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Solar Rebound

The unintended consequences of subsidies*

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Abstract

Many jurisdictions use net metering to record the power exchange between solar photovoltaic panels and the grid, thus valuing home production at the electricity retail rate. However, if over the billing period, production exceeds consumption, the surplus remains freely available for consumption. In Wallonia (Belgium), this system was combined with generous subsidies for solar panels that encouraged households to set-up large installations, possibly exceeding their consumption needs. In this context, we test for a possible rebound effect. Based on a large sample of residential PV installations, we observe that a large proportion of households oversized their installation to benefit from the subsidies and, later ended-up consuming most of their excess production. The effect is econometrically highly significant. There are thus evidence of a strong increase in energy consumption by residential PV owners, that runs counter the original policy design.

Keywords: Rebound effect; Solar PV; Net metering
JEL Codes: C51, Q48, Q58, Q410, Q420

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1 Introduction

With net metering system installed in a house, the exchange of power between a decentralized production unit such as a rooftop photovoltaic panel and the distribution grid is recorded by a single meter that runs backward when energy is supplied to the grid.[1] Over the billing period, this meter only records the net energy imports, the difference between total local consumption and total local production. This energy amount is the sole basis for establishing the consumer's bill. Usually, if there is production in excess of consumption over the billing period i.e. net exports to the grid, there is no additional compensation and the volumetric part of the bill is set to zero. Consumers have thus no incentives to produce more than what they consume but, if they do, they can consume their excess production for free which ought to be a powerful incentive. Indeed, Qiu et al. (2019) document how PV owners in Arizona increase their daily consumption when their daily solar production increases.

Net metering thus values the electricity produced by the PV modules at the retail price which includes grid fees and taxes; this generous pricing is one of the support mechanism used to promote the deployment of distributed generation. However, as shown by Matisoff and Johnson (2017) for the US, net metering alone proved ineffective and needed to be augmented by other instruments to support the investment in solar panels by residential customers. For this reason, government support for solar photovoltaic panels commonly uses a combination of instruments such as subsidies for production and/or investment.[2] The intensity of support to solar PV varies considerably across countries, and this in turn impacts the deployment of solar PV installations.

In this paper, we study the unintended consequences of the solar supporting scheme deployed in Wallonia (southern Belgium) between 2008 and 2014. It featured 3 components: (i) net metering, (ii) volumetric tariff over a long billing period (one year) and (iii) production subsidies through a *tradable green certificate* (TGC) mechanism. We estimate the latter to be generous enough to cover by itself the module installation costs in just a few years. Overall, this scheme encouraged many households to invest in large size installations, eventually larger than their consumption needs (year over year). 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. As already explained, this provides households with "free" electricity once that point has been reached.

These peculiarities make Wallonia a good place to test for a possible *rebound* effect, which

[1]Smart meters record separately inflow and outflow of electricity thus allowing the setting of distinct prices. Brown and Sappington (2017) and Gautier et al. (2018) discuss the optimality of net metering i.e. a single price for the two flows.

[2]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).

refers to "an increase in the energy usage after the introduction of a more efficient (energy-saving) technology".[3] This rebound effect is well-documented in the field of energy and we focus here on a possible direct rebound, 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 if the new technology saves money on the energy bill. Informal discussions in Wallonia with (household) adopters, PV installers and managers at the Distribution System Operator (DSO) lead us to believe that the Walloon supporting scheme pushed 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 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.[4] 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 (e.g., at noon in summer) with respect to its instantaneous consumption, she stores it on the grid and, crucially, it remains freely available for later use (e.g., winter evening). 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.

We venture that two channels may lead to higher electricity consumption for PV owners. Since 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 induces some extra consumption. Additionally, households with an oversized installation, generate a production surplus that is freely available for consumption. A rational household will compare this zero-price electricity with other costly energy vectors and should, in all likelihood, substitute some of the

[3] 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.

[4] 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.

latter by the former, ultimately increasing their electricity consumption. We have thus identified a potential *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 owning a PV installation in the jurisdiction of the dominant DSO of Wallonia, totaling well over 90 000 clients. In addition to the meter records, we collect the size and date of installation of the PV system. We then construct for each installation three variables: the yearly average consumption before and after the PV installation (kWh per day) as well as 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 true consumption, we add to the net import recorded by the meter, the estimated production of the PV modules using detailed weather information and monitoring data from the Transmission System Operator.

Next, we compare the consumption of prosumers before and after the installation of the solar panels (± 2 years).[5] We define an installation as *oversized* if the capacity of the modules is larger than the recent past consumption; otherwise, it is *undersized*. After discarding erroneous meter readings, our useable database contains about 35 000 undersized installations and 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 oversized 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 against the previously held idea in the literature that PV generation exceeding total consumption at the monthly level was a rare occurrence. Taking into account several control variables, including the variations in retail electricity prices across areas and in temperatures, we estimate that most of this free electricity available for prosumers who oversized their installation ends-up being consumed onsite. The sheer scale of this rebound effect is obviously a direct consequence of the particular institutional context that offered both positive net income with the TGC, thus encouraging large installations, and free electricity storage on the grid (aka the giant battery) through net metering.

Two methods have been developed 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

[5] De Groote et al. (2016) and Oberst et al. (2019) show that households 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.

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 without being linked to the change we focus on. For this reason, our econometric analysis controls for changes in temperatures and prices. The use of a control group does not seem to be appropriate because prosumers and non-prosumers have different characteristics; prosumers typically own a house and belong to the upper income brackets in order to be able to foot the initial solar panel investment (cf. footnote 5). Finally, our large sample (over 65 000 households) 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.

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. Of the few papers dealing with a solar rebound effect, the evidences is mixed. This may indicate that the consumer's behavior is context specific and depends 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 fail to identify 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 a 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. Lastly, Qiu et al. (2019) identify an important rebound effect associated with PV adoption in Arizona, finding that generating 1 kWh triggers an additional consumption of 0.18 kWh by prosumers. Thanks to daily records, they are able to show that consumption increases almost simultaneously with production. Under net-metering, the marginal price of electricity, be it (local) solar or (grid) conventional, is always equal to the retail price. Hence, there is no change in the marginal price of energy after a PV installation and, a priori, no reason to increase consumption. However, as solar households manage to decrease their energy bill, their average electricity price is lower. According to Ito (2014), 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.

At the outset, we aim to highlight two original elements in our approach. Firstly, we work with a near exhaustive sample of 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. Secondly, the institutional context in Wallonia was highly specific with a combination of net metering and, a generous TGC creating the conditions for investing into an oversized installation.[6]

A key consequence of our findings is that because household consumption and production are almost never simultaneous, our identified solar rebound effect might have a substantial and negative carbon impact. Observe indeed that solar production peaks in summer while household consumption peaks during winter. On the one hand, the thousands of Walloon prosumers under consideration add further demand to the peak winter electricity load which is served by coal, natural gas and oil power stations whose carbon emissions are very large. On the other hand, the same group exports green electricity to the grid during the central hours of the summer, thus displacing nuclear power (from any western European country due to the highly meshed network centered on Belgium) whose carbon emissions are nil. Future policy design should therefore be careful to prevent such an undesirable inter temporal swapping.

The paper is organized as follow. In Section 2, we present the main features of the PV sector in Wallonia and we estimate the net present value of a PV installation. In Section 3, we describe our data and our empirical methodology. Our main results are presented and discussed in Section 4. We further illustrate the rebound effect by performing panel econometrics in Section 5. Finally, section 6 concludes. In Appendix 6, we develop a theoretical model to discuss the income effect and the zero-marginal price effect associated with solar panels.

2 Photovoltaic development in Wallonia

2.1 Public support to rooftop PV

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

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

[6] In 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.

and after PV installation. Such a strategy is impossible for the ensuing *Qualiwatt* scheme. As a support scheme for small scale PV installations, *Solwatt* relies on a tradable green certificates (TGC) mechanism: each MWh of electricity produced from a renewable source is entitled a 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 must comply with a renewables portfolio standard (RPS) whereby a given percentage of their electricity must be certified from renewable sources. 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 was 1 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 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, replaced by *Qualiwatt* whereby new PV installations were no longer eligible for TGC but received a fixed premium per installed kWp to guarantee the return on investment. Installations made during the *Solwatt* period continue to receive TGCs, as specified in Table 1, after the fading out of the mechanism in 2014.

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

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

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 $\hat{q} = q - k$, the difference between electricity consumption q and production k. It is however of the utmost importance to note that in Wallonia, whenever total PV production exceeds total consumption over the billing period ($k > q$ or $\hat{q} < 0$), no payment accrues to the consumer; the registered consumption used for the bill 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 $\hat{q} < 0$, the consumer's bill is almost zero. This also implies that, whenever $\hat{q} < 0$, the excess production is supplied freely to the grid. Therefore, this excessive production can be consumed by the households at no cost.

2.2 PV deployment in Wallonia

After 2008, the number of PV installations in Wallonia increased dramatically as shown on Figure 1. Starting from virtually zero installations in 2007, there were 133 000 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* alternative. After the end of *Solwatt*, the number of new installations was considerably reduced, with 4 200 and 6 000 new PV installations in 2015 and 2016 respectively, far from the 48 000 new installations registered in 2012.

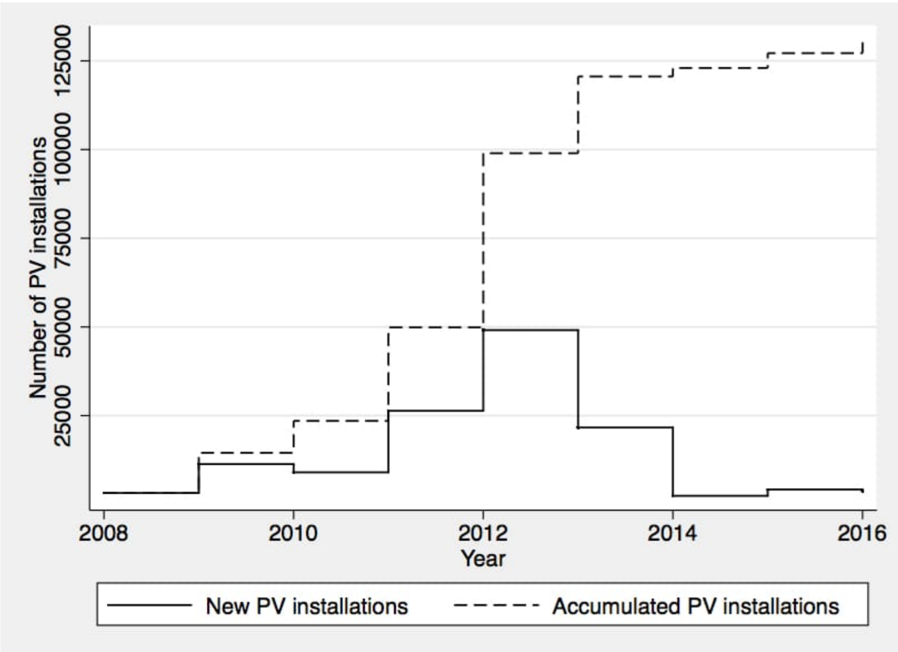

Figure 1: PV installations in Wallonia, 2008-2016

2.3 Net present value of a PV installation

In this section, we estimate the net present value (NPV) of a photovoltaic installation in Wallonia when supported by the *Solwatt* program.

2.3.1 Capacity Factor β

We first need a precise estimation of the solar panels electricity production for a typical Walloon household. For that task, we construct a monthly capacity factor β_m using two sources. The first

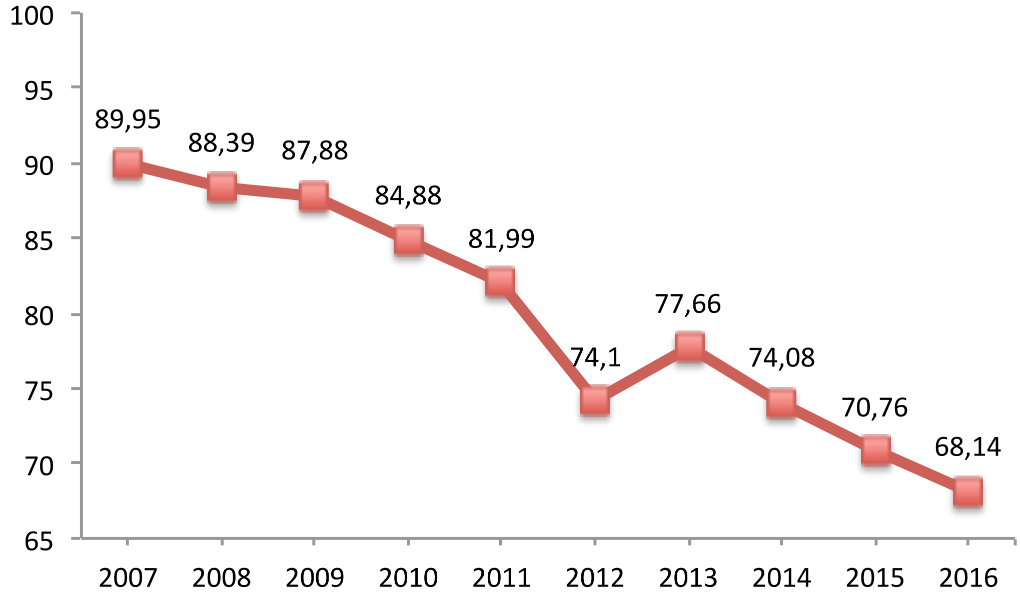

Figure 2: Price of green certificate, 2007-2016

and most reliable 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 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 inso far as the photovoltaic power potential is sufficiently uniform across the Walloon region. The irradiation map displayed on the left panel of Figure 3 shows a large variation across north and south of Europe with Wallonia at the southern tip of Belgium, squeezed 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.

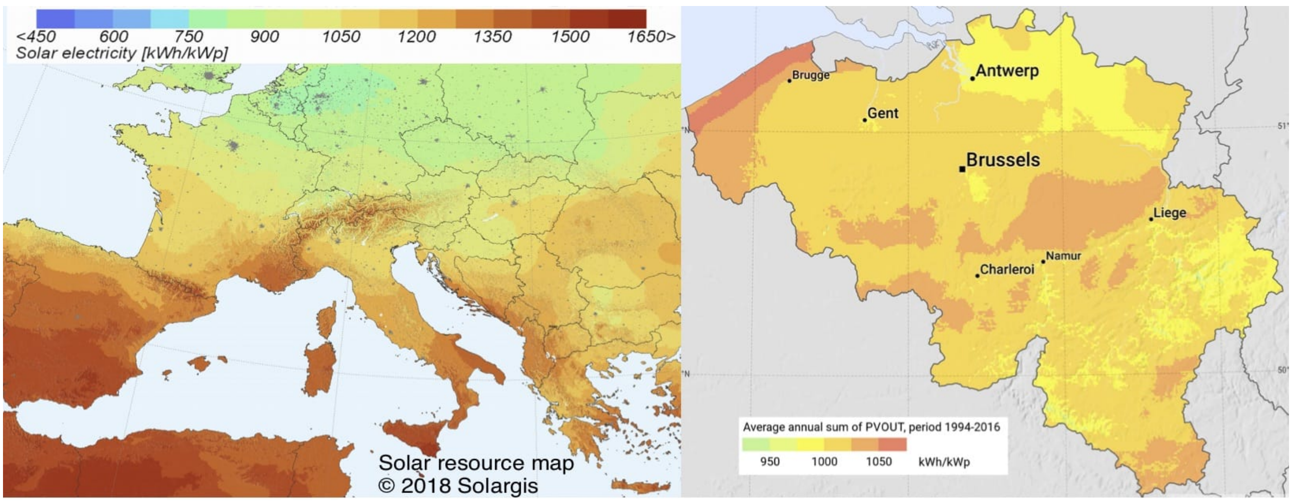

Figure 3: Photovoltaic power potential in Europe & Belgium

Prior to 2012, we use the "daily sunny time" 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 capacity factor series is shown on Figure 4. 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 solar rooftop panels. The average capacity factors for each year are reported in Table 2.

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 Capacity Factor in Wallonia

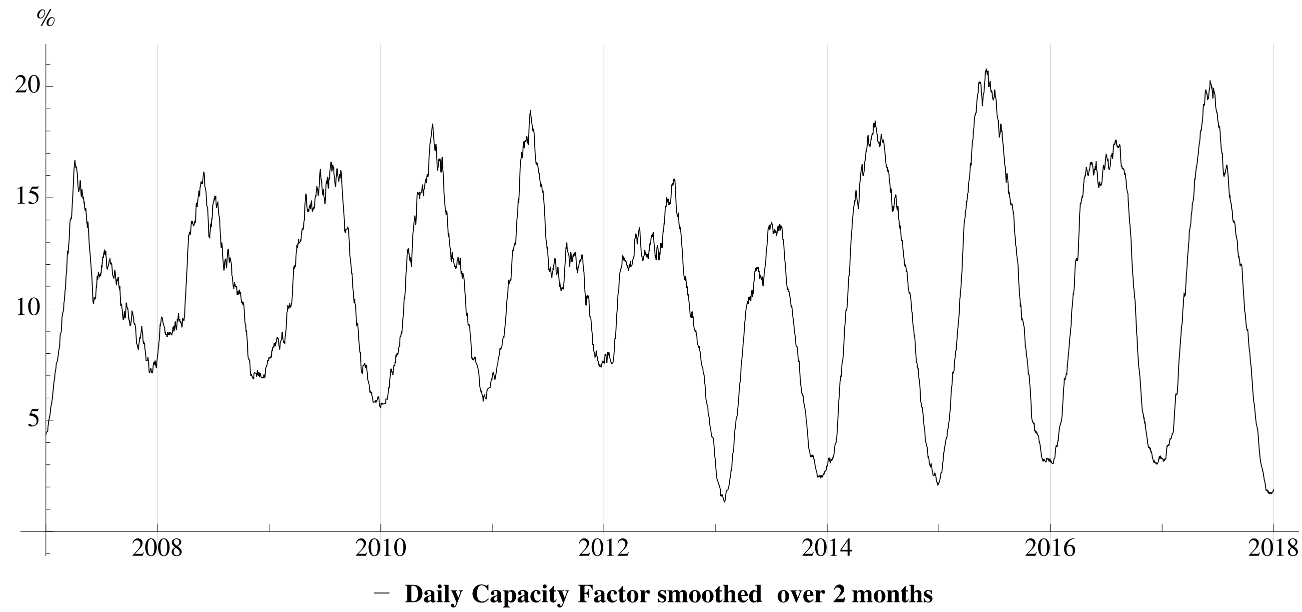

Figure 4: Daily capacity factor β_m, fitted values

One may object that the actual production of a PV installation could 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 issue threatens the validity of our study. Firstly, as we mainly record consumption for no more than two years after the PV installation, panels are still new and well functioning. Furthermore, the panels benefit from a two year compulsory guarantee from the installer. Second, differences between a south and a south-east orientation will change the production by at most 5% (for a 35° roof inclination). 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. 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.

2.3.2 Net present values

An installation benefiting from the *Solwatt* mechanism will be granted TGCs 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 β and applying a loss of power of 0.5% per year. From that, we compute the corresponding TGC endowment and we estimate its value. We provide three estimations based on three different TGC prices: the low one is based on a constant TGC price equal to the price floor of 65 €, the medium one is based on the true market price for the TGC up to 2016 and on the price floor for 2017 onwards; lastly, the high estimate is based on a constant price equal to the TGC price at the installation date. To compute the NPV, we use an interest rate of 3%.[7] We compare the NPV of the TGC endowment with the system PV module price computed by the IEA for Belgium (IEA, 2015).[8] The NPV and cost shown in Table 3 are both expressed in € per Wp.

Year	Program	NPV TGC (€/Wp)			Cost (€/Wp)
		low	med	high	
2008	Solwatt 1	4.88	5.85	6.98	5.8
2009	Solwatt 1	4.88	5.46	6.93	5.2
2010	Solwatt 1	4.88	5.34	6.70	4.2
2011	Solwatt 1	4.88	5.22	6.47	3.4
2012	Solwatt 3	3.02	3.23	3.73	2.7
2013	Solwatt 5	0.75	0.79	0.97	2.3

Table 3: Net present value of green certificates

We observe that from 2008 to 2012, the support provided by the TGC mechanism clearly exceeds the installation cost which implies that solar PV installations were a source of net income for the household. For the year 2013, the support of the TGC is in itself insufficient to make the installation profitable. However, households also benefit from the meter running backwards. Taking

[7] 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.

[8] 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.

a retail price in the range of [0.15-0.25] €/kWh, the NPV of the net metering, based on the same parameters as above, is in the range of [1.98-3.31] €/Wp. Once this additional revenue is taken into account, the investment in solar PV is again profitable under all the different versions of the *Solwatt* program.

3 Empirical Strategy

3.1 Data Source and Description

The 262 municipalities of Wallonia are serviced by 7 distinct DSOs. The largest one ORES, covering 191 municipalities, derives from the merger of seven smaller DSOs and maintains the distinct tariffs of the pre-merger zones which involve substantial differences. The areas of Wallonia where ORES distribute electricity are shown on Figure 5.

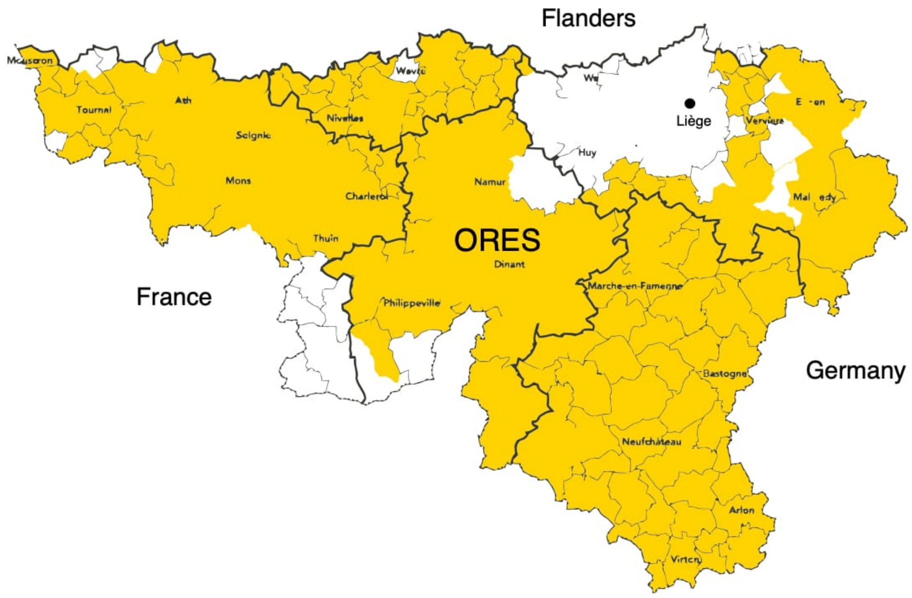

Figure 5: Areas of Wallonia covered by ORES

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. For each anonymized EAN in the ORES distribution zone, we collect location (zip code), the yearly meter readings (meter index and reading date) from 2010 to 2017, the PV installation date and the effective power of the PV modules (kWp).[9] Our dataset contains close to 100 000 EANs. The meters used are mostly mechanical (able to return to zero) and read about once a year, making it impossible to obtain a more granular information. Meter reading, used for billing, is performed either by a representative of the DSO or by the client and transmitted by mail, phone or online to the DSO. Clearly, some readings are erroneous, forcing us to apply an error detection algorithm.

[9]The effective power is the minimum of the inverter power and the panel power in case they differ.

There are different types of meters in use: the single meter (most common), 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 on weekdays) and the consumption during the off-peak period (outside peak) with different rates for the two periods. Net metering applies to both dual meters.[10] 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.

3.2 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.[11] For households equipped with a day/night 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.

Over a billing period going from t_1 to t_2, the EAN is billed for the B kWh read on his meter. Whenever the PV installation date τ is prior to t_2, we know that local electricity production k starts offsetting household consumption so that the meter only records net imports $q-k$. 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. 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 β_t is the previously estimated daily PV capacity factor. The total consumption over the period is then $Q = B + D$. Recall that net metering makes the consumption decision at every moment completely independent of how much is being produced on the house roof at that same moment since the distribution network acts as a giant battery.

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

[10] If a 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.

[11] We control for meter moving back to zero after a complete revolution since they have either 5 or 6 digits.

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 6 with one randomly chosen (true) household.

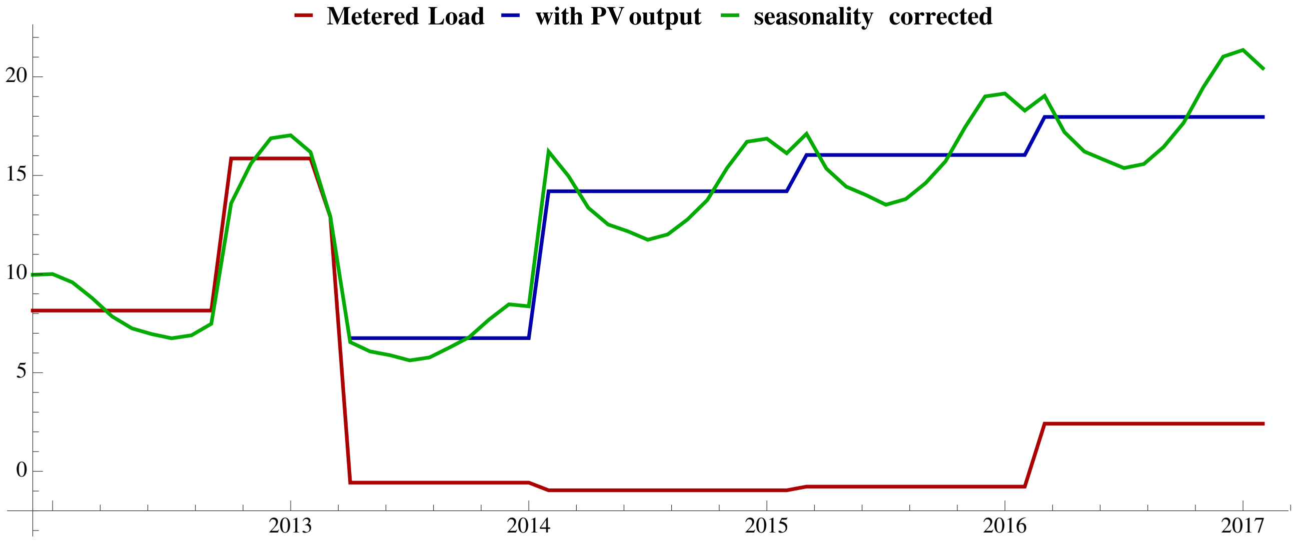

Figure 6: Reconstructed Household Load Curve including PV output

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. 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). Using this reconstruction procedure, we obtain for each billing period and each household an average daily consumption.

4 Estimating the Solar Rebound Effect

4.1 Income and zero-marginal price effects

Our econometric test of a solar rebound effect builds on a formal model of household behavior developed in the appendix. In this model, households optimize their PV investment, their consumption of energy and a composite good. We identify two channels for a rebound effect. The first is an income effect as the TGC provides an additional net income to PV owners. As long as energy is a normal good, we should observe an increase in electricity consumption for PV owners. The second channel comes from a zero-price effect. Indeed, the generous support offered by the *Solwatt* program motivates households to oversize their installation beyond their need (on a yearly consumption basis), since the cost of the PV was covered by the TGC. Once, a household possesses a PV module producing more than what it consumes, the excess production is available to consumption for free. Households with an oversized installation are thus exposed to zero price electricity. We expect these households to consume some of this free electricity. Our objective is to test this conjecture.

4.2 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 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 remained entitled, even if the connection date was posterior. Accounting for the delay between the ordering of solar panels and the connection date, we select all the installations with a connection date ranging from January 2008 to April 2014. At any rate, there were few installations in 2014 (see Figure 1) as the end of the program was largely anticipated. For each EAN, we estimate the consumption over 2 years *prior* to the PV installation, taking place at date τ, and a *posteriori* for 2 years: $\underline{q} = \frac{1}{24}\sum_{t=\tau-24}^{\tau-1} q_t$ and $\overline{q} = \frac{1}{24}\sum_{t=\tau}^{\tau+23} q_t$. Our sample contains over 65 000 observations for which we were able to estimate both $\underline{q}$ and $\overline{q}$.

To disentangle the income and the zero-marginal price effects, we split our sample in two groups. We construct a group of *undersized* installations in which the installation capacity is insufficient to cover the past consumptions (for $t < \tau$, $q_t \leq k_t$) and a group of *oversized* installations that have a larger capacity than their past consumption (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 looking at the two quartiles and the median.

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 7, we plot the daily consumption before and after for each individual observation i.e. the ratio $\overline{q}/\underline{q}$. If an observation lies above (below) the 45° line, the consumption increases (decreases) after the PV installation. In the oversized

Quantile	25%	25%	50%	50%	75%	75%
PV installation	Before	After	Before	After	Before	After
Full Sample	9.0	10.4	13.0	14.3	18.8	20.7
Undersized	14.0	13.	18.4	17.8	27.1	26.7
Oversized	6.9	9.0	9.7	12.0	12.5	16.5

Table 4: Daily consumption (kWh)

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.

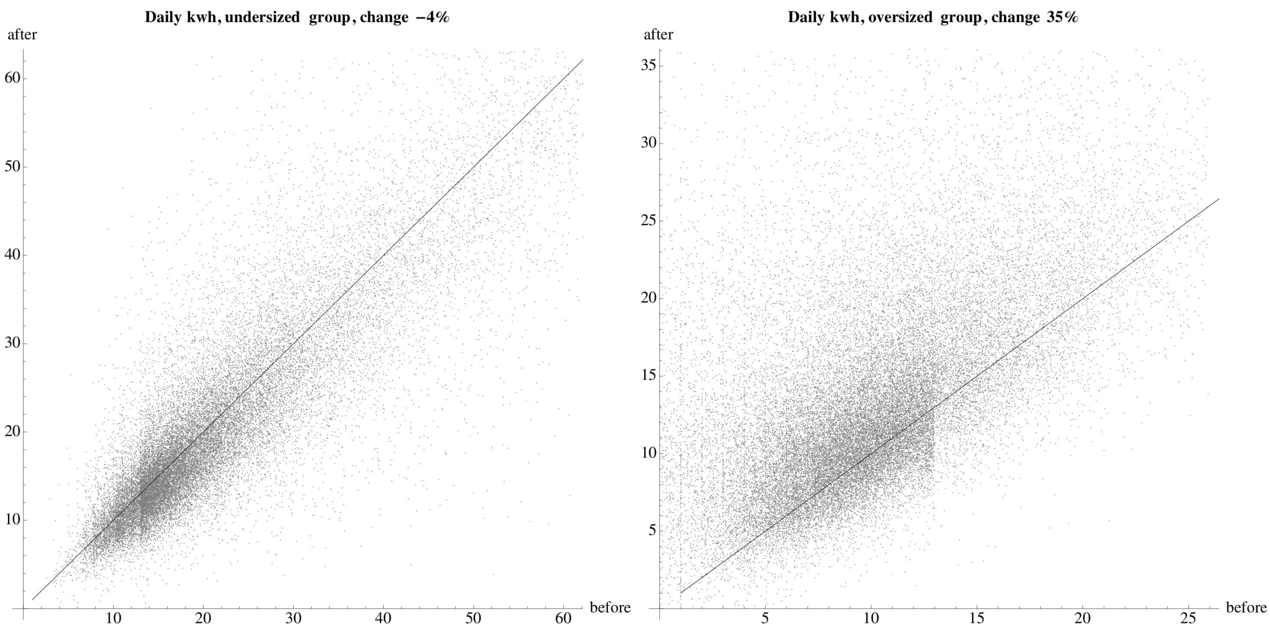

Figure 7: Consumption before and after PV installation

To further illustrate the change of behavior after solar panels have been installed, we write $\frac{\overline{q}}{\underline{q}} = \frac{k}{\underline{q}} \times \frac{\overline{q}}{k}$ 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 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 (really) needs and if $\frac{\overline{q}}{k} = 0.9$, it consumes 90% of its production. These figures imply that, for this household, $\frac{\overline{q}}{\underline{q}} = 1.17$ i.e. consumption increases by 17% after the PV installation.

On Figure 8, we sort our sample of 65 000 households along variable $\frac{k}{\underline{q}}$ 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. Absent any rebound effect, we should have a curve given by the inverse function as, for a constant consumption ($\overline{q} = \underline{q}$), the ratio $\frac{\overline{q}}{k}$ is the inverse of $\frac{k}{\underline{q}}$. On the figure, oversized households appear to the right of 100 (by construction) 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 the potential green electricity onto the Belgian grid.

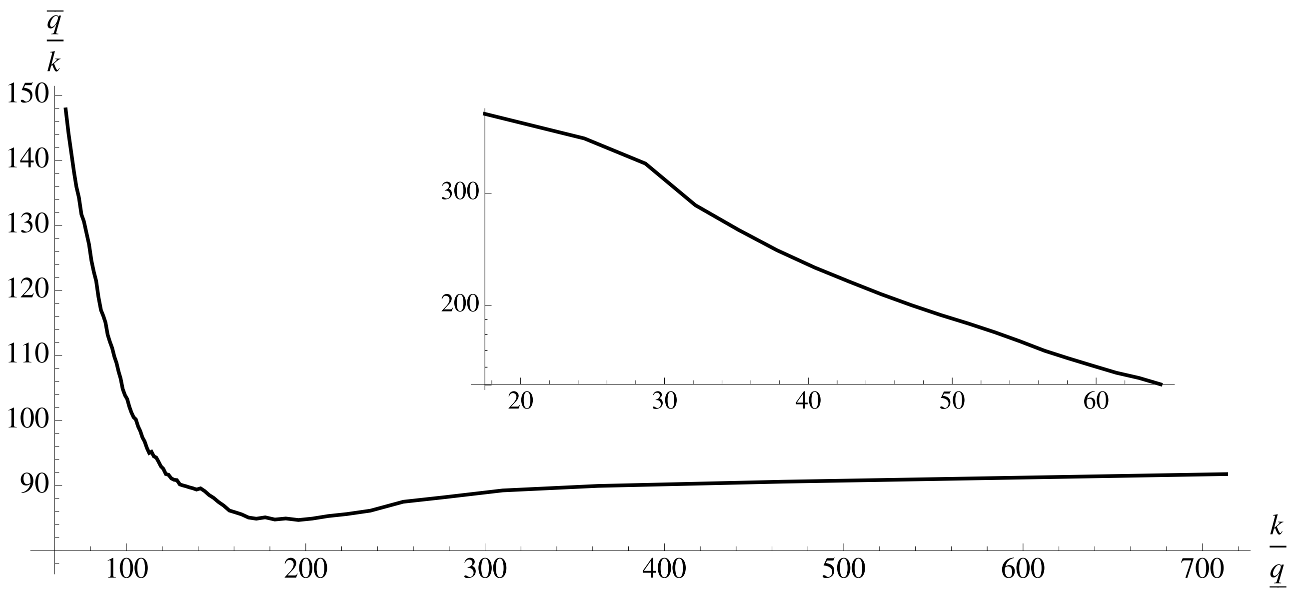

Figure 8: Consumption before/after, oversized group

4.3 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 τ (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 τ as temperature is an important driver of electricity consumption. For that, we construct the monthly average temperature ζ_t 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 τ 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 65 638 observations with a R^2 of 23%. Results are reported in Table 5.

Variable	Estimate	Standard Error	t-Statistic	P-Value
α	0.977	0.17	5.737	10^{-9}
Tariff	-0.136	0.018	-7.391	10^{-13}
$\tilde{k}$	-0.026	0.005	-5.198	10^{-7}
θ	0.869	0.007	130.74	10^{-330}
$\Delta\zeta$	1.111	0.067	16.483	10^{-61}

Table 5: Estimation Results

According to 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 in our data. 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 θ, the coefficient found is quite large. Our estimation shows that an additional daily production of 1 kWh *of free electricity* is consumed by the producing household at an 87% rate. Only a small fraction (13%) is supplied to the network. We have therefore characterized an extremely substantial rebound effect for households who have oversized their installation. This behavior is driven by the zero-marginal price effect.

We have implicitly argued that Walloon households invested into PV either to partake in the ecological transition or take advantage of the generous subsidies; once PV is producing, prosumers are frequently faced with a zero electricity price and thus logically consume more of this normal good. But since households are not randomly allocated into the PV/no-PV groups, we must also consider other motives that could reverse the underlying causality. Some households might be hit by a positive electricity demand shock such as the arrival of a new person in the house, the acquisition of an energy hungry appliance, an expansion of the building or the start of a commercial activity. Whenever this happens (during our study period), the household anticipates a steep bill rise and may decide to invest into subsidized PV to reduce his overall charge. He will size the PV system approximatively to meet his new additional future consumption (if roof and legal limits permit). Under this alternative motive for PV installation, the post PV installation yearly consumption of electricity ought to rise by the entire PV generation. Checking for this possibility in our 70 000 sample, solely 4.5% of our sample has increased load in such a manner. We may thus conclude that for an overwhelming majority of Walloon households, the appearance of zero-cost electricity was an unexpected by-product of their decision to invest into PV, not the driver of their original decision. The panel estimation further confirms that there is a specific time trend for households installing oversized installations and we observe a progressive increase in consumption after the installation of solar PV.

5 Panel Estimation

In the previous section, we compared the consumption of a prosumer before and after the PV installation over a time frame of 24 months; we identified a strong zero-price effect whereby households oversize their installation to benefit from the generous subsidies and then consume most of their production, leading to a substantial increase in consumption. Causality might, however, be reversed with households oversizing their installations in order to consume more, for instance to buy an electric vehicle (EV), instal air conditioning or a heat pump (both hypothesis being illustrative of a rebound effect). In this section, we investigate this question further by way of a panel estimation to identify specific trends in consumptions for some group of prosumers.

Our quasi exhaustive sample contains the yearly meter reading of about 90 000 households over 7 years. As previously explained, we reconstruct their average consumption per billing period. We may thus use a panel estimation to explain their consumption while taking into account unobserved individual differences (heterogeneity). To allow a precise estimation of explanatory variables, the billing date is recorded as a month so that our panel becomes strongly unbalanced. The panel model is

$$q_{it} = \alpha + \beta^{\intercal} x_{it} + \epsilon_{it} \tag{2}$$

The dependent variable q_{it} is the electricity consumption of household i at date t, expressed in kWh per month. The vector of observed variables x_{it} contains information about the PV installation, the subsidy program, and at the municipal level income, population density and electricity tariff. In particular, we use the following variables. A time trend (**month**) capturing the long term evolution of consumption; variable **pvsize** measuring the capacity of the PV installation is scaled in kWh/month instead of kWp for comparability with q_{it}, variable **subsidy** distinguishes between the various stages of the support programs. For installations undertaken during the *Solwatt* period, the variable subsidy is equal to the number of TGC granted (see Table 1). For those undertaken during the *Qualiwatt* period, the variable subsidy is equal to zero. We expect a significant income effect to yield positive coefficients for both **pvsize** and **subsidy**. Variable **oversize** is a dummy variable equal to one if the installation is oversized. We interact this dummy variable with the time trend to capture a specific time trend for prosumers with an oversized installation: **free_elec** = **month**×**oversized** (thus zero prior to the PV installation). We expect a positive coefficient for this free electricity variable since owners of an oversized installation should increase consumption over time as they realize they have freely available electricity. Variable **tariff** is the average distribution tariff in cents per kWh for the corresponding zone (GRD). We expect the coefficient for this variable to be negative as a higher price tends to depress demand. Finally, 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: Sample Descriptive Statistics

We use three different estimation techniques. The robust least squares estimator for model (2) is shown in the first column (pool) of Table 7. The fixed effects model amounts to specify a different constant α_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 this latter model. The Breusch–Pagan test for random effects yields an extremely large value that far exceeds the critical value for any reasonable significance level. We 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. Energy savings and more efficient energy appliances explain this declining trend which is also observed at a more aggregated level. The coefficient for **pvsize** is positive and significant: households with larger PV systems tend to consume more, corroborating 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 from the most generous subsidy scheme do not consume more for a given PV size. The coefficient for **oversized** is negative: households who oversize their PV installation consume less than those who don't but this is because they belong to the smaller consumer group. Interestingly, the positive coefficient for **free_elec** 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. Finally, the coefficient for **tariff** has the expected negative sign: consumption increases with the mean income in the municipality while the negative **density** coefficient indicates it decreases with population density.

6 Concluding remarks

In this paper, we test the existence of a rebound effect for solar PV installations in a specific institutional context, combining generous support to production and net metering. In Wallonia, the *Solwatt* supporting scheme for small-scale residential PV production turned out to be so generous that many rational households found it profitable to oversize their installation as the support of the TGC already covered the module installation cost. This combined with net metering offered these investors an opportunity for consuming "free" electricity, whenever their oversized installations generated in excess of their usual needs (over a year). Our empirical evidences demonstrates that this phenomenon took place on a massive scale and that oversized PV households consumed almost entirely their free energy surplus. There are thus strong evidence of a significant rebound in consumption associated with the adoption of solar PV.

We take this rebound to be a direct consequence of the wrongly 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. Furthermore, the instrument may not be the most appropriate supporting scheme as households 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 energy consumption by prosumers. Regulators and the government should always remember that consumers react strongly to powerful financial incentives, in a manner that is perfectly consistent with rational behavior.

Another policy implication of the net metering system is that households rarely auto-consume their excessive production when the billing period is so long (cf. Gautier et al. (2018)). As the meter is running backwards, excessive production can be stored on the grid for free 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 to periods where it is produced at a higher cost using carbon-intensive generators is certainly not environmentally friendly. Evidence collected from a survey among prosumers in Wallonia by Gautier et al. (2019) suggests that heating is the preferred vector for increasing consumption. However, with mechanic meters recorded every year, it is not possible to measure load displacement and we can only document an aggregate increase in consumption. By contrast, the evidence provided by Qiu et al. (2019) based on daily meter recording show that prosumers increase their consumption when their production increases i.e they increase their auto-consumption (possibly because the star meter reduces the window of opportunity for deferred consumption).

Finally, when computing the carbon impact of solar PV, one should take this important rebound effect into account. Indeed, the additional consumption is partially substituting other energy vectors. Electric heating and heat pumps replace fuel or gas heating, electric mobility replaces internal combustion engines, etc. However, this work cannot be done with the data currently collected by the DSO as we have only information about the yearly consumption. We hope to be able to develop a sample of closely monitored households to perform this study in the future.

Appendix

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 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
- ρ: PV module price in €/kWp
- β: the capacity factor of a typical PV installation

- k: production of the PV installation in kWh, with

$$k = \beta\tilde{k} \tag{3}$$

- η: subsidy for PV production in €/kWh
- q: consumption measured in kWh
- $\hat{q}$: registered (net) consumption in kWh, with

$$\hat{q} = q - k \tag{4}$$

- 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
- $\bar{k}$: 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

$$\max_{q,z,k} u(q,z) \tag{5}$$

$$z + p\max[0,\hat{q}] + \rho\tilde{k} \leq w + \eta k, \tag{6}$$

$$\tilde{k} \leq \min[\bar{r},\bar{k}] \tag{7}$$

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:

$$\frac{u_q(q_0,z_0)}{u_z(q_0,z_0)} = p, \tag{8}$$

$$z_0 = w - q_0 p. \tag{9}$$

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: $\tilde{k}_1 = \min[\bar{r}, \bar{k}]$. 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:

$$\frac{u_q(k^*, w^*)}{u_z(k^*, w^*)} = p, \tag{10}$$

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 $\tilde{k}_1 = \min[\bar{r}, \bar{k}]$ 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 **income effect** when $\tilde{k}_1 \leq \tilde{k}^*$ and both an income and a **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 Δw to the prosumers, arising from the PV subsidy. Suppose that $\hat{q} \geq 0$, this extra income is equal to:

$$\Delta w = \tilde{k}_1(\beta\eta - \rho) + pk_1. \tag{11}$$

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 $w + \Delta w$:

$$\max_{q,z} u(q, z) \tag{12}$$

$$z + pq \leq w + \Delta w. \tag{13}$$

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

$$\frac{u_q(\bar{q},\bar{z})}{u_z(\bar{q},\bar{z})} = p, \tag{14}$$

$$z = w + \Delta w - p\bar{q} \tag{15}$$

It is easy to check that for $\tilde{k}_1 \leq k^*$, the solutions $(\bar{q}, \bar{z})$ and (q_2, z_2) are identical. We therefore measure the income effect by the differences in consumption $(\bar{q} - q_0)$ and $(\bar{z} - z_0)$. 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 $(\bar{q}, \bar{z})$, the consumer has free electricity if $\bar{q} \leq k_1$, 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 $q_1 - \bar{q} \geq 0$ 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 $\bar{q} - q_0$. When $\tilde{k}_1 \geq k^*$, we have both an income effect $\bar{q} - q_0$ and a zero marginal price effect $q_1 - \bar{q}$. 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.

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

$$\max_{q,z,k} u(q,z) \tag{16}$$

$$z + p\hat{q} + \rho\tilde{k} \leq w + \eta k, \tag{17}$$

$$\tilde{k} \leq \min[\frac{q}{\beta}, \bar{r}, \bar{k}] \tag{18}$$

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 (18). 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.

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