owners' separate consumptions, as would be convenient in multi-apartment buildings applications, is not favoured with the aforementioned schemes.

Since January 2018 a new legislative framework exists that supports the operation of energy communities. Following this, an update of the regulations concerning self-consumption by prosumers was issued, in March 2019. According to this update there is a new category described, namely for energy communities, which may be used for multi-apartment buildings. Owners of apartments may form an energy community (at least 5 members are required) and install one PV system in order to use the PV energy, under a virtual net-metering scheme, for their consumptions. The injected to the grid PV energy is virtually compensated with consumed energy of the members of the energy community, based on predefined share percentages. Needless to say that the regulated charges for this energy are not avoided. The updated regulations for self-consumption, among others, allow for other RES technologies than PVs, as well as storage systems, to be used, and allow for the production and consumption units to be connected at different voltage level (Medium or Low Voltage Grid).

New regulations for net-metering, virtual net-metering, including Energy Communities, are defined in the following Decision issued by Ministry of Environment and Energy [29].

Italy

For PV plants, different incentive schemes were established starting from 2009, with a decreasing reward for the generated electricity in the successive years (19 GW of total PV capacity at the end of 2017). Direct incentives on the produced electricity are no longer in place since 2016, but smaller RES based plants (below 500 kW) can still access to the *net metering* scheme with energy flows hourly metered by bi-directional smart meters. Regarding buildings, the early and partial transposition of RED II EU directive on the promotion of renewable resources [11], defining the concepts of *collective self-consumption* and *Energy Community*, was started by Law-decree 169/2019. The regime is provisional, and the legislator's objective is to test those schemes in view of the full transposition: For this reason, in this phase some requirements allow the development of small initiatives with a limited impact on the overall system.

The decree-law wants to encourage the construction of new plants from renewable sources (max 200 kW each), aimed at satisfying the requests of the collective self-customers located in the same building or block of buildings.

The decree-law introduces the concept of *shared energy* which is "equal to the minimum, in each hourly period, between the electricity produced and fed into the grid by renewable sources plants and the electricity taken from all the associated end customers". For this shared energy, an explicit incentive will be defined, and it could be combined with tax deductions already in place for new RES plants.

The national regulatory authority (ARERA) has launched a consultation about the value of the tariff components that do not apply to the shared energy; besides, it identified the regulatory model to be applied to collective self-consumption. The proposed model is a "virtual" one and consists in continuing to apply the current regulation and to return later the tariff components that must not be applied to the shared energy. In particular, since collective self-consumption occurs at the distribution level, the variable components of transmission grid charges could be exempted. In any case, both the Decree Law and the consultation act require members to use the existing distribution networks for the sharing of energy. Finally, the discussion about new Closed Distribution System will be relaunched, even if it concerns particular layouts as airports or industrial sites, without residential customers.

Japan

Excess electricity purchase program for residential PV systems (<10kW) was initially started in 2009 in Japan. Purchase price was 48 JPY and period was 10 years, and 30% of self-consumption rate was assumed. For the non-residential systems smaller than 500kW including residential PV systems larger than 10kW, purchase price was 24 JPY and period was 10 years, and some amount of self-consumption was also required. In 2012, Japanese feed in tariff low was started and the same purchase period and self-consumption rate were used for the "tariff" calculation for residential PV systems. For the systems larger than 10kW, self-consumption was no more required and purchase period was changed to 20 years. This change impacted Japanese PV market a lot, which was originally dominated by residential PV market but share of >10kW systems were rapidly grown including utility scale mega-solar. For the capacity basis, share of utility scale PV systems a largest. However, in terms of the number of systems, relatively smaller systems (>10kW with 20 years purchase period) was huge. This caused problems in local community due to the poorly maintained small size systems.

In 2020, major revision of the feed in tariff program was applied for the systems smaller than 50kW (non-residential, >10kW). More than 30% of self-consumption rate was newly required for normal operation, and the black start capability for islanding operation in emergency situation such as black out of the grid due to a big disaster are also required.

From the November 2019, 10 years purchase period of residential PV systems was start expiring for the systems which was installed in or before 2009. Those PV systems are already financially paid back but still be able to generate electricity. Currently purchase price for this kind of "graduated from FIT" systems are between 7 to 11 JPY/kWh, and retail price of electricity is around 24 to 26 JPY/kWh, and thus installation of battery storage systems is start booming. Although the market size is still small, self-consumption of PV electricity by using battery storage or EVs is expected to be more popular in Japanese residential and small size PV market.

Netherlands

In the Netherlands self-consumption has not officially been defined as a required measure to realize the sustainable energy transition, even though the potential of this measure could be great given the fact that the installed capacity of PV systems in the Netherlands is growing explosively. In 2018, for instance, it doubled to 4,4 GWp [30] out of which 51% was installed in residential areas, leading to a close to 3% share of solar power in national electricity production. In 2019 this development continued with an additional installed nominal power of 2.4 GWp, representing a growth of 53% and resulting in a total installed nominal PV power of 6.9 GWp [31] out of which 27% residential PV systems and 73 % commercial systems. Though in 2017 the annually added capacity had a 49-51% share for commercial and residential PV systems respectively, this has changed in a 73-27% distribution in 2019, in particular due to the increasing SDE+ subsidy for commercial parties. For self-consumption mechanisms the residential PV market is most important, where LCoE's of residential PV systems (15–24 EURct/ kWh for residential rooftop systems and 6–15 EURct/kWh for community owned systems in 2019) seems most of the time in favour for this mechanism, as compared to the consumer price of electricity delivered by the grid which is in the order of 22 EURct/kWh [32]. Net metering, is the main financial benefit for individual self-consumption of households that supply PV power to the electricity grid, which subsequently can deducted from the grid power fed to a household, at a similar rate of the consumer price for electricity purchased from the grid. Alas, from 2023 this regulation will be slowly phased out until 2031. As can be observed in Figure 2, self-consumption is best possible in Autumn, Winter and Spring when the domestic energy demand is high and the PV power production is relatively low.

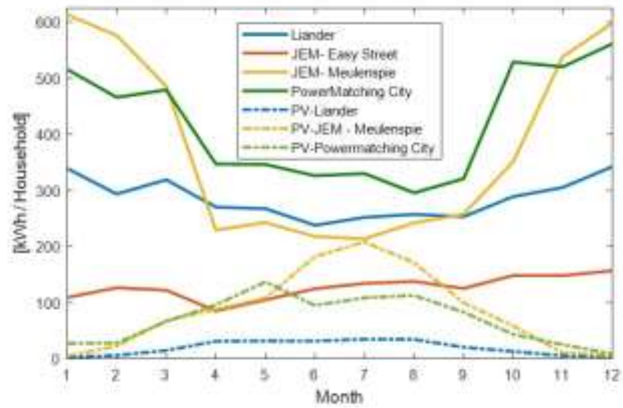

Fig. 2. Monthly electricity consumption and PV production profile over the year in Dutch smart grid pilots [33]

Collective self-consumption in apartment buildings with PV systems is managed by the housing association in case of rental apartments or the owners associations in case of owner-occupied apartments. The owner association is a compulsory cooperative for all owners of apartments in the Netherlands; it operates on the basis of democratic principles.

In the first case, namely rental apartments, the PV system and technical hardware solutions to provide PV power to the building's common electricity demand, and/or individual apartments should be provided by the housing association. For investments in PV systems greater than 15 kWp, the SDE + scheme (Subsidy for Renewable Energy) can be applied for by commercial entities such as housing associations. It provides a compensation for PV electricity per kWh produced for two categories: a) PV power between 15 and 1000 kWp, b) PV power greater than 1000 kWp. For instance in Spring of 2019, the compensation ranged from 9 EURct /kWh to 10,1 EURct / kWh..

In the second case of owner associations, purchase of the PV system and hardware solutions for distribution of PV power to the common demand and/or individual apartments will be arranged on the basis of (1) private investments of the members of the owner association, (2) a loan from the National Energy Saving Fund provided that the building has more than 10 apartments or c) by means of the Postcoderoos regulation (ZIP code regulation). Under this national scheme, members of a cooperative receive an energy tax discount on their energy bill for locally, sustainably generated electricity, such as PV power.

With regard real experiences with self-consumption in the Netherlands, only a few studies have been conducted so far. For instance, on individual self-consumption of households with PV systems, among which an extensive study in the framework of ERA-Net smart grid plus project CESEPS [33, 34], which was executed at and coordinated by University of

Twente [35]. In this study, measured time series of energy data of 217 households from three smart grid pilot projects in the Netherlands (Jouw energy moment, JEM, in Breda, Power-matching City in Groningen, and Profit for All in Amersfoort) and a public reference dataset with smart meter data from 70 households (provided by Liander), were evaluated for one year to get insights in the performance of smart grid technologies, among which PV systems, but also heat pumps and micro-CHP. The data was analysed to determine energy performance indicators in the Dutch climate with its strong variation of irradiance (Fig. 2.)

It was found that for this set of 287 households with a monthly electricity consumption of 100–600 kWh) and a PV production of 4–200 kWh, the median self-consumption appeared to be 50–70%. This can be mainly explained by the relatively small installed nominal power for PV systems in these pilots, ranging from 0,4 – 2 kWp, in combination with a high residential electricity consumption, meaning that often PV electricity can be directly consumed on the moment that it is generated. This situation automatically implies that in these neighbourhoods a substantial share of PV electricity production by individual households is consumed within the local community.

In the future, more studies need to be executed to evaluate how effectively self-consumption mechanisms can be applied in the Netherlands.

Spain

The Royal Decree 244/2019 [36] has substantially changed the rules about self-consumption electricity from PV systems in apartment buildings from April 2019. These rules abolish the previous Royal Decree 900/2015 [37] (popularly known as "sun-tax rule") and regulate not only PV, but any other renewable system in a self-consuming regime.

The most important new rules are briefly described below and are considered very attractive for expanding self-consumption in apartment buildings:

- With the previous regulation, only one person or entity could act as self-consumer, and the energy produced by the self-consumer system was charged except in insular power systems. With the current regulation collective self-consumers can be supplied by only one system ("shared self-consumption") and the energy produced is not charged.
- Under the previous regulation, the generating systems should be inside the self-consumer network or coming from a direct connection to it. Under the current regulation, the generating system can also be in proximity (from a system connected to the same feeder, closer than 500 m, or located in an area with the same first 14 digits of the cadastral reference) to the customer.
- There are 2 types of self-consumers: with and without net metering.
- The generating systems with nominal capacity ≤ 100 kW have simplified technical and administrative rules: (i) with net metering: no registration in the energy producer register is required, but registration is needed in a new register for self-consumption; and (ii) without net metering: the registration is ex officio and the connection should only fulfil the technical rules currently in force (Reglamento Electrotécnico de Baja Tensión).
- All self-consumers must belong to the same modality of self-consumption.
- The generating systems with a nominal capacity ≤ 15 kW placed in urban areas are exempted from requesting access and connection to the distribution grid if the nominal capacity of the generating system is lower than the capacity contracted by the consumer to the utility.
- The generation system can't be directly connected to the interior electric installation of one of the associated consumers.
- The criteria for self-consuming the collective energy produced is freely defined in terms of fixed coefficients by the producer and consumer and, alternatively, in relation to the power contracted by each consumer. Fixed coefficients mean that any surplus of electricity assigned to one consumer but to consumed can't be shared with other consumers but injected to the grid.
- No limits about maximum power of the generating system and no second meter is required.
- Energy surpluses have similar tolls and taxes as for all electricity producers.
- The consumers and producer will be jointly and severally liable vis-á-vis of any breach of this regulation.
- The meters used must be only a basic equipment for invoicing prices and taxes.

In addition, the Circular letter 3/2020 of the National Markets and Competency Commission [38] will regulate the access tolls to the grid, making very attractive the share of electricity between buildings connected under a voltage below 1 kV. Also, a new circular letter expected to be published in summer 2020 will introduce transparency and more flexible rules to obtain access and connection to the power grid, and a new royal decree will also regulate the access and connection to the grid. Moreover, the Spanish Energy and Climate National Plan submitted to the European Commission last March includes the policies for promoting collective self-consumption and the obligation to regulate the Citizens Energy Communities and Renewable Energy Communities.

However, the transformation of fixed coefficients into dynamic coefficients in the regulation for sharing the energy between neighbours in a community building is still missing. As the Directive (EU) 2018/2001 on the promotion of the use of energy from renewable resources considers mandatory to share energy in buildings after 30 for June 2021 (art. 21.4), the introduction of dynamic coefficients is expected not to be before this date.

Sweden

In Sweden the main business model for small distributed PV are the self-consumption business model with avoided costs during self-consumption, and revenues for the excess electricity. During self-consumption the distributed PV owner avoid the Nord Pool spot price, the surcharge for the Swedish green electricity certificate system and electricity trading surcharge, along with the variable grid fee that is based on consumed kWh. The savings on grid fees very much depend on where in Sweden the PV system is located, as Sweden host about 170 grid operators and each grid operator have its own grid fee structure where the fixed and variable part varies.

The tax savings included the VAT that is excluded for all self-consumed electricity. With regards to the energy tax there are size limits set for the exception at self-consumption:

- The owner of one or more PV systems with a total power of less than 255 kW_p does not have to pay any energy tax on the self-consumed electricity.
- The owner of several smaller PV systems that has a total power of 255 kW_p or more, but where all the individual systems that are below 255 kW_p, report and pay a reduced energy tax of 0.005 SEK/kWh on self-consumed electricity from the PV systems.
- The owner of a single PV system that exceeds 255 kW_p pays the normal energy tax of 0.353 SEK/kWh on the self-consumed electricity produced in that facility, but 0.005 SEK/kWh in energy tax on the self-consumed electricity from other PV systems if these systems have a power capacity that is less than 255 kW_p.

For the excess electricity, the base revenue for distributed PV owner comes from selling the electricity, the green electricity certificates and guarantees of origin to their electricity retailer. Several utility companies have introduced compensation schemes for buying the excess electricity produced by distributed PV. The offers and compensation vary usually between 0.25 and 0.70 SEK/kWh [39] between different utilities, and usually depends on if the utility buys guarantees of origin and the green electricity certificates, and if the PV systems has been acquired from the utility or not. Furthermore, distributed PV systems smaller than 43.5 kW are entitled to compensation from the grid operator for the excess electricity that is fed into the low voltage grid. This reimbursement corresponds to the value of the energy losses reduction in the grid that the excess electricity entails. The compensation varies between different grid operators and is typically between 0.02 and 0.10 SEK/kWh [39]. The third revenue stream for the excess electricity is a feed-in-premium. The feed-in-premium works as a tax credit and is 0.60 SEK/kWh for renewable electricity fed into the grid. To be entitled to receive this tax credit the fuse may not exceed 100 amperes at the connection point. The basis for the tax reduction is the number of kWh that are fed into the grid at the connection point within a calendar year. However, the maximum number of kWh for which a system owner can receive the tax credit may not exceed the number of kWh bought within the same year. In addition, one is only obliged to the tax credit for a maximum of 30 000 kWh per year.

Collective self-consumption from a PV system in an apartment building is allowed in Sweden if all the apartments share the same grid subscription. The general approach for a solution using this option is that the electricity is included in the rent, but that electricity consumption is being measured internally by the housing company/society and the monthly rent is affected by this consumption. Collective self-consumption where the electricity is transported over a grid that is covered by a grid concession is currently not allowed. But a recent governmental investigation is suggesting changing the law so that an internal low voltage grid for energy sharing between buildings and facilities may be built and used without a permit within a single property.

Switzerland)

Self-consumption of electricity generated by PV systems has always been allowed in Switzerland. Since 2014, rules for self-consumption are explicitly stated in the Swiss energy law. The rules which apply to self-consumption have been modified several times since then. Three basic self-consumption schemes are available today:

- Single family home (one electricity customer and one PV system connected to the customer): Consuming its own solar electricity, the customer saves the cost for energy, the cost for the grid and the cost for fees and taxes. Self-consumed electricity safes thus about 20 euro cents per kilowatt-hour.
- One or several buildings, option "DSO" (several electricity customers and one or several PV systems): The DSO still supplies every household directly. However, the DSO does the virtual self-consumption calculation for the whole self-consumption area and deducts the costs for energy, grid and taxes from the bills of the end customers, if the electricity consumed by any of the customers was produced locally. The main condition which applies to this scheme is, that within the self-consumption area the public grid cannot be used.
- One or several buildings, option "self-consumption society": Instead of being supplied individually by the DSO, the customers who want to consume their own electricity can gather together and act as one single customer towards the DSO (German: "Zusammenschluss zum Eigenverbrauch", French: "Regroupement dans le cadre de la consommation propre"). In consequence this single customer gets market access for buying electricity if the total consumption of the parties reaches 100 MWh per year. If the people living in the apartment buildings are tenants, then the PV system owner is not allowed to sell the solar electricity to a higher price than what the tenants would have paid for conventional electricity supply. Furthermore, he is obliged to share the

profit of the PV system with the tenants (after a deduction of 2 % interest covering his risks as an investor).

Up to 30 kW no production meter is needed. The production and consumption can be measured with only one meter using 2 registers for independent measurement of consummation and feed-in. Measurements are usually manually read out either once a year or once in 3 months.

For 30 kW and more, separate production measurements are required. Data is usually measured in a temporal resolution of 15 min and is read out automatically once a day. The reason for this measurement is the Guarantee of Origin.

United States of America

In the past the vast majority of residential-scale PV systems in the U.S. are interconnected under net metering agreements which generally have received broad support in the most of the 50 states which typically regulate the rules related to interconnection. Technical requirements of PV systems are defined by IEEE 1547-2003. As a new revision of the standard, IEEE 1547-2018, has been released in April, 2018. Multi-family buildings (e.g. duplexes and townhouses) in the U.S. often have one energy meter per residence and thus regulatory barriers to install PV systems on these buildings are typically minimal for owner occupied units. Homeowner associations (HOAs) are also common across the U.S., particularly for condominiums and newer construction neighbourhoods of various configurations of multi-family residences. These associations often provide communal services to the members and the procurement and operation of PV systems located on the roofs of residences within the HOA can be part of the HOA contract. This allows a potential route to PV access even for condominium dwellers who do not have direct access to the roof space.

Self-consumption supportive tariffs are relatively new in the U.S. Recent developments in Hawaii and a settlement-derived self-consumption offset rate approximately 1¢ higher than the calculated equivalent net metering rate in Arizona [40] are examples of the nascent changes from net energy metering to rates encouraging self-consumption. However, self-consumption incentives are fairly small and may not significantly drive consumer demand and house-level energy storage integration it may lead the way for further self-consumption developments. Many states allow the size of interconnected PV systems to be limited in estimated annual energy generation equal to a particular fraction (i.e. 80%) of the estimated annual energy usage of the residence. These practices somewhat limit the need for self-consumption policies to reduce aggregate grid impacts. However, these same practices do potentially impact the ease and cost of installing PV on apartments and condominiums as an actual electrical connection to individual unit's electrical panels and energy meters; complicating PV installation compared to if one energy meter for a whole building was allowed.

Many utilities in the U.S. are also implementing programs that allow for access to solar power for all customers regardless of physical access constraints. These programs usually are effectively utility owned or procured large scale systems which are located within the general region but are not specifically co-located with the customers benefiting from the system's generation, thus the benefit of self-consumption in these cases cannot be realized.

III. Technical Aspects

Around the world, there is a wide range of residential PV prices, from below USD 1 000 per kWp to as much as USD 3 500 per kWp. This can be explained only in part by the degree of local competition between dealers and installers as well as differences in labour costs. Another major factor is the lack of competition between countries regarding installation services due to national differences in installer certification and local administrative and permitting requirements.

Across different states the tax, levy and subsidy regimes for PV energy equipment purchases and electricity sales differ substantially. The same is true for permit fees or connection charges as well as other administrative costs. These may be applied on a per-installation basis (and can be as high as USD 1000), or on an installed power basis, or a combination of both.

In general, self-consumption of PV generation is incentivized by low volumetric rates (close to wholesale tariffs) paid to prosumers for export of excess PV generation. Applying PV generation to aggregated building loads to increase self-consumption can technically be achieved through an embedded network (EN) or using a secondary distribution and metering arrangement.

Use of an EN to aggregate building loads affords access to commercial retail tariffs at the gateway meter, which typically include lower volumetric rates, smaller variation between peak and off-peak rates, and higher fixed and capacity charges. However, this is in conflict with regulations in a number of countries. Although these can create bill savings for customers, they may reduce the financial benefits of adding PV (or battery storage) to an EN. Nevertheless, although the economic case for battery storage is dependent on substantial future capital cost decreases (to a greater extent than for individual households), addition of PV can add significant customer value to an EN for many buildings. Regardless, most of these benefits can be achieved also with "commercial" schemes, using the public network for the energy exchanges within the residential building [41].

Beside the regulation and tax differences the relative cost of the system and network fees amidst overall electricity retail prices for the residential and commercial (industrial) sectors have a huge impact on the level and attractiveness of self-consumption.

This part of the retail price affects the network operators' income by self-consumption, but on the other hand could be used for network integration, storage and self-consumption support purposes.
Today network fees for residential customers are often based on the contractual power and on the energy consumption. With the introduction of smart meters this scheme could be changed to the maximum load or feed in power. Another possibility are dynamic network tariffs, which take into account the time of delivery during the day and metered every quarter of an hour similar to already existing commercial tariffs. This would reduce on one side the financial advantage of self-consumption. On the other side optimization of self consumption also with the help of additional batteries would reduce the maximum load and maximum feed in power. This could lead to a lower network fee for the self-consumption client and increase the potential share of distributed generation that could be connected to the existing network for the DSO.

To this aim some software tools [42] have been developed to plan and configure residential self-consumption architectures (Fig. 3) also including smart converters and hybrid energy storage systems to control and optimize produced/consumed energy flows. Case study analyses would allow the identification of technical/economic indices and operating guidelines for the auto-produced-self-consumed energetic resources in building scenarios and EN.

The following analyzes two self-consumption case studies according to tools proposed facilities.

The batteries aided self-consumption configuration is characterized by a PV generation system, a battery storage system and a set constituted by different loads, as schematically reported in Fig.4. In addition, a Vehicle to Grid (V2G) system is included considering the opportunity to increase the configuration flexibility by taking advantages of the Electric Vehicle (EV) batteries to store or supply energy.

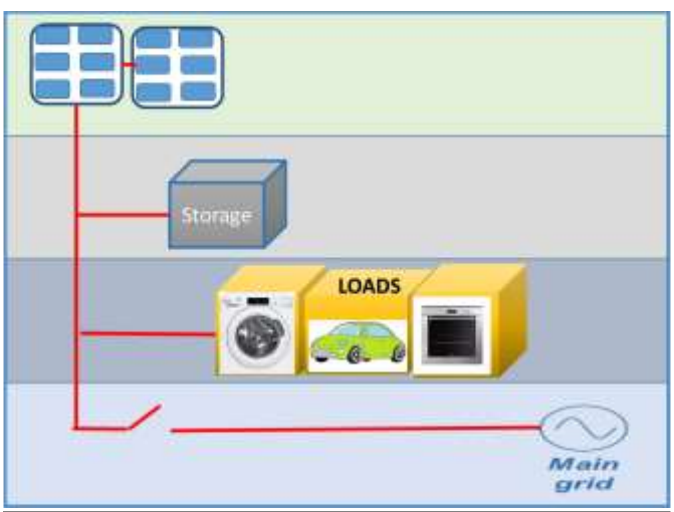

Fig. 3 Schematic representation of residential self-consumption architectures

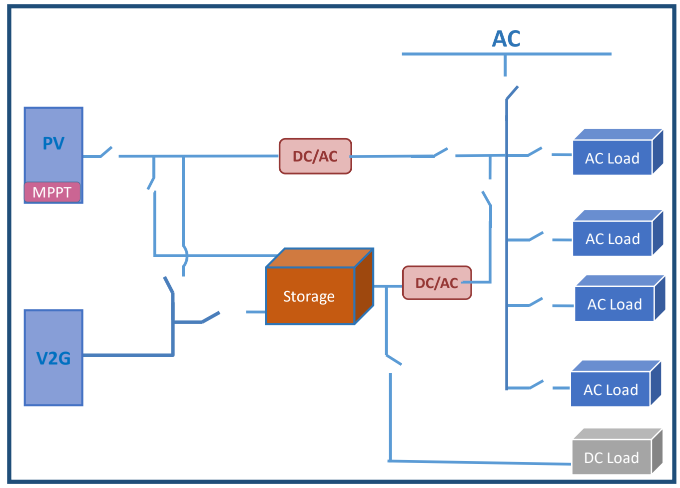

Fig. 4 Batteries aided self-consumption configuration

Case study 1: Batteries aided self-consumption

The PV generated energy can be suitably converted by an inverter interface to fulfill loads consumption. It can also be stored to satisfy energetic requirements during night-time or PV production lack.

The careful design and sizing of the systems and devices of this energy configuration, together with the adoption of an adequate control strategy is well suited to applications in NZEB and residential AC micro-networks, not only including single-family homes but also apartment buildings and residential clusters.

It is worth noting this configuration efficiency strongly depends on the PV power maximization by Maximum Power Point Tracking (MPPT) systems, the battery optimized management and on the conversion interface performances (Smart converters, inverters, etc).

Furthermore, the number of DC loads, mobile and portable devices as well as EC for people mobility (electric bikes, electric scooters and electric cars) and lighting systems is seeing an increase in our daily lives. If the recent diffusion of these DC load is considered, the analyzed configuration can be completed by a DC line to supply direct-current consumption.

In such context, different control strategies can be adopted according to the specific installation geo-localization, to the available surfaces for PV generators placement and the citizens energetic requirements. Artificial Intelligence (AI) techniques can elaborate interesting generation/consumption match solutions to guarantee the continuous real time energy balance and the main grid absorption minimization.

Case study 2: Hybrid storage aided self-consumption

A hybrid storage system constituted by battery and Supercapacitor devices characterizes the second self-consumption configuration reported in Fig. 5.

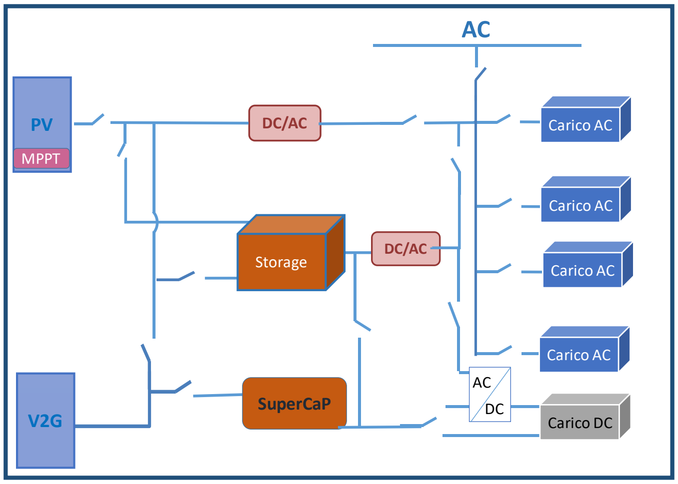

Fig. 5 Hybrid storage aided self-consumption configuration

These hybrid storage systems represent promising solutions since these devices are able to face sudden peak absorption with a very fast dynamic.

Energetic absorption profiles are well known in case of residential users. They are characterized by peak absorption at evening and night-time with a great number of mobile devices to be charged and energivorous load appliances such as ovens and washing machines, etc.

The joint control of the hybrid (battery + Supercapacitor) storage allows users to make the best use of the battery to fulfill the electric energy requirements and, at the same time, Supercapacitor satisfies absorption peaks ensuring the supply continuity, efficiency and reliability.

Future guidelines and national regulations would provide technical, economic and funding mechanisms to enhance the adequate application and diffusion of self-consumption architectures.

It is worth noting the suitable management of aggregated self-generated and locally consumed or stored RES can contribute to increase the main grid reliability contributing to prevent and/or reduce imbalance conditions and instability.

To this aim different energetic platforms have been developed to the management of distributed and self- consumable energetic resources and storage also employing ICT and blockchain techniques.

Last but not least there is a wide spread of financing costs in the different countries. The influence of financing was already presented earlier [43].

IV. Conclusions

For over 50 years scientists, engineers and industry have worked hard to decrease the hardware costs of photovoltaic solar electricity generation systems. Already in 2017, the costs of direct current (DC) electricity in central Europe at the PV module level had dropped to less than 0.02 USD/kWh. Since then it is the technology with the lowest cost for electricity generation. Even if the low DC generation cost is only a part of the total, as there is an additional cost component to provide the electricity to the customer where and when it is needed, photovoltaic solar electricity is one of the lowest cost options to de-carbonise our electricity supply.

Increased self-consumption of PV electricity can help to accelerate the transition to a decarbonised electricity system. The utilisation of apartment roofs for PV installations play an important role to reach this goal. To enable the participation of people living in these buildings, appropriate regulatory and legal conditions, which enable a secure and fair financing of the necessary grid infrastructure and providing economic benefits for residential PV system operators and the society is necessary.

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