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Photovoltaic self-consumption is now profitable in Spain: Effects of the new regulation on prosumers' internal rate of return

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ABSTRACT:

Whereas Spain used to have one of the most restrictive photovoltaic self-consumption (PVSC) regulations in the world, the new regulation (RD-L 15/2018 & RD 244/2019) improves the economic conditions of PVSC systems, simplifies administrative procedures and allows shared self-consumption. We analyze the impact of the new PVSC regulation on residential, commercial and industrial prosumers' profitability (internal rate of return). We provide a wide range of results that allow us to explore future profitability depending on the evolution of installation costs, the opportunities of shared self-consumption or storage, and even the potential emergence of new business models. We find that all segments obtain now positive profitability in average conditions. Whereas the residential segment has the lowest profitability level, it has the highest potential by decreasing installation costs and increasing the share of self-consumption, given its higher retail prices. Finally, we identify potential new business models by exploiting the prices and costs differentials across segments and maximizing the share of self-consumed electricity. PVSC systems with industrial costs exploiting residential markets could achieve 35% profitability by reaching 75% self-consumption, and even higher than 40% when self-consumption exceeds 85%.

1. Introduction

Spain used to have one of the most restrictive photovoltaic self-consumption (PVSC) regulations in the world between 2015 and 2018 (RD 900/2015, 2015). This regulation prevented the economic viability of PVSC installations by neglecting any remuneration for the surplus electricity exported to the grid for residential prosumers on the one hand, and by setting a backup charge on the self-consumed electricity for commercial and industrial segments on the other hand.

The new regulation was passed in October 2018 (RD-L 15/2018, 2018) and further developed in April 2019 (RD 244/2019), improving prosumers' economic conditions and simplifying administrative procedures. These changes increased the profitability of PVSC installations and might set the basis for the emergence of new business models. We analyze the profitability (reflected in the internal rate of return) of residential, commercial and industrial PVSC installations to assess, first, how this regulation improved the situation of PV prosumers compared to the former regulation. Second, we provide a wide range of results to show profitability depending on system location, position and cost; and to explore the potential benefits of storage, demand management and shared self-consumption by assessing the trade-off between installation costs and the share of electricity self-consumed. Finally, we examine the potential for new business models exploiting the prices and costs differentials across segments and system conditions as well as their potential to maximize the share of electricity self-consumed within the PVSC system. We therefore update and expand our previous study on the former Spanish PVSC regulation (López Prol and Steininger, 2017), confirming that the current regulation implements the three main recommendations we had made in our previous paper: (i) removing the backup charge on the self-consumed electricity, (ii) remunerating the surplus electricity exported to the grid, and (iii) allowing shared self-consumption.

Given the rapid cost decline of PV, there is a rich literature analyzing the evolution of PVSC profitability, both at country level (see, e.g. Chiaroni et al., 2014 for the case of Italy) and comparative analyses across countries (see De Boeck et al., 2016 for the major EU markets, and Rodrigues et al., 2016 for the main markets worldwide). Lately, the focus has shifted towards analyzing PVSC profitability without subsidies to assess its competitiveness (see Cucchiella et al., 2016 for the residential segment in Italy, and Lang et al., 2016 for residential and commercial buildings in Germany, Switzerland and Austria). For the case of Spain, there are profitability assessments under different regulatory and

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economic conditions (Colmenar-Santos et al., 2012; Talavera et al., 2014). More recently, Gallego-Castillo et al. use an optimization model to study the impact of the current regulation on PVSC in residential buildings in Spain, concluding that these systems can provide savings ranging between 14 and 32% of the prosumers' electricity bills (see Gallego-Castillo et al., 2020 for the original version (in Spanish) and Gallego-Castillo et al., 2020a for an updated version).

We contribute to this literature by providing a qualitative analysis of the current Spanish regulation as well as a quantitative assessment of its impact on the profitability distinguished for prosumers of the residential, commercial and industrial segments. One of the main challenges of this literature is the lack of generalizability due to the fast evolution of PV costs, the variability of many of the parameters that determine PV profitability across installations and the unpredictability regarding the future evolution of electricity prices. We aim to overcome this problem by providing profitability thresholds for a wide range of potential values of the main variables rather than specific profitability results for particular cases. In this way, the interested audience can assess the approximate profitability of PVSC under different system configurations and economic conditions beyond those used for the baseline assumptions.

The remainder of the paper is structured as follows: Section 2 describes the new PVSC regulation comparing it with the former and summarizes the risks and opportunities of PVSC for different stakeholders voiced in the policy arena during the last years. Section 3 explains the method and data used for the profitability calculations. Section 4 presents the results and Section 5 concludes.

2. The new self-consumption regulation

2.1. Description and impact of the policy change

The first difference between the former and the current regulation is that whereas the former was passed in the form of a Royal Decree (RD 900/2015), the current takes the legal form of a Royal Decree-Law (RD-L 15/2018). Although both legal acts emanate from the government, the RD-L has to be ratified by the parliament and has therefore law status, higher than the lower legal status of the RD ("reglamento"). Consequently, a parliamentary majority would be necessary to change this regulation again. This higher legal status is aimed at providing more legal certainty to investors after years of arbitrary and even retroactive regulatory changes related to the PV sector (see Del Río and Mir-Artigues, 2012 for an analysis of the first PV support policies in Spain; López Prol, 2018 for a comparison of PV policies in Germany and Spain; and Mir-Artigues et al., 2015, 2018a for an assessment of the retroactive policies on PV profitability).

Whereas the general principles of the new regulation are laid out in the RD-L 15/2018, the details about the economic, technical and administrative conditions of PVSC are specified in the RD 244/2019. In general, the new regulation improves the situation of PV prosumers. On the one hand, it simplifies the technical and administrative requirements. On the other hand, it improves the economic viability of the PV systems by removing the backup charge and recognizing the right of prosumers to sell the surplus electricity to the grid. Indeed, the regulation explicitly mentions three guiding principles (RD-L 15/2018 p. 97434, own translation): "(i) right to self-consume electrical energy without charges, (ii) right to shared self-consumption by one or several consumers […], (iii) principle of technical and administrative simplification, especially for low power installations".

These principles are relevant because both the exemption of any charges on self-consumption and the possibility of shared self-consumption between several end-consumers are explicitly recognized as rights. Additionally, this regulation specifies that the surplus electricity exported to the grid should be treated "in the same conditions as any other production installation" (art. 5 title II). Removing the backup charge increases the economic incentive for self-consumption, remunerating the surplus electricity reduces the incentive for going off-grid, and allowing shared self-consumption can boost PVSC in urban areas and help maximize the share of electricity self-consumed over the total produced, minimizing thus the impact of PVSC to the electricity system. Finally, the simplification of administrative procedures reduces related soft-costs and information barriers likely to hinder the expansion of residential installations. All these measures improve the profitability of PVSC (Fig. 1) and are coherent with the agreements reached in 2018 between the European Parliament, Council and Commission to amend the European directive on renewable energy (Directive, 2009/28/EC). Whereas the former regulation differentiated between two types of grid-connected installations, the current regulation unifies the main precepts to any type of self-consumption grid-connected installation. According to the former regulation, type 1 installations (mainly residential) could not sell the surplus electricity to the grid. Type 2 installations (mainly commercial and industrial) could sell their surplus electricity to the grid, but faced a backup charge on the electricity self-consumed. Since residential prosumers export most of the electricity generated to the grid and commercial and industrial prosumers self-consume a higher share of their generation, this setting prevented the economic viability of PVSC systems for all segments (see López Prol and Steininger (2017) for a detailed analysis of the former regulation and Mir-Artigues et al. (2018b) for an assessment of an actual installation with real data). The current regulation abolishes the backup charge and recognizes the right of prosumers of any segment to be remunerated for the electricity they export to the grid in the same conditions as any other generator (Table 1).

All PV prosumers are now exempt of any charge on the self-consumed electricity and can sell their surplus electricity to the grid at wholesale prices. However, the RD 244/2019 establishes two types of prosumers depending on the remuneration mechanism (Table 2):

(i) On the one hand, PV prosumers can opt for a simplified *monthly net billing* system, through which the revenues of the surplus electricity sold to the grid are directly discounted from the electricity bill with a monthly credit. The surplus electricity sold to the grid is valued at either wholesale price when the prosumer has their electricity contract with a regulated retailer, or at a price agreed by the parties in case of a free market electricity retailer. The advantages of this option are that it allows simpler administrative and technical requirements, the electricity exported to the grid is exempted from the grid-access charge and the

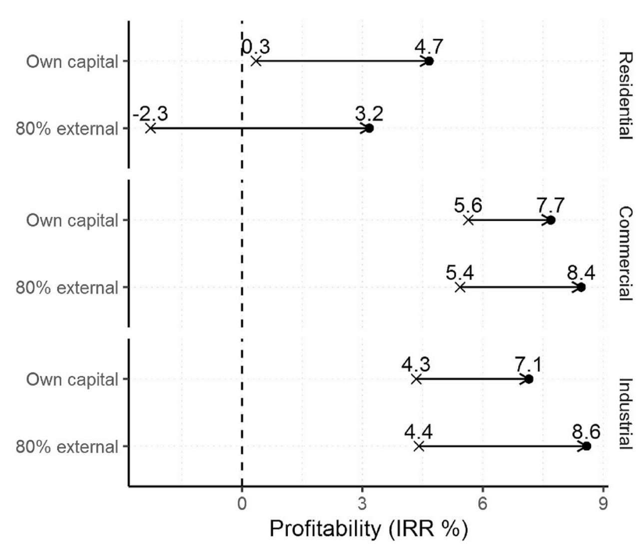

Fig. 1. Profitability change from the former (cross) to the current (dot) regulation for average prosumer from the residential, commercial and industrial segment with own capital or 80% externally financed investment.

Table 1
Changes with respect to the former self-consumption regulation.

	Residential	Commercial/industrial
Former (RD 900/2015)	- No backup charge - Surplus electricity not remunerated	- Backup charge on self-consumed electricity - Surplus electricity remunerated at pool price
Current (RD-L 15/2018, RD 244/2019)	- No backup charge on self-consumed electricity - Surplus electricity remunerated "in the same conditions as other producers"	

Table 2
Advantages and disadvantages of both types of PV self-consumption for prosumers.

Net billing	Direct sell
+ Simplified procedures + No grid-access charge for surplus electricity + Savings are not taxable - Max. savings energy part of the electricity bill - Monthly billing - Installed capacity ≤100 kWp	- Same requirements as any other producer - Grid-access charge for surplus electricity - Generation tax and taxable income + No maximum profits + No monthly limits + No maximum installed capacity
Higher profitability, limited total profits	Lower profitability, unlimited total profits

generation tax, and since the profits are realized as savings, they are not taxable. However, this PVSC type is limited to a maximum of 100kWp installed capacity, the total profits from the surplus electricity are limited to the energy part of the prosumer's electricity bill (i.e. the maximum saving from the electricity sold to the grid is the value of the electricity bought from the grid). Finally, since the energy credit is monthly, seasonality cannot be compensated, so the optimal size of the PVSC system will be lower and therefore total profits will also be lower.

(ii) Alternatively, PV prosumers can *direct*ly *sell* their surplus electricity to the grid as any other producer at wholesale price minus the 7% generation tax[1] and the corresponding grid-access charge (0.5 €/MWh). In this case, profitability would be lower and administrative and technical requirements higher, but their total profits are neither constrained by a maximum installed capacity nor by a monthly billing.

The current regulation improves the profitability of all segments. Residential prosumers can now sell their surplus to the grid, and commercial/industrial segments are now exempted from the backup charge. With the new net billing policy, the residential segment in average conditions moves from negative or negligible returns to positive profitability of between 3.2 and 4.7%, and both the commercial and industrial segments surpass the 5% profitability threshold (Fig. 1). At current installation costs and average conditions, all segments obtain positive returns below 10%. Fig. 1 should be viewed as a lower bound of the impact of the regulation for two reasons: the current regulation reduces (i) soft costs related to administrative procedures and (ii) legal uncertainty by increasing the legal status of the regulation. This entails that (i) the profitability difference is higher than shown in Fig. 1 (since we do not include soft costs), and (ii) the required return of investment is likely lower due to the lower policy risk. The method and data for the calculation of these average values are presented in Section 3, and Section 4 presents a detailed analysis of PVSC profitability in different conditions.

[1] Although the RD-L 15/2018 suspends the generation tax to lower electricity prices, this suspension is intended to be temporary as indicated in the RD-L itself.

2.2. Risks and opportunities of PV self-consumption

There has been an intense policy discussion in Spain and the rest of Europe about PVSC during the last years. In this section, we summarize the main arguments voiced in the policy arena regarding the risks and opportunities of PVSC (Table 3). While our analysis focuses on the impacts of the current regulation on prosumers' profitability, in this section we discuss some potential implications at the macro (climate change mitigation and economic effects) and electricity system (consumers, producers and electricity system as a whole) levels.

At the macro level, climate change mitigation is one of the main motivations of the RD-L 15/201. A favourable PVSC regulation is expected to boost investment contributing to the decarbonization of the electricity system. Given the urgency to decrease carbon emissions and the deviation of the actual emissions levels from the 2 °C target, it is urgent to promote investment in renewable energy technologies to speed up the decarbonization process (IEA, 2017a). Investments in PVSC could likewise trigger further investment, and thus innovation in other complementary technologies, such as smart appliances and electric vehicles to maximize the share of self-consumption, or building-integrated PV to further reduce installation costs. The risks that PVSC poses to decarbonization are twofold. On the one hand, the levelized costs of electricity (LCOE) of small scale systems is higher than the LCOE of ground-mounted utility-scale installations (IRENA, 2018). This entails that abatement costs are higher for PVSC than for large scale PV. On the other hand, provided that solar energy has virtually zero marginal cost, the wrong perception of "free electricity" (or even the right perception of lower marginal cost electricity), could cause a rebound effect (Deng and Newton, 2017) such that electricity consumption increases and offsets the ecological benefits of the technological switch.

PVSC can have positive macroeconomic effects derived from the potential technological spill-overs, the emergence of new business models, and the creation of employment in the energy sector (Fragkos and Paroussos, 2018). Additionally, a higher share of solar in the energy mix would reduce fuel imports, improving both energy security (Gökgöz and Güvercin, 2018) and the balance of payments (Vaona, 2016) for net energy importer regions. On the other hand, PVSC could reduce government tax revenues, as the savings provided by PVSC are not taxable.

At the electricity system level, PVSC may have heterogeneous effects for different types of consumers and producers, as well as for the electricity system as a whole. PVSC presents an opportunity for the democratization of electricity generation, as it allows a wide range of actors, from residential to industrial agents, to become renewable energy investors, rather than being an investment reserved only for large energy companies. PVSC could have unintended distributive effects

Table 3
Risks and opportunities of PV self-consumption.

Level	Scope/ Stakeholder	Risks	Opportunities
1. Macro	**1.1. Climate Change mitigation**	- Higher abatement cost - Rebound effect	+ Capital mobilization + Technological spill-over
	1.2. Economy	- Lower tax revenues	+ New business models + Employment + Balance of payments
2. Electricity system	**2.1. Consumers**	- Higher retail prices - Distributive effects	+ Lower wholesale prices + Democratization
	2.2. Producers	- Lower wholesale prices	+ New business models
	2.3. System	- Integration costs	+ Lower peak demand

across consumers. Since part of the grid cost is charged in the variable component of the electricity tariff, prosumers would be transferring part of the grid costs to non-prosumer electricity consumers (Eid et al., 2014; Picciariello et al., 2015).

The net impact of PVSC on electricity prices is uncertain. Variable renewable energy technologies tend to depress wholesale electricity prices due to the merit order effect. This effect has been quantified for many countries such as Italy (Clò et al., 2015), Spain (Gelabert et al., 2011), Germany (Dillig et al., 2016; Martin de Lagarde and Lantz, 2018; Sensfuβ et al., 2008) and California (Woo et al., 2016), among others. However, retail prices could increase due to the incentives provided to renewable energy (Trujillo-Baute et al., 2018) or due to the integration costs caused by variable renewables to the electricity system (see Hirth et al., 2015 for a comprehensive review of integration cost and Ueckerdt et al., 2013 for a quantification for Germany). Decreasing wholesale electricity prices would be beneficial for consumers but could jeopardize the financial viability of utilities and electricity generators. Utilities could benefit, however, from the new business models emerging from PVSC, such as aggregation or demand management.

Finally, PVSC has impacts on the electricity system as a whole, independently of how these potential costs or benefits are then allocated to the different participating agents. On the one hand, integration costs could increase total system cost. On the other hand, electricity consumers have traditionally had an inelastic demand (Labandeira et al., 2017), entailing high marginal costs of peak demand (Li and Pye, 2018). The incentives created by PVSC to maximize the share of electricity self-consumed could increase prosumers' demand management and therefore demand elasticity, reducing thus the cost of peak demand.

In summary, PVSC presents significant opportunities but also potential risks for different stakeholders that should be considered by policymakers to ensure a swift, balanced and just transition.

3. Method and data

The profitability of a self-consumption installation depends on the capital as well as operation and maintenance costs of the system compared to the benefits provided by the electricity generated. This electricity is either self-consumed, in which case it is valued at the variable part of the retail price (at which the electricity would be bought from the grid otherwise); or sold to the grid at wholesale price. The total value of the electricity exported to the grid is limited by the value of the electricity bought from the grid in the net billing scheme. In the direct sell scheme there is no such constraint, but the exported electricity would face a grid-access charge and electricity tax. Fig. 2 summarizes this simplified characterization introducing the notation used in the next section.

3.1. Calculation of the internal rate of return

Amongst the many potential profitability indicators that can be applied to PV installations (Nofuentes et al., 2002; Talavera et al., 2012), the internal rate of return is one of the most widely used for both wholesale production (Talavera et al., 2016) and self-consumption (Talavera et al., 2014). We build upon the evaluation method of the internal rate of return as specified by López Prol and Steininger (2017).

In order to calculate the internal rate of return of PVSC investments, the net present value (NPV) is equated to zero (Eq. (1)) and solved for the discount rate (d). Equation (1b) represents the benefits of self-consumption: the savings from the self-consumed electricity plus the revenues of the surplus electricity exported to the grid. β is therefore the share of electricity self-consumed, E_{PV} is the annual PV yield, ps is the price of the saved electricity (i.e. the variable part of the retail price), δe is the energy part of the backup charge and pg is the price of the electricity exported to the grid, from which the effect of the grid access charge (γ) and the generation tax must be subtracted (λ). A_s and A_g are their respective discount factors. Equation (1c) represents the installation costs, being the first addend the part not financed and second the externally financed part of the investment. α is therefore the share of the investment externally financed, i and Nl are the financing conditions: the interest rate and maturity of the loan respectively; and the last elements are the discount factors of the financed part of the investment during the maturity of the loan. Equation (1d) reflects the operation and maintenance costs (assumed to be an annual 1% of the installation costs), and (1e) is the fixed part of the backup charge (δc).

$$NPV = 0 = \tag{1a}$$

$$\beta * E_{PV} * (ps - \delta e) * A_s + (1-\beta) * E_{PV} * [(pg-\gamma) * (1-\lambda)] * A_g \tag{1b}$$

$$-(1-\alpha) * PV_{IN} - PV_{IN} * \alpha * i * \frac{(1+i)^{Nl}}{(1+i)^{Nl}-1} * \frac{1-\left(\frac{1}{1+d}\right)^{Nl}}{1-\left(\frac{1}{1+d}\right)} \tag{1c}$$

$$-(0.01 * PV_{IN}) * \frac{K_{PV} * \left(1-K_{PV}{}^{N}\right)}{1-K_{PV}} \tag{1d}$$

$$-\ \delta c * \frac{K_{\delta c} * \left(1-K_{\delta c}{}^{N}\right)}{1-K_{\delta c}} \tag{1e}$$

To account for the different value of cash flows over time, all economic variables have to be discounted. Thus, A_s and A_g are the discount factors for the savings derived from the electricity self-consumed and the revenues from the surplus electricity exported to the grid respectively. Likewise, $K_{PV}$is the discount factor of the operation and maintenance costs, $K_{\delta c}$ is the discount factor of the constant part of the backup charge, and K_{ps} and K_{pg} are the discount factors of the electricity saved and exported to the grid, respectively, according to their corresponding escalation rates ε_x and the degradation rate of the PV system (dg).

$$A_s = \frac{K_{ps} * \left(1-K_{ps}{}^{N}\right)}{1-K_{ps}} \ ; \ A_g = \frac{K_{pg} * \left(1-K_{pg}{}^{N}\right)}{1-K_{pg}} \tag{2}$$

$$K_{PV} = \frac{\left(1+\varepsilon_{PVom}\right)}{1+d} \ ; \ K_{\delta c} = \frac{\left(1+\varepsilon_{\delta c}\right)}{1+d}; \ \ K_{ps} = \frac{\left(1+\varepsilon_{ps}\right) * (1-dg)}{1+d}; \quad K_{pg} = \frac{\left(1+\varepsilon_{pg}\right) * (1-dg)}{1+d} \tag{3}$$

Given the parameter variability across installations, we do not only present specific profitability results for different cases but also provide the profitability thresholds at different levels, (usually 0%, 5% and 10%) depending on different system conditions. In other words, we want to find the installation cost (PV_{IN}), price of the saved electricity (ps) and share of the investment externally financed (α) for which the internal rate of return (d) is 0%, 5% and 10% given all the other parameters. For that purpose, we isolate the interest variable from equation (1). Provided that there is no backup charge anymore (i.e. $\delta e = 0$ and $\delta c = 0$), we find the breakeven installation cost by solving

$$PV_{IN} = \frac{\beta * E_{PV} * ps * A_s \ + \ (1-\beta) * E_{PV} * [(pg-\gamma) * (1-\lambda)] * A_g}{(1-\alpha) \ + \ \alpha * i * \frac{(1+i)^{Nl}}{(1+i)^{Nl}-1} * \frac{1-\left(\frac{1}{1+d}\right)^{Nl}}{1-\left(\frac{1}{1+d}\right)} \ + \ 0.01 * \frac{K_{PV} * \left(1-K_{PV}{}^{N}\right)}{1-K_{PV}}} \tag{4}$$

When the investment is financed with own capital (i.e. $\alpha = 0$), this equation can be simplified to

$$PV_{IN} = \frac{\beta * E_{PV} * ps * A_s \ + \ (1-\beta) * E_{PV} * [(pg-\gamma) * (1-\lambda)] * A_g}{1 \ + \ 0.01 * \frac{K_{PV} * \left(1-K_{PV}{}^{N}\right)}{1-K_{PV}}} \tag{5}$$

Where the numerator is simply the sum of savings and revenues, and the denominator is 1 plus 0.01 times the discount factor of the operation and maintenance costs.

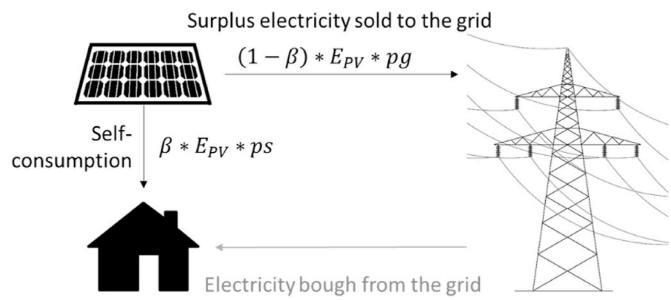

Fig. 2. Electricity flows and their value. E_{PV} is the electricity generated by the PVSC system, β is the share of electricity self-consumed, *ps* is the price of the electricity saved (i.e. the variable part of the retail price) and *pg* is the price of the surplus electricity exported to the grid (i.e. wholesale price).

Likewise, we can find the breakeven price of the saved electricity for each required profitability level by isolating *ps* (again assuming own capital, i.e. $\alpha = 0$)

$$ps=\frac{PV_{IN}+(0.01*PV_{IN})*\frac{K_{PV}*\left(1-K_{PV}{}^{N}\right)}{1-K_{PV}}-(1-\beta)*E_{PV}*[(pg-\gamma)*(1-\lambda)]*A_g}{\beta*E_{PV}*A_s} \quad (6)$$

Where the numerator is the sum of installation costs and operation and maintenance costs minus the revenues of the surplus electricity exported to the grid, and the denominator is the share of electricity self-consumed (β) times the electricity yield (E_{PV}) times the discount factor of the electricity savings (A_s).

Finally, to explore the effect of financing conditions, i.e. the trade-off between the interest rate and the share of the investment externally financed we isolate the latter (α) as

$$\alpha=\frac{\beta*E_{PV}*ps*A_s+(1-\beta)*E_{PV}*[(pg-\gamma)*(1-\lambda)]*A_g-(0.01*PV_{IN})*\frac{K_{PV}*\left(1-K_{PV}{}^{N}\right)}{1-K_{PV}}-PV_{IN}}{PV_{IN}*i*\frac{(1+i)^{Nl}}{(1+i)^{Nl}-1}*\frac{1-\left(\frac{1}{1+d}\right)^{Nl}}{1-\left(\frac{1}{1+d}\right)}} \quad (7)$$

Table 4
Data summary.

	ps	δ	PV_{IN}	*i*	β
	Variable part[a] of the retail electricity prices (and total) (€c/KWh)	Backup charge[b] (€c/kWh)	Installation cost (€/Wp)	Interest rates (%)	% of energy self-consumed
Residential	16.38	4.9	1.69	6.71	33.27
Commercial	9.31	1.94	1	4.88	41.36
Industrial	6.65	1.63		3.36	75
Source	Eurostat & CNMC (2016, 2014)	RD 900/2015	IEA (2017b)	ECB	PV Parity & EPIA (2011)

	ε_p	E_{PV}	*dg*	*N*	*Nl*	γ	λ	*pg*
	Escalation rate of electricity prices[c] (%)	PV yield[d] (kWh/Wp)	Degradation rate (%)	Lifetime of the system (years)	Maturity of the loan (years)	Grid-access charge (€/MWh)	Generation tax (%)	Wholesale electricity prices (€c/KWh)
Value	2	1461	0.8	25	10	0.5	7	4.21
Source	EPIA (2011)	PVGIS database 2012 Šúri et al. (2007)	Jordan and Kurtz (2012)	Manufacturer's warranty	UNEF	RD 1544/2011	L 15/2012	OMIE

*Operation and maintenance (O&M) costs are assumed to be 1% of the installation costs at 2% annual escalation rate.

[a] The variable part is calculated as the product of the fixed share of the grid-access charge over the total (:38) and the total grid access charge & capacity payments (CNMC, 2016:91).

[b] For C and I, the result is the weighted average of the backup charge for each period (RD 1544/2011) and the total consumption for each period and segment (CNMC, 2014:50).

[c] Both retail and wholesale.

[d] Country average optimal tilt. See Fig. 3 for irradiation/PV yield ranges depending on panels' position (optimal, horizontal or vertical).

Where the numerator is the sum of savings of the self-consumed electricity and revenues of the surplus electricity exported to the grid minus operation and maintenance costs and installation cost, and the denominator is the installation cost multiplied by financing conditions (since we are exploring the effect of financing, we do not assume here own capital as in eqs. (5) and (6)).

3.2. Data

The input data used in this analysis are the same as in López Prol and Steininger (2017) and are summarized in Table 4. We update the installation costs according to the latest information provided by the International Energy Agency in the PV trends report 2017 (IEA, 2017b) and the PV yield of the system according to the latest data provided by PVGIS (2012 database based on Šúri et al., 2007).

The installation costs for residential PV systems in Spain according to the PV trends report 2017 lie between 1.4 and 1.5 €/Wp, we take the lower bound and sum the 21% value added tax reaching a total of 1.69 €/Wp. Installations costs for commercial and industrial systems range between 0.8 and 1.2 €/Wp. We assume the average 1€/Wp. Although we use these average values for the representative installation of each of the segments, since these parameters vary widely across installations, we provide our results for a wide range of potential values of not only installation costs (Figs. 3 and 4), but also solar irradiation/PV yield (Fig. 3), share of electricity self-consumed (Figs. 4 and 8), financing conditions (interest rates and share of the investment externally financed, Fig. 7) and retail and wholesale electricity prices levels (Fig. 5) and their potential evolution (Fig. 6).

We define three different segments depending on their costs and prices: residential segment has higher installation (1.69€/Wp) and financing (6.71%) costs and higher retail electricity prices[2] (16.38 €c/kWh), but lower share of electricity self-consumed (33.27%). Industrial segment has lower installation (1€/Wp) and financing costs (4.88%) and retail electricity prices (6.65 €c/kWh), but higher share of electricity self-consumed (75%). Finally, the commercial segment has the same installation costs as the industrial (1€/Wp), whereas all the other parameters lie between the residential and industrial values: 3.36% financing costs, 9.31 €c/kWh retail prices and 41.36% electricity self-consumed. For the exploration of new business models (Section 4.4), we will combine values from different segments as explained in the section itself. We assume a 25-year investment lifetime. This is aligned with previous literature (e.g. De Boeck et al., 2016), and together with the annual 0.8% annual degradation rate fits the warranty conditions commonly offered by producers.

We present our main results with own capital (i.e. no external financing), but analyze the effects of financing the investment to assess the direct effect of the new regulation (Fig. 1), the trade-off between interest rates and the share of the investment externally financed (Fig. 7), and the potential emergence of new business models (Fig. 8). Likewise, we focus on the net billing system (i.e. neither generation tax nor grid-access charge on the surplus electricity exported to the grid) rather than the direct sell to the wholesale market but compare their profitability differentials in Fig. 6. In Section 4.4. we expand the analysis to other business models that could make use of the direct sell system.

4. Results: potential PV self-consumption profitability

Whereas the results presented in Fig. 1 are representative installations of the residential, commercial and industrial segments in average conditions, the profitability of PVSC installations varies dramatically depending on the different system conditions. The most obvious sources of variability are the solar irradiation depending on the location and position of the panels, conditions explored in section 4.1. Besides, PV modules and battery costs continue to fall rapidly, which together with the development of demand management technologies (such as smart meters and appliances) might increase the share of self-consumption achieved by PV prosumers; these possibilities are explored in section 4.2. The future of electricity prices is uncertain, whereas the increasing penetration of variable renewables tends to reduce wholesale electricity prices due to the merit-order effect, the internalization of externalities could pressure both retail and wholesale electricity prices up. These scenarios regarding the evolution of electricity prices are studied in Section 4.3. Finally, in Section 4.4 we explore the effects of financing the investment and the potential for new business models exploiting prices and costs differentials across segments.

Sections 4.1 to 4.3 present the results as profitability thresholds at three different levels: 0%, 5% and 10%, such that not only one specific configuration is presented, but a wide range of results depending on the specific variables considered in each section. Likewise, we present the results for own capital investments, focusing on the effects of financing in Section 4.4 (where the depicted profitability thresholds are 0%, 4% and 8% instead).

While we provide a general illustration of the trade-off between installation costs and self-consumption share, more detailed analysis with individual installation's microdata would be needed in order to optimize the system size to maximize profitability ex-ante, such as the method proposed by Jiménez-Castillo et al. (2019). This pre-optimization of the system size is even more relevant for prosumers under the net billing remuneration mechanism, since the maximum amount of monthly profit is limited by their monthly electricity consumption. The optimal size of the system is therefore constrained by the point at which the value of the excess electricity exported to the grid equals the value of the electricity consumed in a given month.

4.1. Profitability ranges depending on system location and position and installation costs

The two fundamental determinants of PV profitability are solar irradiation and installation costs. Fig. 3 shows plausible profitability ranges by illustrating the 0% (solid line), 5% (dashed line) and 10% (dotted line) profitability thresholds depending on these two factors.

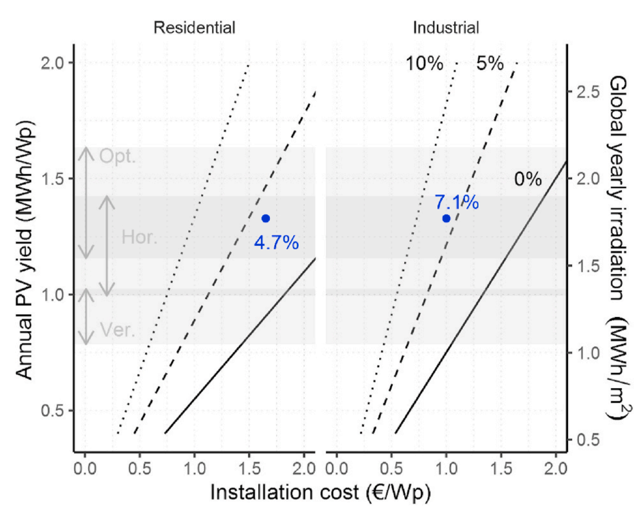

Fig. 3. Prosumers' profitability (0% (solid line), 5% (dashed line) and 10% (dotted line) internal rate of return (IRR)) for residential and industrial segments depending on solar irradiation/PV yield (75% performance rate) and installation costs. Average values indicated in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

[2] Unless otherwise stated, retail prices in this paper refer only to the variable part of the total, since this corresponds to the savings derived from self-consumption.

The influence of location is given by solar irradiation (right vertical axis), which is translated into annual electricity yield assuming 75% performance rate (left vertical axis). Along these two axes, three different panel positions are also illustrated: vertical (Ver.), horizontal (Hor.) and optimal tilt (Opt.). Since commercial and industrial segments have similar results, we present here only the two extreme cases: residential and industrial.

At current installation costs, residential PVSC installations with horizontal panels obtain positive returns across the whole irradiation range, but always below 5%. Optimally inclined panels in high irradiation areas could, however, surpass the 5% threshold. At 1€/Wp installation costs, even vertical residential installations could achieve up to 5% profitability in the best locations. Horizontal installations would achieve profitability between 5% and 10% across the irradiation range, and optimally inclined panels in the best locations would surpass 10%. At 0.5€/Wp installation costs, PVSC profitability for the residential segment would be higher than 10% even with vertical panels in the worst locations.

The returns for industrial installations are positive in the current circumstances even for vertical panels in the worst locations, but always below 10% even in the best locations with optimally inclined panels. If total installation costs reached 0.5€/Wp, vertical installations in good locations could achieve 10% profitability and horizontal installations would surpass that value even in the worst locations.

Given the same installation costs, profitability is higher for residential than for industrial installations due to higher electricity prices and therefore higher potential savings from self-consumption, even though the share of self-consumption is more than double for the industrial segment (75% vs 33%). For instance, at 1€/Wp, the plausible profitability range for industrial would lie between 0% and 10%, whereas residential installations could surpass 10% profitability in high irradiation locations with optimally inclined panels.

4.2. The potential of storage and demand management

Another key determinant of PVSC profitability is the share of electricity self-consumed over the total electricity generated by the PV system. Fig. 4 shows the profitability ranges depending on installation costs and share of electricity self-consumed. The relevance of this trade-off is that by increasing the present value of the installation costs (for instance, by also investing in batteries or smart appliances), the share of self-consumption can also be increased. Fig. 4 illustrates therefore whether storage or demand management devices are profitable depending on how they contribute to increasing the present value of installation costs and the share of electricity self-consumed.

Residential prosumers could obtain 10% profitability by either achieving ~75% self-consumption share at current installation costs; 1€/Wp installation cost at the current share of self-consumption (33%); or by self-consuming ~88% the electricity generated even at 2€/Wp. There is a trade-off between oversizing the installation to get lower costs per kWp and higher absolute profits, and undersizing it to maximize the share of self-consumption and profitability.

Commercial prosumers could achieve 10% profitability by self-consuming about two-thirds of the electricity generated or by reducing their installations costs about a third. The industrial segment could not achieve 10% profitability only by increasing its self-consumption share, and installation costs should fall even more than the commercial segment to achieve the same profitability level.

The residential segment has the highest sensitivity to the share of electricity self-consumed due to the larger difference between the savings derived from self-consumption (i.e. the variable part of the retail electricity price) and the revenues derived from the surplus electricity sold to the grid (i.e. wholesale price). The slope of the profitability thresholds represents the potential of storage and demand management to increase profitability. Residential segment has the highest slope entailing that a low increase in the share of self-consumption allows to significantly increase the present value of the installation cost achieving the same profitability level. Thus, although the residential segment has the lowest profitability of the three segments due to its higher installation costs and lower self-consumption share, it also has the highest potential to boost profitability by maximizing the self-consumption share and decreasing unit installation costs.

This analysis reveals that (i) storage and demand management are the most promising measures that investors can adopt to increase PVSC profitability, (ii) their potential is higher in the residential segment due to the higher differential between retail and wholesale prices, but (iii) they are subject to diminishing marginal returns as their potential declines as profitability increases (as revealed by the decreasing slopes of the profitability thresholds in Fig. 4).

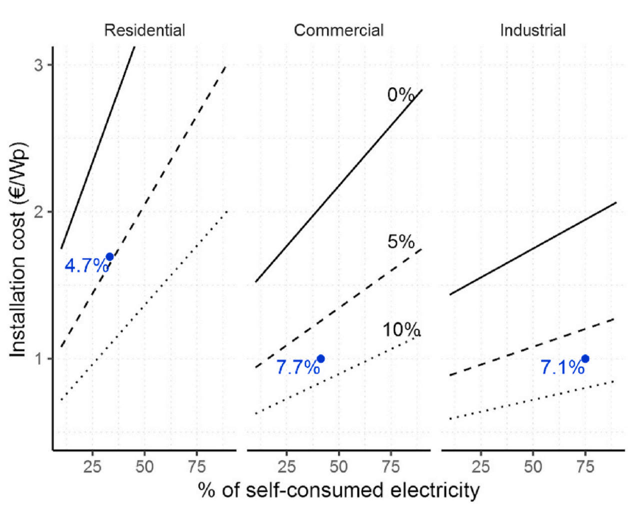

Fig. 4. Prosumers' profitability (0% (solid line), 5% (dashed line) and 10% (dotted line) internal rate of return (IRR)) for residential, commercial and industrial segments depending on the share of self-consumed electricity and installation costs. Average values indicated in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

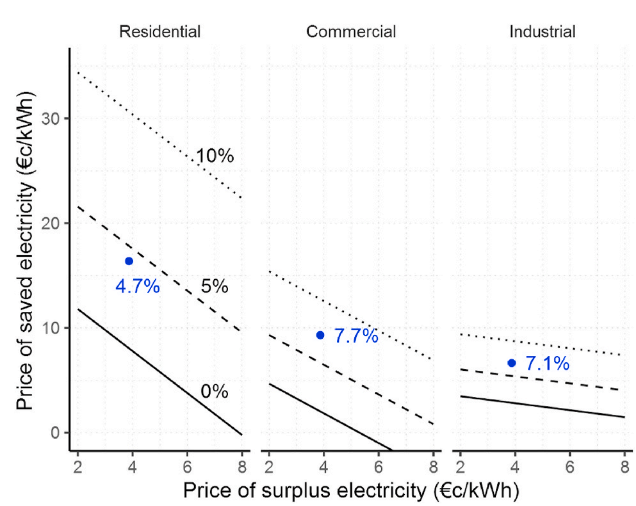

Fig. 5. Prosumers' profitability (0% (solid line), 5% (dashed line) and 10% (dotted line) internal rate of return (IRR)) for residential, commercial and industrial segments depending wholesale (price of surplus electricity) and (variable part of) retail (price of saved electricity) electricity prices. Average values indicated in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4.3. Retail and wholesale electricity prices

Electricity prices also determine the profitability of PVSC installations. On the one hand, the difference between the variable part of the retail price (the savings of self-consumption) and the wholesale price (the revenues of the surplus electricity exported to the grid) determines the potential benefits of storage or demand management (Fig. 4). On the other hand, the higher electricity prices (both retail and wholesale), the higher the profitability of PV self-consumption.

Fig. 5 shows the profitability ranges for all plausible combinations of the variable part of the retail price and the wholesale price. The sensitivity of the different segments to changes in wholesale/retail prices is given by their self-consumption share. Therefore, the industrial segment with a high share of self-consumption (75%) has high sensitivity to the retail prices and residential segment with low share of self-consumption (33%) has high sensitivity to the wholesale electricity prices. This is illustrated in Fig. 5 by the distance between thresholds and their respective slopes. Since the residential segment does not self-consume a high share of the electricity produced, achieving 10% profitability would require doubling (the variable part of) retail electricity prices. On the opposite, since the industrial segment is able to self-consume most of the electricity produced, it could achieve more than 10% profitability at a retail price of only 10€c/kWh.

We have so far referred to the variable part of retail prices. Increasing the fixed share of retail prices would harm prosumers' profitability by reducing the potential savings derived from self-consumption. However, such a change in the retail price structure could be necessary to properly reflect the fixed cost of the grid and to avoid prosumers free-riding the rest of consumers by avoiding the part of the grid cost included in the variable part of the retail price. An alternative approach would be to maintain volumetric tariffs with part of the grid cost charged in the variable part but increase the grid-access charge on the surplus electricity exported to the grid. This alternative approach has two main advantages: (i) avoiding changing the retail tariff structure by increasing the fixed part, which would likely have a regressive effect on electricity consumers, reduce incentives for energy savings and reduce the profitability of PV self-consumption; (ii) increasing the differential between savings from self-consumption and revenues from surplus electricity sold to the grid, which would increase the value of, and therefore incentivize, storage and demand management.

The evolution of both wholesale and retail prices is uncertain. Whereas on the one hand there are factors pushing prices up, such as the internalization of externalities (e.g. carbon prices), there are also factors depressing electricity prices, such as the merit order effect caused by the expansion of renewables with low variable costs or the contraction of demand. Fig. 6 shows the sensitivity of the profitability results with respect to the annual escalation rate of the price of saved electricity (retail), and the price of the surplus electricity exported to the grid (wholesale). All segments are more sensitive to the evolution of retail prices, as the main gains of PVSC derive from the savings from self-consumption rather than from the benefits of exporting the surplus electricity to the grid. The industrial segment is the most sensitive to the evolution of retail prices as it self-consumes most of the electricity generated (75%), whereas the self-consumption share is lower for the residential and commercial segments (33% and 41% respectively). In any case, within the range of ±5% annual escalation rate, profitability is always positive and remains below 10% internal rate of return.

Fig. 6 also illustrates the profitability difference between the two possible schemes: direct sell and net billing. The profitability difference between both options shown in Fig. 6 is small because it only captures the effect of the 0.5€/MWh grid-access charge and the 7% electricity tax on the value of the surplus electricity exported to the grid. However, other factors reduce the final profitability of the direct sell scheme, such as the additional soft costs and the fact that income is taxable whereas savings are not. Most importantly, and influencing the comparison reversely, the total gains from the net billing scheme are limited to the potential savings from the electricity bill, whereas the direct sell mechanism does not face such constraint. The choice between systems is therefore mainly influenced by the scale of the project and the absolute profits rather than by the profitability differential.

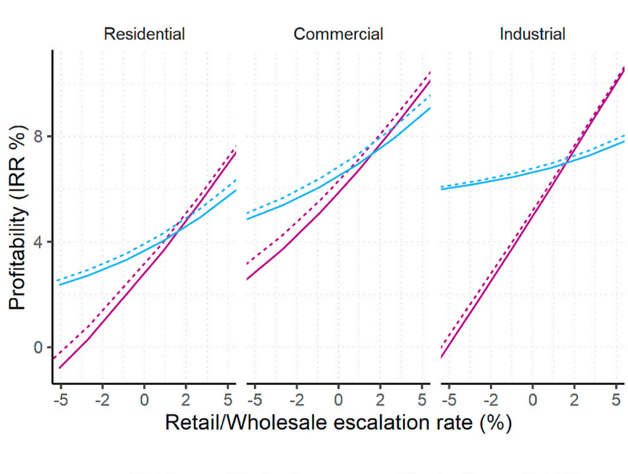

Fig. 6. Profitability depending on wholesale and retail prices annual escalation rates for the three segments and both schemes, direct sell and net billing.

4.4. The effect of financing and the potential emergence of new business models

We have considered so far own capital investment. The general effect of financing the investment is to reduce profitability when the interest rates are higher than the internal rate of return (residential segment in the current conditions) or to increase it otherwise (commercial and industrial segments). However, the effects of the financing conditions are non-linear, as shown in Fig. 7, and depend on whether the internal rate of return is higher than the interest rates.

Given current conditions, residential prosumers would achieve higher profitability by minimizing the share of the investment externally financed. Commercial and industrial segments can however increase their profitability by maximizing the share of the investment externally financed, given that their internal rate of return is higher than the

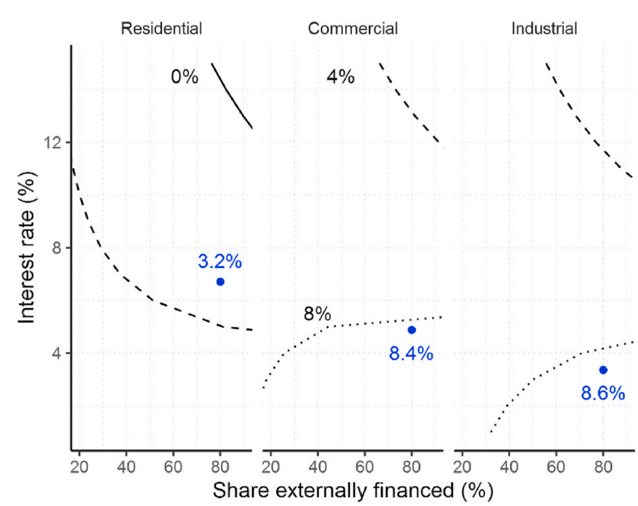

Fig. 7. Prosumers' profitability (0% (solid line), 4% (dashed line) and 8% (dotted line) internal rate of return (IRR)) for residential, commercial and industrial segments depending on the share of the investment externally financed and the interest rate. Average values indicated in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

interest rates. Both segments are approximately along the 8% profitability threshold.

Three factors could trigger the emergence of new business models related to PVSC: (i) the differential in retail electricity prices and installation and financing costs across segments, (ii) the opportunities of shared self-consumption and demand management to maximize the share of self-consumed electricity, and (iii) the higher information asymmetries, risk aversion and transaction costs characteristic of the residential segment. Third parties could exploit the high profitability potential of residential markets (due to their high retail prices) while having the low costs of industrial prosumers. Likewise, aggregating and optimizing loads could increase the share of electricity self-consumed and maximize its value through price arbitrage with the wholesale electricity market. Finally, these types of new business models could overcome the information asymmetry and risk aversion of residential consumers reaching markets that would not be developed otherwise.

Fig. 8 illustrates this potential profitability differential by comparing the profitability of the residential segment under a net billing scheme with own capital (since financing the investment is not profitable for this segment) with the two hypothetical situations: (i) A PVSC system with residential retail prices, industrial financing conditions (3.36% interest rate and 80% externally financed) and installation cost (1€/Wp) selling their electricity directly to the wholesale market (i.e. facing the 7% generation tax and the 0.5€/MWh grid-access charge on the surplus electricity sold to the grid); (ii) idem with double installation costs (2€/Wp), representing higher system costs derived from, e.g. electricity storage facilities or demand management devices. Fig. 8 illustrates profitability as a function of the share of self-consumed electricity to integrate the potential of these types of new business models to increase the self-consumption share by aggregating final consumers/prosumers or providing additional electricity storage or demand management services.

A PVSC system operating in the residential market with industrial costs could increase profitability from the 4.7% average of the residential segment up to ~15% (left arrow in Fig. 8), even facing the generation tax and grid-access charge on the surplus electricity exported to the grid characteristic of the direct sell PVSC mechanism to avoid any limitation on total profits. If this system were able to achieve 75% self-consumption (for instance, by aggregating final consumers to the system), profitability would increase to ~35% (left arrow in Fig. 8) and even higher than 40% from 85% self-consumption onwards. Even at double installation costs (2€/Wp, for instance, including battery storage or smart devices in the installation), a PVSC system operating in the residential market with industrial costs could obtain ~10% profitability, the same as in the standard residential case (although it would be harder for a residential installation alone to achieve 75% self-consumption).

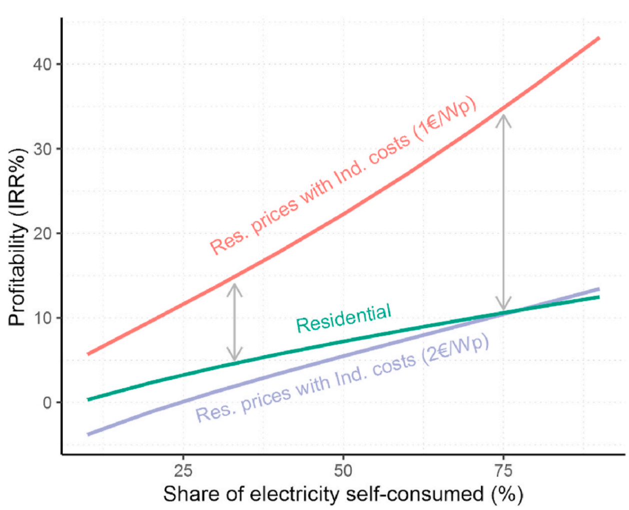

Fig. 8. Profitability (internal rate of return, %) depending on the share of electricity self-consumed for three different configurations: (i) direct sell system with residential prices and industrial financing and installation costs (red); (ii) average residential net billing with own capital (green); and (iii) direct sell system with residential prices and industrial financing costs and 2€/Wp installation cost (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

For these new business models to thrive, further regulatory developments are necessary. Dynamic coefficients among the consumers of a shared PVSC (rather than constant as currently specified in the RD 244/2019) would allow the dynamic maximization of self-consumption within the PVSC system, allowing the emergence of aggregators to realize this dynamic optimization process. More flexibility in the conditions for shared PVSC systems (e.g. increasing the maximum distance (currently 500 m) for shared PVSC system connected through an external network) would increase the number of application for PVSC systems and likely improve their profitability by allowing a higher share of self-consumption and decreasing unit costs thanks to economies of scale and reduced transaction costs.

5. Conclusions and policy implications

The profitability of PV self-consumption installations of all segments (residential, commercial and industrial) in average conditions is now positive under the current Spanish regulation (RD-L 15/2018 and RD 244/2019), which improved the economic and administrative conditions of prosumers with respect to the former regulation (RD 900/2015). The new regulation removes the backup charge on self-consumed electricity, allows remuneration for the surplus electricity exported to the grid, simplifies administrative procedures and recognizes the right to shared self-consumption, implementing thus the main recommendations we had laid out in our analysis of the former regulation (López Prol and Steininger, 2017).

Prosumers can now choose between a simplified monthly net billing procedure, where the profits of the surplus electricity sold to the grid are directly discounted from the electricity bill, or a general system where they can directly sell the surplus electricity to the grid in the same conditions as any other producer. Whereas the net billing system provides higher profitability (because profits are realized as savings and are therefore not taxable, and the surplus electricity exported to the grid is exempted from the generation tax and the grid-access charge), total profits are limited by the value of the energy part of the electricity bill, the monthly billing and the maximum installed capacity of 100 kWp. On the opposite, the general system would yield lower profitability but total profits are not constrained by any of the aforementioned conditions.

The residential segment has the lowest profitability levels, but the highest potential due to the high retail electricity prices. This potential could be realized by maximizing the share of electricity self-consumed and by continuing the declining trend of unit installations costs. New business might emerge exploiting the price and costs differentials across segments, i.e. harnessing the high retail prices of the residential segment with the lower installation and financing costs of commercial and industrial segments, and exploiting the possibility of shared self-consumption to maximize the share of electricity self-consumed. Further regulatory development is however necessary to allow the emergence of these new business models, such as allowing dynamic coefficients between the members of a shared PVSC system and third parties to operate connecting prosumers, consumers, retailers and the wholesale market.

Whereas this regulation improves the situation of PV prosumers in all segments, it has some risks related to its potential distributive effects and integration costs to the electricity system caused by increasing PV penetration. Further research should explore these potential risks, as well as the specific configurations and value creation logic of different types of business model innovations that could capture the opportunities we have identified. Tracking these risks and opportunities will improve policy responsiveness to best exploit potential synergies between different policy objectives, such as cost-efficient decarbonization and social fairness.

CRediT authorship contribution statement

Javier López Prol: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization, Funding acquisition. **Karl W. Steininger:** Investigation, Writing - review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Glossary

PV: photovoltaic
PVSC: photovoltaic self-consumption
RD: Royal Decree
RD-L: Royal Decree-Law
ps*:* retail electricity price (€/kWh)
pg*:* wholesale electricity prices (€/kWh)
δ*:* backup charge (variable part in €/kWh and fixed part in €/kWp)
$\mathbf{PV_{IN}}$*:* installation cost (€/kWp)
$\mathbf{PV_{OM}}$*:* operation and maintenance costs (€/kWp)
i*:* Interest rates (%)
α*:* share of the investment externally financed (%)
β*:* % of electricity self-consumed (%)
$\boldsymbol{\varepsilon_p}$*:* escalation rate of electricity prices (%)
$\boldsymbol{\varepsilon_{PVom}}$*:* escalation rate of operation and maintenance costs (%)
$\mathbf{E_{PV}}$*:* electricity generated by the PV system (kWh/kWp y^{-1})
dg*:* degradation rate (%)
N*:* lifetime of the system (years)
Nl*:* maturity of the loan (years)
γ*:* grid-access charge (years)
λ*:* generation tax (%)