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ORIGINAL ARTICLE

PV adoption: the role of distribution tariffs under net metering

Axel Gautier[1,2,3] · **Julien Jacqmin**[4]

Abstract The deployment of decentralized productions units (DPU) like rooftop solar panels is a major challenge for a transition towards greener energy sources. Under a net metering system where the meter runs backward when there is excessive PV production, the electricity produced by a solar panel is valued at the retail price. Higher retail prices thus encourage the deployment of DPU. To identify this relationship, we use data from Wallonia where tariffs are paid on a mostly volumetric base and where there are 13 different tariff zones. Using various specifications, our results suggest that in a municipality where the distribution tariff is one eurocent per kWh higher, the investment in solar PV is, all else equal, around 8% higher.

Keywords Renewable energy · Distribution tariffs · Residential PV panels

JEL Classification Q42 · L51 · D12

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✉ Axel Gautier
agautier@uliege.be

Julien Jacqmin
julien.jacqmin@neoma-bs.fr

1 HEC Liege, LCII, University of Liege, Bat B31, Quartier Agora, Place des orateurs 3, 4000 Liege, Belgium

2 CORE, UCLouvain, Louvain-la-Neuve, Belgium

3 CESifo, Munich, Germany

4 NEOMA Business School, 1 Rue du Marechal Juin, 76130 Mont-Saint-Aignan, France

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1 Introduction

The traditional electricity system faces many challenges with the transition towards greener energy sources. New modes of production do not only have an impact at the production stage. A key issue for the distribution system operators (DSO) is to integrate distributed production units (DPU), like residential solar panels, that are connected to the low voltage grid. By installing solar panels, households do not only produce the green energy that they consume, they are also using the grid to make power exchanges. Indeed, a grid-connected DPU can import electricity when the production is insufficient to cover its consumption and export the excessive power when production exceeds consumption. Regulation of these exchanges is of prime importance to provide adequate incentives for investment and to ensure the financial viability of the distribution grid. The regulated grid tariff has to reconcile these two dimensions.

There are different methods to price these power exchanges between a DPU and the grid. The two main systems to measure power exchanges with the grid are the net metering scheme where there is a single price for both imports and exports and a net purchasing scheme where the prices are differentiated. Several EU countries (like Denmark, Poland, Austria, Cyprus, Greece, Hungary, Latvia, Netherlands and Belgium) and 43 US States use a net metering system. From Brown and Sappington (2017a, b), Gautier et al. (2018), and Schittekatte et al. (2018), we know that net metering and net purchasing provide different incentives to invest in DPU and share the burden of network costs differently. Net metering has been criticized for providing inadequate incentives for investment in DPU, leading to overinvestment compared to the social optimum. Furthermore, the system fails to provide incentives for auto-consumption or storage. Following the suggestions from the European Commission (2015a) and the IEA (2014), some countries are phasing out their net metering system and switch to a net purchasing system.

In a net metering system, the solar production is implicitly valued at the retail price of electricity. Consequently, the return on investment is higher in areas where the retail price is higher and we should expect a larger deployment of DPU in those places. Our objective is to measure this relationship. Currently, many authors, such as Cai et al. (2013) or Schittekatte et al. (2018), use simulation models to estimate the optimal grid tariff for the distribution grid, taking into account the impact on investments in DPU. Our paper provides an empirical estimation of the impact of the grid tariff on investment. Such an estimation is of prime importance as it can be used to better calibrate tariff simulators that provide enlightened recommandations to regulators.

We use municipality-level data from 2008 to 2016 from the Walloon region, the southern region of Belgium. We focus on residential PV investments, which, as of today, have been done by close to 10% of the households. PV panels are integrated to the energy system via a net metering system. Hence, this electricity produced by the PV is valued at the retail price, which is made by about 40% of distribution tariffs, and the remaining 60% is composed of other, mostly commodity-related, costs and taxes. Our estimation strategy takes advantage of one peculiar institutional feature of Wallonia: Tariffs are set differently according to 13 different geographical zones, while other components of the retail price depend on market forces, policies and regulations impacting homogeneously the region. One key additional advantage of our setting is that the tariff-related part of the bill is almost fully dependent on the amount of electricity consumed. Hence, in this peculiar context, investing in PV helps reduce to close to zero an annual energy bill that for an average household would range between 700€ and 1100€ depending on the municipality where the household lives. These savings accrue for the lifetime of the PV installation and of the net metering system.

Overall, using a two-way fixed effects model, we do find that higher energy prices due to the prevalence of higher consumption-based tariffs provide a significant incentive to invest in residential PVs. Using various estimation approaches taking advantage of our cross sectional and temporal variation in tariffs, we find that an increase in the distribution tariff by one eurocent per kWh leads to an increase of around 8% in the amount of new PVs installed yearly. Hence, regulated grid tariffs strongly influence the residential investment in solar PV.

The determinants of the emergence of renewable energy sources in the energy system have already received much attention from the literature since the first analysis from Menz and Vachon (2006). Interests in investments in solar panels by residential households are much more recent.[1] Our analysis is directly linked to the literature looking at the effectiveness of the various policy implemented to boost PV adoption like up front subsidies and production subsidies. For example, Hughes and Podolefsky (2015) find using Californian data that upfront rebates have had a large and significant impact on residential PV adoption.[2]

Using U.S. state-level data, Matisoff and Johnson (2017) study whether the presence of a net-metering policy, as measured by a dummy variable, has had an impact as well. They find that a net metering scheme, on a stand-alone base, is ineffective in encouraging households to invest in PVs. However, coupled with financial incentives, especially in the form of upfront cash incentives, net metering does have a positive and significant impact. Hence, financial incentives and net metering policies complement each others. We contribute to this literature by looking at a setting where a net metering system is generalized but where the generosity of the system varies with respect to the energy bill saving implied due to the heterogenous distribution tariffs in place.[3] Hence, our work is also closely linked with the one of Germeshausen (2018) who study, using German data, the impact of a feed-in tariff system where the generosity varies depending on the PV installation size.

1 See Vasseur and Kemp (2015), De Groote et al. (2016) and Jacksohn et al. (2019) for studies looking at the various determinants behind PV adoption.

2 Despite sizable yearly returns, production subsidies could still lead to an under-investment in solar PV. The reasons why are similar to the one behind the "energy efficiency paradox" [see a.o. Jacobsen (2015) or Houde and Myers (2019)]. Apart from budget constraints and informational asymmetries concerning bill saving potential, behavioral biases are also likely to play a role. Production subsidies will be undervalued by consumers due to their intrinsic myopia, their expectations regarding the commitment to the future subsidies and the uncertainty regarding the lifetime of the PV installation. De Groote and Verboven (2019) find using Flemish data about PV installation that the implicit discount rate is equal to 15%, well above the conventionally assumed market rate.

3 Compared to Crago and Chernyakhovskiy (2017) who look at the impact of the average electricity price on PV adoption with U.S. county-level data, all of our homeowners have access to a net metering system. In addition, there is no increasing block rate in Wallonia and the source of the retail price variation is more precisely defined in our setting as it comes from the heterogeneous tariffs.

The paper is organized as follows. Section 2 provides a background of the energy sector in Wallonia, and more precisely about the policy context surrounding residential PV investments and tariff regulations. Section 3 discusses our empirical strategy while Sect. 4 presents the data. Our results are presented in Sect. 5. In Sect. 6, we conclude.

2 Residential PV in Wallonia

Belgium is composed of 3 regions: Brussels, Flanders and Wallonia. Wallonia is the largest in area and has more than 3.5 millions inhabitants. It is composed of 262 municipalities. Alike other European Union countries, the electricity sector is vertically disintegrated. In terms of energy policy, regions have the responsibilities to meet the targets about electricity production from renewable sources and to regulate the distribution of electricity. All other production as well as transmission issues are regulated at the national level.

2.1 Support to solar energy in Wallonia

Residential solar PV installations of less than 10 kWp are the focus of this paper. As shown on Fig. 1, by the end of 2016, Wallonia had more than 130,000 households, around 10% of the household population, with PV installed in their residence, with a total capacity of 699 MWp. These installations produced 686 GWh of electricity in 2016. A striking fact described on this graph is that the most fruitful year in term of PV investments was the year 2012, even though the price of PV panels have continuously decreased since then. The main reason behind this shape is the very generous support system present in Wallonia and progressively discarded after 2012.

Starting in 2008, Wallonia installed several mechanisms to support the deployment of small-scale solar panels by households.[4] The supporting mechanism for residential installations is composed of up front and production subsidies (Newell et al. (2019)).

Up front subsidies During the period 2008–2011, investments in solar PV were eligible for an income tax rebate. The federal government supported investments in energy saving technologies, including solar panels, by allowing household to deduct installation expenses from their taxable incomes.

Different premia were offered to support investments in solar PV. The Walloon government offered an investment premium from 2008 to March 2010. The premium was calculated as a percentage of the investment and was capped at 3500€. In addition, some local governments (provinces and municipalities) decided to offer an additional premium for the investment. In the timespan of our study, households in 80 municipalities have benefited from a local support mechanism at some point in time. The municipal support was rather modest in size, on average 400€ and defined as a lump sum, a rebate in percentage of the investment made with a cap or conditional on receiving other grants.

[4] At the end of 2007, before our sample period and before the specific supporting schemes, there were only 36 photovoltaic installations with a cumulated power of 128 kW.

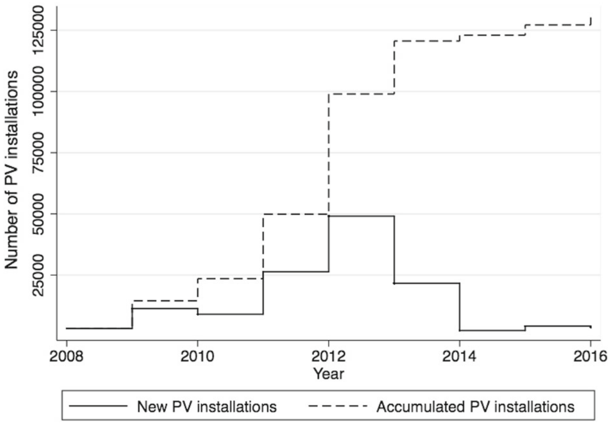

Fig. 1 New/accumulated PV installations in Wallonia (2008–2017)

Production subsidies: Net metering Households who install solar panels are making two types of exchange with the grid: imports from the grid when local production is insufficient to cover consumption and exports to the grid when production exceeds the consumption. To measure the exchanges with the grid, households are equipped with a single meter and the meter runs backwards when electricity is exported. This system is known as net metering. The meter measures net imports of energy, consumption minus production and net imports are used as the basis for the energy billing. With net metering, the energy produced by the solar panels is implicitly valued at the energy bill price, which is well above its market value.[5] In Wallonia, households are not equipped with smart meters and the index of the meter is recorded annually. This recorded index is the basis for the yearly electricity bill. There is no credit for the excessive production and should the yearly production exceeds the yearly consumption (i.e. a negative index on the meter), there is no additional payment for these net exports and the bill is based on a zero consumption level. With net metering, a higher grid tariff increases the return on PV investment. Hence, it is an implicit form of financial support for decentralized energy production.

Production subsidies: Solwatt and Qualiwatt To support the production of green energy, Wallonia chose also a tradable green certificate (GC) mechanism. Green certificates are awarded for the production from certified renewable sources at a rate of 1GC per MWh of green electricity produced. Energy retailers must use the GC to certify that a given percentage of their energy supply is green. To that end, GC are traded on a dedicated market and the regulator added a price floor at 65€ and a price ceiling at 100€. With a granting rate of 1 GC per MWh, solar panels were initially not profitable. In 2008, the *Solwatt* plan changed this granting rate to 7 GC per MWh for solar PV installations of less than 10 kWp and extended the grant period. The technology started to spread quickly as the mechanism was quite generous with an estimated direct support of 588 € per MWh produced (Boccard and Gautier (2015)).

[5] Note that the pricing is independent from the quantity of electricity consumed. Hence, there is no increasing/decreasing block pricing in place. For a setting where tiered tariffs are in place see (Borenstein (2017)).

Table 1 Grant rate and grant period of GC, Solwatt mechanism

Grant rate (GC/MWh)	Grant period (years)	Application period
7	15	Jan. 2008–Nov. 2011
7	10	Dec. 2011–Mar. 2012
6	10	Apr. 2012–Aug. 2012
5	10	Sep. 2012–Mar. 2013
1,5	10	Apr. 2013–Feb. 2014

As from 2011, the grant rate and the grant periods were modified (see Table 1) but this change applied to new installations exclusively. The generous granting of GC to solar panels and the high level of adoption disequilibrated the GC market that was in excess supply. In March 2014, the Solwatt system was replaced by a new supporting scheme named *Qualiwatt*. The main objective of Qualiwatt is to limit the subsidies to solar installations. The Qualiwatt program guarantees the return on investment by paying a yearly premium during 5 years. A PV owner benefits from energy savings and the premium to cover the investment cost. To estimate the energy savings (and therefore, the premium to be paid), the regulator estimates the production of a reference installation for a period of 8 years and value this production at the retail price. Therefore, as the net metering compensation is part of the return, a higher network tariff implies a lower premium. Under Qualiwatt supporting scheme, the benefit of a higher grid tariff is partially offset by a lower premium.[6] The premium is paid by the DSO and its cost is included in those of the public service obligations imposed to the DSO. The Qualiwatt mechanism was over in June 2018 and from this time new PV installations no longer get a premium via this medium or any other except net metering.

2.2 Distribution tariff

With the unbundling of the electricity system, the distribution of electricity is operated by local regulated monopolies. There are now 7 of them active on the territory of Wallonia covering from one municipality to more than 150 of them. There is no uniform pricing for the distribution in Wallonia. The largest DSO is ORES and across its regulated territory 7 different tariff zones are in application (see Fig. 2).[7] On average, as of 2017, distribution tariffs make 37% of the resident's final electricity bill (CWaPE (2017)). The regulated distribution tariff covers the cost of the grid cost but not only. There are several public service obligations imposed to the DSO, mainly social tariffs and public lightening, that are covered by the distribution tariff. In the recent years, the costs of those obligations, especially those linked to the social tariff have been on the rise.

Energy tariffs are regulated. In Belgium, energy regulation is done at two levels. At the federal level, a national regulator (CREG) is in charge of regulating the transport grid. At the regional level, three regional regulators, one per region, are in charge of

[6] The energy savings used to compute the Qualiwatt premium are not based on the life-cycle of the PV installation, typically 20 years, but on a 8 years period.

[7] ORES is the result of a merger between 7 DSO and the merged entity continued to apply different tariffs for the pre-merger territories.

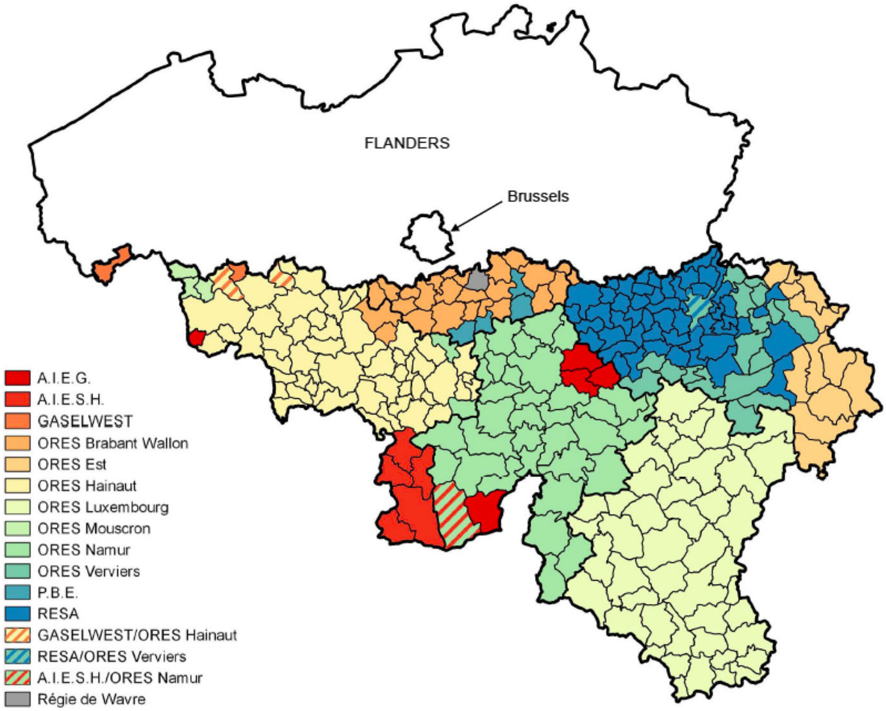

Fig. 2 Map of Belgium with the 13 geographical tariff zones in Wallonia

the promotion of renewable energies and the public service obligations. The regulation of the distribution tariffs was in the hand of the national regulator until 2014 and in the hand of the regional regulator since then. In principle, a regulatory period lasts for 5 years and, during this period, the regulator uses the same methodology for fixing the tariffs. The CREG adopted a cost-plus methodology for the period 2008–2012. In 2013, anticipating the transfer of competency to the regional regulator, it prolonged its methodology for an additional 2 years (2013–2014). After the transfer of competency, the regional regulator in Wallonia continued to use the same methodology until 2018. There are thus three different regulatory periods during our sample period: 2008–2012, 2013–2014 and 2015–2016 with a homogeneous tariff methodology.

In this cost plus regime, at the beginning of the regulatory period, the DSO estimates its budgeted costs and revenues for the entire period. Upon approval by the regulator, a yearly tariff is calculated to cover the budgeted costs with the revenues. Tariffs are not constant during a regulatory period and their evolutions reflect those of the budgeted costs and revenues. Positive or negative departure from the budgeted costs and revenues are accounted in specific regulatory balance sheets. Once they are approved by the regulator, these balances are added to or subtracted from the costs to be recovered and the future tariffs are adapted accordingly. However, due to different administrative and judicial problems, the regulators did not approve these regulatory balances for a while. In 2013, these balances were not yet approved for the years 2010–2012 and not yet integrated in the tariffs for the years 2008 and 2009. DSO accumulated credit during this period (approximately 107 m€ for the period 2008–2014). It is only from 2015 that these regulatory balances have been integrated in the distribution tariffs, but only partially as the regulator wants to spread these accumulated credits over several years.

These specific institutional features are important as they limit the risk of reverse causality in our analysis. The rapid deployment of solar PV, mostly during the Solwatt period, was largely unanticipated in the tariff methodology of 2008. Consequently, the costs of solar PVs for the DSO (lost income, possible additional grid costs) were not included in the distribution tariff until the next period. Furthermore, there was no take back during the following regulatory periods as regulatory balances were frozen. For these reasons, the rapid deployment of PV had no direct and immediate influence on the distribution tariff and reverse causality is not a concern in our particular institutional setting.

One particularity of the distribution bill in Wallonia is that it is for the most based on the volume of electricity consumed (Hinz et al. (2018))[8]. For an average consumption of 3500 kWh per year, an average resident of Wallonia will have a bill related to the distribution of electricity that depends only at around 5% from fixed/capacity charges.[9] The rest depends on the volume of electricity consumed. This reliance on the volumetric part is one of the highest observed in Europe, only equalled by the one observed in Hungary and the UK (European Commission (2015b)).

Figure 3 reports the evolution of volumetric tariff (including VAT) for the 13 tariff zones for the period 2008–2016. As we can observe, distribution tariffs have been on the rise over the past 10 years, with the exception of the year 2014 where a transitory change in the VAT rate was applied. During our period of observations, the average tariff went from 7.8 to 10.5 eurocent/kWh. Although this rise has been heterogenous across Wallonia. Even if there is some within variation (0.92), most of the variation is between (1.39) the tariff zones. This heterogeneity reflects differences in local costs of distributing electricity (including the cost of public service obligations) and differences in the relative efficiency of the DSO. Unfortunately the cost-plus system in place is not effective to identify the two. On average, the difference between the highest and the lowest tariff is equal to 6 eurocent/kWh which creates a substantial difference in the final energy bill of consumer.

For solar PV owner, a 1 eurocent difference in the distribution tariff translates into an additional saving of 10€ per MWh produced. This means that, in 2016, an installation producing 1 MWh has an *extra* yearly return of 73.8 € in the municipalities served by GASELWEST where the distribution tariff was the highest (14.60 eurocent/kWh) compared to municipalities served by AIEG where it was the lowest (7.22 eurocent/kWh). With a lifetime of over 20 years for a solar panel, the implicit subsidy given via the net metering system to solar PV installation in place varies substantially from one tariff zone to the other.[10]

[8] Note that there is no coincidental peak pricing system in place as discussed in Baldick (2018).

[9] These fixed charges are assigned as being related to the rent of the meter and are between 15 and 20 €per year. For a prosumer exporting weakly more than importing electricity, this fixed part of the bill will always have to be paid to the DSO.

[10] To produce 1 MWh in Wallonia, the installation should have a capacity of 1 kWp. Such an installation costs less than 2000€ in 2016.

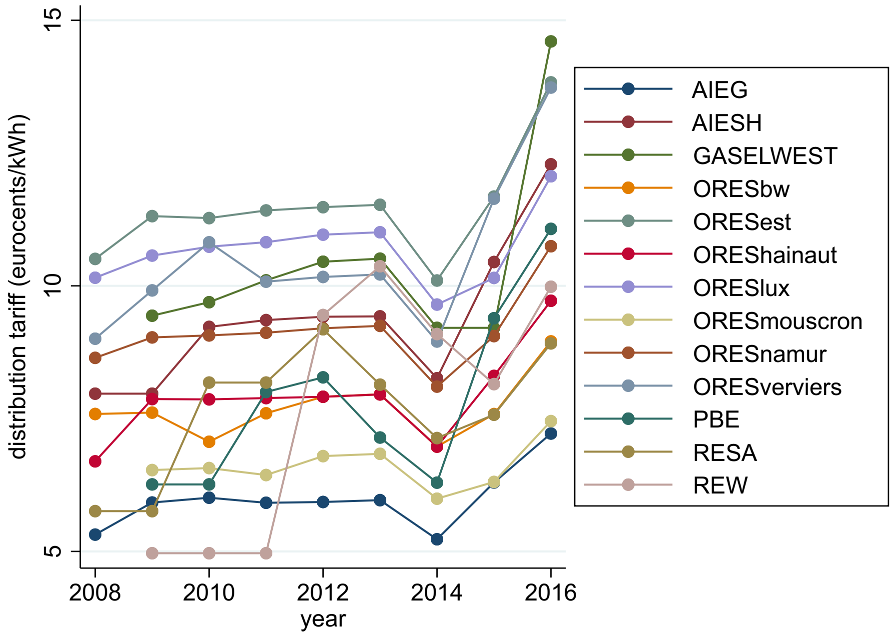

Fig. 3 Distribution tariffs in the 13 tariff zones in Wallonia (2008–2017)

3 Empirical strategy

Our objective is to study whether residents are responsive to energy costs when deciding to invest in a PV installation using a closed-form approach. For this purpose, we exploit the variation of energy costs across Wallonia using municipality-level panel data. This variation is due to the distribution tariffs that vary according to the 13 geographical tariff zones in place, while the rest of the energy bill is on average similar across the region as they rely on market forces and regulations effective at the regional and supra-regional level.

Let $Y_{i,t}$ denote the number of new PV installations in municipality i in year t. We model $Y_{i,t}$ as a function of our explanatory variable and control variables. A first specification can be written as follows:

$$Y_{i,t} = \alpha + \beta tariff_{i,t} + \gamma X_{i,t} + \mu_i + \phi_t + \mu_i t + \epsilon_{i,t} \qquad (1)$$

where α is a constant term, $tariff_{i,t}$ is our explanatory variable, $X_{i,t}$ is a vector of municipality-level covariates and $\epsilon_{i,t}$ is a mean-zero error term. We also include municipality dummies μ_i and year dummies ϕ_t. Finally, $\mu_i t$ is a municipality-specific time trend.

Taking advantage of the panel structure of our data allows us to control for various sources of unobserved heterogeneity. Municipality fixed-effects help us to implicitly consider municipality-specific omitted variables that are constant over time. We think for example of locational aspects like the size of the municipality, geographic coordinates or solar radiation/orientation.[11] Year fixed-effects control for broader trends in adoption of PV due to changes in prices or overall awareness of solar panels. More importantly, they also implicitly control for policies set at the regional and national level impacting the electricity bill. Municipality-specific time trends are also included in order to capture the different trends in uptake due for example to supply side conditions. In addition, control variables will diminish the presence of the omitted variable bias by taking explicitly into consideration some form of heterogeneity evolving across time and place that is measurable. Overall our analysis hinges on the assumption that $tariff_{i,t}$ is not correlated with unobserved factors $\epsilon_{i,t}$ that could also affect $Y_{i,t}$. In addition, we will also explicitly control for various factors related to housing characteristics, socioeconomic aspects and the political context.

A linear model, as the one presented in Eq. (1), is not well-suited to accommodate the nonnegative distribution of the dependent variable. We therefore use a Poisson quasi-maximum likelihood estimator with conditional fixed effects as it is better able to model the conditional expectation of our dependent variable (Wooldridge (1999)). This approach does not rely on the assumption of mean variance equivalence. It also provides robust standard errors that accommodate arbitrary patterns of correlation among the observations for each municipality. We will in addition show that our results are robust to using a least square dummy variable or a negative binomial approach.

One important thing to note is that in most of our specifications we have lagged by 1 year our main explanatory variable. Hence, we use $tariff_{i,t-1}$ as an explanatory variable instead of $tariff_{i,t}$. There are a number of explanations for this assumption. First of all, one theoretical explanation is that households do not necessarily respond to contemporaneous tariffs but to lagged tariffs, as stipulated on their electricity bill which is received only later after the consumption of electricity. Households might find it difficult to evaluate how new tariffs might impact their returns to invest in solar panels as electricity consumption is only paid ex-post (Ito (2014)). As discussed in Jacqmin (2018), there might as well be delays due to administrative and installation reasons. Beside these explanations, using a 1-year lag is also suggested by the Akaike Information Criterion (AIC) and the Schwartz Criterion (BIC). A bi-product of the 1-year lag between our explanatory and dependent variable is that it helps us get rid of the strict exogeneity assumption, conditional on the fact that unobserved variables are serially uncorrelated. Note however that analyzing contemporaneous data does not change the quality of our results.

By looking at the impact of today's tariff on tomorrow's investment, we implicitly assume that consumers believe that tariffs, and more generally energy prices, follow a random walk. Hence, today's tariffs are "the best predictors" of future tariffs. Focusing on gasoline prices, Anderson et al. (2013) find that consumer's expectations about price evolution tend to follow this pattern.

One last issue to discuss relates to endogeneity. Our identification strategy takes advantage of the variation of tariffs and hinges on the exogeneity assumption. One worry raised first by Cai et al. (2013) is that tariffs are impacted by PV installations in order to recover the mostly fixed costs of the grid. As already mentioned, this is

[11] Note that the region is quite small in size, a bit more than 16,000 km^2 and homogenous in term of climate condition.

unlikely in the context analyzed here. For various institutional reasons that we detailed above, the distribution tariffs were not responsive to the changes in the DSO revenues and the rapid deployment of solar PV in Wallonia had no direct influence on the grid tarif. Hence, we believe that reverse causality is not a concern in our particular institutional setting.[12]

4 Data

The CWaPE, the regulatory body responsible for the energy sector in Wallonia, collects information about the PV systems installed by residents. We have data since 2008, and PV installations were scarce before then. Registration to the regulator is compulsory to be eligible for the subsidizing schemes. This information is aggregated at the municipality level for each years. The main reasons for this are because the information at the sub municipality level is imprecise and all our control variables are only available at the municipality/year level. We have information about both the number of installations and the production capacity of each installation in kilowatt-peak. There are two important things to note. First we have to drop six municipalities where two distribution system operators are active.[13] We end up with 256 municipalities remaining out of the 262 present in Wallonia. Second, the presence of municipalities where no PV panel were installed in a given year is very limited as it is only the case in 14 out of 2295 municipality/year observations. $\#\, of\, new\, PV$ and *capacity of new PV* will be our two dependent variables measuring the new PV investments made in year t in municipality i.

Our explanatory variable is *tariff* and is computed in eurocent per kWh. It is the distribution tariff (VAT included) paid for each kilowatt per hour of electricity consumed and is measured in eurocent. Tariffs are set by the CREG (until 2014) and the CWaPE (since then) separately for each of the 13 tariff zones of the region.[14] This data was also provided by the CWaPE.[15]

We also control for various factors split into three categories: housing, socioeconomic and political factors. All these factors have in common that they both vary across municipalities and across the years considered. The two housing factors we control for are *% apartment* and *% built after 1981*. The former which is the share of apartment is expected to negatively impact the number of installations as it can be complex to install solar panels on buildings where multiple households live together.

[12] Further investigations along these lines would require the use of instrumental variables. However, due to data limitations it is a rather challenging task. As tariff zones and DSO are not organized along the same boundaries, it makes it difficult to find DSO related informations fulfilling the criteria of a suitable instrument. Second and foremost, due to recent changes in the authority in charge of regulating DSO, limited comparable data about DSO is available.

[13] As we do not know the precise address of the investment and the distribution system operator frontier within the municipality, it is complicated to give a weight of the importance of the two DSOs or to use the same discontinuity as Ito (2014) with household level data.

[14] Remark that taking the log of the tariff or including the (comparatively small) fixed part of the tariff as a control variable does not impact our results.

[15] Note that the tariff data is missing for some DSO for the year 2008. We still analyze our data as if it was balanced.

The latter is the ratio of the number of buildings constructed after 1981 divided by the total supply of buildings. As apartments are less suited for PV installations, as they require an investment on a roof which is owned by multiple owners, we expect the coefficient of *% apartment* to have a negative sign. For the other housing factor considered, it is a priori unclear how it could affect investments in PV installations.[16]

We control for socioeconomic factors. *% unemployed* is the percentage of unemployed inhabitants. More unemployment is expected to negatively influence our dependent variable as investments in PV require a high up-front cost which is less likely to be available for unemployed people. *Population (log of)* is the number of inhabitants. We can expect that in municipalities with more inhabitants there will be more PV installations, as there will be more potential investors. *Median Income (log of)* is the median income net of taxes and we expect that municipalities with wealthier inhabitants will invest more. *Average age* is the average age of the inhabitants and we expect that all else being equal younger people will be more aware of the PV investments possibilities than older people. Hence we anticipate a negative sign for this control variable. *% foreigners* measures the percentage of households with a foreign nationality. As foreigners are likely to come from a less well-off socioeconomic background and to be less aware of the subsidies available (due to linguistic issues and a more general lack of information), the coefficient of this variable is likely to be negative. All these control variables come from Walstat, the official statistical source of the Walloon Region.

Finally we control for what we call political factors. *Local subsidies* is the level of the up-front subsidies granted to PV installers at the municipality and province level. After adding one unit due to the presence of zero's, we took the log of the subsidy which is granted on a per installation base. This information was collected by ourselves from various sources, including the administration of the municipalities/provinces themselves.[17] Remark that the level of these local subsidies is relatively small compared to what can be earned via the green certificate system or the net metering system.[18] *% green* is the percentage of votes received by the green party at the regional elections that took place in 2004, 2009 and 2014 at the canton level. We do not consider municipal election results as for those elections political parties do not always participate under their usual name and often form ad-hoc electoral lists with other party members. We expect this variable to be a good proxy of the awareness of citizens towards renewable energy sources.

Descriptive statistics are available in Table 2.

[16] Unfortunately we do not have data about the share of households that rent instead have own the place where they live on a yearly base. However, we believe that this factor is rather stable over the years of our sample.

[17] When the subsidies were provided in the form of a percentage rebate of the up-front investment cost, we transformed this information in a lump sum subsidy approximated by the average capacity of the installation made in each municipality each year and the average cost per kWp that specific year.

[18] The net metering system offers, for an average consumer with an installation of an average size, an implicit subsidy of more than 900 € annually. On average local subsidies are of about 400 € and granted the installation year only.

Table 2 Descriptive statistics ($N = 2295$)

Variable	Mean	*SD*	Min	Max	Source
Dependent variables					
# of new PV	56.139	82.403	0	1330	CWaPE
Capacity of new PV (kWp)	322.38	476.111	0	7527.208	CWaPE
Independent variables					
tariff (eurocent/kWh)	8.817	1.671	4.967	14.601	CWaPE
% apartment	6.814	6.767	0	60.7	Walstat
% built after 81	22.167	7.113	5.4	41.6	Walstat
% unemployed	8.644	3.372	2	22.7	Walstat
Population (log of)	9.073	0.807	7.214	12.22	Walstat
Median income (log of)	9.941	0.142	9.63	10.364	Walstat
% foreigners	6.588	5.688	1.47	50.4	Walstat
Average age	40.372	1.584	35	46.9	Walstat
Local subsidies (log of)	1.1629	2.3665	0	7.231	Self-collected
% green	14.353	6.3562	4.37	31.83	IBZ

5 Results

Our empirical approach is to estimate the impact of tariffs on the decision to invest in PV installations. All our specifications consider municipality- and year-fixed effects. The reported standard errors are robust and clustered at the municipality level. Table 3 looks at whether the quality of our main result is impacted by changes in the definition of our two main variables of concerns: $\# of new\, PV$ and $tariff(t-1)$. In Tables 4 and 5, we look at the robustness of these main results with respect to different subsamples and methodologies.

Regression (1) is our preferred specification where we compare the number of newly installed PV installations with the lagged distribution tariffs. We observe that $tariff(t-1)$ has a positive and significant impact on the number of PV installations. Due to the log-linear nature of our estimator, we have that, all else equal, an increase in one eurocent of the volumetric distribution tariff leads to an increase in 8.7% in the number of new PV installations. The other coefficients are not statistically different from zero because of the absence of a relationship or because the time- and place-varying measures are absorbed by the fixed effects and time trends.

In regression (2), we take advantage of the availability of data concerning the capacity of each new PV installations. For this reason, we use the total newly installed capacity each year in each municipality as a dependent variable. In line with what we have observed so far, we see that an increase in one eurocent of the tariff leads to an increase of about 7% of the capacities installed.

In regression (3), we take the mean capacity of the new PV installation for each municipality and use it as a dependent variable. In this case, we do not observe a significant relationship between our variables of concern. This means that higher

Table 3 Main results

	(1) # of New PV	(2) Capacity Of new PV	(3) Average Capacity	(4) Contemp. Tariffs	(5) Transmission Tariffs included	(6) Peak Tariff
Tariff (t−1)	0.087***	0.071***	− 0.04			
	(0.018)	(0.017)	(0.028)			
Tariff (t)				0.046***		
				(0.015)		
Tariff (t−1)					0.042***	
(transmission tariff incl.)					(0.013)	
Peaktariff (t−1)						0.083***
						(0.016)
% apartment	0.02	0.024	0.013	0.007	0.007	0.02
	(0.033)	(0.031)	(0.03)	(0.031)	(0.03)	(0.033)
% built after 81	− 0.066	− 0.062	− 0.02	− 0.061	− 0.038	− 0.064
	(0.044)	(0.042)	(0.037)	(0.04)	(0.049)	(0.043)
% unemployed	0.021	0.038	0.069	0.006	0.057**	0.018
	(0.026)	(0.026)	(0.047)	(0.025)	(0.024)	(0.026)
Population (log of)	0.705	0.42	0.362	0.65	0.842**	0.687
	(0.442)	(0.373)	(0.679)	(0.5)	(0.418)	(0.436)
Median income (log of)	− 0.957	− 0.589	1.04	− 0.803	− 1.203	− 0.971
	(0.878)	(0.826)	(0.708)	(0.87)	(0.806)	(0.875)
% foreigners	− 0.046	− 0.059	− 0.097**	− 0.047	− 0.023	− 0.046
	(0.057)	(0.054)	(0.046)	(0.052)	(0.059)	(0.057)
Average age	0.165*	0.153*	0.142*	0.131	0.173*	0.165*
	(0.087)	(0.085)	(0.085)	(0.082)	(0.091)	(0.086)
Local subsidies (log of)	− 0.002	− 0.003	− 0.003	0.004	0.004	− 0.002
	(0.008)	(0.008)	(0.011)	(0.007)	(0.008)	(0.008)
% green	− 0.005	− 0.001	− 0.003	− 0.002	0.003	− 0.005
	(0.011)	(0.011)	(0.015)	(0.009)	(0.011)	(0.011)
Constant	1.552	2.853	− 14.048	2.323	1.649	1.871
	(9.618)	(9.671)	(9.748)	(10.001)	(9.923)	(9.508)
Year FE	YES	YES	YES	YES	YES	YES
Municipality FE	YES	YES	YES	YES	YES	YES
Municipality level trend	YES	YES	YES	YES	YES	YES
N	2039	2039	2039	2295	1792	2039
Log likelihood	− 7766.31	− 21,106.06	–	− 8664.79	− 6488.54	− 7765.81

Robust standard errors clustered at the municipality level in parentheses
Statistical significance: *($p < 0.1$), **($p < 0.05$), ***($p < 0.01$)

tariffs have an impact on the decision to invest in PV but not on the capacity of the installation made by the resident. In other words, it has an impact at the extensive but not at the intensive margin. This result can be explained by the fact that capacity is constrained by exogenous factors such as rooftop size.[19] Furthermore, when the capacity is sufficient to cover the household's consumption, there is no additional benefit to the net metering system as the bill cannot be negative when there is excess production. The net value is brought back to zero once a year, when the level of the meter is recorded. Following anecdotal evidences, having a zero bill is rather frequent among prosumers.

From regression (4) to (6), we change the definition of our main explanatory variable. In regression (4), instead of lagging our explanatory variable by one year compared to our dependent variable, we compare contemporaneous data. Again, we observe a positive and significant impact of tariffs on the PV investment outcome. Comparing the coefficients of our variable of interest in regression (1) and (4), we see that taking a one year lag for our explanatory variable leads to a larger coefficient. The other coefficients tend, on the other hand, to be rather similar. When using the lagged tariffs, we have that one year of observation is dropped. Despite this, two information criteria (the Akaike Information Criteria and the Bayesian Information Criteria) motivate the use of this approach.[20] Hence, this result confirms the idea that people rather optimize with respect to the information on their bills rather than the price of electricity, as one of the specificity of the electricity market is that bills are paid only after the good in question has been consumed.

From the investors' point of view, another aspect of the energy bill differs from one tariff zone to the other: the transmission tariff. This other tariff, which is less than 10% of the electricity bill, has also tended to increase across time. However, as opposed to the distribution tariff, it differs mostly across time than across tariff zones, as only one tenth of its overall variation is explained by variation between tariff zones. In regression (5), we add together the distribution and the transport tariffs in a single explanatory variable. Once again, we observe a positive and significant impact on PV installations with an increase in one eurocent now leading to an increase in new PV installation of about 4%. This lower parameter can be both explained by the fact that we have one fewer year of observation concerning transmission tariffs and the nature of the variation of transmission tariffs.

In regression (6), we consider the volumetric peak tariff as explanatory variable. Some electricity users have a meter measuring and pricing separately peak and off-peak consumption, off-peak referring to between 10 P.M. to 7 A.M. during the weekdays and the whole week-end. On average $Peaktariff(t-1)$ is 6% higher than $tariff(t-1)$. Assuming that consumers optimize based on this tariff instead does not lead to qualitatively different results as shown in regression (6).[21]

[19] Note that we do not have additional informations whether these new PV installations were (1) the first ones made on the household's rooftop, (2) to increase the production capacity of a previous PV installation or (3) to replace existing PV panels by new ones.

[20] The AIC (resp. BIC) of regression (1) is equal 14694 (14789) while the AIC (resp. BIC) of regression (4) is equal to 16425 (16528).

[21] Note that prosumers with a sizable PV installation have incentives to switch from a peak/off-peak meter to a single meter, even if this change costs about 250€. Indeed, with two meters, the net metering applies independently to both meters and if the peak meter has a negative yearly index (more peak production than the peak consumption), the consumer is not paid for the excess energy supplied. With a single meter, this excess energy can be used to offset the off-peak consumption. The explanation does not lie in the

Table 4 Robustness checks (1)

	(7) ≤ 2013	(8) > 2013	(9) w/o ORES	(10) ORES	(11) GAS
Tariff ($t-1$)	0.09***	− 0.023	0.045**	0.153***	0.091***
	(0.024)	(0.064)	(0.02)	(0.043)	(0.02)
% apartment	− 0.014	0.054	0.02	0.009	0.015
	(0.048)	(0.085)	(0.056)	(0.04)	(0.04)
% built after 81	− 0.172***	− 0.372**	0.005	− 0.11**	− 0.091*
	(0.065)	(0.151)	(0.077)	(0.053)	(0.048)
% unemployed	0.048*	0.082	− 0.048	0.06	0.003
	(0.027)	(0.076)	(0.029)	(0.037)	(0.027)
Population (log of)	2.276	2.553***	4.144	0.56	2.469
	(3.309)	(0.623)	(3.29)	(0.385)	(2.815)
Median income (log of)	0.21	− 2.887	0.251	− 1.4	− 0.92
	(1.555)	(3.839)	(1.4)	(1.098)	(0.946)
% foreigners	0.064	− 0.279	− 0.161	− 0.025	− 0.032
	(0.066)	(0.181)	(0.1)	(0.07)	(0.06)
Average age	0.333*	0.184	0.129	0.187	0.194
	(0.19)	(0.268)	(0.1)	(0.116)	(0.142)
Local subsidies (log of)	− 0.002	− 0.025	0.015	− 0.005	− 0.004
	(0.0)	(0.033)	(0.011)	(0.01)	(0.009)
% green			0.007	− 0.006	− 0.006
			(0.016)	(0.014)	(0.013)
Constant	− 30.202	9.671	− 41.3	6.419	− 16.44
	(32.944)	(42.36)	(38.36)	(11.408)	(30.885)
Year FE	YES	YES	YES	YES	YES
Municipality FE	YES	YES	YES	YES	YES
Municipality level trend	YES	YES	YES	YES	YES
N	1271	768	553	1486	1736
Log likelihood	− 5144.2	− 1790.9	− 2013.4	− 5685.9	− 6662.6

Robust standard errors clustered at the municipality level in parentheses
Statistical significance: *($p < 0.1$), **($p < 0.05$), ***($p < 0.01$)

A first set of robustness checks is presented in Table 4. While the empirical strategy chosen is the same as in regression (1), different subsamples are considered. In regression (7) and (8), we split our sample in two parts, before and after the major change in legislation supporting PV investments that took place in early 2014. First, focusing on the time period when the *Solwatt* system was in place, we observe no major change

Footnote 21 continued
level of the tariffs but in the way the electricity is billed. Prosumers are not paid for the excess electricity exported above the amount imported on the peak and the off-peak meter. Hence, they will be able to valorize a larger amount of electricity with a single meter.

compared to our previous results. Second, focusing on the *Qualiwatt* system, we find that the tariff level has no significant impact on the PV investment decision.[22] This does not come as a surprise as under the Qualiwatt supporting scheme the benefit for the consumer of a higher grid tariff is partially offset by a lower premium. Therefore, the decision to invest should depend less on differences in tariffs, and hence on the presence of a more generous net metering system.

There are seven DSO active in Wallonia and one of them, ORES, has seven different tariff zones. In regression (9) and (10), we look respectively at two subsamples, only focusing on the DSO other than ORES and on ORES only. We observe again that our main result is not impacted by these changes. All else equal a more generous net metering system has a positive and significant impact on the number of PV installations.

Finally, in regression (11), we only focus on the subset of 224 municipalities that are, at least partially, connected to the gas network. The existence of an alternative and relatively cheap energy source can affect the incentives to invest in PV panels.[23] Focusing on these municipalities, we observe that our explanatory variable remains positive and significant. The availability of natural gas does not seem to change the incentives to invest in solar PV. A possible explanation is that electric heating is not widespread in Wallonia and therefore, gas and electricity are not viewed as close substitute. The fact that the coefficient of $Tariff(t-1)$ is even slightly higher than in regression (1) confirms and further strengthen our main result.

Table 5 presents various robustness checks with respect to different estimation strategies. In regression (12) and (13), we first control for the presence of social interaction peer effects in the diffusion of PV panels. These social drivers help overcome non-monetary barriers to adoption via localized knowledge sharing among neighbors. For this purpose, we consider the approach used in the literature by Bollinger and Gillingham (2012), Muller and Rode (2013) or Graziano and Gillingham (2014). In regression (12), we control in addition for the accumulated number of previously installed PV's in the municipality, in addition to the estimation strategy used in our benchmark regression (1). We observe that this does not have an impact on our main result. Surprisingly, we find that peer effects have a negative impact on new PV investments, although this is only mildly significant. One first explanation for these *a priori* negative peer effects is related to the aggregate nature of our data which is only available at the municipality level while peer effects are likely stronger at a more disaggregated level. To further investigate this issue, in regression (13), we include an interaction term between our peer effect measure and our explanatory variable. We now find positive peer effects, though mildly significant, and a negative and significant interaction term. This last result suggests that the impact of tariffs tends to be stronger in municipalities with relatively few peer effects. On the contrary, tariffs have a smaller influence on new PV installations in municipalities where many PV installations were done already.

In regression (14), we do not include a municipality specific time-trend as in regression (1) but we instead consider province specific fixed effects to consider different

[22] Note in addition that in these two subsamples, there was no change in *% green*, as no election took place.

[23] According to CWaPE (2017) gas prices have decreased by 9% in January 2017 compared to December 2006 while electricity prices have increased by 26% for the same period.

Table 5 Robustness checks (2)

	(12) Peer effects	(13) Peer effects	(14) No trend	(15) OLS	(16) Neg. Bin.
Tariff ($t-1$)	0.086***	0.114***	0.075***	0.067***	0.052***
	(0.018)	(0.022)	(0.014)	(0.019)	(0.012)
Previous # of PV	− 0.0003**	0.0006*			
	(0.0001)	(0.0003)			
Interaction term:		− 0.0001**			
previous # of PV * Tariff ($t-1$)		(0.00004)			
% apartment	0.016	0.018	− 0.005	0.028	− 0.005
	0.033	0.034	0.017	0.031	0.008
% built after 81	− 0.057	− 0.053	− 0.094***	− 0.018	− 0.013*
	0.044	0.043	0.021	0.049	0.008
% unemployed	0.04	0.031	− 0.018	0.005	− 0.004
	0.027	0.028	0.022	0.026	0.014
Population (log of)	0.757	0.771	0.672	0.734***	0.525***
	0.464	0.484	0.425	0.157	0.08
Median income (log of)	− 0.898	− 0.859	0.261	− 1.014	0.326
	0.87	0.862	0.364	0.813	0.202
% foreigners	− 0.052	− 0.058	− 0.033	− 0.045	− 0.049***
	0.057	0.057	0.022	0.053	0.009
Average age	0.161*	0.17**	− 0.051	0.092	− 0.107***
	0.084	0.084	0.044	0.068	0.024
Local subsidies (log of)	− 0.002	− 0.003	0.018*	0	0.008*
	0.008	0.008	0.01	0.008	0.004
% green	− 0.005	− 0.004	− 0.005	0.002	0.009*
	0.011	0.011	0.008	0.012	0.005
Constant	0.458	− 0.638	− 0.336	3.023	− 0.887
	9.708	9.667	5.978	8.959	2.381
Year FE	YES	YES	YES	YES	YES
Municipality FE	YES	YES	YES	YES	YES
Municipality level trend	YES	YES	NO	YES	NO
Province level FE	NO	NO	YES	NO	NO
N	2039	2039	2039	2039	2039
Log likelihood	− 7740.9	− 7719.4	− 8299.9		− 6267

Robust standard errors clustered at the municipality level in parentheses
Statistical significance: *($p < 0.1$), **($p < 0.05$), ***($p < 0.01$)

uptakes by province due, for example, to different supply side conditions. This change only marginally impacts our results.[24]

[24] Provinces are another jurisdiction level, with a limited legislative and financial power. In total there are five provinces in Wallonia.

Other estimation strategies are considered in these last two regressions of Table 5. The first one is presented in regression (15) and assumes a linear relationship. Before doing this OLS regression, we first took the log of our dependent variable to which one unit was added due to the presence of zero outcomes.[25] Then, in regression (16), we estimate a negative binomial regression. While Poisson as a quasi-maximum likelihood estimator is consistent independently from how the data is distributed, this approach can be more efficient in the presence of over-dispersion. Overall, both these results tend to confirm further our initial claim that higher distribution tariffs do lead to more PV installed.[26] Hence, a more generous net metering system, due to higher energy costs, leads to more installations.

6 Conclusion

The net metering system is used to integrate decentralized production units, like residential PV installations, in the energy system. As the electricity exported to the grid is implicitly bought at the retail price, this scheme is also a shrouded production subsidy. Using data from Wallonia, we observe that a higher retail price leads to more PV investments, as it helps consumers decrease their energy bill. To show this, we take advantage of the fact that distribution tariffs tend to vary heterogeneously and that this tariff is almost fully computed on a volumetric base. We find that an increase in one eurocent per kWh in the tariff leads to an increase in the number of installation by around 8%. This empirical result relates to the finding of the theoretical literature according to which a net metering system coupled with a tariff structure which is mostly volumetric leads to an inefficiently high deployment of decentralized production units (Brown and Sappington 2017a, b; Gautier et al. 2018). However, we find that higher tariffs do not lead to investments in PV panels of a larger capacity. Hence, energy consumers are responsive to their energy bill at the extensive but not at the intensive margin.

One key limitation of our study is due to the setting of the data analyzed. We are not able to compare the cost-effectiveness of the net metering system as a way to encourage PV installations. As other policies are set at the regional or national level and as local support schemes are relatively small in size, we are not able to see how it fares with respect to other mechanisms granted at the investment or at the production stage. For this purpose, data from other Belgian regions and countries would be required.

One key aspect with this form of subsidy is that it is financed by the DSO, and not by the public finance system. Hence, our work also relates to the literature trying to quantify the impact of decentralized production units on the financing of the grid using numerical models like Cai et al. (2013), Darghouth et al. (2016) or Schittekatte et al. (2018). To our knowledge, none of them had a precise empirical motivation for the parameter that links the energy tariff to the investment decision chosen in their models. We hope to fill this gap.

25 Changing this constant does not influence the quality of our results.

26 Note that similar results are also obtained using the panel Tobit approach.

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