Photovoltaic Power installation in Wallonia: Estimating the rebound effect

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Abstract

In Wallonia (Belgium), the public support for residential solar photovoltaic panels has two interesting features. First, the subsidies for solar production, in the form of tradable green certificates, were particularly generous which encouraged households to have large installations. Second, the region used a net metering system to record power exchanges with the grid. With net metering, the meter runs backwards when power is supplied to the grid. But, if production exceeds consumption on a yearly basis, the production surpluses are freely available for consumption. In this context, we test for a possible rebound effect. Based on a large sample of residential PV installation in Wallonia, we observe in our data and estimations, that a large proportion of households oversize their installation to benefit from the subsidies and, later consume most of their excess production. The effect is highly significant and production surpluses are almost entirely consumed. There are thus evidence of a strong increase in energy consumption by residential PV owners.

Keywords: Rebound effect; Solar PV; Net metering

JEL Codes:

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1 Introduction

Most European countries financially sustain the generation of electricity from renewable sources. Supporting schemes adopted for solar photovoltaic panels (PV) usually combine instruments from the following list: feed-in-tariffs, tradable green certificates, net metering and capital subsidies in the form of grants or tax rebates.\(^1\) The different combinations influence the return on investment that varies considerably across countries, and this in turn impacts the deployment of solar PV installations.

In Belgium, the support to renewable energy production lies with the regional governments of Flanders, Brussels and Wallonia. Each jurisdiction instituted a tradable green certificate (TGC) mechanism combined with a net metering system to support residential PV installations but the details and extent of support vary between regions. This paper focuses on Wallonia where PV support was considerable, as recalled by Boccard and Gautier (2015). The supporting mechanism, in place from 2008 to 2014, had two interesting properties. First, the aid offered by TGCs was generous enough to cover by itself the module installation costs. Second, there was a net metering system whereby the meter runs backwards as soon as instantaneous production exceeds consumption (within the household). Under this regime, electricity produced by the PV installation is valued at the electricity retail price i.e. power injections cancel power withdrawal. As the recorded consumption is the basis for billing, PV owners substantially reduce their energy bill. However in Wallonia, as in most of the jurisdictions using net metering, should the yearly production exceeds the yearly consumption (i.e., a negative index on the meter), no additional payment for these net exports will be forthcoming. In other words, excessive yearly production is supplied freely to the grid. An obvious consequence for the household, at this point, is that increasing electricity consumption can be done at no cost.

These two peculiarities make Wallonia a good place to test for a possible rebound effect, which refers to "an increase in the energy usage after the introduction of a more efficient (energy-saving) technology".\(^2\) Rebound or take-back effects are well know and well-documented in the field of energy. We focus on a possible direct rebound effect, namely a consumption increase following the introduction of a new technology. It may arise as a substitution effect when the new technology changes the relative prices of energy and but also as an income effect. Informal discussions in Wallonia with (household) adopters, PV installers and Distribution System Operator (DSO) managers lead us to believe that the Walloon supporting scheme is pushes households to increase their electricity consumption after installing solar panels. Some households even appear to have intentionally oversized their PV installation in order to benefit from the generous supporting scheme and later installed new electrical appliances (e.g., heat pump, auxiliary

\(^1\)For a comparison of the different mechanism in place in the EU and the associated return, see Campoccia et al. (2009), Dusonchet and Telaretti (2010, 2015).

\(^2\)Jevons (1865) gave a first version for coal consumption. The issue reemerges with Khazzoom (1980)’s similar finding for the case of energy efficiency in home appliances.
electrical heating system, air-conditioner, spa, etc.) to consume their freely available excessive energy production.

To prove this conjecture, we develop the following reasoning. Firstly, we show that the generous support offered by the Walloon TGC implied a positive return on investment for solar PV installations, even in the absence of net metering. In other words, a PV installation generates a net income thanks to the TCG. For this reason, revenue-maximizing households have an incentive to deploy the largest possible PV installation. However, three different set of constraints limit that choice: firstly, rooftop considerations such as size, orientation or inclination, secondly regulation as the support scheme is available for installations of less than 10 kWp and lastly financial constraints that may limit the household’s ability to invest.\(^3\) The next step of our reasoning is to observe that owners of an installation producing more than what they consume (over a year) are supplying for free their excess production to the grid. Interestingly, this is not so on an instantaneous basis but holds true on a yearly basis, as with net metering the grid is acting as a giant storage facility. Indeed, whenever a household has an excessive production with respect to its instantaneous consumption, she stores it on the grid and, crucially, it remains freely available for later use. It is only at year’s end when billing is established that if total yearly production exceeds total yearly consumption, the surplus is lost beyond recall to the DSO.

There are thus two channels that can lead to a higher electricity consumption for PV owners. As the solar investment has a positive net present value, owners of (subsidized) PV modules receive an extra income, and, as long as the income elasticity of electricity is positive, it generates some extra consumption. In addition for the households who have an oversized installation, the production surplus is freely available for consumption. We expect this zero-price electricity to be compared with other costly energy vectors by the household; this should then lead to substitution and an overall higher consumption of electricity. There is thus potentially an *income* effect and a *zero-price* or a *substitution* effect leading to a higher electricity consumption after the installation of PV modules.

To test for this two-pronged rebound effect, we collect consumption data from households equipped with solar PV, the so-called *prosumers*. More precisely, we record the yearly meter reading from 2010 to 2016 of all the households who have a PV installation and who are served by the dominant DSO of Wallonia, totalling well over 90,000 installations. In addition to the meter records, we have the size and date of installation of the PV system. We then construct for each installation three variables: the consumption before the PV installation, the consumption after the installations, both being expressed in average kWh per day and the PV installation size. As the meter runs backwards, we do not observe directly the consumption of a prosumer but rather its net electricity import (consumption minus production). To estimate the consumption, we add to the net import recorded by the meter, the estimated production of the PV modules using

\(^3\)Financial constraints might be the less severe as the market developed solutions to overcome them: loans for PV installations and third-party investments paid back with the trade of the green certificates.
detailed weather information.

We then compare the consumption of prosumers before and after the installation of the solar panels. We define an installation as *oversized* if the capacity of the modules is larger than the recent past consumption; otherwise, it is *undersized*. In our useable data, there are about 35,000 undersized installations and about 30,000 oversized ones. It is expected that prosumers have a higher consumption after the PV installation and that this effect should be stronger for consumers who have oversized their installation. Taking the ratio of consumption after/before, the consumption falls 3% for consumers with an undersized installation and rises by 35% for those with an oversized installation.

Since this latter group is exposed to both an income effect and a zero-marginal price effect, we take these stylized facts as indicative of a significant rebound effect, especially for oversized installations. Our econometric analysis will confirm this initial evidence. Taking into account several control variables, including the variations in retail electricity prices across areas and in temperatures, we estimate that almost all the free electricity available for prosumers who oversized their installation is consumed. The importance of this rebound effect is obviously linked to the particular institutional context that offered both positive net income with the TGC, encouraging large installations and the free storable of electricity on the grid with the net metering system.

In the literature, there are two main methods to test for the rebound effect (see Sorrell et al. (2009) for a review). The first, which we follow, is the so-called quasi-experimental approach; it consists in comparing the demand for energy before and after an energy improvement. The main challenge is to control for confounding factors that could explain the change in energy demand and that are not linked to the change we focus on. For this reason, we use econometric analysis and control for changes in temperatures and prices in our comparisons. The use of a control group does not seem to be appropriate because prosumers and non-prosumers have different characteristics as shown for instance by De Groote et al. (2016). Finally, our large sample with more than 65,000 observations drastically limits the risk of measurement errors. The second approach to measuring the rebound effect consists in performing an econometric analysis to estimate the elasticities of the energy demand, either the price elasticity or the elasticity with respect to energy efficiency.

There are many papers that have estimated the direct rebound effect. Greening et al. (2000) provides a detailed survey. Most of the studies focus on fuel consumption, residential heating & cooling and energy appliances. There are few papers that have focused on the behavior of households equipped with PV modules and the evidences are mixed. This may indicate that the

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4 De Groote et al. (2016) and Oberst et al. (2019) show that households who are installing photovoltaic systems have different characteristics than non adopters. Hence, estimations of the rebound effect based on the comparison of two groups, prosumers and non-prosumers should take these differences into account to avoid selection bias. Our methodology does not suffer from the risk of a selection bias as we compare the same consumers before and after the PV installation.
consumer’s behavior is context specific and depend on the institutional framework in place. For the UK, Keirstead (2007) reports, based on survey data, a self-assessed overall saving of 5.6% in energy consumption. For Germany, Oberst et al. (2019) compare the consumption behavior of a small sample of German prosumers with a matched sample of non-prosumers. They test the impact of being a prosumer on the heating expenses but they do not found a prosumer effect. Accordingly, it means that being a prosumer does not change the household’s behavior compared to a similar non-prosumer household. Wittenberg and Matthies (2016) use questionnaire to compare the energy consumption behavior of prosumers and non-prosumers in Germany. They do not find significant differences in the level of consumption but they report evidence of a high prevalence of demand-shifting activities for prosumers, a behavior that is encouraged by the net billing system in place in Germany. For Australia, Deng and Newton (2017) use billing data of a representative sample of consumers and prosumers in Sidney. They use individual data over the period 2007-2014. According to their estimation, the production of solar energy generates an extra electricity consumption by the prosumers of about 20%. Interestingly, the magnitude of the rebound effect depends on the feed-in-tariff in place and is larger for early adopters benefiting from the most generous feed-in-tariff.

At the outset, we aim to highlight two original elements of our approach. First, we have an exhaustive sample of over 65,000 households. This large dataset allows us to have a very broad picture of the consumption patterns of households in Wallonia and, in particular, to compare their consumption before and after the installation of PV modules in a consistent way. Second, the institutional context in Wallonia was specific with the combination of net metering and the generous TGC creating the conditions for having too large installations and important take-back effects induced by the free energy. Such a policy induces an important increase in electricity consumption by prosumers who use their free electricity for new appliances or instead of other energy vectors. But as consumption and production are not simultaneous, production peaks in summer, consumption in winter, the carbon impact of this rebound effect might be substantial.

The paper is organized as follow. In Section 2, we develop a theoretical model to discuss the income effect and the zero-marginal price effect. In Section 3, we present the main features of the PV sector in Wallonia. In Section 4, we describe our data and our empirical methodology. Results are presented and discussed in Section 5. Section 6 concludes.

2 Theoretical model

In this section, we model the choice of a representative household with respect to investment in solar panels and the ensuing consumption level of electricity. The household is endowed with an income $w$ and consumes electricity and a composite good. Electricity can be bought on the

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5In Flanders, the generous support combining tax cuts and TGC covered the upfront investment cost from 2009 to 2012 (De Groote and Verboven (2019)), creating the conditions for a similar rebound effect.
market at a retail price $p$ or it can be locally produced with solar panels if the household has exercised the option to invest in such an installation.

The solar PV installation is grid connected, which means that 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 consumption. There are different metering technologies to measure the exchanges with the grid. Our model considers the net metering technology currently used in Wallonia whereby household are equipped with a single meter which runs backwards when electricity is exported. The meter then measures net imports of energy ($\hat{q}$), that is the difference between total consumption ($q$) and total production ($k$): $\hat{q} = q - k$. Net imports are used as the basis for the energy billing. However if production exceeds consumption ($\hat{q} < 0$), there is no payment for the excessive energy supplied to the grid and the bill is set to zero. Finally, there is a specific subsidy for green energy production i.e. a certain number of TGC for each MWh produced. We define the variables of the model as follow:

- $\tilde{k}$: PV installation capacity in kWp
- $p$: PV module price in €/kWp
- $\beta$: the capacity factor of a typical PV installation
- $k$: production of the PV installation in kWh, with
  \[
  k = \beta \tilde{k}
  \] (1)
- $\eta$: subsidy for PV production in €/kWh
- $q$: consumption measured in kWh
- $\hat{q}$: registered (net) consumption in kWh, with
  \[
  \hat{q} = q - k
  \] (2)
- $p$: retail price of electricity in €/kWh
- $z$: composite good (normalized unitary price)
- $w$: income
- $\bar{r}$: roof size capacity for PV installation in kWp
- $\tilde{k}$: eligibility threshold for the subsidizing scheme in kWp

We denote the utility of a consumer as $u(q, z)$. The utility function is differentiable, increasing and concave in its two arguments. The consumer’s problem is

$$\max_{q,z,k} u(q, z)$$ (3)

$$z + p \max[0, \hat{q}] + \tilde{p} \tilde{k} \leq w + \eta k,$$ (4)

$$\tilde{k} \leq \min[\bar{r}, \tilde{k}]$$ (5)
The first constraint is the budget constraint stating that the total revenue of the consumer available for consumption sums income and subsidies for PV production; this revenue is used for financing its net electricity consumption, the PV installation and expenditure on the composite good. The second constraint limits the installation size which cannot exceed the roof size nor the eligibility threshold.

Let us first consider the problem of a consumer who has not installed any solar panel ($\tilde{k} = 0$). The solution of his maximization problem ($q_0, z_0$) is given by the following set of equations:

\[
\frac{u_q(q_0, z_0)}{u_z(q_0, z_0)} = p, \quad \frac{z_0}{w_0} = w - q_0 p.
\]

We shall use this consumption levels as a benchmark for comparing with prosumers.

For $\tilde{k} > 0$, the solution to the prosumer’s optimization problem depends on the profitability of the PV panels. We partition the parameter space in three subsets.

**Case 1** $\rho \leq \beta \eta$: for those values, the subsidy offered for production more than covers the investment cost. The investment is highly profitable leading consumers to maximally invest so that the second constraint becomes binding: $\tilde{k}_1 = \min[\bar{r}, \tilde{k}]$. The production of the PV installation is then $k_1 = \beta \tilde{k}_1$.

To characterize the solution, we define a threshold capacity level $\tilde{k}^*$ such that:

\[
\frac{u_q(k^*, w^*)}{u_z(k^*, w^*)} = p,
\]

where $k^* = \beta \tilde{k}^*$ is the production of an installation of size $\tilde{k}^*$ and $w^* = w + \tilde{k}(\beta \eta - \rho) > w$ is the available income for consumption. A consumer with an installation of size $\tilde{k}^*$ chooses $(q^*, z^*) = (k^*, w^*)$. We can now define the optimal consumption levels.

**Proposition 1** When $\rho \leq \beta \eta$, consumers choose the largest possible PV installation $\tilde{k}_1 = \min[\bar{r}, \tilde{k}]$ and,

- if $\tilde{k}_1 \geq \tilde{k}^*$ then $q_1 = k_1$ and $z_1 = w + \tilde{k}_1(\beta \eta - \rho),$
- if $\tilde{k}_1 \leq \tilde{k}^*$ then $(q_2, z_2)$ defined as $\frac{u_q(q_2, z_2)}{u_z(q_2, z_2)} = p$, $z_2 = z_1 - p(q_2 - k_1),$
- $q_1 \geq q^* \geq q_2 \geq q_0$ and $z_1 \geq z^* \geq z_2 \geq z_0$.

Proposition 1 shows that when the installation size is larger than $\tilde{k}^*$, the prosumer consumes all her production and uses her remaining income for the composite good. In such a case, the net imports $\hat{q}$ are equal to zero and the consumption levels $(q_1, z_1)$ are determined by the constraints: consumption of electricity is set to match the production and the consumption of the composite good exhausts all the available income. If the installation is smaller than $\tilde{k}^*$, the prosumer still finds it profitable to buy electricity from the grid at price $p$ and the consumption
levels are such that the ratio of marginal utilities is equal to the ratio of marginal prices. In this case, the prosumer has positive net imports: \( \hat{q} > 0 \) i.e. his production is insufficient to cover all his consumption.

In both cases, prosumers have a higher consumption than in the benchmark case. This consumption increase results from an \textbf{income effect} when \( \tilde{k}_1 \leq \tilde{k}^* \) and both an income and a \textbf{zero marginal price effect} when \( \tilde{k}_1 \geq \tilde{k}^* \); our objective is to disentangle these two effects. Note that the consumption of electricity and of the composite good increases with income. The supporting scheme provides a net income \( \Delta w \) to the prosumers, arising from the PV subsidy. Suppose that \( \hat{q} \geq 0 \), this extra income is equal to:

\[
\Delta w = \tilde{k}_1(\beta \eta - \rho) + p k_1. \tag{9}
\]

To measure the income effect, we derive the optimal consumption levels of a consumer that does not have solar PV but who is endowed with an income of \( w + \Delta w \):

\[
\max_{q,z} u(q, z) \tag{10}
\]

\[
z + pq \leq w + \Delta w. \tag{11}
\]

The solution to this problem \((\hat{q}, \hat{z})\) is defined as:

\[
\frac{u_q(\hat{q}, \hat{z})}{u_z(\hat{q}, \hat{z})} = p, \tag{12}
\]

\[
z = w + \Delta w - p \hat{q}. \tag{13}
\]

It is easy to check that for \( \tilde{k}_1 \leq k^* \), the solutions \((\hat{q}, \hat{z})\) and \((q_2, z_2)\) are identical. We therefore measure the income effect by the differences in consumption \((\hat{q} - q_0)\) and \((\hat{z} - z_0)\). These differences only result from a greater available income as prices remain identical.

With net metering, the price of electricity becomes discontinuous at \( q = k \). Indeed, the price is zero for \( q \leq k \) (i.e. for \( \hat{q} \leq 0 \)) and \( p \) for \( q > k \) (i.e. for \( \hat{q} > 0 \)). There is a zero marginal price effect if there is some extra consumption that would not take place at a price of \( p \) but that would take place at a zero price. At the solution \((\hat{q}, \hat{z})\), the consumer has free electricity if \( \hat{q} \leq k_1 \), equivalently if \( k_1 \geq k^* \). Therefore in this case, under the assumption that \( u_q > 0 \), the consumer will consume all its production and the solution is at a corner: \( q = q_1 = k_1 \) and \( z = z_1 = w + \tilde{k}_1(\beta \eta - \rho) \).

The difference \( q_1 - \hat{q} \geq 0 \) measures the extra electricity consumption when electricity is available for free i.e. the sought after zero price effect.

To summarize, when \( \tilde{k}_1 \leq \tilde{k}^* \), all the variations in consumption are explained by the income effect measured by \( \hat{q} - q_0 \). When \( \tilde{k}_1 \geq k^* \), we have both an income effect \( \hat{q} - q_0 \) and a zero marginal price effect \( q_1 - \hat{q} \). Note finally that consumers who are exposed to a zero-marginal price effect have a zero net import \( \hat{q} \) while those who are only exposed to the income effect have positive net imports. We will use this distinction in our empirical estimations.

\textbf{Case 2} \( \beta \eta \leq \rho \leq \beta (\eta + p) \): for those values, the subsidy is insufficient to cover the investment cost but once the net metering is taken into account, the investment is profitable. This means...
that the investment is profitable as long as $\beta \tilde{k} \leq q$. Taking this into account, the consumer’s program becomes

$$\max_{q, z, k} u(q, z)$$

$$z + p\tilde{q} + \rho \tilde{k} \leq w + \eta k, \tag{15}$$

$$\tilde{k} \leq \min\left\{\frac{q}{\beta}, \bar{r}, \bar{k}\right\} \tag{16}$$

The optimal consumption levels are given by the equality between the ratios of marginal utilities and prices and the installation size is given by the binding constraint (16). The solution corresponding to case 2, $(q_3, z_3)$, satisfies $q_3 > q_0$ and $z_3 > z_0$ since solar PV modules decreases the cost of energy. There is no zero-marginal price in that case since the installation will never be oversized.

**Case 3** $\beta(\eta + p) \leq \rho$, then solar panels are not profitable and $\tilde{k} = 0$ and the consumptions are given by $q_0$ and $z_0$.

## 3 Photovoltaic development in Wallonia

### 3.1 Public support to PV installations

In Belgium, the promotion of renewable energies is delegated to the regional governments of Wallonia, Flanders and Brussels. Regarding residential solar PV installations, the regional government of Wallonia has implemented two specific policies named Solwatt from 2008 to March 2014 and Qualiwatt from March 2014 to June 2018. In addition, Wallonia used a net metering system to record exchanges between the grid and the PV installation. Small-scale residential installations with a power rating below 10 kWp were eligible to these support mechanisms.

The Solwatt scheme is particularly apt for a rebound study because it has been active for a long period. We are thus able to select many households whose electricity bills cover both the before and after PV installation. Such a strategy is impossible for the ensuing scheme. As a support scheme, Solwatt relies on tradable green certificates (TGC). The green certificate mechanism directly supports small scale PV installations: each MWh of electricity produced from a renewable source is entitled a certain number of green certificates. A market for TGCs was created with, on the supply side, producers of green energy and on the buyer side, energy retailers. The latter are submitted to a renewables portfolio standard (RPS) whereby a given percentage of their electricity must be certified from renewables. In this market, there is a price floor of 65 € allowing producers to sell their certificates at this minimum price to the Transmission System Operator ELIA (TSO) and a price ceiling of 100 € which equates the administrative fine for missing certificates.
Before 2008, the granting rate of green certificates was $1 \text{TGC per MWh}$ for solar and wind technologies and the granting period was set to 10 years. The Solwatt mechanism changed both the granting rate, from $1 \text{TGC per MWh}$ to $7$, and the granting period, from 10 to 15 years for the residential PV installations of less than 10 kWp. The attribution period and rate were subsequently adjusted as shown in Table 1. The Solwatt mechanism ended in 2014 and it was replaced by a new mechanism Qualiwatt. With this new supporting scheme, new PV installations are no longer eligible for TGC but receive a fixed premium per installed kWp. Installations made during the Solwatt period continue to receive TGC, as specified in Table 1.

The last crucial characteristic of the Solwatt scheme is to allow net metering for installations below the 10 kWp threshold. Eligible consumers thus see their energy bill being based on their net recorded consumption $\hat{q}$ which is equal to the difference between electricity consumption and production. It is however of the utmost importance to note that in Wallonia, whenever total PV production exceeds total consumption over the billing period, no payment accrues to the consumer; the registered consumption is simply set to zero. This setting is particularly advantageous for Walloon clients as electricity tariffs are almost exclusively volumetric (i.e. based on the registered consumption), with no capacity charge and very small fixed charges (covering the renting of the meter). Hence, when $\hat{q} \leq 0$, the consumer’s bill is almost zero.

### Table 1: Grant rate and grant period of TGC, Solwatt mechanisms

<table>
<thead>
<tr>
<th>Program</th>
<th>Application period</th>
<th>Grant rate (TGC/MWh)</th>
<th>Grant period (years)</th>
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</thead>
<tbody>
<tr>
<td>Solwatt 1</td>
<td>Jan. 2008 - Nov. 2011</td>
<td>7</td>
<td>15 years</td>
</tr>
<tr>
<td>Solwatt 2</td>
<td>Dec. 2011 - Mar. 2012</td>
<td>7</td>
<td>10 years</td>
</tr>
<tr>
<td>Solwatt 3</td>
<td>Apr. 2012 - Aug. 2012</td>
<td>6</td>
<td>10 years</td>
</tr>
<tr>
<td>Solwatt 4</td>
<td>Sep. 2012 - Mar. 2013</td>
<td>5</td>
<td>10 years</td>
</tr>
<tr>
<td>Solwatt 5</td>
<td>Apr. 2013 - Feb. 2014</td>
<td>1,5</td>
<td>10 years</td>
</tr>
</tbody>
</table>

3.2 PV deployment in Wallonia

After 2008, the number of PV installations increased dramatically (see Figure 1). Starting from virtually zero installations in 2007, there were 133000 small-scale PV installations at the end of 2016, with an installed total capacity of 764 MWp. This success story had two unintended consequences. First, the supporting scheme quickly rose to represent a huge cost for the collectivity. For the period 2003-2012, Boccard and Gautier (2015) estimate an overall average support of 588 € per MWh of solar electricity paid by the TGC mechanism. Second, there was an excessive supply of green certificates and disequilibrium on the market. As a consequence, the TGC price fell close to the price floor of 65 € as shown on Figure 2. These developments lead the government to end of the Solwatt program in 2014 and replace it by the less generous Qualiwatt program. After the end of Solwatt, the number of new installations was considerably reduced, with 4200
and 6000 new PV installations in 2015 and 2016 respectively, far from the 48000 new installations registered in 2012.

Figure 1: PV installations in Wallonia, 2008-2016

Figure 2: Price of green certificate, 2007-2016

3.3 Net present value of a PV installation

In this section, we estimate the net present value (NPV) of a PV installation in Wallonia supported by the Solwatt program.
3.3.1 Capacity Factor $\beta$

We shall need a precise estimation of PV electricity production in a typical Walloon household. For that task, we construct a monthly capacity factor $\beta_m$ using two sources. The first and most reliable is the real-time monitoring of PV generation operated by the Belgian Transmission System Operator ELIA since November 2012. We use the data corresponding to the Liège region to compute the instantaneous capacity factor as the ratio of PV generation to monitored PV capacity (measured in MWp). This ratio is the percentage of time where, on average, a PV panel fitted in the Liège region is producing at full capacity. We use the daily average time series. This single time series is adequate insofar as the photovoltaic power potential is sufficiently uniform across the Walloon region. As shown on the irradiation maps displayed on Figures 3-4, there is a large potential variation across the north and south of Europe but little within Wallonia. Finally, we lack information about the orientation of the panels. Differences between a south and a south-east orientation can change the production by 5% (for a 35° roof inclination). Our capacity factor estimate thus corresponds to the average orientation and inclination and we cannot correct for these relatively small differences. The calculation of the PV production and of the household consumption will certainly suffer from small measurement errors but there are no systematic biases.

For the years prior to 2012, we use the series of “minutes of sun per day” published by the Bierset-Liège Airport station of the Royal Meteorological Institute. As there is a strong 82% correlation between the capacity factor and the irradiation data over the period of common recording, we used the fitted values to extrapolate the capacity factor prior to 2012. The complete capacity factor series is shown on Figure 5. Finally, we compute a monthly capacity factor (CF) by taking the average of daily values. From 2007 to 2017 (both included), the long term average CF is 10.8%, meaning that a PV panel of 1 kWp capacity produces in average $0.108 \times 24 \approx 2.6$ kWh per day or 945 kWh per year. Based on the average residential electricity consumption of 7.4 MWh in Belgium over the study period (cf. Eurostat), each person may support her needs with 8 panels. The average capacity factors for each year are reported in Table 2.

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<tbody>
<tr>
<td>CF</td>
<td>10.5</td>
<td>10.8</td>
<td>11.5</td>
<td>10.9</td>
<td>12.1</td>
<td>11.</td>
<td>7.5</td>
<td>10.9</td>
<td>11.7</td>
<td>10.9</td>
<td>10.9</td>
<td><strong>10.8</strong></td>
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Table 2: Estimated Capacity Factor in Wallonia

One may object that the actual production of a PV installation could very well differ from the estimation for three reasons: (#1) defectiveness or wear-and-tear of the installation, (#2) orientation and inclinations of the panels and (#3) local weather conditions. We claim that none of these issues threatens the validity of our study. For #1, as we only look at consumption for two years after the PV installation, panels are still new and well functioning. For #3, we trust engineering studies claiming that orientation alters PV output by no more than 5%. Lastly, solar
irradiation may be taken to be homogeneous over such a small geographic area, Wallonia being approximatively a flat rectangle of 160 km by 100 km.

3.3.2 Net present values

An installation benefiting from the *Solwatt* mechanism will be granted GC for a given period and we estimate the net present value of this TGC allocation. For that, we first compute the production of an installation using the estimated capacity factor $\beta$ and applying a loss of power of 0.5% per year. From that, we compute the corresponding GC endowment and we estimate its value. We provide three estimations based on three different TGC prices ($\eta$): the low estimation is based on a constant TGC price equal to the price floor of 65 €, the medium estimation is based on the true market price for the TGC up to 2016 and on the price floor for 2017 onwards and the high estimation based on constant price equal to the TGC price at the installation date. To compute the NPV, we use an interest rate of 3%.\footnote{De Groote and Verboven (2019) estimate that households in Flanders, where a similar TGC was in place have a discount factor of 15% and that they considerably underestimate the benefits of the TGC mechanism. As a consequence, the adoption rate was lower despite a huge support. The problem we consider here is different as we focus on technology adopters only. The fact that some non-adopters were refrained to invest because of a high discount rate is not really a concern for our analysis.} \footnote{Until 2011, households were eligible for tax credits if they invested in solar PV. This credit, which varied from a maximum of 1200 € in 2006 to 3600 € in 2011, is not included in the reported PV module price.} We compare the NPV of the TGC endowment with the system PV module price ($\rho$) computed by the IEA for Belgium (IEA, 2015).\footnote{NPV and cost in Table 3 are both expressed in € per Wp.} NPV and cost in Table 3 are both expressed in € per Wp.

For the years 2008 to 2012, the support provided by the TGC mechanism clearly exceeds the

![Daily Capacity Factor smoothed over 2 months](image)

Figure 3: Daily capacity factor $\beta_m$, fitted values
<table>
<thead>
<tr>
<th>Year</th>
<th>Program</th>
<th>NPV TGC (€/Wp)</th>
<th>Cost (€/Wp)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>low</td>
<td>med</td>
</tr>
<tr>
<td>2008</td>
<td>Solwatt 1</td>
<td>4.88</td>
<td>5.85</td>
</tr>
<tr>
<td>2009</td>
<td>Solwatt 1</td>
<td>4.88</td>
<td>5.46</td>
</tr>
<tr>
<td>2010</td>
<td>Solwatt 1</td>
<td>4.88</td>
<td>5.34</td>
</tr>
<tr>
<td>2011</td>
<td>Solwatt 1</td>
<td>4.88</td>
<td>5.22</td>
</tr>
<tr>
<td>2012</td>
<td>Solwatt 3</td>
<td>3.02</td>
<td>3.23</td>
</tr>
<tr>
<td>2013</td>
<td>Solwatt 5</td>
<td>0.75</td>
<td>0.79</td>
</tr>
</tbody>
</table>

Table 3: Net present value of green certificates

installation cost. These years correspond to the case 1 in our model. For the year 2013, the support of the TGC is not sufficient to make the installation profitable, so we are clearly not in case 1. In addition to the benefit of the green certificates, households benefit from the meter running backwards. Taking a retail price in the range of \([0.15-0.25]\) €/kWh, the NPV of the net metering, based on the same parameters than above, is in the range of \([1.98-3.31]\) €/Wp. With this additional revenue taken into account, the investment in solar PV is always profitable i.e. there is no year or scenario corresponding to case 3 in our model.

4 Data

4.1 Data Source and Description

There are 7 different electricity distribution companies covering the 262 municipalities of Wallonia today. The largest is ORES covering 191 municipalities. ORES is the result of the merger of seven smaller DSOs and it continues to apply different tariffs in the different pre-merger zones. This means that ORES applies 7 distinct tariffs for electricity distribution with some substantial differences. The areas covered by ORES are shown on Figure 6.

In our sample, the unit of observation is the European Article Number (EAN) which uniquely identifies a point of consumption, typically a household. We limit ourselves to residential EANs, thus excluding commercial and industrial clients. We have for each EAN in the ORES distribution zone, the associated yearly meter readings (meter index and reading date). In addition, we have the PV installation date and the effective power of the PV modules in kWp. Finally, we have the location of the EAN (zip code). The dataset is an exhaustive dataset of close to 100000 EANs that have a PV installation and we have the yearly meter readings from 2010 to 2017.

We select the EANs for which the PV installations was done during the Solwatt period. The program officially ended on the 02/01/2014 but all installations ordered before this date bene-

---

\(^8\)For the years 2008 and 2009, we have \(\text{NPV}_{\text{low}} < \text{Cost} < \text{NPV}_{\text{med}}\).

\(^9\)EAN have been anonymized.

\(^{10}\)The effective power is the minimum of the inverter power and the panel power in case they differ.
fitted from this generous program, even if the connection date was posterior. As there is some delay between the ordering and the connection date, we select all the installations with a connection date ranging from January 2008 to April 2014. In any case, there were few installations in 2014 (see Figure 1) as the end of the program was largely anticipated.

For each EAN, there is a yearly reading of the meter. This is done either by a representative of the DSO or by the client and transmitted by mail, phone or online to the DSO. Reading is supposed to be done at fixed date but in practice, there could be more or less than 365 days between two readings. There are different types of meters, the most common being the single meter, the day/night meters and the exclusive night meter. With a single meter, there is a unique meter to record all consumption. With the day and night meters, there are two adjacent meters to record the consumption during the peak period (7am-10pm weekdays) and the consumption during the off-peak period (10pm-7am weekdays and weekends) with different rates for the two periods. Net metering applies to both dual meters.\textsuperscript{11} An exclusive night meter is used for the consumption during the night period exclusively and it is not frequently used. Infrequently, an EAN may be equipped with several meters.

4.2 Consumption Estimation

For each selected EAN, we estimate the daily electricity consumption for the entire period where we have meter readings. By definition, the total consumption over a billing period is the difference between the indices read on the meter.\textsuperscript{12} For households equipped with a day/night

\textsuperscript{11}If an household is equipped with two meters and its PV production exceeds peak consumption, it can switch to a single meter without having to change the meter since the indexes of the two meters can be aggregated by the DSO before establishing the bill.

\textsuperscript{12}We control for meter moving back to zero after a complete revolution since they many have only 5 digits.
meter, we sum the consumption recorded on the two meters. For households equipped with several meters, we aggregate the various consumptions. We eliminate all EANs with missing, incomplete or incoherent data resulting for example from an (unobserved) replacement of the meter. For each EAN, we estimate the consumption over 2 years prior to the PV installation, taking place at date $\tau$, and $a posteriori$ for 2 years.

Over a billing period going from $t_1$ to $t_2$, the EAN is billed $B$ kWh read on his meter. Whenever the PV installation date $\tau$ is prior to $t_2$, we know that local electricity production starts offsetting household consumption so that the meter only records net imports $q - k$. We typically observe imports during nighttime and exports around noon. Likewise, imports are larger during the winter and exports larger during the summer. To recover the true household consumption $q$, we estimate the daily solar PV production $k$ and sum it over all the billing period; total PV output over the period is thus $D = \tilde{k} \sum_{t=\tau}^{t_2} \beta_t$, where $\tilde{k}$ is the household’s PV size and $\beta_t$ is the previously estimated daily PV capacity factor. The total consumption over the period is then $Q = B + D$. Note at this point that the two-way meter makes the consumption decision at every moment completely independent of how much is being produced on the house roof at that same moment.

Next, to account for the seasonality of daily load, we draw on the synthetic load profile (SLP) computed by Synergrid, the professional association of electricity and gas network managers in Belgium. The SLP for each day is the consumption of a representative household taking into account many elements such as the calendar day, climatic factors, sunrise and sunshine hours, day-off, public or school holidays, etc... DSOs use these curves to estimate the clients’ yearly consumption based on their meter recordings. Practically, we use the SLP curve $s_t$ for the Liège region to estimate the daily consumption at date $t$ as:

$$q_t = \frac{s_t Q + D}{\nu}$$

where $\nu = \frac{1}{t_2 - t_1} \sum_{t=t_1}^{t_2} s_t$ is the average SLP value over the relevant period. The (re)construction procedure is illustrated in Figure 7 with one randomly chosen household.

The red curve displays the average daily load as measured by the meter difference between two readings ($\frac{Q}{t_2 - t_1}$); in this particular case, it becomes almost nil once the PV system is installed. The blue curve is the red one to which we add the average daily PV output ($\beta_t \tilde{k}$) for each billing period (given the panel size), from the installation date on. Lastly, the green curve distorts the blue one with the SLP to account for the load variation across seasons. The household is thus storing energy on the network during the summer and conversely drawing from the network during the winter (on average the blue and green curves are at the same level over any billing period). The last step is to compute the average consumption in each EAN before and after the PV installation, choosing for that task a window of 24 months: $\overline{q} = \frac{1}{24} \sum_{t=\tau-24}^{\tau} q_t$ and $\overline{q} = \frac{1}{24} \sum_{t=\tau+23}^{\tau+24} q_t$. Our sample contains over 65 000 observations for which we were able to estimate consumption $\overline{q}$ and $\overline{q}$. 

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5 Estimating the Rebound Effect

5.1 Statistical Analysis

To estimate a possible rebound effect, we use a quasi experimental approach and compare the household’s estimated consumption before and after the PV installation. The comparison is made over a large and exhaustive sample of prosumers which limits the risk of measurement errors. We believe the Walloon support to PV was so strong that in addition to an income effect, prosumers were potentially exposed to a zero-marginal price effect. The latter induced some of the households to oversize their PV installation relative to their consumption and, the former implies that the extra energy production was available for free for consumption all the year around since the meter was recorded on a yearly basis.

To disentangle the income and the zero-marginal price effects, we split our sample in two groups. In line with our theoretical model, a household is exposed to an income effect only if it has positive net imports. We then construct a group of undersized installations in which the installation capacity is insufficient to cover the past consumptions (for $t < \tau$, $q_t \leq k_t$). All other installations that have a larger capacity than the past consumption are in the group of oversized installations (for $t < \tau$, $q_t > k_t$). The first group should be subject to the income effect only while the second group is expected to display both the income and the zero marginal price effects.

In our sample, we identify about 35,000 households in the undersized group and about 30,000 households in the oversized group. The following table presents the descriptive statistics of our sample.

As shown in Table 4, the average consumption slightly increase after the installation of rooftop PV panels but the evolution differs radically between the two groups. In the undersized group,
the average consumption decreases slightly (-4%) while for the oversized group it increased dramatically (+35%). We further illustrate this statistic with Figure 8, we plot the daily consumption before and after for each individual observation i.e. the ratio $\frac{q_{\text{after}}}{q_{\text{before}}}$. If an observation lies above (below) the 45° line, the consumption increases (decreases) after the PV installation. In the oversized group, three quarters (74%) of the observations lie above the diagonal while they are more equally dispersed for the undersized group with 40% of the installations above the diagonal. These statistics suggest a very substantial rebound effect for households that have oversized their installation. More precisely, they suggest an important zero-price effect and a limited (or even inexistant) income effect.

To further illustrate the change of behavior after solar panels have been installed, we write $\frac{q_{\text{after}}}{q_{\text{before}}} = k \frac{q_{\text{after}}}{q_{\text{before}}}$, where the ratio $\frac{k}{q_{\text{before}}}$ measures the free electricity available to the household should its consumption remain constant; this ratio being greater than 1 in the oversized group. The second ratio $\frac{q_{\text{after}}}{q_{\text{before}}}$ measures the percentage of the electricity produced that is actually consumed. If for instance, $\frac{k}{q_{\text{before}}} = 1.3$, it means that the household produces 30% more than it (really) needs. If $\frac{q_{\text{after}}}{q_{\text{before}}} = 0.9$, it means that it consumes 90% of its production. These figures imply that, for this household, $\frac{q_{\text{after}}}{q_{\text{before}}} = 1.17$ i.e. consumption increases by 17% after the PV installation.

On Figure 9, we sort our 65000 sample along variable $\frac{k}{q_{\text{before}}}$ and group observations into 50 bins,
each representing 2% of the sample. We then compute the mean over the two ratios for the plot. Absent any rebond effect, we should have a curve given by the inverse function as, for a constant consumption \( \bar{q} = q \), the ratio \( \frac{\bar{q}}{k} \) is the inverse of \( \frac{k}{\bar{q}} \).

On the figure, oversized households appear to the right of 100 and very interestingly, the curve becomes flat at about 85% which means that a large swath of households went for oversized panels and consumed most of their PV output, solely putting back 15% of green electricity onto the Belgian grid.

![Graph showing consumption before/after for oversized group](image)

**Figure 7: Consumption before/after, oversized group**

### 5.2 Econometric Estimation

Our objective with the econometric model is to explain the difference between consumption before and after the installation of PV panels. For that task, we use as a depended variable, the difference between the daily consumption after and before date \( \tau \) (both taken over two years):

\[
\Delta q = q_{t|t>\tau} - q_{t|t<\tau}
\]

We explain the variations in consumption by two categories of variables linked to the installation characteristics and to the environment. We have two environmental variables. The first measures the difference in the average temperature before and after \( \tau \) as temperature is an important driver of electricity consumption. For that, we construct the monthly average temperature \( \zeta \), by taking observations from the three airports of Maastricht (Netherlands), Florennes and Beauvechain (both in Wallonia) using daily maximum and minimum temperature. The independent variable we construct is the difference between averages before and after PV installation

\[
\Delta \zeta = \zeta_{t|t>\tau} - \zeta_{t|t<\tau}
\]


The second environmental variable is linked to the price of electricity. There are many electricity retailers in Wallonia offering a large variety of products. To our knowledge, there are no differences in the commercial offers within Wallonia and all the households can pick a contract within the same choice set. There are however differences in the grid tariff charged by the DSO. Grid tariffs are almost exclusively variable i.e. a price per kWh. We then compute for each ORES tariff a variable that measures the average grid tariff after \( \tau \) and we expect that a larger price negatively influences consumption, especially for households with an undersized installation.

The independent variable \( \tilde{k} \) for capacity is the PV installation size in kWp; a positive sign for this variable indicates an income effect since an additional PV panel generates an extra income for the household (cf. Table 3). The last and crucial independent variable measures the available free electricity (if any) for the household. We construct first a dummy variable indicating the existence of an oversized installation \( (k > q) \); the dummy is equal to 1 if the estimated average daily solar powered production is larger than the average past daily consumption of the house. Then, we interact this dummy with the excess solar output \( k - q \). The “oversized” variable \( \theta = (k - q)_{k > q} \) measures the available free electricity. We estimate the following equation:

\[
\Delta q = \alpha + \beta_1 \Delta \zeta + \beta_2 p + \beta_3 \tilde{k} + \beta_4 \theta + \epsilon
\]

We exclude the top and bottom 1% entries with exceptionally large negative or positive consumption since these most likely originate with errors at the meter reading stage. We thus run the equation over a set of 65638 observations with a \( R^2 \) of 23%.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Estimate</th>
<th>Standard Error</th>
<th>t-Statistic</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>0.977</td>
<td>0.17</td>
<td>5.737</td>
<td>( 10^{-9} )</td>
</tr>
<tr>
<td>Tariff</td>
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<td>0.018</td>
<td>-7.391</td>
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</tr>
<tr>
<td>( \tilde{k} )</td>
<td>-0.026</td>
<td>0.005</td>
<td>-5.198</td>
<td>( 10^{-7} )</td>
</tr>
<tr>
<td>( \theta )</td>
<td>0.869</td>
<td>0.007</td>
<td>130.741</td>
<td>( 10^{-3301} )</td>
</tr>
<tr>
<td>( \Delta \zeta )</td>
<td>1.111</td>
<td>0.067</td>
<td>16.483</td>
<td>( 10^{-61} )</td>
</tr>
</tbody>
</table>

Table 5: Estimation Results

Results are reported in Table 5. In our estimations, all the coefficients are significant at the 1% level. The constant is positive, meaning that in average daily consumption increases by 1.35 kWh a day. This increase in consumption is slightly mitigated by the size of the PV installations as the coefficient of \( \tilde{k} \) is negative. Owners of larger PV installations have a lower increase in their consumption but the magnitude of the coefficient is limited. There is no clear evidence of a significant income effect from our estimations. Variations in consumption are also lower when consumers face a higher grid tariff and this evidence is consistent with our model.

Turning to the analysis of the oversize variable \( \theta \), the coefficient is quite large. Our estimation shows that an additional daily production of 1 kWh of free electricity is mostly consumed locally (87%). Only a small fraction (13%) is supplied to the network. Therefore, there is an extremely
substantial rebound effect for households who have oversized their installation. This behavior results from the zero-marginal price effect.

6 Concluding remarks

In this paper, we have tested for a possible rebound effect of solar PV installations in a particular institutional context, combining generous support to production and net metering. In Wallonia, the Solwatt supporting scheme to small-scale residential PV production was so generous that rational households find it profitable to oversize their installation as the support of the TGC covered the module installation cost. Combined with net metering, owners of oversized installations had production surpluses available for free for consumption. Our empirical evidences demonstrate that households massively invested in large scale installations in the sense that they covered more than their past consumption with their PV modules, and that they almost entirely consume the free energy surplus. There are thus strong evidence of a significant rebond in consumption associated with the adoption of solar PV. Our evidence, however, do not conclude on the causality. Households may consume more because they have oversized their installation or they may have oversized their installation to consume more, for example by switching to electric mobility or by installing a heat pump. Both cases are symptomatic of a rebond effect but our evidence are inconclusive on the causality.

Such a rebond is a specific feature of the wrongly designed supporting scheme applied in Wallonia. Net metering has been criticized for providing inadequate price signals and incentives (Gautier et al. (2018)). Generous green certificates make the cost of solar energy expensive and transfer income from non-prosumers to prosumers. Furthermore, the instrument may not be the most appropriate supporting scheme as households discount the future too much (Gautier et al. (2018)). Despite that, neither net metering nor tradable green certificates are in itself problematic. It is the combination of the two that create the conditions for a substantial increase in energy consumption by prosumers. Consumers react strongly to financial incentives, in a sense that may not have been expected by those who designed the scheme, but that is consistent with rational behavior.

Furthermore, if households consume their excessive production, they do not necessarily consume their energy when they are producing, what is called autoconsumption. Indeed, the net metering system does not give any incentive to synchronize production and consumption (Gautier et al. (2018)). As the meter is running backwards, excessive production can be stored in the grid for free until the next meter register, which takes place yearly. This means that the excessive production of the sunny summer days can be stored in the grid and used in the dark cold winter days to heat the house. Such a displacement of consumption from periods where electricity is produced at low cost and low carbon emissions to periods where it is produced at a higher cost using carbon-intensive generators is certainly not environmentally friendly.
Finally, the carbon impact of solar PV should take this important rebound effect into account. But this additional consumption is, at least partially, substituting other energy vectors. Electric heating and heat pumps replace fuel or gas heating, electric mobility replaces internal combustion engines, etc. The carbon impact should take all these elements (rebond, autoconsumption and substitution) into account. However, this work cannot be done with the data currently collected by the DSO as we have only information about the yearly consumption.
References


