# Solar Rebound: The Unintended Consequences of Subsidies*

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**Abstract**

Many jurisdictions use *net metering* to record power exchanges between residential solar photovoltaic (PV) panels and the grid, thus valuing solar power at the electricity retail rate. However, if over the billing period, production exceeds consumption, the surplus remains freely available for consumption. In Wallonia (Belgium), the combination of net metering and generous subsidies for rooftop PV installation encouraged households to set-up large systems, possibly exceeding their consumption needs. We test this potential rebound effect with a large sample of residential PV installations. We observe 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 econometrically highly significant. There is thus evidence of a strong increase in energy consumption by residential PV owners, which runs counter to the original policy design.

**Keywords**: Rebound effect; Solar PV; Net metering

**JEL Codes**: C51, Q48, Q58, Q410, Q420

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# 1 Introduction

Rooftop solar photovoltaics (PV) is a key component of the EU energy policy towards the widespread adoption of renewables energy sources (RES). Beyond helping a community to reduce its reliance on fossil fuels, PV development fosters distributed generation, increases energy security and, essentially in our view, raises consumers' awareness of their electricity consumption determinants. Once their PV panels are installed, though, these newly minted "prosumers" tend to change their consumption habits owing to the lower average price of electricity and, depending on the regulation in place, the marginal price of electricity. In this article, we test for the existence of a solar rebound[1] in a specific institutional context that was prone to generate such a phenomenon. We study the unintended consequences of the PV supporting scheme deployed in Wallonia (southern Belgium) from 2008 to 2014, which combined *net metering* and generous production subsidies known as *tradable green certificates* (TGC).

Under *net metering*, power exchanges with the grid are recorded by a single mechanical meter running backward whenever energy is supplied **to** the grid and forward when grid electricity is fed to the client. Over the billing period, the meter only records the *net energy imports*, the difference between total local consumption and total local production; it is the basis for establishing the bill. Crucially, the Belgian regulation stipulates that if production exceeds consumption over the billing period of one year, the volumetric part of the bill is simply set to zero. In other words, the client is not compensated for supplying electricity to the distribution company[2] but she can still consume the excess output for free. This technicality may create the illusion of "free electricity".

A priori, households have no particular reason to produce more solar electricity than what they consume. We show however that in Wallonia from 2008 to 2014, TGC awards were generous enough to cover the cost of PV panels, thereby inducing households to install the largest possible system. Once that was done, households with a large PV capacity had "free" available electricity. This institutional context was therefore prone to generate a rebound effect i.e. a substantial increase in consumption after the installation of solar PV. [3]

To test this conjecture, we record the yearly meter reading from 2010 to 2017 of all the households owning a PV installation in the jurisdiction of the dominant distribution utility of Wallonia, totaling close to one hundred thousand prosumers. Additionally, we collect the size and date of installation of the PV system which allows us to estimate average consumption before and after the PV installation. We document a substantial rebound effect in three steps. First, we compare prosumers' consumption before and after the installation of the solar panels over a two-year-period.

[1]The original term introduced by Jevons (1865) for coal consumption is given its current meaning by Khazzoom (1980) in the context of energy efficiency for home appliances.

[2]Crucially, this "green" energy is fed to nearby city dwellers, swapping centralized "brown" electricity.

[3]Matisoff and Johnson (2017) show that net metering alone proved ineffective and needed to be augmented with other instruments to support PV adoption by US residential customers.

We distinguish prosumers who have an *oversized* installation, when the PV productive capacity is greater than the recent past consumption, and the complementary class of *undersized* installation which is slightly more numerous. Households with oversized installations have energy available at a *zero marginal price* and are therefore likely to increase their consumption. We observe from our records a 3% consumption fall for undersized installations and a 35% rise for oversized ones.

The econometric analysis confirms this initial evidence. Taking into account several control variables, including the variations in retail electricity prices across areas and in temperatures, we estimate that 61% of this free electricity available to prosumers who oversized their installation ends up being consumed onsite; only 39% is supplied to the grid and contributes to "greening" the Belgian electricity mix. Importantly, this additional consumption is not simultaneous with production as the net metering system allows the prosumer to consume it until the next billing date (one year later). Lastly, a panel estimation enables us to isolate a specific consumption trend for prosumers with an oversized installation; we document how their electricity consumption increases over time after installing PV panels. We thus present convincing evidence of a substantial solar rebound, the sheer scale of which appears to be a direct consequence of the particular institutional context: one which, by offering positive net income with the TGC, encouraged large installations and free electricity storage on the grid through net metering.

Two methods have been developed in the literature to test for the rebound effect (see Sorrell et al. (2009) for a review). The first method – which we follow – is the so-called quasi-experimental approach which compares 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 regarless of the change we focus on. For this reason, our econometric analysis controls for changes in temperatures and prices. Using a control group does not appear to be appropriate because prosumers and non-prosumers have different characteristics; prosumers typically own a house and belong to the upper income brackets for being able to foot the initial solar panel investment.[4] The second method of 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.

Greening et al. (2000) provides a detailed survey of the early literature estimating a direct rebound effect. Most studies focus on fuel consumption, residential heating & cooling and energy appliances. The few papers dealing with a solar rebound effect produce mixed evidence, which suggests that the consumer's behavior may be context-specific and depend on the institutional framework in place. For the UK, Keirstead (2007) relying on survey data, reports a self-assessed overall saving of 5.6% in energy consumption. For Germany, Oberst et al. (2019) compare the

[4] De Groote et al. (2016) and Oberst et al. (2019) show that households installing photovoltaic systems differ characteristically from those who do not. 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 avoids the risk of a selection bias as it compares the same consumers before and after the PV installation.

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 energy expenses but fail to identify a significant 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 a questionnaire to compare the energy consumption behavior of prosumers and non-prosumers in Germany. While they do not find significant differences in the level of consumption, 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 Sydney. They use individual data over the period 2007-2014. According to their estimation, the production of solar energy generates a 20% increase of electricity consumption by prosumers. 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. Lastly, Qiu et al. (2019) identify an important rebound effect associated with PV adoption in Arizona. They use high frequency meter data to monitor the daily consumption of prosumers, find that generating 1 kWh triggers an additional consumption of 0.18 kWh by prosumers and, importantly, that consumption increase is almost simultaneous with solar production. Under the net metering system in place in Arizona, the marginal price of electricity, whether (local) solar or (grid) conventional, is always equal to the retail price. For a given consumption level, however, the average electricity price decreases with solar production. Lastly, Ito (2014) finds that the main driver of energy consumption is not the marginal price but the average price. Hence, a solar rebound can result from a decrease in the average price of electricity post-PV adoption. By contrast, we show here that the solar rebound effect is not driven by a decrease in the average electricity price but by the specific institutional features of the net metering system, for making the marginal price of electricity equals to zero whenever the solar installation is ”oversized”.

The paper is organized as follow. In Section 2, we present the main features of the support schemes for the residential PV installations in Wallonia. In Section 3, we formulate our solar rebound hypothesis. In Section 4, we describe our data and our empirical methodology. Our main results and the evidence attesting a substantial solar rebound are presented and discussed in Section 5. Finally, section 6 concludes.

## 2 Photovoltaic development in Wallonia

In Belgium, RES promotion has been delegated to the regional governments of Wallonia, Flanders and Brussels. Starting in 2008, Wallonia implemented a support scheme for residential solar PV combining production subsidies under the form of tradable green certificates (TGC), net metering and investment subsidies and tax credits, which were available only in the early stages. We focus on the *Solwatt* program in place from January 2008 to March 2014 for small-scale residential installations with a power rating below 10 kWp.

## 2.1 Tradable Green Certificates

The first arm of the *Solwatt* program awarded green certificates to each MWh of electricity generated from a renewable source. A market for TGC was created with, on the supply side, residential RES producers and, on the buyer side, energy retailers. The latter had to comply with a renewables portfolio standard (RPS) whereby a given percentage of their electricity had to be certified from renewable sources. In this market, a 65 € price floor allowed producers a guaranteed sale to ELIA, the Transmission System Operator (TSO) while the 100 € administrative fine for missing certificates acted as a price ceiling.

The initial granting was 7 TGC per solar MWh for 15 years to residential PV installations of less than 10 kWp (against 1 TGC per MWh during 10 years for wind energy). As shown in Table 1, these characteristics were later modified to follow the constant decline in the PV installation costs. The *Solwatt* mechanism ended in March 2014 for orders of PV systems, allowing installations to take place throughout the year. The subsequent *Qualiwatt* program swapped TGCs for a fixed premium per installed kWp to guarantee households a fair return on investment.

| Program | Application period | Grant rate (TGC/MWh) | Grant period (years) |
|---|---|---|---|
| Solwatt 1 | Jan. 2008 - Nov. 2011 | 7 | 15 years |
| Solwatt 2 | Dec. 2011- Mar. 2012 | 7 | 10 years |
| Solwatt 3 | Apr. 2012 - Aug. 2012 | 6* | 10 years |
| Solwatt 4 | Sep. 2012 - Mar. 2013 | 5* | 10 years |
| Solwatt 5 | Apr. 2013 - Feb. 2014 | 1,5 | 10 years |

* Average over the granting period

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

## 2.2 Net metering

The second arm of the *Solwatt* program is the so-called net-metering feature whereby the house mechanical meter records bi-directional electricity flows i.e., runs backwards when energy is exported to the grid; this makes it unnecessary to change the meter when installing PV panels since the inverter is simply connected to the existing one. As a consequence of net-metering, the volumetric part of the electricity bill solely depended on the *net energy imports* $\hat{q} = q - k$ between total local consumption $q$ and total local production $k$. Over the 2008-2014 period, Walloon prosumers were not yet equipped with smart meters able to discriminate inflows from outflows and thus set distinct prices.[5] It is our contention that net-metering created a perverse incentive.

In Wallonia, the billing period is one full year and the charge is essentially based on net energy imports $\hat{q}$ because of a very low fixed contribution. Crucially, the regulation stipulates that if production exceeds consumption over the billing period ($\hat{q} < 0$), the volumetric part of the bill is simply set to zero; the electricity bill of a prosumer is thus equal to $\max[0, p\hat{q}]$, where $p$ is the electricity retail price. A rational person who anticipates that over the year-long billing period, she shall produce more than what she usually consumes, might decide to consume the excess output which is by all means "free " i.e. has a zero marginal price.

Electricity consumption is a well known example of inelastic demand as may be observed during power market spikes when consumers knowingly accept much higher bills to maintain a minimum load. In their meta study, Labandeira et al. (2017) identify an average low elasticity for electricity demand (-0.12) but we argue here that having access to "free electricity" creates an altogether different scenario. Indeed, Elinder et al. (2017) study the change in electricity consumption in apartments following an update in the metering and billing policy from a monthly fixed fee (zero-marginal price) to one based on the true consumption charged at the retail price. These authors document an immediate load reduction by a quarter after the introduction of a positive marginal price. Jessoe et al. (2020) report similar findings for commercial contracts. These behavior land credit to the possibility of a "zero marginal price" rebound in our study.

### 2.3 Investment subsidies

Lastly, under *Solwatt*, households who invested in solar PV were able to benefit from an upfront investment subsidy covering 20% of the investment cost (with a maximum of 3500 €) in 2008 and 2009 and from a tax credit until 2011, increasing from 1200 € in 2006 to 3600 € in 2011.

### 2.4 PV deployment in Wallonia

As may be gauged from Figure 1, starting from virtually zero PV installations in 2007, the *Solwatt* program met with tremendous success since 133 000 systems had been installed by the end of 2014, totaling 764 MWp of productive capacity. The subsequent *QualiWatt* program was less successful with solely 4 200 and 6 000 new installations in 2015 and 2016 respectively, far from the 48 000 registered in 2012. The figure also shows an increase in the average installation size during the *Solwatt* period, followed by a decline at the end of the program.

The *Solwatt* success had two unintended consequences. Firstly, the financial cost of the supporting scheme quickly rose to represent a huge burden for the collectivity. Over the period 2003-2012, Boccard and Gautier (2015) estimate an overall average support of 84 (average TGC price) $\times 7 = 588$ € per MWh of solar electricity paid out by the TGC mechanism. This is a considerable

[5] cf. Brown and Sappington (2017) and Gautier et al. (2018) on the optimality of net metering

when compared with other European countries RES support schemes. Secondly, the excessive TGC supply brought about disequilibrium on the market, pushing the price down to the ex-ante fixed floor of 65 €/MWh (see Figure 2). These development forced the government to terminate *Solwatt* and replace it a less generous alternative that was met with less enthusiasm.

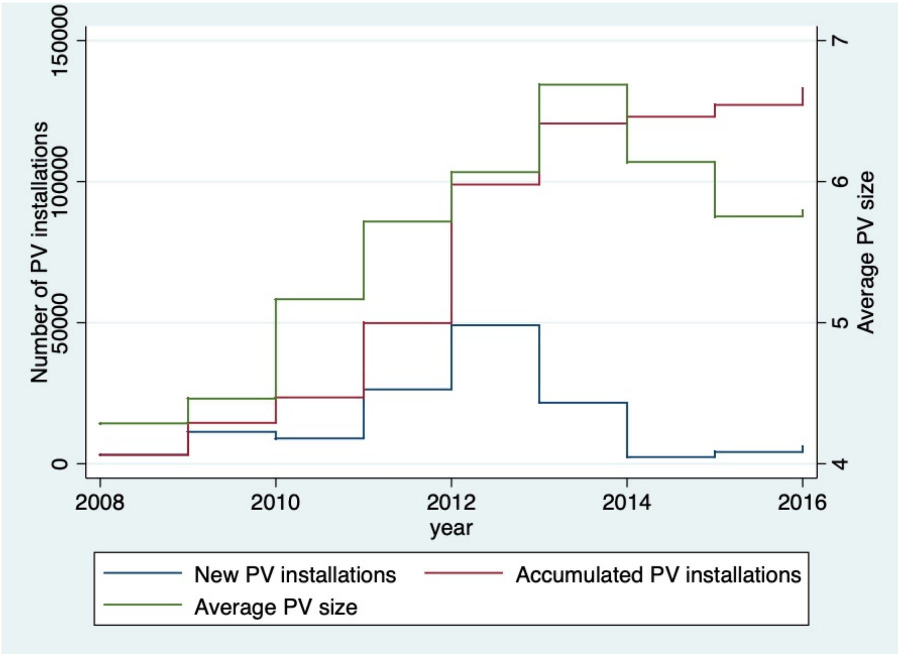


Figure 1: Number and average size of PV installations in Wallonia from 2008 to 2016

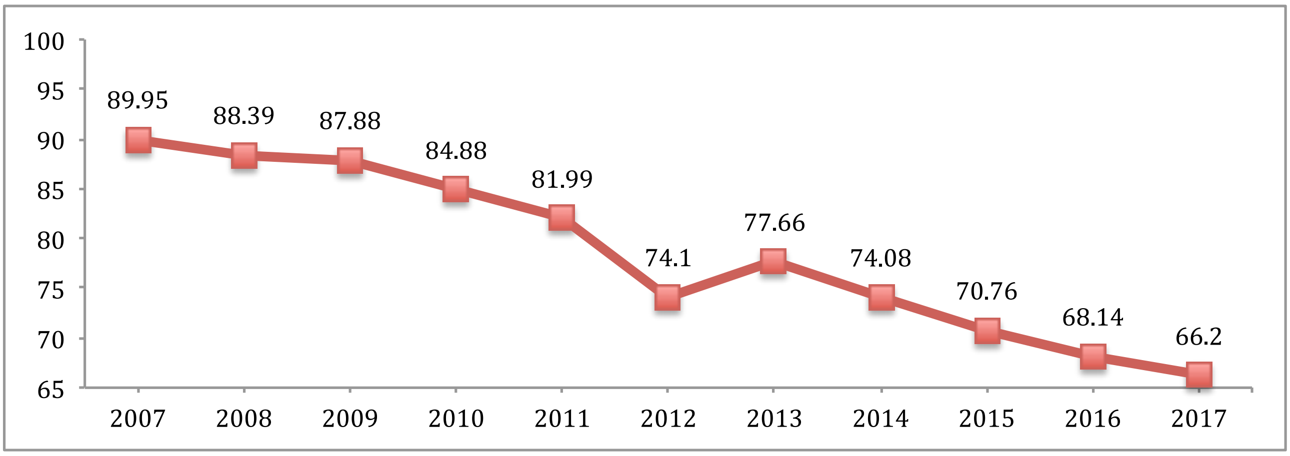


Figure 2: Price of a green certificate (€) between 2007 and 2016

# 3 Solar rebound

In this section, we make the theoretical case for a solar rebound and proceed to present how we estimate electricity consumption once a PV system has been fitted on the house roof, solely from bills and the PV system size, in the absence of a smart meter allowing precise PV output readings.

## 3.1 The investment decision

Consider the PV investment decision for a prospective prosumer, that is to say, the choice of a capacity $\tilde{k}$, measured in kWp. Such an installation will produce $k = \beta\tilde{k}$ kWh, where $\beta$ is the (local) capacity factor, the average number of full production hours over a calendar year.

The PV investment cost, net of investment subsidies, is $C$ €/kWp. Production subsidies (TGC) are granted on the basis of the solar production $k$. Let us denote by $\rho$ the present value of the green certificates obtained for each unit of capacity. Formally, if the support scheme grants $\psi$ green certificates per MWh during $T$ years (see Table 1) and TGC are traded in year $t$ at the average price of $p_t$ (Figure 2), we have $\rho = \sum_{t=1}^{T} \delta^{t-1}[\beta_t \psi p_t]$, where $\delta$ is the discount factor. Now, whenever $\rho > C$ holds true, rational households should invest up to the maximum capacity, irrespective of savings on their actual electricity bill. This maximum capacity, in turn, is determined either by the rooftop size[6], the 10 kWp eligibility threshold for the *Solwatt* program or some financial constraint.[7]

We claim that, for most of the years when it was in place, the support provided by the *Solwatt* program guaranteed $\rho > C$. To prove this, we first need a precise estimation of the solar panels electricity production for a typical Walloon household (since we do not have any reading at the source). For that task, we construct a regional capacity factor $\beta_t$ using the monitoring of solar generation by the TSO together with some older solar irradiation data from the meteorological institute (cf. Appendix A). Next, we use this capacity factor to estimate $\rho$ and compare with the installation cost $C$.

**Capacity factor** Table 2 displays the yearly average values for $\beta_t$. In the long run, the 10.8% CF means that a 1 kWp PV panel produces $0.108 \times 8760 \approx 945$ kWh per year. A residential consumer with a yearly consumption of 3 600 kWh, the Walloon average, could cover it with a system of $\frac{3600}{945} \approx 3.8$ kWp size, a figure well below the legal limit for the *Solwatt* program.

| Year | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | **Mean** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CF | 10.5 | 10.8 | 11.5 | 10.9 | 12.1 | 11. | 7.5 | 10.9 | 11.7 | 10.9 | 10.9 | **10.8** |

Table 2: Estimated yearly solar photovoltaic capacity factor in Wallonia, 2007-2017

**Solar NPV**

Combining our components, we derive the TGC net present value under the different guises of the *Solwatt* mechanism. We first compute the production of a PV system using the estimated capacity factor $\beta$, applying a loss of productive power of 0.5% per year (*wear & tear*). Applying the adequate factor, we derive how many TGCs the household will receive every year. To compute

[6]To give an idea, 1 kWp installation requires a surface of approximately 6.6 square meters.

[7]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.

a monetary value, we use three different TGC prices: the low one $\rho_1$ is based on a constant TGC price equal to the price floor of 65 €; the medium one $\rho_2$ is based on the true market price for the TGC up to 2016 and on the price floor from 2017 onwards; lastly, the high estimate $\rho_3$ is based on a constant price equal to the TGC price at the installation date. The latter scenario is the likely one used by consumers when planning their PV system. Lastly, we adopt an interest rate of 3%.[8]

We may now compare our estimated TGC NPV $\rho$ with the system cost $C$ of a PV module, both in € per Wp. We provide in Table 3 two estimates for the investment cost $C$. The gross cost $C_1$ refers to the price reported by IEA (2015) for Belgium. The net cost $C_2$ is the gross cost from which we subtract the investment subsidies and the tax credits when they were available. As both the tax credit and the premium were capped, we compute $C_2$ for a reference installation of 4 kWp (which benefited from the highest subsidy).

With net metering, the solar production is valued at the retail price $p$ and the benefit of net metering accounts for $\mu = pk$. For the retail price, we use the Belgian electricity price for residential consumer $p$ provided by Eurostat at the date of installation; we assume this price increases by 2% per year.[9] Finally, the NPV of the PV system is $\pi = \rho_3 - C_2 + \mu$ for the most likely projection performed by a potential acquirer. The associated payback time is also computed. The PV installation is supposed to be operational over a period of 20 years.

| Year | Program | $\rho$ (€/Wp) | | | $C$ (€/Wp) | | NPV $\pi$ | Payback time |
|---|---|---|---|---|---|---|---|---|
| | | $\rho_1$ | $\rho_2$ | $\rho_3$ | $C_1$ | $C_2$ | (€/Wp) | (years) |
| 2008 | Solwatt 1 | 4.88 | 5.85 | 6.64 | 5.8 | 4.02 | 5.87 | 4.78 |
| 2009 | Solwatt 1 | 4.88 | 5.46 | 6.60 | 5.2 | 3.42 | 6.16 | 3.99 |
| 2010 | Solwatt 1 | 4.88 | 5.34 | 6..38 | 4.2 | 3.3 | 6.17 | 3.89 |
| 2011 | Solwatt 1 | 4.88 | 5.22 | 6.16 | 3.4 | 2.5 | 7.01 | 2.65 |
| 2012 | Solwatt 3 | 3.14 | 3.43 | 3.58 | 2.7 | 2.7 | 4.47 | 3.68 |
| 2013 | Solwatt 5 | 0.75 | 0.79 | 0.90 | 2.3 | 2.3 | 2.05 | 7.18 |

Table 3: Present value of TGC, NPV of installations and payback time

**Oversizing**

As may be observed from Table 3, the net present value of the TGC is larger than the investment cost except for the latest period (April 2013- February 2014). Our hypothesis regarding the strong incentives incorporated in the *Solwatt* program is thus borne out. Consequently, households who

[8] De Groote and Verboven (2019) estimate that households in Flanders, where a similar TGC scheme was in place, had a discount factor of 15% and systematically under-estimated the benefits of the TGC mechanism. As a consequence, the adoption rate was lower there despite this generous support. This is a different problem from the one we face here as we only focus on technology adopters. The fact that some non-adopters were refrained to invest because of a high discount rate is irrelevant to our analysis.

[9] This is a conservative estimate as the average electricity price for residential consumers in Wallonia increased by 53% from 2007 to 2018 according to a study published by the regulator CREG (2019).

decided to invest into PV panels before April 2013 had every incentive to install the largest possible system given the constraints they faced (rooftop size, eligibility threshold, financial constraint). This is apparent from Figure 1 where the average installation size grew with time but decreased sharply after the end of the *Solwatt* program.

**Proposition 1** *The Solwatt program encouraged households to install large PV systems, possibly oversizing the size corresponding to their prior consumption.*

Given her past average yearly consumption $\underline{q}$, a prospective PV buyer will first compute the notional system size $\tilde{k}$ that would be large enough to cover her needs on a yearly basis, as a way of seizing the usefulness of rooftop panels. If the solution to $\underline{q} = \beta\tilde{k}$ meets the aforementioned constraints, the decision maker may choose this particular focal PV system size. But, motivated by the generous TGC mechanism, she may rationally "overshoot" her strict needs and install what we henceforth call an *oversized* system ($k > \underline{q}$). We conjecture many households did so.

### 3.2 Consumption and Rebound

We now turn to the households' electricity consumption decision, posterior to the PV installation. As already explained, the prosumer bill for a solar production $k$ and a consumption $q$ is equal to $\max[0, p(q-k)]$. The marginal price of electricity is equal to zero for consumption levels below the solar production and to the retail price of electricity ($p$) for consumption levels above. Hence, households producing less than what they consumed in the past ($k < \underline{q}$) face the same marginal cost of electricity as before. Contrariwise, households with an oversized installation face a marginal cost of zero up to the point where their consumption equate their production. We can therefore claim that:

**Proposition 2** *Households with an oversized installation ($k > \underline{q}$) have free electricity to consume.*

The proof is obvious, for in the absence of any change in their consumption pattern, oversized households produce more solar electricity than they use, the excess output $k - q$ being exported to the grid. Per net metering, their electricity bill remains nil meanwhile $q \leq k$, they may thus freely consume their excess production.

Importantly, as the meter is read only once a year for billing, this free electricity does not need to be consumed synchronously with production; households thus benefit from free electricity as long as their yearly consumption is lower than their yearly solar production.[10] They may decide to buy new electricity appliances (air-conditioning, spa, swimming pool, etc.) to increase their electricity consumption or switch over to another energy vector, e.g. from gas and fuel for heating

[10] Qiu et al. (2019) observe consumption increasing in lock step with solar production because households are fitted with smart meters and differential prices.

to additional auxiliary electric heating and a heat pump, or, from gas for cooking to an electric cooker, or acquire an electric vehicle.

In addition to this substitution effect, households investing in solar panels may also be exposed to an *income effect*. Indeed, as solar PV is a net source of income over the long run, prosumers may consume additional electricity since it is a normal good. However, this impact does not accrue immediately but is spread over the granting period of the TGC (up to 15 years) and we know from De Groote and Verboven (2019) that households heavily discount these future benefits. For this reason, it is not clear that households will immediately increase their electricity consumption and this mitigates the income effect.

At the outset, we have shown that the institutional features of the *Solwatt* program generate the potential for a substantial rebound effect through the income and zero-price channels, we shall now test.

# 4 Empirical Strategy

## 4.1 Data Source and Description

Wallonia's 262 municipalities are serviced by a number of *distribution system operators* (DSO). Our data source is the major one, ORES, which covers 191 municipalities and results from the merger of 7 former smaller DSOs. This operator has maintained the substantially different pre-existing tariffs and this discriminatory element shall be used in the analysis. The areas of Wallonia where ORES distributes electricity are shown on Figure 3.

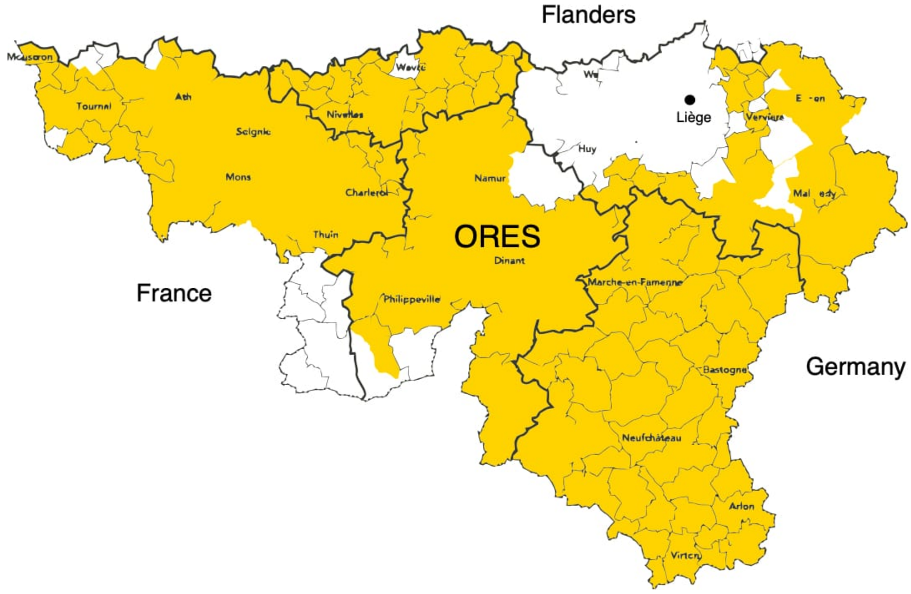


Figure 3: Areas of Wallonia covered by ORES

The sample unit is the *European Article Number* (EAN) uniquely identifying a consumption point, typically a household. We exclude commercial and industrial clients which were not eligible for support. Over the remaining residential EANs, our sample is exhaustive with respect to clients equipped with a solar panels. For each of the nearly 100 000 anonymized EAN, we collect the location (zip code), the yearly meter readings (meter index and reading date) from 2010 to 2017, the PV installation date and the effective power in kWp of the PV modules (minimum between inverter power and panel power). We select households who installed solar panels during the *Solwatt* period and we eliminate from the sample households who installed solar PV prior to 2010 since we cannot observe their behavior prior to the installation date.

The meter reading is performed about once a year either by a DSO employee or by the client, and transmitted to the DSO by mail, phone or online; the recorded figure is used to compute consumption (and the bill) by difference with the previous reading. Clearly, some readings are erroneous, forcing us to apply an error detection algorithm; to err on the safe side, we exclude the top and bottom 1% observations with exceptionally large negative or positive recorded consumption. Furthermore care must be taken that most meters are mechanical and thus to return to zero after reaching the upper bound. We also account for the variety of meter types in use: the single meter (most common), the day/night meters and occasionally the exclusive night meter. Infrequently, an EAN may be equipped with several meters.[11]

## 4.2 Consumption Estimation

For each sampled EAN, we estimate daily electricity consumption. The billed amount is the difference between the indices read on the meters at two successive visits, performing aggregation when necessary; we eliminate at this point all EANs with missing, incomplete or incoherent data resulting, for example, from an (unobserved) replacement of the meter. Over a billing period going from dates $t_1$ to $t_2$, the EAN is billed for the $B$ kWh read on his meter. Whenever the PV installation date $\tau$ is prior to $t_2$, we know that local electricity production $k$ starts offsetting household consumption so that the meter only records net imports $q - k$.[12] To recover the true household consumption $q$, we estimate the daily solar PV production $k$ and sum it over the billing period to obtain $D = \tilde{k} \times \sum_{t=\min[t_1,\tau]}^{t_2} \beta_t$ where $\tilde{k}$ is the household's PV size and $\beta_t$ is the estimated daily PV capacity factor. The total consumption over the period is then $Q = B + D$. Since the billing period is not fixed, we rescale all figures by the period length so as to work with the daily consumption.

Unlike an off-grid consumer that must store her PV output in batteries order to consume it when needed, a grid-connected household (everyone in our sample) has no rational motive to consume more electricity during daytime and less during nighttime. Indeed, the TGC revenue

[11] When solar output is larger than peak consumption, the DSO recommends to switch from a day/night meter to a single meter. This can be done without having to change the meters since the indexes of the two meters can be aggregated by the DSO before establishing the bill.

[12] Typically, a household imports electricity during the night and exports around noon. Likewise, imports are larger during the winter and exports larger during the summer.

only depends on much sun Wallonia receives over a year not when it actually shines while reverse metering brings about a saving that is also accruing over a whole year, leaving the household free from worrying when to consume or not. We thus assume that rational prosumers do not alter their temporal consumption profile after installing PV panels, though it may be systematically higher. The weather induced seasonality of daily load is accounted for using the so-called *synthetic load profile* (SLP)[13] which ORES uses to estimate her clients' yearly consumption on the basis of their meter recordings. We employ the Liège SLP curve $s_t$ to estimate the daily consumption at date $t$ as

$$q_t = \frac{s_t}{\nu} \frac{Q}{t_2 - t_1} \tag{1}$$

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 4 with one randomly chosen (true) household. The red curve displays the average daily load as measured by the meter difference between two readings ($\frac{B}{t_2-t_1}$); 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 ($\frac{D}{t_2-t_1}$) 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. One thus observe that prosumers store energy on the network during the summer and draw it during the winter (on average the blue and green curves are at the same level over any billing period).

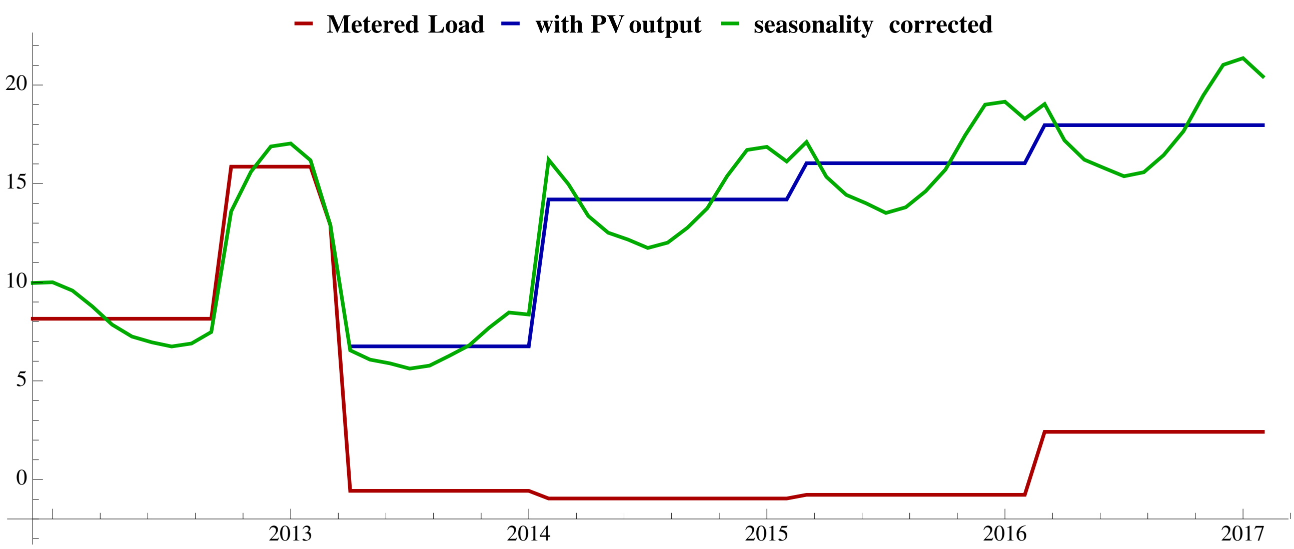


Figure 4: Reconstructed household load curve including PV output

Our reconstruction procedure of electrical load may err for three possible reasons, firstly because of defectiveness or wear-and-tear of the installation, secondly due to the orientation and inclination of the panels and, thirdly as a consequence of local weather conditions. None of these

[13]The SLP for each day is the consumption of a representative household taking into account the calendar day, climatic factors, sunrise and sunshine hours, day-off, public or school holidays, etc... It is computed by Synergrid, the professional association of electricity and gas network managers in Belgium.

however impacts our study. In the first case, as our time frame does not extend beyond two years after the PV installation, panels are still new and well functioning (and covered by a two-year compulsory warranty from the installer). In the second situation, professional installers inform us that a non optimal orientation, a failure to directly face south, caused by the roof structure may reduce production by up to 10% i.e., actual output will hover at ±5% around the regional mean metered by ELIA, the Belgian TSO. Since this technical factor is randomly distributed across the sample, it only increases the error variance in the econometric estimation and does not generate a systematic error into either overestimating or underestimating PV output.[14] Lastly, weather conditions and thus solar irradiance may be taken to be homogeneous over Wallonia whose geographical footprint is about $160 \times 100$ km$^2$, as may be checked from Figure 7 (in Appendix).

### 4.3 Reverse Causality

We aim to identify a possible change in household electricity consumption around the date of PV installation; this is performed under the implicit assumption that households invest in a PV system either to partake in the ecological transition or take advantage of the governmental subsidies. To properly identify a solar rebound, we must account for possible confounding factors which could make causality run reverse. Indeed, if an event generates a sustained increase of electricity consumption, the household may decide to invest into PV (as this is financially attractive) in order to lower its bill, in which case the rise in electrical load after the PV installation is no rebound.

We believe there are only three situations which could potentially trigger an increased electricity consumption and, thereby motivate the household to invest in a PV system. The first one is when the household size increases (e.g., newborn) but, as shown by Kavousian et al. (2013) (and the literature cited within), this criterion is a secondary determinant of electrical load; it is thus very unlikely to trigger the PV investment decision. The second possibility is when a major renovation takes place. It may be a building expansion in which case electrical consumption will only increase for the added lightning since detached houses in Wallonia (a key characteristic of our sample) rarely use electrical heating. If the renovation is an improved insulation aimed at saving on heating expenses, it should have no impact upon power load (for the aforementioned reason).[15] Lastly, the household may decide to switch heating source from natural gas or fuel to electricity and install PV panels to contribute to her planned increased power load. In our sample where PV panels are affixed to the roof, all dwellings must be detached houses; for these characteristics,

[14] Likewise, if income is observed at county level instead of city level, the variable becomes less informative but not a source of bias.

[15] Matching the number of Walloon households to yearly renovation permits (recovered from StatBel (2021), we compute that a maximum of 1 200 units out of the 65 000 in our raw sample might have undertaken such a renovation, far less than the number actually eliminated with the criteria in the text.

there is agreement among professionals that electric heating represents $\frac{2}{3}$ of the electricity bill. Applying this identification criterion allows us to isolate and **exclude** 4.5% of the sample where such a major load jump is observed.[16] For the remaining sample, we are thus confident that households invest into PV as a response to the government program so that their sizing choice and subsequent behavior does not obey a preexisting motive. Notice finally that electric vehicles (EV) were sparse in Wallonia during the period under consideration with only 305 registered EV at the end of 2014 (cf. Iweps (2021)). Therefore, the acquisition of an EV cannot be reasonably considered as a motive for investment in solar PV.

# 5 Estimating the Solar Rebound Effect

## 5.1 Statistical Analysis

We employ a quasi experimental approach to compare household electricity consumption before and after their PV installation. Specifically, we compute the mean daily consumptions $\underline{q} = \frac{1}{24}\sum_{t=\tau-24}^{\tau-1} q_t$ and $\overline{q} = \frac{1}{24}\sum_{t=\tau}^{\tau+23} q_t$ over 2 years *before* and *after* the PV installation date $\tau$. This requirement reduces our sample down to 62 731 households. The exogenous variables included in the analysis are the electricity price and the median income, both at postal code level. Wallonia is geographically too small to employ solar radiation or temperature at city level but the latter is still used a temporal marker to eliminate the spurious impact of cold and hot years.

To disentangle the theoretical *income* and *zero-marginal price* effects upon electricity consumption, a first sensible approach is to identify households that are exposed to both effects from those solely exposed to the first one. To that end, we classify households in two categories by comparing their solar production with their pre-installation consumption. We distinguish between <u>oversized</u> PV systems that produce more than the past consumption and <u>undersized</u> ones that produce less. Due to the legal 10 kWp limit, an oversized system is typically found for a small house or small household which are those having a low historical power load. Lastly, one should bear in mind that oversized and undersized households may differ by some unobservable characteristics, but as we compare the same consumers before and after the PV installation, we can control for the time-invariant unobservables.

Theoretically, the *undersized* group should be subject to the income effect only (as they always draw from the grid) while the *oversized* group is also expected to display the zero marginal price effect. In our sample, a slight majority of households oversized their PV installation as may be gauged from Table 4 presenting descriptive statistics looking at the two quartiles and the median.

[16] By doing so, we also eliminate all the houses that experience a large renovation and that have been left empty during the work period.

| Quantile | 25% | 25% | 50% | 50% | 75% | 75% |
|---|---|---|---|---|---|---|
| | Before | After | Before | After | Before | After |
| Full Sample | 9.5 | 10.4 | 13.3 | 14.2 | 19.2 | 20.6 |
| Undersized | 14.0 | 13.0 | 18.4 | 17.8 | 27.1 | 26.6 |
| Oversized | 7.5 | 8.9 | 10.1 | 11.8 | 12.8 | 16.1 |

Table 4: Daily consumption in kWh/day before and after PV installation

We observe that average consumption slightly increases after the installation of rooftop PV panels (+5%) but the evolution differs radically between the two groups. In the undersized group, the average consumption decreases slightly (-4%), whereas for the oversized group it increases markedly (+23%). We illustrate this statistic on Figure 5 where we plot the daily consumption before and after PV installation for each individual observation i.e. the ratio $\overline{q}/\underline{q}$ of *ex-post* and *ex-ante* load. 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[17] while they are more equally dispersed within the undersized group with 40% of the installations above the diagonal. These statistics suggest a very substantial rebound effect for oversizing households, an important zero-price effect and a limited income effect.

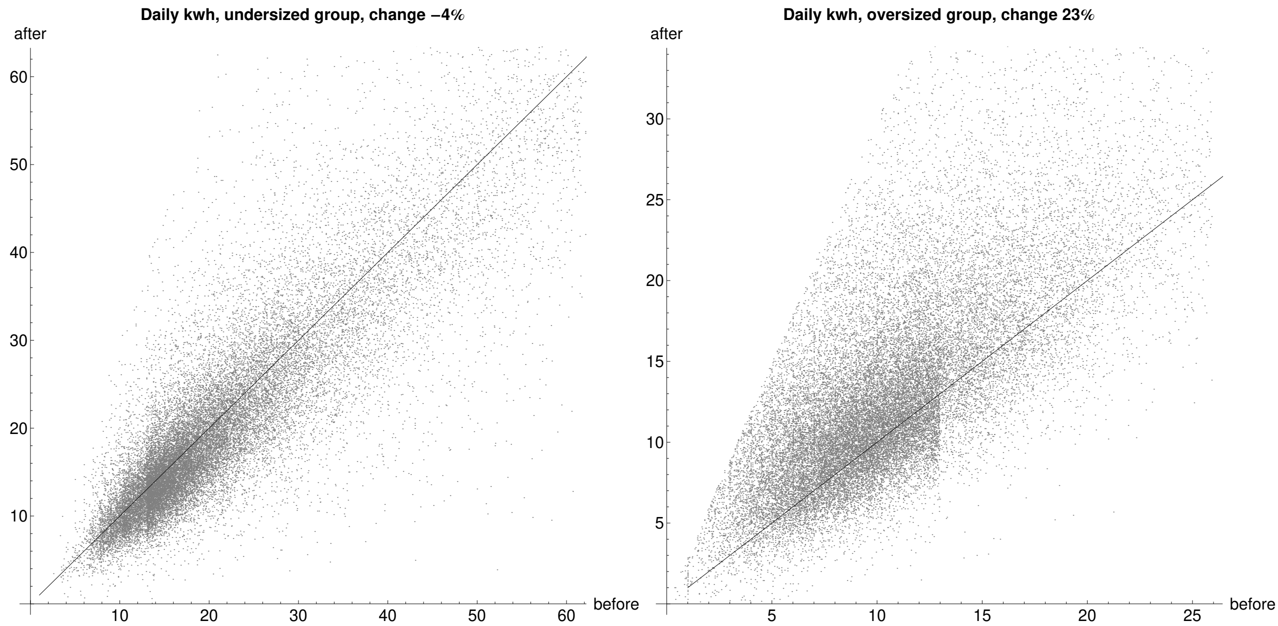


Figure 5: Daily consumption in kWh/day before and after PV installation, Left panel undersized installations, right panel oversized installations

To illustrate how behavior changes after solar panels have been installed, we write the ratio $\frac{\overline{q}}{\underline{q}} = \frac{k}{\underline{q}} \times \frac{\overline{q}}{k}$ where the first ratio $\frac{k}{\underline{q}}$ 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

[17] The clean upper limit to the cloud is the equation post-PV load = 3× pre-PV load, corresponding to households eliminated to account for a possible reverse causality.

ratio $\frac{\overline{q}}{k}$ measures the percentage of the electricity produced that is actually consumed. If for instance, $\frac{k}{\underline{q}} = 1.3$, the household produces 30% more than it (historically) needed and if $\frac{\overline{q}}{k} = 0.9$, it consumes 90% of its production; with this example, $\frac{\overline{q}}{\underline{q}} = 1.17$ i.e. consumption increases by 17% after the PV installation. On Figure 6, we sort our sample along the first ratio $\frac{k}{\underline{q}}$ and group observations into 50 bins, each representing 2% of the sample. We then compute the mean of the two ratios in each bin to produce the plot; both scales are percentages and the plot is divided in two parts to allow a clear view. Absent any rebound effect, the graphical representation should be the standard hyperbole ($x \to \frac{1}{x}$) since for a constant consumption ($\overline{q} = \underline{q}$), the ratio $\frac{\overline{q}}{k}$ is the inverse of $\frac{k}{\underline{q}}$. What we observe on Figure 6 is quite different; firstly, the minimal panel size impedes the curve from rising too high on the left hand side. More importantly, for oversized households located to the right of 100 (by construction), the curve becomes flat at about 85% instead of continuously falling (if there were no rebound). This means that a large swath of households invested into "oversized" panels and then chose to consume most of their PV output, solely putting back 15% of the potential green electricity onto the Belgian grid.

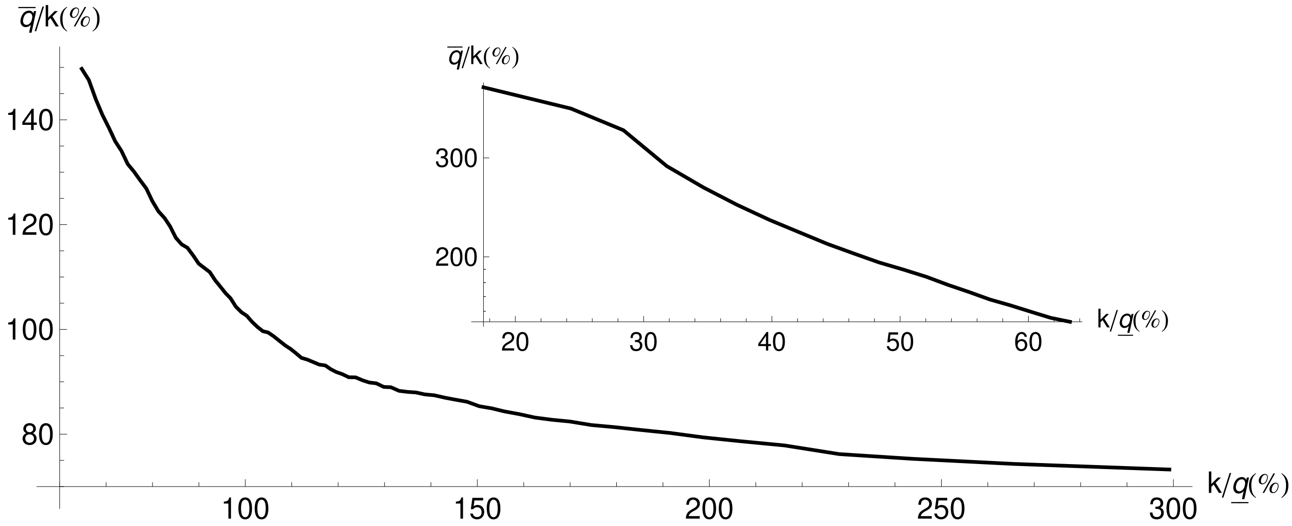


Figure 6: Consumption-Production ratio depending on relative installation size

## 5.2 Econometric Estimation

To further study the consumption change after the adoption of a PV system, we set as a dependent variable the difference between daily consumption after and before the installation date $\tau$:

$$\Delta q = \overline{q} - \underline{q} \tag{2}$$

Our exogenous variables are linked to the installation characteristics and the environment. We first measure the difference in the average temperature 2 years before and 2 years after $\tau$, this because temperature is an important driver of electricity consumption. We use the monthly average temperature $\zeta_t$ recorded at the airports of Maastricht, Florennes and Beauvechain which together cover neatly the ORES distribution area. The independent variable we construct is the difference between averages before and after PV installation

$$\Delta\zeta = \frac{1}{24}\sum_{t=\tau}^{\tau+23}\zeta_t \quad - \quad \frac{1}{24}\sum_{t=\tau-24}^{\tau-1}\zeta_t \tag{3}$$

The second regressor is the electricity price. Since all commercial retail offerings are available across the whole of Wallonia, households in our sample face the same opportunities (no bias). However, distribution company ORES has maintained the distinct grid tariffs previously existing within its 7 historical areas; as a consequence, the full electricity price $p$ differs among cities. The third variable is the median income measured at city level. Next, we use the PV installation size $\tilde{k}$ (kWp); a positive sign for this variable would indicate 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 free electricity (if any) available to the household. We construct first a dummy variable indicating that the household owns an oversized installation: $\theta = 1$ if $k > \underline{q}$ and $= 0$ otherwise. In a second step, it is interacted with the excess solar output $k - \underline{q}$ to create an "oversized" variable $\tilde{\theta} = \theta \times (k - \underline{q})$ measuring the available free electricity. We estimate the following equation with results reported in Table 5.

$$\Delta q = \alpha + \beta_1 \Delta\zeta + \beta_2 \mathrm{Inc} + \beta_3 p + \beta_4 \tilde{k} + \beta_5 \theta + \epsilon \tag{4}$$

In the first specification, all coefficients are significant at the 1% level except for the tariff (non significant) and the constant (significant at the 5% level). The positiveness of the temperature parameter indicates that electricity consumption increases more when the weather is hotter after PV installation (e.g. air-conditioning). The negative income sign indicates that richer households have increased consumption less than poorer ones. The constant is negative (-0.6) and the coefficient of PV size is positive (0.1). This means that daily consumption decreased in average for PV installations with a size less than 6 kWp and increased for larger installations. The dummy variable for oversized installations is positive meaning that households with oversized installations consume significantly more electricity after they installed solar panels. The estimated consumption increase is in average equal to 3.28 kWh/day or approximately 1.2 MWh/year.

In the second specification, the tariff has a negative sign indicating that people paying a higher price for their electricity have increased consumption less than others. Turning to the analysis of the oversize variable $\tilde{\theta}$, the large coefficient found means that for every additional daily production of 1 kWh *of free electricity*, 69% is consumed by the household and only 31% is supplied to the network. We have therefore characterized an extremely substantial "solar rebound" for households who had previously oversized their installation. This behavior is driven by the zero-marginal price effect; one of the uses, personally communicated to us by a variety of actors, is the temporal swapping of central heating by a portable electric radiator.

| | (1) | (2) |
|---|---|---|
| Constant $\alpha$ | -0.609$^{**}$ | 1.530$^{***}$ |
| | (0.241) | ( 0.242) |
| Temperature $\beta_1$ | 0.801$^{***}$ | 0.789$^{***}$ |
| | (0.067) | (0.067) |
| Income $\beta_2$ | -0.076$^{***}$ | -0.073$^{***}$ |
| | (0.009) | (0.009) |
| Tariff $\beta_3$ | 0.013 | -0.035$^{**}$ |
| | (0.017) | (0.018) |
| PV Size $\beta_4$ | 0.107$^{***}$ | -0.005 |
| | (0.005) | (0.005) |
| Oversized dummy $\beta_5$ | 3.285$^{***}$ | |
| | (0.048) | |
| Oversized $\beta_5$ | | 0.691$^{***}$ |
| | | (0.008) |
| Observations | 62 731 | 62 731 |
| $R^2$ | 0.09 | 0.13 |

Standard errors in parentheses

$^{*}$ $p < 0.05$, $^{**}$ $p < 0.01$, $^{***}$ $p < 0.001$

Table 5: Change in consumption after installing a PV system

## 5.3 Panel Estimation

We have thus far identified an unexpected (for the government) by-product of the PV investment decision, a powerful increase in electric consumption for households having chosen a PV system large enough to cover their historical consumption. In this section, we investigate this question further by way of a panel estimation to identify specific consumption trends among Walloon prosumers whom we are following for up to 8 years while accounting for unobserved individual differences (heterogeneity). Because the billing date is recorded at monthly granularity, our panel is strongly unbalanced (each household is present only about 8 times among 100 possible dates). The panel model is

$$q_{it} = \alpha + \beta^{\intercal} x_{it} + \epsilon_{it} \tag{5}$$

The dependent variable $q_{it}$ is the electricity consumption of household $i$ at date $t$, expressed in kWh per month. The vector of exogenous variables $x_{it}$ is described with basic statistics shown in Table 6. We first include a time trend (**month**) capturing the long term evolution of consumption, **pvsize** measuring the capacity of the PV installation (scaled in kWh/month using a common capacity factor instead of kWp for comparability with $q_{it}$), the variable is equal to zero prior to installation. Variable **subsidy** distinguishes between the various stages of the support program; it is the same for all households but falls with time (see Table 1). Variable **oversized** is a dummy equal to one if the installation is oversized.[18] We interact it with the time trend to capture a specific time trend for prosumers with an oversized installation: **free_elec** = **month**×**oversized** (it is thus zero prior to the PV installation). Variable **tariff** is the average distribution tariff in cents per kWh for the corresponding tariff zone of the DSO. Lastly, we employ two control variables at the municipal level, the median income (**income**) and the population density (**density**).

| | mean | min | max | sd |
|---|---|---|---|---|
| oversized | 0.38 | 0.00 | 1.00 | 0.48 |
| pvsize | 242 | 0 | 778 | 235 |
| tariff | 9,252 | 5,993 | 14,883 | 1,603 |
| subsidy | 55 | 0 | 105 | 36 |
| income | 22,334 | 15,671 | 34,399 | 2,744 |
| density | 411 | 24 | 1,997 | 475 |
| Free_Elec | 20 | 0 | 94 | 28 |
| Observations | 785200 | | | |

Table 6: Panel sample descriptive statistics

We employ three different estimation techniques in a first step which omits variable **free_elec**. The robust least squares estimator for model (5) is shown in the first column (pool) of Table 7. The fixed effects model amounts to specify a different constant $\alpha_i$ for each household; results are shown in the second column (FE). The random effects model treats the heterogeneity across individuals as a random component; results are shown in the third column (RE). In line with standard econometric recommendation, we favor the latter model, all the more so as we aim to make an unconditional inference about the average behavioral change. The Breusch–Pagan test for random effects yields an extremely large value that far exceeds the critical value for any reasonable significance level; we thus conclude that there is strong evidence of individual heterogeneity. This finding leads us to run an additional series of regressions, adding **free_elec**, our main variable of interest, to the set of explanatory variables. In the following discussion, we refer to the random effects models presented in Columns (3) and (6).

We observe a negative time trend, meaning that consumption is declining over time. This is no surprise as energy savings and more efficient appliances are being adopted in Belgium. The coefficient for **pvsize** is positive and significant: households with larger PV systems tend to consume more, which corroborates the presence of an income effect. It should be noticed that the coefficient for **subsidy** is positive but not significant, which means that the households who benefited

[18]Recall that once the investment decision has been taken by the household, the system capacity becomes an exogenous factor for consumption planning.

from the most generous subsidy scheme do not consume more for a given PV size. Unsurprisingly, the coefficient for **oversized** in the panel regression is negative: households who oversize their PV installation consume less than those who do not, but this is mostly because they belong to the group of smaller houses, those for which the maximum 10 kWp installation more than covers their needs. Interestingly, the positive coefficient for **free_elec** in model (6) indicates a specific time trend for the prosumers with an oversized installation: electricity consumption in oversized PV homes increases with time; households progressively increase their consumptions when they realize that they have free electricity. This specific time trend for the electricity consumption of households who have free electricity available is a clear argument for our solar rebound hypothesis. The increase in consumption is not contemporaneous with the investment in PV. Rather, households who have free electricity progressively increase their load and consume their production surplus. The coefficient for **tariff** has the expected negative sign. Finally, we observe that consumption increases with the mean income in the municipality while the negative **density** coefficient indicates it decreases with population density (possibly because houses are smaller).

# 6 Conclusion

In this article, we test for the existence of a rebound effect relative to solar PV installations in a specific institutional context that combines generous production support and net metering. We use a large household sample from Wallonia, southern Belgium, to derive a broad picture of electrical consumption patterns, allowing a comparison of pre and post PV installation in a consistent way. We show how the supporting scheme lead many rational households to oversize their PV installation, as green certificates revenue covered the initial investment cost. Once done, net metering gave these households an opportunity for consuming "free" electricity as soon as their oversized installations generated in excess of their usual needs (over a year). Our empirical evidence demonstrates that this phenomenon took place on a massive scale and that oversized PV households consumed about two third of their free electricity surplus. We thus obtain strong evidence of a significant rebound in consumption associated with the adoption of solar PV.

We view this rebound as a direct consequence of the poorly designed supporting scheme applied in Wallonia. Net metering has been criticized for providing inadequate price signals and incentives by Brown and Sappington (2017) and Gautier et al. (2018). Next, excessively generous green certificates make the cost of solar energy socially expensive, and transfer income from non-prosumers to prosumers, which tends to be fiscally regressive given their respective income classes. Furthermore, this instrument may not be the most appropriate since it has been shown that households tend to discount the future too much (cf. De Groote and Verboven (2019)). Despite these shortcomings, neither net metering nor tradable green certificates are in themselves problematic. It is the combination of the two instruments that creates the conditions for a sub-

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| | Pool | FE | RE | Pool | FE | RE |
| month | -2.708*** | 2.158* | -1.910*** | -3.268*** | 0.479 | -2.891*** |
| | (0.14) | (0.90) | (0.15) | (0.21) | (1.06) | (0.22) |
| oversized | -289.9*** | 157.7*** | -229.8*** | -363.1*** | -2.446 | -361.6*** |
| | (8.88) | (12.06) | (9.02) | (10.52) | (13.42) | (10.12) |
| pvsize | 0.987*** | 0.257*** | 0.880*** | 1.009*** | 0.342*** | 0.931*** |
| | (0.02) | (0.03) | (0.02) | (0.02) | (0.02) | (0.01) |
| tariff | 0.00918*** | -0.0181*** | -0.00444*** | 0.00886*** | -0.0191*** | -0.00623*** |
| | (0.00) | (0.00) | (0.00) | (0.00) | (0.00) | (0.00) |
| subsidy | 0.0836 | 0 | -0.0946 | 0.126* | 0 | -0.0307 |
| | (0.06) | (.) | (0.06) | (0.06) | (.) | (0.06) |
| income | 0.0170*** | -0.0631*** | 0.00150 | 0.0177*** | -0.0545** | 0.00193 |
| | (0.00) | (0.02) | (0.00) | (0.00) | (0.02) | (0.00) |
| density | 0.0430*** | -2.154*** | -0.0224*** | 0.0460*** | -1.840*** | -0.0210*** |
| | (0.01) | (0.39) | (0.01) | (0.01) | (0.38) | (0.01) |
| Free_Elec | | | | 1.450*** | 2.923*** | 2.543*** |
| | | | | (0.23) | (0.32) | (0.23) |
| Constant | | 2757.4*** | 480.2*** | | 2498.1*** | 511.2*** |
| | | (349.99) | (26.25) | | (372.75) | (25.67) |
| Observations | 785200 | 785200 | 785200 | 785200 | 785200 | 785200 |
| $R^2$ | 0.09 | 0.00 | | 0.09 | 0.00 | |

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 7: Panel estimation results

stantial increase in electricity consumption by prosumers. Regulators and the government, therefore, should keep in mind that consumers react, strongly and rationally, to powerful financial incentives.

Another unintended policy implication of the particular combination of support instruments studied here is that households rarely auto-consume their excessive production when the billing period is so long (cf. Gautier et al. (2018)). As their meter runs backwards, excessive production is freely stored on the grid until the next meter reading, which might be as far ahead as one year. This means that the excessive production of the sunny summer days can be stored on the grid and used during 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[19] to periods where it is

[19]The marginal generation technology in these "valley" hours tends to be nuclear, be it Belgian, French or Swiss.

produced at a higher cost using carbon-intensive generation technology[20] is certainly not environmentally friendly inso far as the $CO_2$ emissions saved during the summer are dwarfed by the additional winter emissions. Policy design should therefore be careful to prevent such an undesirable inter temporal swapping.[21] Evidence collected from a survey among prosumers in Wallonia by Gautier et al. (2019) suggests that heating is the preferred vector for increasing consumption (electric heating and heat pumps replacing fuel or gas heating). However, with mechanic meters recorded every year, it is not possible to measure load displacement and we can only document an aggregate increase in power load. Our next endeavor will be to monitor a sample of smart-meter equipped households to conduct this study in the future.

# A Capacity Factor Construction

We estimate a monthly capacity factor using two sources. The first and most reliable one is the real-time monitoring of all Belgian PV generation by the Transmission System Operator ELIA since November 2012. We use the data corresponding to the Liège region to compute the daily capacity factor as the ratio of PV generation to monitored PV capacity (measured in MWp). This single time series is adequate since the photovoltaic power potential is quite uniform across the Walloon region: the irradiation map displayed on the left panel of Figure 7 shows a large variation across northern and southern Europe, with Wallonia, lying at the southern tip of Belgium between France and Germany, being in the low range. The close up shown on the right panel reveals irradiation homogeneity within Wallonia, with is a maximum 10% difference between extremes.

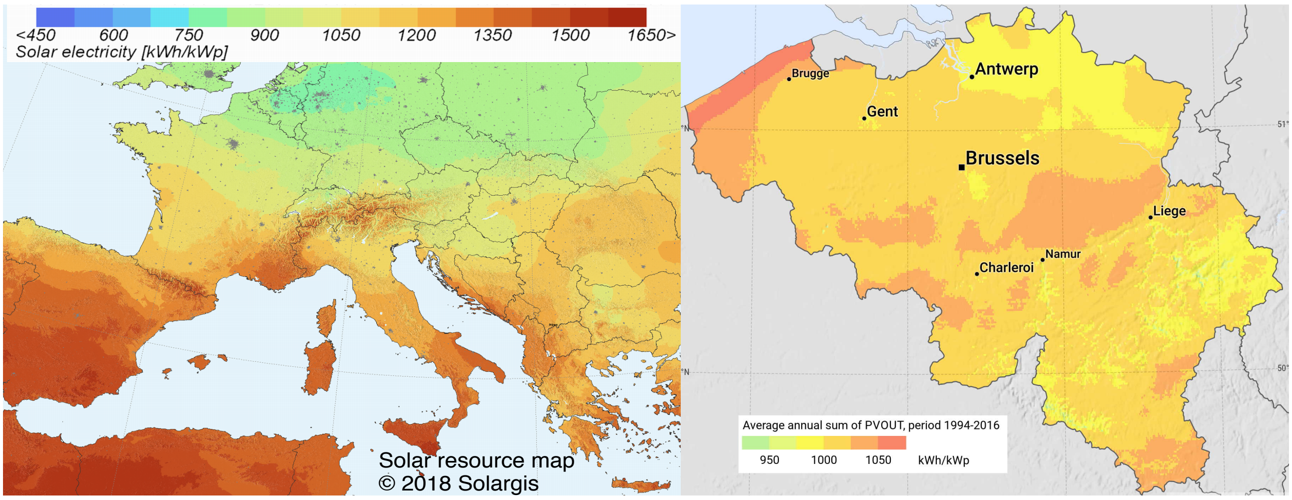


Figure 7: Photovoltaic power potential in Europe & Belgium

[20]The marginal generation technology in these "peak" hours tends to be coal or natural gas.

[21]As shown by Qiu et al. (2019), smart meter and differential tariff leave prosumers with little opportunity for deferred consumption even if they have battery storage, thus solving this issue.

For the period prior to 2012 , we use the “daily sun minutes” series published by the Royal Meteorological Institute (RMI) for the Liège Airport station. As there is a strong 82% correlation between the ELIA and RMI series over the period of common recording, we use the fitted values to extrapolate the capacity factor prior to 2012. The complete daily series is shown on Figure 8

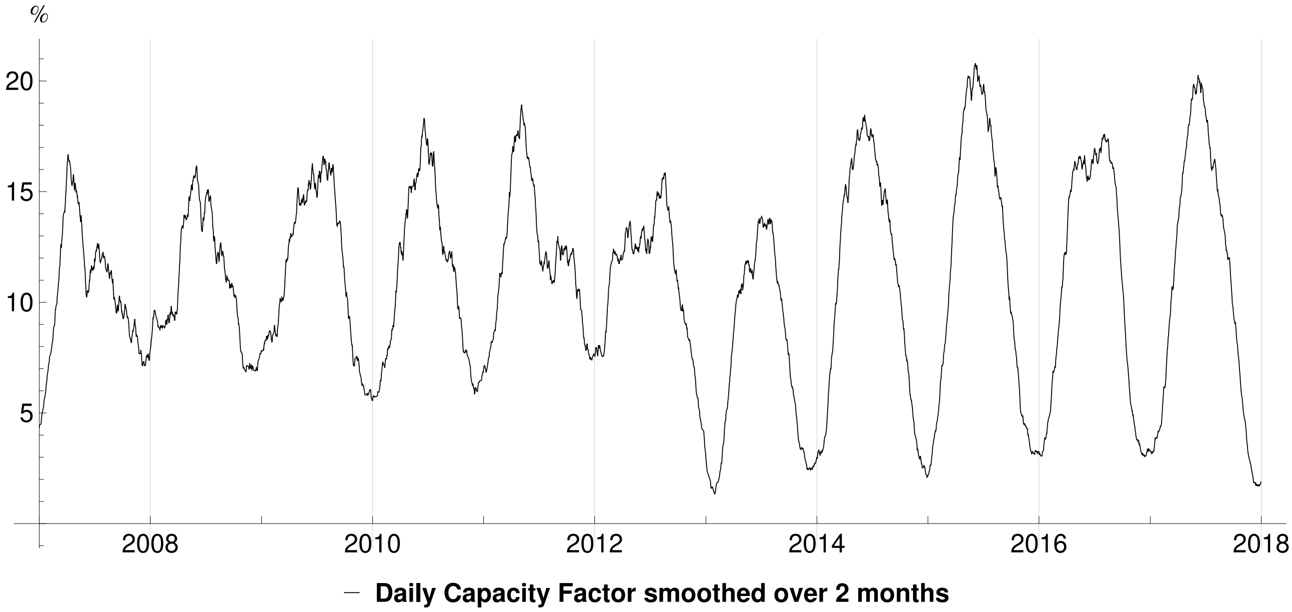


Figure 8: Daily capacity factor $\beta_m$, fitted values

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