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Photovoltaic distributed generation – An international review on diffusion, support policies, and electricity sector regulatory adaptation

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ABSTRACT

In recent years, the diffusion of photovoltaic distributed generation (PVDG) has played a key role in achieving climate and energy policies goals. This increase stems from both the decline of technology costs and also from the support policies adopted worldwide. Yet, the achieved diffusion levels and the related impacts vary across locations. By applying a new analytical approach to thirteen international case studies, the study provides an exhaustive systematization of policies and regulatory adjustments of PVDG diffusion, focusing on the electricity distribution sector. The goal is to identify possible common patterns and path dependence trajectories. The results show that the policy impacts and the regulatory adjustments vary mostly according to the category of the support policies implemented. In countries where feed-in tariffs (FiTs) have been introduced, the main concern is the increasing cost of policies maintenance. The regulatory adjustments are mostly PV specific involving, in most cases, the reduction of the FiTs. In regions where net metering policies have been implemented, otherwise, the impacts are predominantly related to cost-shifting issues, thus requiring regulatory changes which can also be prosumers' specific, but that attempt to correct allocative distortions through electricity tariffs.

1. Introduction

Photovoltaic distributed generation (PVDG) support has become a central part of climate and energy policies [1]. Conceptually, PVDG is characterized as distributed given its usage, and connection to the electricity system. In terms of usage these systems are installed with the purpose of self-consumption and are therefore located close to the loads. Regarding connection to the electricity system these systems are tied to the Medium-Voltage or Low-Voltage segments of the grid, or installed behind the meter at the consumer's facilities [2,3]. This technology allows a source of clean electricity in areas with limited or no electricity access, as well as a source of competitive renewable electricity for more developed countries engaged in sustainability transitions [4]. Moreover, growing deployment of photovoltaic (PV) can result in social and environmental benefits, including job creation or decarbonization of the electricity sector [5]. A combination of growing support schemes for low-carbon electricity sources, and improved technological competitiveness have contributed to its diffusion. From 2009–2017, the cost of PV modules decreased by over 85% [1]. In 2016, PVDG accounted for 29% of the 74.8 GW total solar annual installed capacity at a global level [6]. By 2030, PVDG installed capacity is expected to reach 546 GW, corresponding to 62.6% of total photovoltaic capacity [7].

The observed growth and the expected increase of PVDG, nonetheless, represent a significant challenge [8]. The integration of PV systems in distribution grids, growing costs of support policies, and the allocation of grid costs among prosumers and non-photovoltaic customers are some of the issues to be addressed in years to come [9]. The combination of these dimensions gains further relevance when considering that the growth on PVDG diffusion depends on both an adequate PV policy support framework as well as on an electricity distribution sector that is ready for a scenario with high shares of variable distributed generation. This context creates a compelling case for analysis on what drives PVDG diffusion, possible impacts and regulatory adjustments [10,11].

The policy and institutional arrangements differ from country to country, and depending on the national governance structure, can also diverge within a country. We categorize previous studies on the

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dynamics of PV according to their focus on:

- *Support policies design* characteristics – studies describing existing and in-the making policies, aiming to provide clarity and guidance for policy-makers, as well as investors on the exiting levels of support and associated requirements [12–15];
- *Diffusion results assessment* – studies analysing how PVDG evolved over time considering implemented support policies [16–19] and
- *Support policies impacts* – studies reviewing investment decisions and technology competitiveness [20–24].

Building on one hundred references in existing literature, we survey PV support policies, related diffusion processes, and integration issues in electricity distribution systems through a review of thirteen international experiences. These include: Brazil, California, Hawaii, Nevada, New York, Japan, Belgium, France, Germany, Italy, Portugal, UK and Australia, covering four continents. The novelty of this work lies on two main aspects: first, a new analytical method was adopted, grounded on five specific criteria. Secondly, literature survey was complemented with information only possible to obtain directly from experts. Consequently, several workshops with representative policy makers and stakeholders were organized from 2016 to 2017 and interviews were locally conducted between 2015 and 2017. The five criteria were originated from the building of a large platform of up-to-date data, gathered considering different sources of information.

The main objective of this study is to provide an analytical framework that discloses new evidence and allows supporting public bodies in the assessment and selection of policies, while providing potential investors with useful information on this global industry.

The paper is organized as follows. Section 2 describes the methodology adopted. Section 3 presents the case studies. In Section 4, applying the criteria analysis approach, a discussion of the illustrative case studies is presented. Finally, in Section 5 some conclusions are conveyed and future work developments are suggested.

2. Methodology

The review of international experiences presented in this study results from data collected through not only desk based research but also, and more relevantly, from information just possible to gather from a series of multi-stakeholder workshops, and expert interviews. Fig. 1 summarizes the review strategy adopted. In the first stage of the research, the multi-stakeholder workshops and specialists interviews supported the selection of the international cases and the criteria applied on the analysis. In the second stage, data for the cases and criteria selected was obtained from primary and secondary sources. Primary data collection was carried by an extensive review of existing literature on each case, adding up to one hundred references. Secondary data was obtained from the expert interviews.

A series of 10 multi-stakeholder workshops were conducted between May 2016 and October 2017 (Table 1). These events were structured around pressing issues related with distributed generation and electricity sector regulatory challenges. Participating stakeholder included policy makers, regulators, researchers and academics, electric utilities, and industry representatives.

Between July 2015 and December 2016, 20 interviews with experts from key institutions in Europe and in the USA were conducted (Table 2).

The case studies definition was supported by the workshops' presentations and expert interviews. North and South America, Asia, Europe, and Oceania cases were selected given their geographical representativeness, support policy pioneering and diffusion diversity (Table 3).

Likewise, the selection of analysis criteria was also enabled by the workshops and interviews. Our analytical approach combines three domains: PV specific support aspects, PV diffusion levels, and electricity distribution system characteristics. In addition to defining the analysis categories, we structured the three large domains into a hierarchy of analysis (Fig. 2).

By defining a criteria hierarchy, we explore PV diffusion trajectories across cases. The rationale for the different criteria is presented as follows.

2.1. Criterion 1 – 'PV distributed generation electricity compensation time frame'

We start by identifying the time frame of PV electricity generation compensation mechanisms in each region. The time frame of the available compensation is a critical support policy characteristic as it signals the flexibility to PV unit owners on the use of excess electricity generated. For instance, recent PV support policies oriented toward self-consumption have shorter compensation time frames, to incentivise local consumption of generation and matching of system capacity with local needs [14]. Conversely, net metering policies often span larger compensation time frames, from months to years depending on the location. The existence of a compensation time frame gives producers the possibility to use the electricity distribution grid as a zero cost storage solution, thus resulting in a higher incentive for PV diffusion as the producers can use the excess generation to offset their electricity bill over a large period of time, thus increasing the obtained benefits of

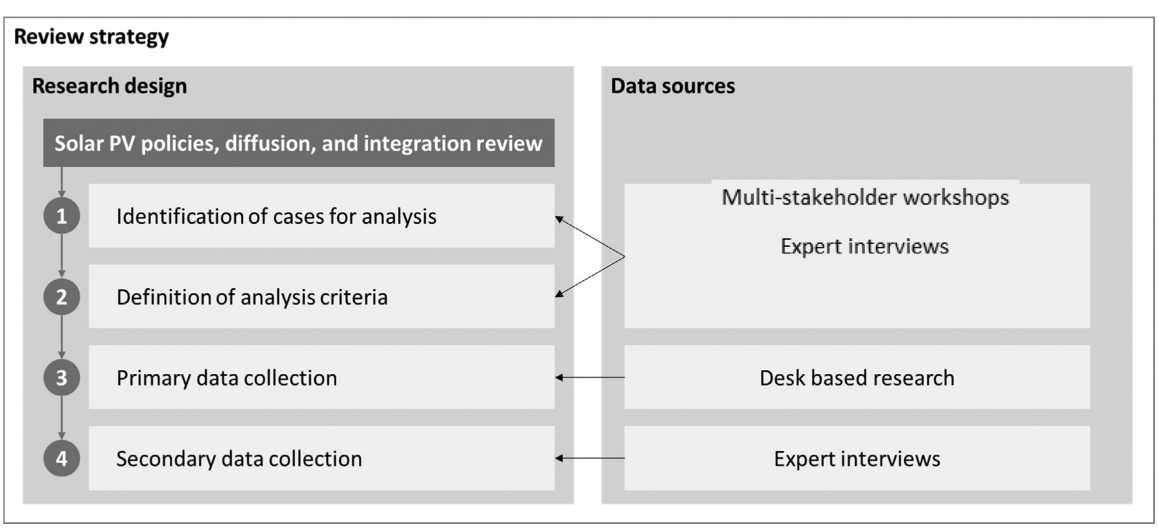

Fig. 1. Review strategy.

Table 1
Multi-stakeholder workshops.

Workshops	Theme	Date	Location	Participating stakeholders
4	Impacts of distributed energy resources for electricity distribution	2016–2017	Rio de Janeiro Brazil	Policy Makers Regulators
	Electricity sector regulatory challenges International experiences with distributed generation Electricity sector of the future			Researchers and Academics Electric utilities Industry
3	Electricity sector regulatory challenges	2016–2017	Portugal	Policy Makers Regulator
	Electricity sector regulatory challenges Electricity sector regulatory challenges			Researchers and Academics Electric utilities Industry
2	European Union electricity sector regulatory challenges Electricity sector regulatory challenges	2017	Brasília Brazil	Policy Makers Regulator Researchers and Academics
1	Electricity sector regulatory challenges	2017	São Paulo Brazil	Policy Makers Regulator

Table 2
Expert interviews.

Expert interviews	Stakeholder	Location
1	ENEL	Italy
1	Regulatory Entity for Energy Services (ERSE)	Portugal
2	Aachen University (EON Research Center), BNetzA	Germany
2	Électricité de France (EDF), EDF Research Center	France
2	University of Las Vegas, Desert Research Institute	Las Vegas
3	Public Utilities Commission of Nevada, Nevada Governor's Office, NV Energy	Nevada
1	Pacific Gas and Electricity Company	California
2	National Renewable Energy Laboratory, Rocky Mountain Institute	Colorado
3	California Public Utilities Commission, California Energy Commission, Lawrence Berkeley National Laboratory	California
3	Hawaii Public Utilities Commission, Hawaii State Energy Office, Hawaiian Electric Company	Hawaii

Table 3
International cases for review.

Region	Americas	Asia	Europe	Oceania
Case	Brazil California, USA Hawaii, USA Nevada, USA New York, USA	Japan	Belgium France Germany Italy Portugal United Kingdom	Australia

owning a distributed generation unit [20,25,26]. Rolling-over compensation mechanisms, however, can cause negative impacts on distribution utilities financial sustainability and lead to cost-shifting issues, as grid costs avoided by PV customers are increasingly shifted to non-photovoltaic customers [9].

In our study, we consider the following compensation time frames:

- Real-time compensation, for the cases where the is no roll-over of excess generation and
- Rolling over compensation, for the cases where producers can accumulate credits resulting from excess generation and use them to reduce future electricity bills [27].

2.2. Criterion 2 – 'Existence of complementary support policies'

Secondly, we identify the existence of additional support policies beyond electricity compensation. Complementary support policies can be observed as an indicator of strong engagement in the promotion of PV distributed generation diffusion at a certain region. The need of complementary policies can be a sign that the local PV market is not yet mature enough to evolve [28,29]. As PV diffusion support policies are strong drivers for distributed generation, this indicator can be considered as a proxy on market development. Therefore,

- *No* support policies indicate a market with significant maturity to thrive driven by market forces, instead of support policies;
- *Existence* of support policies indicates the need to push for market development, for which market forces are not sufficient.

2.3. Criterion 3 – 'Share (%) of PV distributed generation on load'

Criterion 3 relevance is to provide an understanding on the impact of policies in terms of share of PV distributed electricity generation in relation to the region's load. This criterion results in a comparable metric of diffusion, which allows for understanding performance of distributed generation in relation to the regions total load [30,31].

Therefore, we consider two levels of diffusion:

- $<$ 3%, classified as regions with restricted contribution of PV and
- $\geq$ 3%, classified as regions with substantial contribution of PV.

2.4. Criterion 4 – 'General electricity distribution regulatory changes on tariffs'

The analysis of general changes in the electricity distribution tariffs is conducted to provide a complementary perspective on broader aspects beyond the PV specific policy framework. As it has been previously reported, increased shares of PV are a goal of climate and energy policies to deliver the ambition of a low carbon economy. However, the rising participation of PVDG deepens the uncertainty regarding DSOs revenue and worsens the risk of cross subsidies between customers, exposing weaknesses of current network tariffs structure, which foresees the recovery of utilities' fixed costs through mostly volumetric rates. In this set up, the transition to a more decentralized electricity system requires a reassessment of distribution tariff design

Domain	Criteria Hierarchy	Analysis categories	
PV support policies	**Criterion 1**		
	PV distributed generation electricity compensation time frame	Real-time compensation	Rolling over compensation
	Criterion 2		
	Existence of complementary support policies	No support policies	Existence of support policies
PV diffusion	**Criterion 3**		
	Share (%) of PV distributed generation on load	< 3%	≥ 3%
Electricity distribution sector adaptation	**Criterion 4**		
	General electricity distribution regulatory changes on tariffs	No general changes implemented	General changes implemented
	Criterion 5		
	Specific electricity distribution regulatory changes targeting PV distributed generation issues	No specific PV related changes implemented	Specific PV changes implemented

Fig. 2. Analysis criteria.

and even of distribution regulation frameworks, in order to ensure that DSOs can provide a secure and reliable grid while guaranteeing equity across ratepayers. Criterion 4 is then indispensible to help identifying general changes in the tariffs' structure, for which we consider two main cases:

- No general changes implemented, as an indicator that the existing regulatory framework is sufficient and
- General changes implemented, as an indicator of adaptation efforts at the electricity distribution level.

2.5. Criterion 5 – 'Specific regulatory changes targeting PVDG generation issues'

With the inclusion of Criterion 5 we analyse the existence of specific regulatory action implemented as a response to concerns arising from PVDG. This indicator gives a perspective on electricity distribution sector adaptation to the integration of distributed generation PV. For this criterion, we consider the following situations:

- No specific PV related changes implemented, as an indicator that the existing regulatory framework is adequate to existing levels of PV diffusion and
- Specific PV changes implemented, as an indicator of adaptation efforts at the electricity distribution level to accommodate the existing levels of PV diffusion.

3. Results

This section is divided in 13 sub-sections, devoted to the disclosure of results on Brazil, California, Hawaii, Nevada, New York, Japan, Belgium, France, Germany, Italy, Portugal, UK, Australia.

3.1. Cases description

3.1.1. Brazil

The net metering scheme for micro and mini photovoltaic generation was first introduced in Brazil in 2012, and revised in 2015 (through the Normative Resolution 687, from ANEEL). Apart from self-consumption, when exporting net excess electricity to the grid, prosumers receive energy credits, based on the amount of active power, which can be compensated over a period of 60 months [32]. The compensation does not imply a financial transaction, but a physical, one-for-one compensation. PV systems up to 75 kW (micro generation), and between 75 kW and 5 MW (mini generation), are eligible to the net metering. Although the commercialization of electricity surpluses is forbidden, the regulation enables photovoltaic customers to exploit four "business models": *i*) local self-consumption; *ii*) remote self-consumption, i.e. the transferring of electricity generation to another site, owned by the same private individual or company; *iii*) enterprise with multiple consumer units, which allows the installation of PV systems in condominiums; and *iv*) the shared generation, through which legal or private individuals can create a cooperative (or a consortium) and install a PV system, sharing the electricity generation [32]. Other support measures, such as tax exemptions, are available, but they differ widely among states. In response to these policies, 0.6 GW of micro and mini photovoltaic systems were installed in the country until 2016 [32]. These systems generated 53.6 GWh in 2016, meeting 0.01% of Brazil's load [33].

3.1.2. California, USA

One of the main policies supporting PV distributed generation in California is the Net Energy Metering (NEM), adopted in 1995 [34]. According to NEM, when exporting electricity to the grid, prosumers receive energy credits proportional to the full electricity retail rate, and valid for two years [33]. Other support policies include: the solar Investment Credit (ITC), a federal investment tax credit available both for residential and commercial customers; and the California's Renewable Portfolio Standard (RPS), which requires that 50% of electricity retail sales must be served by renewable sources by 2030 [36,37]. In 2016, and in response to the support policies, California registered 4.7 GW of net-metered distributed PV capacity [38]. During the same period, the small-scale photovoltaic generation was 8.23 TWh (3.2% of the state's load) [39–41]. In an attempt to mitigate cost-shifting from net-metered customers to non- photovoltaic households arising from this scenario, the NEM program was revised in June 2016, [42]. Interconnection fees ($75-$150), based on the historical interconnection costs, non-bypassable charges of approximately $0.03 per kWh consumed from the grid, and time-of-use (ToU) tariffs compulsory for new photovoltaic consumers were implemented [43]. It is also worth noting that in 2015 the California residential rate structure had been revised in order to better reflect the costs of providing electric services [44]. One of the goals of the reform was to promote the gradual convergence of the four-tiered rate structure down to just two-tiers, to be completed in 2017 [42,43]. Additionally, it was determined that ToU rates must be implemented for all residential customers until 2019 [42].

3.1.3. Hawaii - USA

Hawaii transitioned from a net-metering oriented scheme, toward a self-consumption oriented scheme. This shift resulted in a reduction of the support given by the policy framework, toward one that motivates the diffusion of systems for self-consumption, rather than systems planned to provide excess generation. Currently, prosumers have two options: the Customer Self-Supply (CSS) scheme and the Customer Grid-Supply (CGS). The CSS supports solar installations designed to self-consumption, as the customers are not compensated for the electricity exported to the grid. Photovoltaic systems up to 100 kW, on the other hand, are eligible for the Customer Grid-Supply (CGS) program, according to which customers receive a pre-approved credit for electricity sent to the grid (lower than the retail rate) and are billed at the retail rate for electricity they use from the grid [45]. Excess credits do not receive any kind of remuneration [45]. Additionally, in both schemes prosumers have to pay a minimum monthly bill of US$ 25, to cover grid fixed costs [45]. Another key measure related to the promotion of a better management of residential consumption was the approval, in 2015, of a pilot program, offering time-of-use rates for household customers. The participation is voluntary and limited to 5.000 participants [46].

Moreover, Hawaii has also a set of fiscal and financing support schemes: Hawaii's Renewable Energy Technology Tax Credit, GreenSun Hawaii Program, and the Honolulu Solar Loan Program. As a result of these policies, small-scale photovoltaic generation reached 760 GWh in 2016, corresponding to 8% of Hawaiis's electricity load [39–41].

3.1.4. Nevada - USA

PV support policies currently available in Nevada include a net metering mechanism, adjusted in 2015 to overcome cost-shifting concerns between consumers with and without PV systems. Systems with a maximum installed capacity of 1 MW are eligible to the scheme, according to which the credits generated are valid for a period of one year [47]. The 2015 net metering reform included a higher monthly fixed charge (and the consequent reduction of the volumetric component), to cover system costs related with distributed generation, and a lower value for excess energy sent back to the grid, linked to utilities' avoided costs [48–50]. Yet, these changes caused a negative impact on the photovoltaic market growth, and were revoked in May 2017 [51]. The previous NEM rates were re-established for all customers. Other support policies available in the state comprise the Solar Generations Programme, providing an incentive based on systems capacity, and a fiscal incentive instrument, through the Renewable Energy Systems Property Tax Exemption. Nevada is the tenth U.S. state with the highest distributed photovoltaic installed capacity, with an amount of 0.2 GW, as of May 2017 [52]. In 2016, small scale photovoltaic systems reached a total generation of 372 GWh [40]. This amount represented approximately 1.03% of the state's electricity load [39].

3.1.5. New York

PV support policies include a net metering scheme, implemented in 1997. Currently, it is available for systems with a maximum installed capacity of 25 kW, ensuring that excess generation exported to the grid receives credits valid during one year [53] Reflecting apprehensions about the impacts of PV diffusion on distribution utilities, the net metering scheme evolved from excess generation valued at retail prices, to a scheme based on the avoided-costs resulting from the excess energy supplied by the PV installations [53]. The NY Sun programme complements this scheme, providing financial support to residential, commercial, and industrial consumers [54]. In addition, New Yorkers benefit from a fiscal incentive through the Solar Energy System Equipment Credit [55]. Reflecting such support policies, New York figures are among the top five states in the U.S. in terms of distributed PV Installed Capacity, with a total of 0.6 GW [52]. The small-scale PV generation reached 82 GWh in 2016, which was equivalent to 0.6% of the state's load [39–41].

3.1.6. Japan

Japan has been an early promoter of PV energy. Its initial support policies have focused on providing investment and financing aid. In 2003, a Renewable Portfolio Standard (RPS) system was introduced. In 2012, the country adopted a FiT, replacing the RPS and revising the existing purchasing scheme [56]. According to the FiT scheme, in 2016, systems with a capacity up to 10 kW received 31 ¥/kWh injected into the grid, guaranteed for 10 years. Larger scale systems, with a capacity greater than 10 kW, received 24 ¥/kWh generated in the system, guaranteed for a period of 20 years [56]. The total cost of the FiT scheme was about ¥ 2.3 trillion in 2016, resulting in a surcharge on the electricity bill of 2.25 ¥/kWh [57]. In an attempt to contain the policy cost, a partial revision of the FiT was approved in February 2016 [56]. The introduction of a new authorization system for PV projects, the termination of the tax relief on photovoltaic installations (depreciation of 30% in the first year) and the creation of reverse auctions for large scale systems were some of the measures approved [57].

During the time since the implementation of the FiT policy, photovoltaic distributed capacity has risen from less than 2 GW in 2009 to 32 GW in 2016 [58,59]. PV distributed systems generated 30.5 TWh in 2015, representing 3.2% of the country's electricity load [59–61].

3.1.7. Belgium

Belgium is divided in three regions (Flanders, Wallonia and Brussels), having each its own regulator, responsible for promoting renewable energy sources at the regional level [62]. In Flanders, PV generation is supported by a net metering scheme, available for systems bellow 10 kW, and a quota system, based on tradable green certificates, valid for systems above 10 kW [63,64]. In Wallonia, PV systems less than or equal to 10 kW are eligible for the net metering scheme, which allows the compensation of credits through one year, and for Qualiwatt, a direct capital subsidy paid on a yearly basis, that can be received additionally to net-metering [64,65]. A quota system is available for systems higher than 10 kW. In Brussels, a net metering scheme is also in place, but the eligibility is limited to photovoltaic systems up to 5 kW [66]. Photovoltaic production can additionally receive green certificates. The number of certificates/kWh varies according to the system installed capacity. In the last years, the green certificate system has been fading-out in the three regions. The recent reforms reflect the need of controlling the increase of PV capacity and the decrease of PV systems costs [62].

A significant growth of PV installed capacity followed the support policies implemented. At the end of 2016, Belgium reached 3.43 GW of PV capacity (mostly residential and commercial systems), of which 2.4 GW are installed in Flanders [66]. The electricity generation from PV distributed systems was equivalent to 4% of Belgium electricity load in 2016 [68]. In order to address challenges related to the sustained increase of PV capacity, a "prosumer tariff" specific to small PV systems (< 10 kW), varying from 78 to 135 €/KW per year, was implemented in Flanders in 2015 [69,70].

3.1.8. France

In 2006, a FiT was introduced to support PV expansion. The policy has been reformed over the years, so the benefits granted to photovoltaic systems have been consistently reduced. In its last update, the FiT at EUR 0.058 /kWh available for plants larger than 100 kW was abandoned [71]. Only plants installed on buildings with a maximum capacity of 100 kW are eligible to the current policy, which secures a tariff for a 20-year period, with a digressive schedule over time [72,73]. As of July 2016, building-integrated systems no larger than 9 kW were entitled a 0246€/kWh. Simplified building-integrated systems with a capacity up to 36 kW, received 0133 €/kWh, while plants between 36 and 100 kW received 0126 €/kWh injected into the grid [73]. A fiscal incentive is also available for renewable energy technology acquisitions, in addition to a Value Added Tax reduction incentive, available for PV systems only. Since 2009, PV capacity has grown from 0.2 GW to 6.2 GW in 2016. In 2015, the share of PVDG in electricity load was 1.4% [74]. While this value still represents a considerably small amount of overall capacity, debate has been growing over the financial impacts PV expansion will have due to greater investments in grid infrastructure [75,76]. Still, although the need for specific charges to PV customers has been widely discussed, such as the creation of an injection tariff, regarding the electricity exported to the grid, until this date, no regulatory changes addressing the impacts of distributed generation was implemented [77].

3.1.9. Germany

The main policy for promoting photovoltaic energy in the country has been (FiT), introduced in 2000. The policy has been reformed over the years, and the value of FiT was significantly reduced, although remains unaltered for installations with a capacity inferior to 100 kW. As a result, Germany experienced an increase of small-scale photovoltaic capacity. Subsequently, in 2016, the PV capacity connected to the low voltage grid reached 23 GW, representing 57% of the total PV installed capacity [78]. In the same year, the electricity generated in small-scale PV systems totalled 28.5 TWh, corresponding to 5.5% of the total electricity load [79,80]. As a consequence of the expansion of renewables in general, and PV in particular, the country needed to consider expanding and upgrading its electricity grid, in order to address issues of bottlenecks, as well as grid stability [78]. At the same time, growing concerns surrounding the costs of the FiT (disproportionally caused by PV technologies), which resulted in surcharges on households' electric bills reaching 6.35 Eurocent/kWh in 2016 (approximately 25% of the average household electricity price in Germany), have sparked discussion about reforming the current support system for renewables [81].

3.1.10. Italy

FiTs for photovoltaic installations were first established in 2004, with the introduction of the *Conto Energia* [82]. From 2005 to 2012the mechanism was revised five times [83,84]. The FiT scheme ceased on 2013, July, after reaching a cumulative cost of € 6.7 billion per year [85,86]. Currently, most PV plants with self-consumption are supported by a net billing scheme called *Scambio Sul Posto*, valid for systems with capacity of up to 500 kW [87]. Other support policies, such as tax credits and a simplified purchase resale arrangement (*ritiro dedicato*), and *Sistemi Efficienti di Utenza* (SEU), through which the producer sells electricity directly at the customer's address (free from grid and system fees), through a direct, private network, are also available in the country [85,88,89].

In 2016, there were 732,053 PVDG installed in Italy, corresponding to a capacity of 19.3 GW [87]. The PVDG met 6.2% (17.8 TWh) of the electricity load in the same year [87]. In order to deal with some impacts related to the diffusion, and to reduce the cross-subsidies associated to the previous tariff structure, in 2015, the electricity tariffs were amended. The goal of the reform was to replace the progressive structure by a non-progressive rate design, with an increased share of fixed (€/year) and demand components (€/kW/year) [90].

3.1.11. Portugal

The Portuguese PV support policies have shifted from generous incentives for distributed generation through FiTs, to a less financially attractive self-consumption oriented policy framework. Adjustments to the FiT scheme occurred amidst the country's financial crisis and consequential public policy spending required adjustments. The current FiT framework provides lower compensation for electricity generated, and allows for self-consumption, with compensations for excess energy at below wholesale market rates, or small-scale production, accessible through competitive bidding. The installed distributed PV capacity in the Portuguese market evolved from 0.01 GW in 2008 to 0.2 GW in 2015 [91]. In 2016, the gross electricity generated in distributed photovoltaic systems corresponded to 0.96% (441 GWh) of the country's electricity load [92]. Reflecting this increase, a growing debate has evolved over the need to adapt the tariff structure to better address the discrepancy between revenue and costs for the electricity sector, caused by the expansion of distributed generation.

3.1.12. United Kingdom

In the United Kingdom the promotion of PVDG is based on a combination of a quota system and a FiT scheme. The quota system with tradable green certificates (Renewable Obligations Certificates – ROCs) was initially introduced in 2002 [93]. PV systems higher than 50 kW are eligible to the system. PV plants between 50 kW and 5 MW must choose between the ROCs and the FiT [94]. The FiT scheme, for PV systems with a capacity of less than 5 MW, was implemented in 2010 [95,96]. It is based on a two-part payment: a generation tariff (FiT), over the total electricity generation (including self-consumption), and an export tariff, a feed-in premium (FiP) which remunerates the electricity fed into the grid [14]. From 2011 to 2015the policy was revised several times. The values of both generation and export tariffs were progressively reduced, new digression mechanisms were implemented and the duration of FiT payments was reduced from 25 to 20 years [97]. Until March 2017, there were 788,026 FiT PV installations all over the country, what was equivalent to a total capacity of 4.54 GW [98]. Approximately 3.5 TWh of electricity was generated by PVDG in 2016, representing 1.2% of the country's load [98,99].

3.1.13. Australia (Victoria)

In 2011, at a country level policy, Australia implemented the Small-Scale Renewable Energy Scheme, according to which small-scale renewable generators receive tradable green certificates, proportional to their electricity output [100]. At the state level, a FiT scheme was implemented in Victoria in 2009, guaranteeing a minimum premium tariff, for excess electricity fed back into grid, at $0.60/kWh to PV systems with an installed capacity up to 5 kW [101]. The scheme was subject to many revisions, and the premium tariff was progressively reduced, reaching a minimum of $0.05 in 2016, available for systems with less than 100 kW [102]. However, from 1 July 2017, solar customers on the current minimum FiT rate moved onto a new minimum tariff of 11.3 cents. This new tariff intended to better reflect the value of the electricity customers provide to the grid [103].

In 2016, the electricity generated from PV systems with a capacity up to 100 kW corresponded to 1.58% of the state electricity load [104]. As a result, Victoria faces a decrease of average electricity consumption, which associated to an increase of peak load (related to the growing use of air-conditioners), has increased the distribution grid idleness [105]. This scenario led to reforms in the distribution tariff structure. The major changes were the creation of demand charges and the introduction of ToU tariffs, both on an opt-in basis for customers with an annual demand of less than 40 MWh [106].

3.2. Criteria hierarchy analytical results

We categorise the 13 international cases into the previously defined criteria hierarchy. Table 4 provides insights on cases' distribution that

Table 4
International case studies criteria hierarchy categorisation results.

PVDG electricity compensation time frame (C1)			Existence of complementary support policies (C2)			Share (%) of PVDG on load (C3)			General electricity distribution regulatory changes on tariffs (C4)			Specific regulatory changes targeting PVDG issues (C5)		
C1	Real-time	AU,FR, DE, UK,HI, PT, JP	C2	No	PT	C3	< 3%	PT	C4	No	PT	C5	No	
													Yes	PT
										Yes		C5	No	
													Yes	
							> =3%		C4	No		C5	No	
													Yes	
										Yes		C5	No	
													Yes	
				Yes	AU, FR, DE, UK, HI, JP	C3	< 3%	FR, UK, AU	C4	No	FR	C5	No	
													Yes	FR
										Yes	UK, AU	C5	No	
													Yes	AU, UK
							> =3%	DE, HI, JP	C4	No	DE, JP	C5	No	
													Yes	DE, JP
										Yes	HI	C5	No	
													Yes	HI
	Roll-over	BR, CA, IT, NV, NY, BE	C2	No		C3	< 3%		C4	No		C5	No	
													Yes	
										Yes		C5	No	
													Yes	
							> =3%		C4	No		C5	No	
													Yes	
										Yes		C5	No	
													Yes	
				Yes	BR, CA, IT, NV, NY, BE	C3	< 3%	BR, NV, NY	C4	No	BR, NY, NV	C5	No	BR
													Yes	NY, NV
										Yes		C5	No	
													Yes	
							> =3%	CA, IT, BE	C4	No	BE	C5	No	
													Yes	BE
										Yes	CA, IT	C5	No	
													Yes	CA, IT

are discussed in Section 4.

4. Discussion of results

The classification of the selected representative international case studies provides a perspective on the status of the PV market and how it is being integrated within electricity distribution. Considering our first criteria, 'PV distributed generation electricity compensation time frame', the sample of cases is distributed across both real-time compensation, and roll-over compensation schemes. Regarding the second criteria, 'Existence of complementary support policies', it is observed that most of our representative cases have complementary support policies in place. In terms of PV Share (%) of PV distributed generation on load, the obtained result is mixed. From the analysis of criteria 4, 'General electricity distribution regulatory changes on tariffs', once again we observe that part of the regions studied do not have introduced any general changes. Attending to criteria 5, 'Specific electricity distribution regulatory changes targeting PV distributed generation issues', we conclude that, except for Brazil, all other studied regions have implemented changes to tackle issues related with distributed generation.

Building on the analysis presented, we now focus on the relationships between the different criteria, following the hierarchy structure defined for the selected criteria.

Considering the relationship between 'Existence of complementary support policies', and 'Share (%) of PV distributed generation on load', we observe that the share of PVDG does not seem to be uniquely explained by the existence of complementary support policies. Although the majority of cases evidence complementary policies, it is not sufficient to support a conclusion on a pattern in terms of PV diffusion level, as in half of the situations the share of PV distributed generation on load is less than 3%.

We now analyse the relationship between 'Share (%) of PV distributed generation on load' and 'General electricity distribution regulatory changes on tariffs'. While the selected cases are distributed across the various alternatives, we observe that, among cases with a lower share of PVDG, general electricity distribution changes on tariffs have not been implemented in most of them. On the other hand, half of the countries with a share greater than 3% implemented regulatory changes. Thus, although lower shares can be related to no regulatory changes in tariff, at this point, the relation between high shares and the presence of regulatory changes can not be assumed in general. However, considering that most countries which have implemented general electricity distribution regulatory changes on tariff, present a share of PV distributed generation on load higher than 3%, it can be considered as an indicator that general changes may be implemented in order to address issues related to the increasing penetration of PV systems. Thus, the increasing penetration of PVDG seems to highlight the need for structural changes on distribution tariffs regulation, as it characterizes a scenario of challenges to distribution companies and regulators. Regulatory adaptation is important to maintain an equitable and fair allocation of grid costs among prosumers and non-photovoltaic customers. Thus, in a scenario with a high share of PVDG, the traditional regulation models can be challenged, and regulators address these matters through the implementation of new tariff structures and through the adaption of the distribution regulation models. Consequently, the share of PVDG on load can be, preliminarily, pointed out as a factor to explain the presence (or absence) of general changes on electricity distribution regulation.

In terms of the relationship between 'Share (%) of PV distributed generation on load' and 'Specific regulatory changes targeting PV distributed generation issues', we uncover that specific regulatory changes targeting PVDG were implemented in all the case studies. An exception made for Brazil, where PVDG share on load is still minimal and the lowest among the cases analysed. As presented in the cases description, these transformations usually take the form of regressive amendments of the net metering and FiTs policies, or even the creation of charges applied specifically to PV customers. Although specific changes have been introduced in regions with both real-time and roll-over compensation schemes, these were driven by different reasons. In cases with real-time compensation schemes, the regulatory changes mainly address the growing support policies costs. Roll-over compensation schemes, otherwise, have led to cost allocation distortions, demanding regulatory adjustments able to promote a better allocation of grid costs between distribution grid users.

Finally, it is important to note that, in the majority of cases, specific regulatory changes involve a simpler, and faster, decision-making process, in comparison to general changes, as they are usually taken in the scope of wider PV support policies revisions. General electricity distribution regulatory changes on tariffs, nevertheless, tend to be more complex, as they represent structural changes in the distribution grid tariffs design or even in the distribution regulation model, as observed in the situation of the United Kingdom.

While revisions of PV support policies are frequent in our set of case studies, occurring even on an annual basis, changes on grid tariffs structure, for example, are usually implemented through tariff revision processes, which commonly occur with wider time lags. We conclude, that only in five cases general changes have already been adopted, although in twelve of the thirteen cases regulatory changes targeting PVDG issues have been implemented, Thus, general changes can be considered a step further in the path to a distribution sector regulation more suitable to the new electricity sector technological paradigm, characterized by the increasing decentralization of electricity supply.

5. Conclusions

It was possible to report that PVDG diffusion has increased worldwide, evidencing a global trend. Yet, as a consequence of the divergence support policies adopted worldwide, disparate levels of PVDG diffusion have been reached and there is not a single pattern to rely on. As a result, challenges related to the increase of support policies cost maintenance and cost-shifting issues have come into light. With the foregoing in mind, and scrutinizing the outcomes of the several international workshops held, and through the consultation, *in loco*, of key stakeholders', adding to an extensive literature survey, we were able to identify the impacts of PVDG diffusion on the distribution sector and systematized the regulatory adjustments which have been implemented in an attempt to mitigate those impacts. A sample of 13 cases, analysed considering the five criteria selected through a novel approach, offered a state-of-the-art review and disclosed information about which topics should policy makers account for.

One of the main takeaways is that the majority of the countries have been implementing successive regulatory changes, specific or general, in an attempt to mitigate impacts related to the increasing participation of PVDG. Regardless of the share (%) of PV DG on load, the impact verified in each case study was found to be associated to the compensation scheme adopted. Roll-over schemes adopters face an exponential growth of policy costs, leading to digressive adjustments of FiT. Real-time compensation policies (in most cases net metering), on the other hand, lead to impacts on distribution companies' revenues and distortions of grid cost allocation between customers. The regulatory changes observed in these cases are the key to the need of reducing the shift of grid costs avoided by net-metered customers to non-photovoltaic customers. Thus, including measures such as the creation of specific tariffs to PV customers, or even the revision of grid tariffs structure, are topics to be addressed by energy regulators. Additional international experiences, for example the inclusion of African countries not herein considered, could be added to the analysis to enlarge the geographical scope of this study.

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