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DISSERTATION

BEYOND SAVINGS: UNCOVERING THE SOLAR REBOUND EFFECT ACROSS ENERGY-MONITORED PORTUGUESE HOUSEHOLDS

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"The sun, with all those planets revolving around it and dependent on it, can still ripen a bunch of grapes as if it had nothing else in the universe to do."

- Galileo Galilei

GLOSSARY

DGEG – Direção-Geral de Energia e Geologia

EU – European Union

FiT – Feed-in Tariffs

GHG – Greenhouse Gases

LCOE – Levelized Cost of Electricity

OLS – Ordinary Least Squares.

PAE+S – Programa de Apoio Edifícios + Sustentáveis

PV – Photovoltaic

RE – Rebound Effect

RES – Renewable Energy Sources

RMSE – Root Mean Square Error

SE – Standard Error

SRE – Solar Rebound Effect

VAT – Value-added Tax

ABSTRACT, KEYWORDS AND JEL CODES

Climate change and geopolitics are changing the paradigm of the energy systems towards Renewable Energy Sources. Particularly, photovoltaic systems are fast to roll out and have shown reducing costs, making it a fast-growing source of renewable energy. However, residential PV systems come with a drawback: the Solar Rebound Effect (SRE).

This empirical study analyzed a panel data from a sample of 640 Portuguese energy-monitored households for the year 2024 that originates from a large energy provider in Portugal. The findings reveal an average increase of 1.7% on Energy Consumed per additional 1 kWh produced by photovoltaics. However, different regions, registration maturity and consumption levels exhibit heterogeneity, raising the results up to a 6.2% increase.

The implications of these results extend beyond the household consumption behavior, affecting energy policy, grid operators and long-term planning of the energetic system. Policy makers should account for benefit losses on incentives and should account for the SRE on the planning of the energy systems. Moreover, providers might experience both tangible and intangible losses as a secondary consequence of household dissatisfaction due to diminished financial returns of PV systems.

Keywords: Energy Policy, Renewable Energy, Rebound Effect, Energy Economics

JEL Codes: D12, Q41, Q42

As alterações climáticas e a geopolítica estão a mudar o paradigma dos sistemas energéticos para as fontes de energia renovável. Em particular, os sistemas fotovoltaicos são rápidos de implementar e têm tido custos decrescentes, fazendo destes uma fonte de energia renovável de rápido crescimento. Contudo, os sistemas fotovoltaicos residenciais têm uma desvantagem: o Efeito de *Rebound* Solar.

Este estudo empírico analisou dados de painel de uma amostra de 640 casas portuguesas com monitorização de energia no ano de 2024 com origem num grande comercializador de energia português. Os resultados revelam um incremento médio de 1.7% na energia consumida por cada 1 kWh adicional produzido pelos sistemas fotovoltaicos. Contudo, diferentes regiões, maturidade de registo e níveis de consumo mostram heterogeneidade, elevando estes resultados até ao incremento de 6.2%.

As implicações destes resultados vão além do comportamento de consumo das próprias casas, afetando a política energética, operadores de rede e o planeamento de longo prazo do sistema energético. Os decisores políticos devem considerar perdas nos benefícios dos incentivos e considerar o efeito no planeamento dos sistemas energéticos. Além disso, os comercializadores podem sofrer perdas tangíveis e intangíveis como consequência da insatisfação dos utilizadores residenciais devido aos menores retornos financeiros dos sistemas fotovoltaicos.

Palavras-Chave: Política Energética, Energias Renováveis, Efeito Rebound, Economia da Energia

Códigos JEL: D12, Q41, Q42

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BEYOND SAVINGS: UNCOVERING THE SOLAR REBOUND EFFECT ACROSS ENERGY-MONITORED PORTUGUESE HOUSEHOLDS

By Miguel D. Cardoso

1. Introduction

Climate change, along with countries' increasing strategic interest in achieving energetic autonomy and reducing reliance on foreign nations, is driving an energy transition towards electrification and both increased investment and weight of renewable energy sources (RES) in the energy mix. While RES still represent a small percentage of the global energy production supply (12% in 2023), the adoption rate has been rising sharply, with clean energy growth outpacing that of fossil fuels by a ratio of two-to-one since 2019. (International Energy Agency, 2024) At the European Union level, the efforts have intensified with the release of the REPowerEU program, which aims for 45% renewable energy uptake and nearly 600 GW solar photovoltaic (PV) capacity by 2030.

While the large-scale integration of intermittent RES may help reduce Greenhouse Gas (GHG) Emissions, and has zero marginal-cost of generation, it also comes with significant challenges for our energy systems and market operations, such as increased variability, lower market values, stranded costs and, in the specific case of distributed rooftop PV generation, an induced Solar Rebound Effect (SRE). (Henriot & Glachant, 2013)

The S*olar Rebound Effect* is a behavioral phenomenon in which residential customers change their consumption patterns following the installation of a PV system, increasing the total energy consumption due to the lower average energy costs. Such an effect distorts the investment returns, financial and environmental benefits, and effectiveness of solar PV incentives, as an increased supply does not induce full substitution between PV and grid energy. In fact, it is estimated that there can be up to 30% of counterfactual reduction of solar generation, offset by increased consumption. (Aydın et al., 2023; Boccard & Gautier, 2021; Oliver, 2023)

While significant evidence has been found regarding the existence of SRE, no literature was found for Portugal or the Iberian Region. For a region with high solar irradiance and sunrise hours, and a solar capacity installed of 5.6 GW in 2024, an estimate of such an effect is crucial for policy makers, investors, and clients. (DGEG, 2024)

In fact, understanding the full extent of the impacts driven by the ongoing energy transition is essential to guide our energy policy. Therefore, this thesis aims to address that gap by focusing on the research question “How does the Solar Rebound Effect (SRE) impact residential energy consumption patterns in Portugal?”.

The present study empirically analyzes the consumption and production patterns of a sample of 640 households provided by a large electricity supplier over the course of one year. We start by reviewing current literature on Chapter 2, after which Chapter 3 will describe the model and theoretical framework; we then describe the data used in Chapter 4 and discuss the results on Chapter 5, with final considerations on Chapter 6.

2. LITERATURE REVIEW

2.1. Photovoltaic development in Portugal

Portugal has seen substantial growth in renewable energies in the last decade, achieving an impressing share of 76,2% of RES on the electricity production mix in 2024, according to DGEG (2024). While photovoltaics still only constitutes around 16% of the RES production, it has exhibited rapid expansion, particularly in the residential and commercial sectors, with the distributed PV installed capacity growing over 500% only over the course of the last 5 years. (DGEG, 2024) FIGURE 1 shows the evolution of the decentralized PV capacity and production in Portugal over the last years.

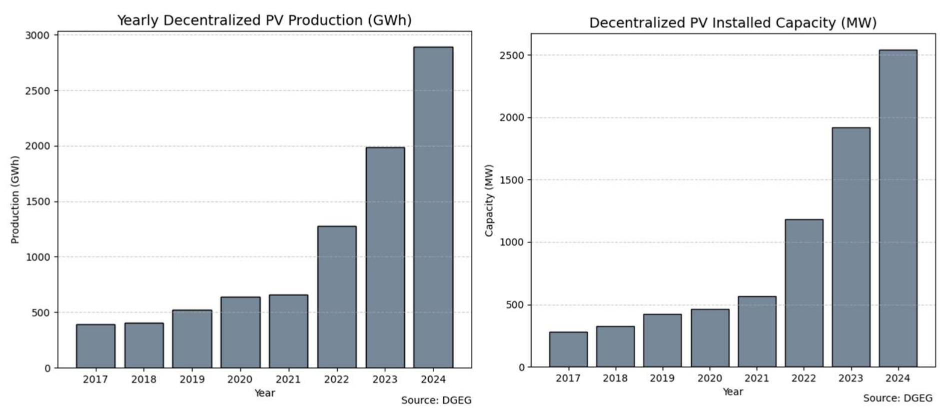

FIGURE 1 – Yearly electricity production, in GWh, and installed capacity, in MW, of decentralized photovoltaic energy for Portugal (2017-2024)

High sunlight availability hours and privileged geographical positioning, associated with the declining costs of installation and ownership, added to relevant public incentives, set Portugal as a promising market for rooftop PV systems development and enhance its economic attractiveness. (Obi & Bass, 2016)

The subsidies and incentives for the adoption of these technologies, such as *Programa de Apoio Edifícios + Sustentáveis (PAE+S)* or *Vale Eficiência* have fostered the adoption of rooftop PV systems, in line with the country and European Union's strategic objectives for carbon emission reduction and energy autonomy. In terms of fiscal policy instruments, a reduced Value-Added Tax (VAT) rate of 6% was applied for the acquisition of PV systems, instead of the general 23% level, but this incentive was discontinued in July 2025.

Primary motivations for "prosumers" – a term often used to designate consumers who are also producers – to adopt household PV systems include savings on the electricity bill and environmental concerns. Most PV systems have the capacity to be integrated with the electric grid, allowing owners to sell excess output to the grid and being remunerated for that generation by signing a contract with the supplier of last resort or with another supplier on the free market. Another option is the storage of surplus energy for usage in non-solar hours, but this requires the acquisition of a battery system, which can still have significant costs. (Camilo et al., 2017; Camilo & Santos, 2023; Vasseur & Kemp, 2015)

A different type of compensation for injected energy is net-metering, where the household is "credited" for the energy injected to the grid during the time that production exceeds the household consumption. These credits can then be used for later electricity consumption from the grid when production is not enough to supply the house's energy demand, meaning that the customer is only billed for the net electricity usage. While this trade is essentially purely electrical, as no actual remunerations nor payments take place for energy injected, such a scheme allows for a virtual valorization of surplus electricity at the complete retail rate. (Camilo et al., 2017; Poullikkas, 2013)

Each country implements distinct net-metering schemes, reflecting different policy approaches and objectives. In some cases, these frameworks allow for payment to the prosumer when the amount of electricity exported to the grid exceeds the imported quantity. Other models, however, impose a "cap" at the end of each billing cycle. The policy design of the net-metering schemes can influence the economic attractiveness and financial viability of rooftop PV adoption, as well as its broader impact on household energy behavior. (Dufo-López & Bernal-Agustín, 2015; Watts et al., 2015)

2.2. The (Solar) Rebound Effect

First postulations of a "rebound effect" (RE) can be found as early as the 19th century with the so-called «Jevon's paradox». William Stanley Jevons' findings state that energy-efficiency improvements possibly increased energy consumption, instead of the expected reduction. Jevon observed such a phenomenon when an increase in efficiency of coal combustion resulted in increased coal consumption. (Jevons, 1866)

This effect has been defined as the phenomenon where an increase in energy efficiency results in an increase in demand and has been extensively studied in the literature. As a result, this increased consumption offsets part of the expected savings of reduced marginal costs. (Beppler et al., 2023; Berkhout et al., 2000).

But estimates for such effects depend on the boundaries defined, as the RE may manifest from three different mechanisms. Direct rebound effects occur when a particular energy service sees improvements in its energy efficiency, which decreases the effective price of that service, and consequently leads to an increase in consumption, offsetting the expected energy savings. Indirect effects manifest when the lower effective price of an energy service leads to changes in demand for other goods, services, and production factors that also require energy – for example, savings from a more efficient appliance, like a refrigerator, increases the purchasing power for a household, leading to greater spending elsewhere. (Sorrell & Dimitropoulos, 2008)

Lastly, these effects can be examined economy-wide, as a fall in the real price of energy services propagates throughout the value chain, decreasing the price of intermediate and final goods, which triggers price and quantity adjustments across the economy – naturally, such an effect can be observed in greater scale for energy-intensive goods and sectors. (Sorrell & Dimitropoulos, 2008) Specifically, this dissertation will focus on the direct solar rebound effects, on the microeconomic level, because while the indirect and economy-wide factors are important to comprehend the full extent of a rebound effect, they are difficult to study empirically, as they involve general equilibrium adjustments.

Significant evidence of a RE following the adoption of residential rooftop photovoltaic (PV) system – a Solar Rebound Effect - has been found, with counterfactual reduction estimates from 10-30%. (Oliver, 2023) This means that consumers could increase consumption by nearly one-third of the amount generated by their panels, instead of offsetting existing electricity consumption on a one-for-one basis with solar generation. While the 'rebound effect' is typically associated with changes in energy efficiency, the SRE is rather driven by a perception of PV generation as a zero-marginal-cost and zero-emission source of electricity. (Beppler et al., 2023)

Therefore, the solar rebound can be defined similarly, as the elasticity of electricity consumption with respect to an increase in PV output. However, in the case of energy-efficiency RE, both substitution and income effects are observed while in the solar rebound context the substitution effect is different and may not exist at all. This is because the energy-efficiency RE is based on the lower marginal cost of a specific good, while the solar generation reduces the marginal cost of usage for all electricity-using household goods and services. (Oliver et al., 2025)

Moreover, it appears that the observation of the SRE is somewhat delayed from the installation of the PV systems. Customers first observe drops in their electricity bills, and only then consumption increases, suggesting behavioral drivers relating to how people view solar electricity. (Beppler et al., 2023) This is consistent with Ito (2014)'s findings that consumers respond more strongly to a variation in the average price of electricity rather than the marginal price.

The SRE can be analyzed in the light of the classic household's constrained utility maximization problem: for a utility function $U(e, x)$, subject to the budget constraint $M = pe + x$, where p denotes the price of electricity e and x a numeraire with normalized price of 1. Acquiring a PV system translates into a decrease in electricity expenditure which, in turn, increases the attainable utility. If we assume that electricity is a normal good, then standard microeconomic theory states that a positive net effective change in income results in a non-negative change in total electricity consumption. This means that acquiring a PV system results in higher disposable income and, therefore, greater electricity consumption. (Beppler et al., 2023; Pellini, 2021)

Alongside the income effect, other behavioral drivers may come into play. For once, a moral licensing mechanism, where the act of acquiring a more eco-friendly source of energy "justifies" the increase in the consumption – a negative spillover, associated with the indirect rebound effect. On the other hand, there could be a co-adoption phenomenon, where the consumer adopts additional energy-intense technologies (e.g., heat pumps, electric vehicles, or air conditioning systems) that are perceived as more sustainable or economically viable when powered by self-generated solar electricity. (Dütschke et al., 2018; Palucci et al., 2024)

The psycho-behavioral explanations for the SRE are, however, outside of the scope for this study: we will study the economic and policy implications of the SRE regardless of whether such rebound effect derives from economic or psychological motivations.

Another factor that comes into play is the adequacy of the installation size: if a client adopts a system that generates more electricity than what the household consumes, then under a net-metering scheme these households face a marginal cost of zero, up to the point where their consumption is equal to their production. In cases where net-metering policies include a cap on the accumulation or rollover of credits, oversized installations would be producing "free" electricity, creating an incentive for increased consumption. (Boccard & Gautier, 2021)

The occurrence of the SRE appears to be limited to rooftop decentralized production, as utility-scale installations decouples the consumption decision from the supply of solar-generated electricity. Even though there are merit-order effects that may lower wholesale equilibrium prices of electricity, for both small- and utility-scale, the retail prices do not directly follow a decrease in wholesale electricity prices, due to quite complex Levelized Cost of Electricity (LCOE) determinants. Moreover, the net-metering scheme is only available for prosumers and an income effect is not expected to be observed at significant levels in the case of utility-scale. In addition, neither could we expect to observe other determinants such as moral licensing – as the consumer is not aware of the origin of their electricity – or co-adoption – which happens at the household level. (Oliver, 2023)

2.3. Policy and Implications

One of the primary motivations for incentives on distributed photovoltaic energy, like *Programa de Apoio Edifícios + Sustentáveis (PAE+S)* or *Vale Eficiência,* is to reduce Green House Gases emissions. However, the growing evidence on the SRE means that these policy efforts are getting offset by focusing on household systems and might need to be reevaluated to account for such effects. (Oliver, 2023)

While these programs are associated with subsidizing installation costs – for PAE+S it can reach 85%, excluding VAT -, Boccard & Gautier (2021) found that under a policy scheme where fixed costs are subsidized, consumers are induced to acquire oversized systems that exceed their energetic needs. Therefore, in the absence of any change in their consumption pattern, these households produce more solar electricity than they use, creating an incentive for higher consumption, and therefore eroding partly the environmental gains expected for these policies.

The SRE is closely linked to the specific design of net metering policies, as different schemes can either incentivize or hinder this effect. For instance, in schemes where excess generation credits are forfeited at the end of the billing cycle (i.e., a "zero cap" true-up), then a household is incentivized to maximize their consumption up to the production level, as it is perceived as virtually “free electricity”. The shorter the cycle, the stronger the incentive becomes, since the prosumer has a shorter time window for using such credits in future consumption. (Boccard & Gautier, 2021; Oliver et al., 2025)

If a prosumer does not follow a net-metering scheme, then the design of feed-in tariffs is of utmost importance: if the value of exporting electricity to the grid is unattractive, households then lack an incentive to do so and may increase consumption to try and match production. However, overly generous tariffs, combined with a lack of dynamic adjustments to the regulatory and policy framework that accounts for the various changing associated costs, can impose a positive net cost on the system, turning the FiT schemes unsustainable. (Pyrgou et al., 2016)

There is significant evidence on the inverse relationship between solar PV adoption and households with low annual incomes, meaning that if the policy designs do not address these economic barriers to accessing renewable technologies, then efforts to mitigate climate change could be hindered, and existing socioeconomic disparities may be exacerbated, reinforcing energy inequality. (Memtimin et al., 2025). Moreover, the SRE is associated with higher total system costs and higher wholesale electricity prices. Increased costs of the SRE therefore fall on the entire consumer base, implying regressive impacts from the SRE which further aggravates equity concerns. (Delic & Bucksteeg, 2025)

Policies oriented towards reducing carbon emissions need to accurately estimate the SRE, possibly redirecting subsidies and incentives towards utility-scale installations, as the SRE is a phenomenon specific to rooftop generation that offsets these intended benefits. Moreover, certain business models from energy companies involve covering the installation cost of PV systems, retaining ownership of the asset, while the prosumer pays for only for the generated and consumed electricity. For these private investors, there might be an increased incentive to redirect capital for utility-scale facilities, in order to maximize financial return by avoiding the SRE. (Oliver, 2023)

Because the deployment of PV requires high private capital investment, it is essential that Portugal maintains a high confidence level from stakeholders in the energy market, which should compel the government and institutions to thoroughly evaluate deployment and, especially, changes and removal of benefits and policies, as uncertainty may deter investors. (Figueiredo et al., 2019)

Most predictions for global energy consumption set the average annual growth rate to diminish in the medium term, but these scenarios may be imprecise if the SRE is not accounted for, since these projections consider the increased energy efficiency – which is offset by rebound effects of different natures – and electrification with increasing shares of RES. As a significant part of this growth is powered by distributed PV deployment, not considering the SRE may lead to underestimations. Forecasting energy demand adequately is essential for system planning and energy policy and is particularly crucial for grid operators and regulating agents. (International Energy Agency, 2024)

From a welfare perspective, the implications of the SRE are mixed and context-specific. Under certain conditions, when the marginal utility of increased electricity use exceeds the associated marginal external costs, the SRE can represent a net gain in welfare for households and society. If a solar PV system is operating in a clean electricity system and temperate climate, then the SRE can increase welfare; conversely, if these conditions are not observed, as if the same PV generation occurs in a coal-driven energy system with hot climate and dense population, it is likely to deliver welfare losses. Policy designs that ignore these welfare dynamics risk misrepresenting the true economic and social impacts of widespread PV deployment, particularly if they assume static or declining electricity demand. (Oliver et al., 2025)

A high level of distributed PV generation comes with its challenges for the power grid. In the short run, the inherent PV output uncertainty, combined with the SRE, may lead to uncertainty from both the demand and generation sides, thereby complicating load forecasting, which may be hardened if models do not account for the behavioral shifts linked to solar adoption. In the medium run, the grid operators and regulatory bodies must direct their investments towards making grids more reliant to the physical challenges posed by the interconnection of distributed generated systems; moreover, (inter)national policies on PV adoption must reflect adequate planning, which is only possible by accounting all effects, including the SRE. In the near future, several utilities and system operators may begin to enforce more stringent regulations regarding the inter-connection of PV systems with the grid. (Obi & Bass, 2016; Shafiullah et al., 2022)

While households decide to adopt solar panels for a variety of reasons, the main motivation is savings on the electricity bill, especially for later adopters. As the SRE offsets the expected reduction on electric consumption from the grid, it erodes the financial gains expected for such investments. Therefore, adopters must consider this effect to accurately evaluate the return on their investments, and retailers should include it in their estimates upon presenting their proposals and estimates in order to set realistic expectations. Unrealistic overestimations can lead to customer dissatisfaction, potentially turning adopters into detractors for the selling companies and the technology, ultimately deterring the deployment of residential photovoltaics. (Marikyan et al., 2023; Palm, 2020; Vasseur & Kemp, 2015)

3. Methodology

To estimate the SRE, our empirical strategy will be based on a panel data analysis of households' consumption and production levels over the year 2024 following the model

$$\ln e_{c_{t,i}} = \alpha + \beta_1 e_{p_{t,i}} + \beta_2 e_{p_{t-1,i}} + \beta_3 e_{p_{t-2,i}} + \delta_i + \gamma_t + \epsilon_{i,t}$$

where $e_{c_{t,i}}$ and $e_{p_{t,i}}$ denote Energy Consumed and Energy Produced at day t for household i, respectively. Because households may shift their consumption between days with higher solar irradiation, we introduce lagged variables $e_{p_{t-1,i}}$ and $e_{p_{t-2,i}}$. As this behaviour does not change overall household consumption, not taking into account such an effect could lead to an incorrect estimate of the SRE. (Aydın et al., 2023) Lastly, δ_i represents the household fixed effects, γ_t represents day-specific fixed effects, capturing house- and time-variant unobserved factors, respectively, and $\epsilon_{i,t}$ denotes the error term. As discussed in Chapter 2., our analysis will focus on the direct SRE at the household level, rather than indirect or economy-wide effects.

By deriving both sides of our model, it should be intuitive that:

$$(1) \qquad \frac{d \ln(e_c)}{d\, e_p} = \eta^{PV} = \beta_1 + \beta_2 + \beta_3$$

In this context, η^{PV} corresponds to the semi-elasticity of energy consumption with respect to Energy Produced. We also define the Solar Rebound Effect Coefficient (R) as:

$$(2) \qquad R = 1 + \eta^{PV}$$

Specifically, R is a measurement on the direction and intensity of the Rebound Effect and the factor of possible lost Energy Consumption savings due to PV output. For example, if η^{PV} is 0.1, then we expect Energy Consumed to increase by a factor of 1.1 per 1 kWh of Energy Produced:

$$(3) \qquad e_p + 1\ kWh \rightarrow (1 + \beta_1 + \beta_2 + \beta_3) e_c$$

$$(4) \qquad \Delta e_p = 1 \rightarrow \%\Delta e_c = 100 \times (\beta_1 + \beta_2 + \beta_3)\%$$

To build intuition for interpretation, we start by defining the concept of 'zero rebound': if Energy Consumption remains constant as Energy Production increases, then

$\eta^{PV} = 0$ and $R = 1$. For $R > 1$ or $\eta^{PV} > 0$, we observe a *Rebound Effect*, as Energy Consumption increases as a result of an increase in Energy Produced, thereby eroding the expected benefits of PV Energy Production. Conversely, in the case of $R < 1$ or $\eta^{PV} < 0$ we observe a '*super-conservation'* phenomenon that happens when Energy Produced actually induces a decrease in Energy Consumed.

While most of the literature on the SRE employs a specification with both consumption and production in absolute kWh terms, the present study adopts a model with a log-level specification. The motivation for this empirical strategy is two-folded: first, it helps to address heteroskedasticity and outlying observations which are to be expected in a large-scale set of household energy data; secondly, the functional form adopted appeared to be the best option to describe the available data. A log-log specification would not be suitable for this analysis as there are observations where $e_{p_{t,i}}$ is zero, corresponding to days where there was no Energy Produced for that household in that day.

In order to determine the Standard Error (SE) for η^{PV}, we observe that, by rearranging the terms of (1):

$$(5) \qquad \beta_1 = \eta^{PV} - \beta_2 - \beta_3$$

Therefore, our model can be rewritten as:

$$(6)\ \ln e_{c_{t,i}} = \alpha + (\eta^{PV} - \beta_2 - \beta_3)\, e_{p_{t,i}} + \beta_2 e_{p_{t-1,i}} + \beta_3 e_{p_{t-2,i}} + \delta_i + \gamma_t + \epsilon_{i,t} =$$
$$= \alpha + \eta^{PV}\, e_{p_{t,i}} + \beta_2\left(e_{p_{t-1,i}} - e_{p_{t,i}}\right) + \beta_3(e_{p_{t-2,i}} - e_{p_{t,i}}) + \delta_i + \gamma_t + \epsilon_{i,t}$$

This reparameterization allows us to obtain the SE for η^{PV} by conducting an auxiliary OLS regression. To address heteroskedasticity and serial correlation, SEs are calculated as cluster-robust. Specifically, to control for correlation derived from household-specific characteristics and persistent within-household behavioral patterns, alongside seasonal effects, SEs were clustered at household-season level.

4. DATA

We obtained a sample of 640 households from a large electricity supplier, which includes measurements of Active Energy Produced (e_p), Active Energy Grid Consumed (e_g), Active Energy Self-Consumed (e_s) and Active Energy Injected (e_i) during the period of 2024. The total energy consumption for the household can be determined by the sum of the grid consumption and the self-consumption from solar output, and the total energy produced by the PV system can also be decomposed into the amount of energy that is self-consumed by the household and the component exported to the grid:

$$e_c = e_g + e_s \tag{7}$$

$$e_p = e_s + e_i \tag{8}$$

We also gathered secondary information for these households such as the district and city, geographical coordinates and year of registration within the measuring system – which, for solar households, can be read as date of installation. The definition of these variables can be found in Table I.

TABLE I

VARIABLE DEFINITIONS

	Variable	Description
Dependent Variable	e_c	Active energy consumed by the household measured in kWh
Major Explanatory Variable	e_p	Active energy produced by the household's PV system measured in kWh
Other Explanatory Variables	e_g	Active energy consumed from the electric grid by the household measured in kWh
	e_s	Active energy consumed by the household from the PV produced energy in kWh
	district	Categorical variable that identifies household's location district
	city	Categorical variable that identifies household's location city
	nuts_2	Categorical variable that identifies household's NUTS II location
	maturity	Categorical variable that identifies how long the household was registered on the measurement system
	coordinates	Household's location coordinates

The observations were obtained with a frequency of 15-minute intervals over the course of the year 2024. FIGURE 2 shows the distribution of the average daily production and consumption in 2024 for our sample and the descriptive analysis of these variables can be found in Table II.

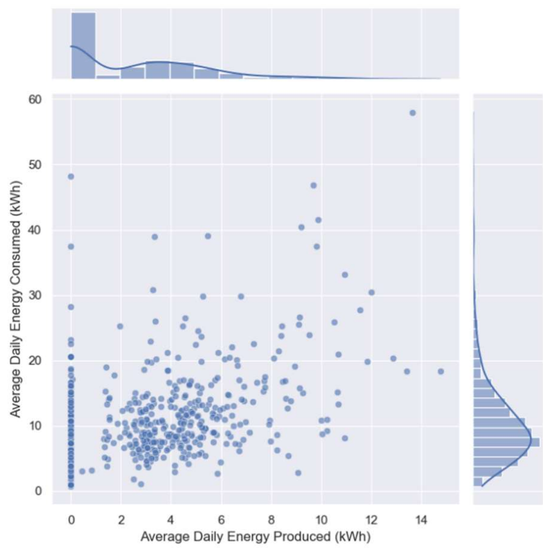

FIGURE 2 – Average daily energy produced and consumed, in kWh, by each household in 2024

Our sample contains around 43.3% of non-solar households, which is possible because the data gathered originates from an energy metering system that can be subscribed by non-solar users who want to monitor their consumption. While using a standard control group of non-solar households might not be appropriate, since prosumers and non-prosumers generally differ in key socioeconomic characteristics and consumption patterns, these households tend to be similarly energetically aware and literate, making them suitable for comparison. (Aydın et al., 2023; Boccard & Gautier, 2021)

Regarding maturity, we observe a gap where no household in our sample was registered 4-5 years ago, and only 8 were registered 3-4 years ago, due to the effects of the COVID-19 pandemic.

TABLE II

DESCRIPTIVE STATISTICS

		Daily Energy Consumed (kWh)				Daily Energy Produced (kWh)*			
	Num. of Households	min	max	avg	std	min	max	avg	std
All Households	640	0,001	206,346	10,449	9,027				
Solar Households	363	0,001	206,346	12,174	9,768	0,000	25,614	4,716	3,389
Non-Solar Households	277	0,07	121,448	8,188	7,365				
NUTS II									
Norte	204	0,491	188,648	10,921	10,075	0,000	25,614	4,479	3,391
Centro	133	0,002	121,448	10,18	8,815	0,000	18,541	4,018	2,932
Oeste e Vale do Tejo	62	0,51	60,176	8,357	5,735	0,058	17,105	4,092	2,841
Grande Lisboa	21	0,176	119,104	11,205	11,289	0,085	16,909	6,67	3,626
Península de Setúbal	27	0,385	75,859	10,042	7,832	0,000	17,277	4,887	3,107
Alentejo	113	0,001	82,128	10,083	7,189	0,000	20,962	4,667	3,025
Algarve	80	0,598	206,346	11,766	10,25	0,000	23,058	6,744	4,225
Maturity									
1-2 years	47	0,545	92,922	10,005	7,917	0,000	17,277	5,351	3,281
2-3 years	185	0,001	206,346	11,08	9,079	0,000	23,058	4,942	3,521
3-4 years	8	2,35	188,648	19,015	19,261	0,094	25,614	5,019	4,705
5+ years	400	0,002	121,448	10,037	8,697	0,000	21,763	4,374	3,175

*NOTE: Daily Energy Produced statistical description was conducted using only Solar houses, as non-solar houses do not produce energy by definition.

The geographical concentration of the sample can be found on FIGURE 3, showing diverse spatial variety of the sample, including various climatic zones and socioeconomic contexts within mainland Portugal.

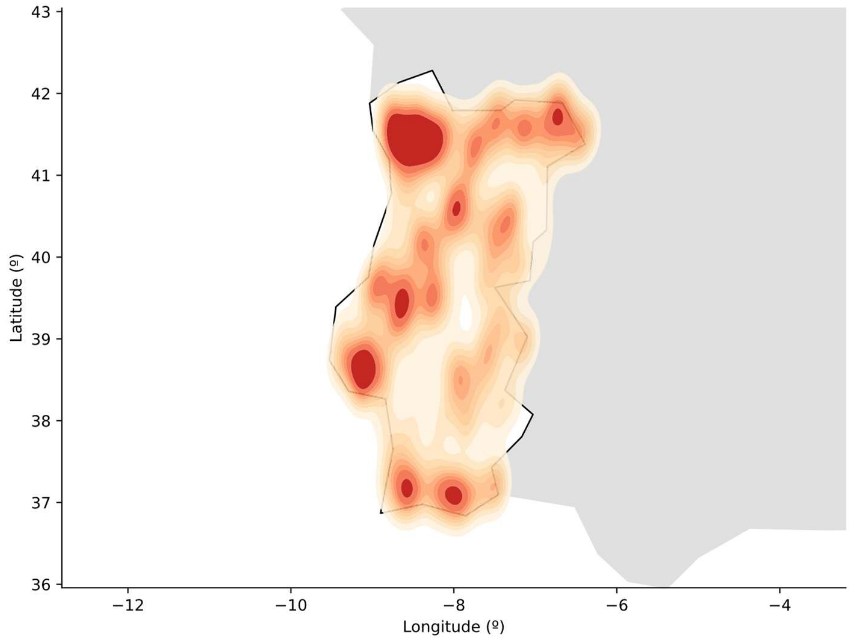

FIGURE 3 – Household geographical density heatmap

The two-dimensional kernel density estimate plot in FIGURE 3 highlights areas where there is a higher concentration of households. Major urban areas are more concentrated, whereas rural regions display more sparse distributions in our sample. For instance, even though *Alentejo* has a bigger share of households in our sample than *Grande Lisboa*, the dispersion of households in this region is reflected in a lower density representation.

Regarding Energy Produced e_p, FIGURE 4 displays the average daily solar energy production, disaggregated by month, showing pronounced seasonal variation. Unsurprisingly, production increases in the summer, with the highest peak values recorded during July and August around 1:30pm, later than in the winter. In addition to higher peak output, the time span of production is also extended in the summer months - the broader production window is a result of longer daylight hours in the summer season, resulting in an overall increase in daily energy output during those months.

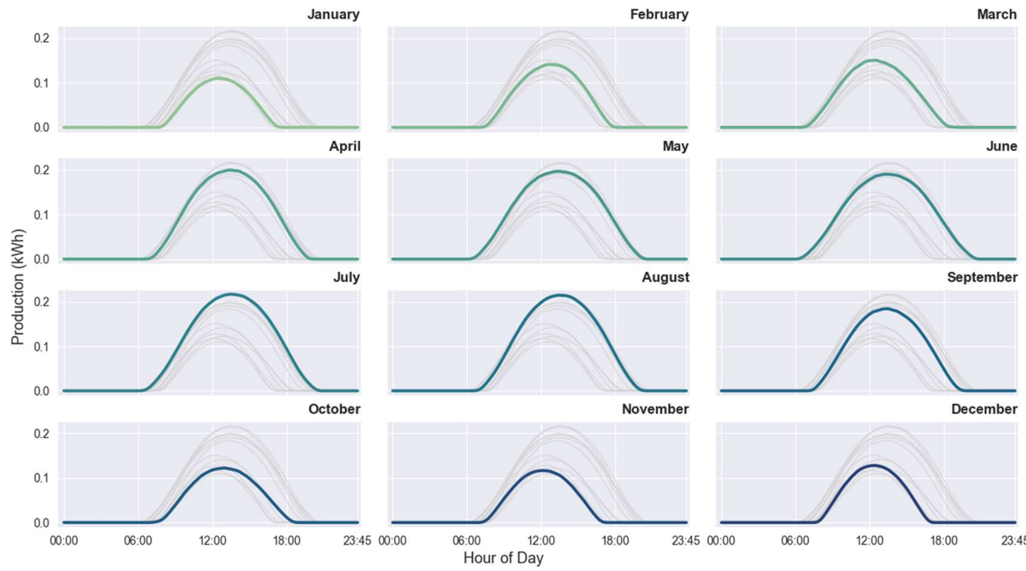

FIGURE 4 – Average electricity production of solar households, in kWh, by time and month (at a 15-min observation frequency)

Finally, we can compare the average energy consumption e_c between solar and non-solar households on FIGURE 5, disaggregated by month. We can observe that non-solar households consume on average less electricity than solar households in all months of the year. Solar households present two clear peaks of consumption (around 12am and around 8pm), with the first peak surpassing the second between May and September, corresponding to months with high solar irradiance. While non-solar homes also present two consumption peaks, the 12pm is damped and systematically lower than the second.

This observation may suggest that prosumers may change their consumption patterns by shifting consumption to high solar-output hours, particularly during months where this output is high as a result of high solar irradiance. This observation can be a strong indicator of a potential SRE and, as stated by Aydın et al. (2023), such variation between seasons suggests short-term responses to energy production variations rather than structural or long-term changes in household energy-consuming capacity.

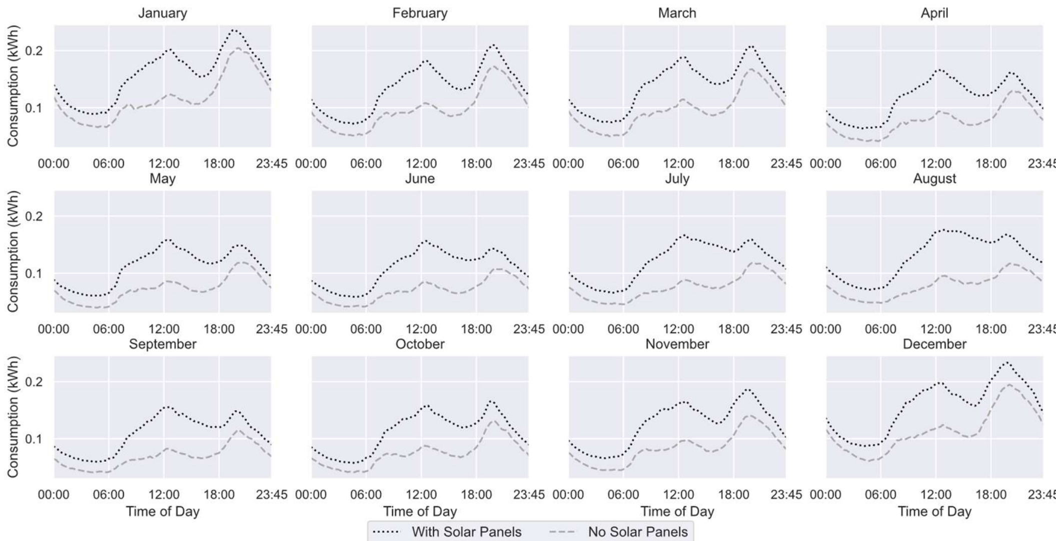

FIGURE 5 – Average electricity consumption, in kWh, by time and month, disaggregated between solar and non-solar households (at a 15-min observation frequency)

5. RESULTS

5.1 Daily Analysis

We start by conducting the panel data analysis with an observation frequency of a day by performing an Ordinary Least Squares (OLS) regression on the data described on Chapter 4. using R software. Table III shows the results for three different model specifications, where we progressively introduce the lagged variables.

TABLE III

DAILY ANALYSIS RESULTS

	(1)	(2)	(3)
Total Effect ($\beta_1 + \beta_2 + \beta_3$)	0.01517*** (0.002)	0.01628*** (0.003)	0.01708*** (0.004)
β_1	0.01517*** (0.002)	0.01220*** (0.003)	0.01093*** (0.002)
β_2		0.00408* (0.002)	0.00199^{+} (0.001)
β_3			0.00416** (0.002)
Constant	1.68210*** (0.047)	1.67581*** (0.045)	1.62951*** (0.045)
Observations	234,240	233,600	232,960
Adjusted R^2	0.6656	0.6662	0.6667

***p < 0.001, ** p < 0.01, * p < 0.05, $^{+}$ p <0.1
Standard Errors were computed as clustered at household-season level and heteroskedasticity-robust (HC1).

The empirical results show an estimate for η^{PV} of 0.01708, which translates into an estimated rebound factor of $R = 1.01708$. This implies that solar households increase their consumption levels by 1.71% for each 1 kWh produced by the PV systems. As $R > 1$ or $\eta^{PV} > 0$, we are under strong evidence of a SRE.

At a 95% confidence level, we expect the value for η^{PV} to be between 0.01010 and 0.02405, highlighting precision and robustness of the results. While the impact magnitude may appear modest, it should be looked at in the context of semi-elasticity, demonstrating a consistent response in which households partially offset the intended benefits of solar energy generation.

Modeling the SRE closer to the theoretical definition of a semi-elasticity improves the interpretability of the results. However, the numerical values of the estimates are hard to compare directly with other estimates of the SRE, since those studies have mostly used a level-level specification. Nonetheless, our estimates provide valuable insights into directionality, significance, and relative magnitude of the rebound dynamics.

We observe relevant statistical significance in model (2) regarding the effect of the previous day β_2. When introducing another lagged variable β_3 in the specification of model (3), β_2 loses significance and magnitude while β_3 becomes strongly significant. On one hand, we observe that intertemporal spillovers are relevant and present, showing that the SRE extends beyond a single day, as households may shift their consumption towards a day with higher PV output. On the other hand, the weakening of β_2 once β_3 is included suggests autocorrelation between these lagged variables: in model (2), β_2 may partially capture persistent effects, while model (3) redistributes explanatory power between the lagged variables. This observation, however, does not affect the statistical significance of the total effect, which remains highly significant across models, highlighting the robustness of η^{PV} estimates.

The reported Standard Errors are computed as heteroskedasticity-robust to address potential heteroskedasticity in our model, which is to be expected in a large micro-level dataset since the assumption of homoskedasticity is unlikely to hold. Concretely, different household characteristics and consumption patterns, intensified by the comparison between solar and non-solar households, can introduce heteroskedasticity in the error structure, which if let uncorrected could lead to biased inferences. Moreover, the SE were computed as clustered at the household-season level; as a result, confidence intervals are fairly conservative and result in more cautious significance inference.

An important note for our interpretation is the sample selection. While using non-solar households that subscribe to a monitoring service may allow us to make a more direct comparison with solar homes – as these households share relatively similar energy awareness – the observed impact of solar production is expected be greater when compared to standard users who do not actively monitor their consumption. Therefore, the results presented may also be conservative relative to the broader Portuguese population.

Even with modest impact at the individual level, the compound aggregate effect of SRE with widespread PV system adoption can pose significant challenges at system-level for grid management. The bidirectional energy flow of prosumers introduces uncertainty in forecast and development of infrastructures, which is further amplified by the SRE. For once, the daily SRE can increase grid strain, and the changes in intra-day load and production patterns, particularly feed-in offset and increased peak or off-peak loads, altering the planning paradigms. Furthermore, as solar production is non-dispatchable, grid operators may experience difficulties in load balancing. (Poier & Bucksteeg, 2025)

Balancing the SRE of residential systems with the merit-order effect of utility-scale photovoltaics is important for energy policy and the orientation of both private investment and public incentives. Namely, investing in utility-scale parks may avoid the SRE, but also reduces equilibrium electricity prices. In this sense, these results are useful to carefully design the energy system. (Oliver, 2023)

For system-wide long-term planning, the SRE must be accounted in modelling for planning, namely in scenario reports and system-planning studies. In terms of economic impacts, the SRE increases total system costs and, in an environmental perspective, GHG abatement effectiveness and cost depend on how the rebound demand is satisfied. These results also emphasize the need for further cross-border grid capacity expansion, as a way of spurring regional balancing options across Europe. (Delic & Bucksteeg, 2025)

At the household-level, the 1.7% increase in household consumption per additional 1 kWh produced partially offsets the expected financial savings from reduced grid reliance. This effectively distorts the net financial benefits of the PV installation and therefore increases the payback period for the household's investment. (Aydın et al., 2023) As prosumers may not *perceive* the increased consumption, the contrast between the expected cost-benefit analysis and the real savings can result in dissatisfaction with the investment. (McCarthy, 2022)

Dissatisfaction from adopters can, in turn, have secondary consequences. As peer-effects have a significant role, detractor behavior may hinder the context for prospective adopters and therefore inhibit the diffusion of PV systems. (Snape, 2016) Furthermore, inaccurate projections that fail to account for the SRE may result in erosion of trust in the commercial provider, reputational damage and loss of revenue. (Smith & van Moorsel, 2010)

From a public policy perspective, handling the residential SRE may involve specific measures and interventions aimed at ensuring increased energy efficiency and literacy in households to minimize rebound dynamics within households. Moreover, poorly designed support schemes can even induce a greater Solar Rebound Effect, as discussed in Chapter 2., which underscores the need for careful policy designs in order to avoid unintended consequences. (Boccard & Gautier, 2021; Poier & Bucksteeg, 2025)

5.2 Heterogeneity Analysis

To comprehensively understand the Solar Rebound dynamics, it is not only important to analyze the overall behavior of households but also to carefully examine how such an effect may vary across different contexts. In this sense, heterogeneity analysis allows us to identify how the SRE is shaped by different conditions and aspects of the households.

We start by looking at regional differences, as different local climates and behavioral aspects may influence the magnitude and nature of the SRE. To explore these regional differences in greater detail, we estimate the SRE separately for sub-samples corresponding to each NUTS II region of our sample. The results for this analysis are shown in FIGURE 6.

The results show pronounced regional variation, with regions like *Alentejo* and *Centro* presenting estimates of $\eta^{PV}_{Alentejo}$= 0.04006 and η^{PV}_{Centro}= 0.03221, significantly higher than the national estimate. This means that, for *Alentejo*, a 1 kWh increase in the photovoltaic production is expected to lead to a 4% increase in energy consumption, which is more than double the estimate obtained for the national sample.

On the contrary, *Algarve* region presents a very reduced effect ($\eta^{PV}_{Algarve}$= 0.00555) and *Península de Setúbal* shows a negative estimate ($\eta^{PV}_{P.\ Setúbal}$= -0.0197). These results do not necessarily conflict with the evidence of a positive SRE at the national level but, instead, stress the heterogeneity of responses across different regions. However, *Península de Setúbal* and *Grande Lisboa*'s results should be interpreted with caution as they result of particularly small sub-samples, which may lead to less reliable estimates.

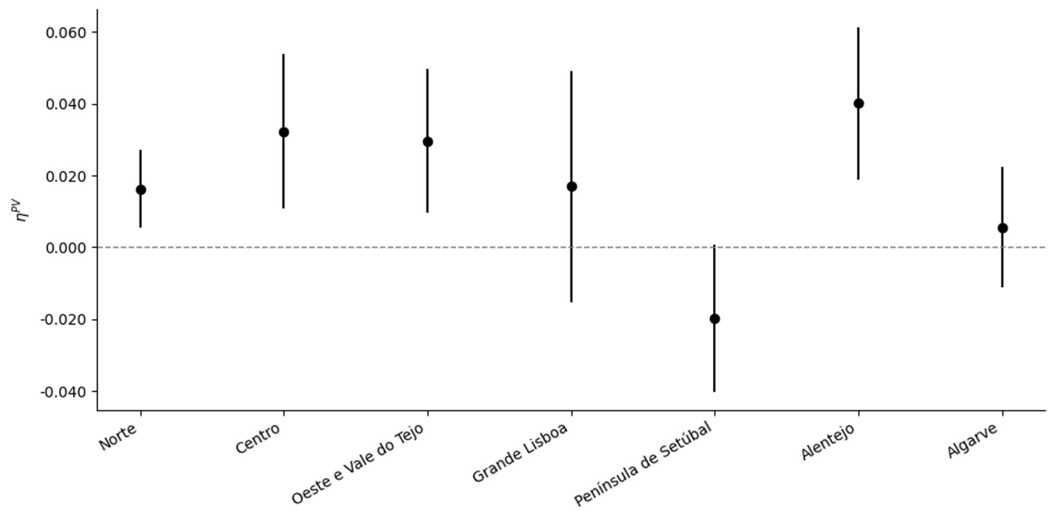

FIGURE 6 – Rebound effect by NUTS II

NOTE: Each point indicates the estimate for the corresponding NUTS II region and the lines indicate the corresponding 95% Confidence Interval. Standard Errors were computed as clustered at household-season level and heteroskedasticity-robust (HC1).

Such a pronounced variation highlights that regional differences, such as climate, physical and socioeconomical factors, strongly shape rebound dynamics, creating heterogeneity even in a relatively small country such as Portugal. These differences may even arise *ex-ante*, influencing the installation decision phase and baseline consumption. In fact, the spatial structure of cities directly influences both energy consumption and the likeliness of adopting PV systems, with urban density being a key factor determining solar potential of building block. (Akrofi & Okitasari, 2022; Kanters & Wall, 2014) It is likely not a coincidence that *Grande Lisboa*, a densely populated metropolitan region, is the least represented in our sample, as high population density areas are often associated with low PV capacity penetration. (Snape, 2016)

Moreover, socio-economic characteristics also have implications on both the consumption and production behavior. Factors like disposable income, average household age, education levels, gender, and employment status affect the pattern of household energy usage. (Kostakis, 2020) In terms of adopting photovoltaics, socio-economic and peer effects play a determinant in the local dissemination of these systems – first, these characteristics influence the decision to acquire photovoltaic installations; in addition, households are more likely to install PVs when they observe a community uptake of that system, with local structures and organizations, if present, further amplifying these effects by providing trusted channels for knowledge dissemination and promoting meso-level interactions that catalyze peer effects. (Balta-Ozkan et al., 2021)

These results stress the need for energy policy to consider the geographically diverging nature of low carbon transition, as uniform approaches are likely to fail at capturing relevant variations on local energy practices variation.

Next, we observe the impact of maturity in the rebound dynamics, by contrasting the most recently registered households ("*1-2 years*" category) with the oldest households registered ("*5+ years*" category). The estimates can be found on FIGURE 7.

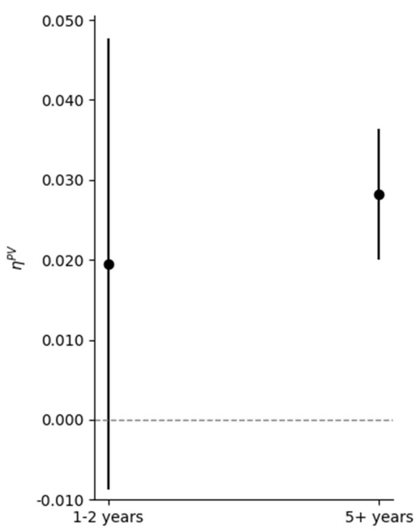

FIGURE 7 – Rebound effect by maturity

NOTE: Each point indicates the estimate for the corresponding time of registration and the lines indicate the corresponding 95% Confidence Interval. Standard Errors were computed as clustered at household-season level and heteroskedasticity-robust (HC1).

From our results, we observe that results for the maturity of "*1-2 years*" ($\eta^{PV}_{1-2\ years}$= 0.01953) are statistically irrelevant due to a large confidence interval, which prevents us from drawing significant conclusions by comparing it with the national estimate or the most mature households.

However, the result for "*5+ years*" yields a result (η^{PV}_{5+yea} = 0.02821) significantly higher than our estimate for the full sample. This result can be interpreted as an expected increase of 2.82% on Energy Consumption per additional 1 kWh produced by the most mature PV systems.

The SER is expected to increase energy usage significantly in the first year after installation of PV systems, with a gradual diminishing impact over time until it stabilizes. (Nguyen et al., 2024) In this light, the result for houses with more maturity suggests that, in the long term, lasting changes in the consumption patterns occur. These shifts may be driven by a combination of behavioral adjustments and structural changes in the households, such as co-adoption. The large confidence interval for the period "*1-2 years*" may, in turn, suggest high variability, as a reflection of a transitional behavioral adaption as short-term responses, that tend to stabilize over time.

Next, we turn to heterogeneity in the SRE by examining household consumption quartiles. The results are displayed in FIGURE 8, allowing us to explore how the rebound effect varies across the distribution of demand.

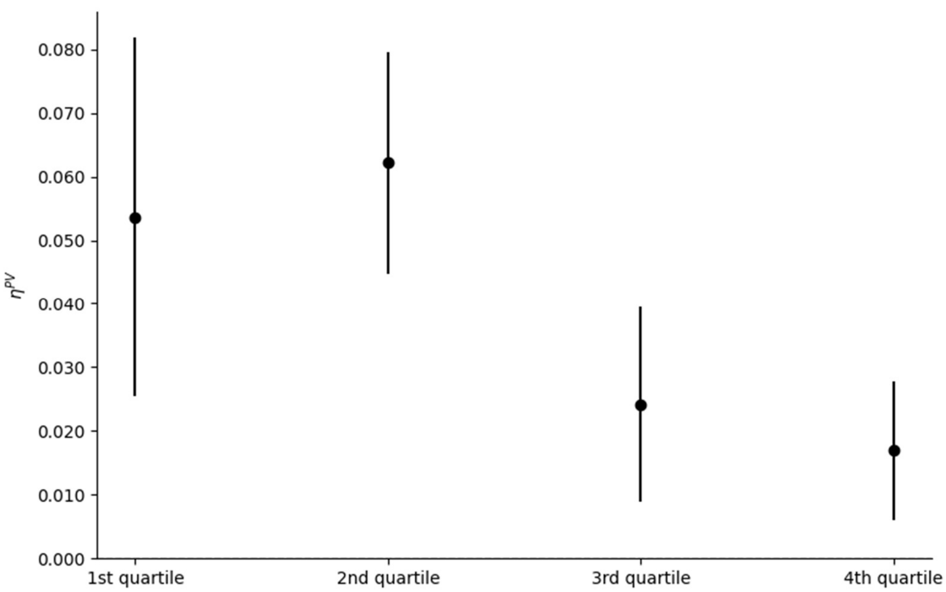

FIGURE 8 – Rebound effect by consumption quartile

NOTE: Each point indicates the estimate for the corresponding quartile of consumption and the lines indicate the corresponding 95% Confidence Interval. Standard Errors were computed as clustered at household-season level and heteroskedasticity-robust (HC1).

The analysis result shows that the first two quartiles have large rebound effects ($\eta^{PV}_{1^{st}quartile}$= 0.05361 and $\eta^{PV}_{2^{nd}quartile}$= 0.06222) whereas the third and especially the forth quartiles exhibit smaller magnitudes, close to the overall estimate ($\eta^{PV}_{3^{rd}quartile}$= 0.02415 and $\eta^{PV}_{4^{th}quartile}$= 0.01694). These estimates show that lower consuming households respond more strongly to PV output, with expected increase of up to 6.2% per additional kWh produced.

Such results are in line with the findings of Poier & Bucksteeg (2025), since its findings show a relevant effect of the pre-installation consumption on the SRE. While smaller pre-consumption levels revealed a more significant increase in energy consumption, high-consuming households showed a reduced SRE.

For households with small or medium consumption levels, the marginal utility of increasing energy consumed is plausibly higher, as the perception of “free” electricity may allow those households to satisfy previously constrained demand. Conversely, high-consuming households may already be operating closer to their intended comfort level, and thus having less responsiveness to PV production and promoting conservation.

The SRE is conditioned by a combination of behavioral and contextual factors, but our findings suggest diminishing marginal returns on households with greater consumption levels. As the SRE is not uniform across households, distortions in intended benefits are heterogenous and interventions to account for such effect must consider these particularities.

Lastly, it should be noted that these results have large confidence intervals due to the combination of small-sample sizes and cluster-robust specification. While this limits precision, it strengthens the reliability of possible inference by avoiding overstated significance levels. The coherence of results with theoretical expectations signals that these findings hold interpretative value while further research may be helpful to corroborate them.

6. CONCLUSION

This study aimed to explore the directionality, magnitude and implications of the SRE in energy-monitored Portuguese households.

By analyzing a panel dataset of Portuguese solar and non-solar houses throughout the year of 2024, it was possible to conclude that a rebound effect exists in the context of residential households with energy monitoring. While the results may appear of modest impact, with an expected increase of 1.7% in Energy Consumption per additional 1kWh produced, high heterogeneity was observed. Regional differences may raise this increase to around 4%, while mid-consuming households may surpass the 6% increase per 1 kWh. Such results highlight the need to account for heterogeneity, namely in terms of region, consumption level and maturity.

The implications for these results extend beyond the households themselves, with impact for numerous actors and stakeholders, such as providers, grid operators and policymakers. The SRE influences system and grid planning, introducing uncertainty and altering the load patterns. In terms of energy policy, it is useful to comprehensively understand the rebound dynamics as, for once, they influence the effectiveness of benefits and incentives and, in turn, the policy designs can influence the magnitude of the SRE. It might also be relevant to review the Net-Metering policies considering the results. Furthermore, the balance between residential and utility-scale PV systems must take into consideration all the externalities for the design of the energy system. Financial returns are distorted for the acquiring households and system providers can experience tangible and intangible losses, either for transactional sales or As a Service. As a secondary effect, the diffusion of this technology can be inhibited due to dissatisfaction among users. Public policy interventions directed at promoting energy literacy and efficiency are recommended to mitigate the SRE.

Regarding limitations, the reduced secondary data available for household characteristics did not allow for exploring further heterogeneity in rebound dynamics. Future research may include details about heterogeneity in household sizes, income, efficiency or energy literacy. Moreover, the sample of non-solar houses is not representative of the broader population, but rather reflects more energy-aware households, limiting the generalization of the findings: the rebound can be expected to be higher using a truly representative sample. Lastly, the proportion of solar and non-solar households does not reflect the true proportions of the broader Portuguese population, as there is still a small share of solar households and reliable data was not found on the real-word distributions.

Future research may also include a difference-in-differences approach, to further examine the temporal dynamics of the rebound effect and strengthen the causal inference of the PV systems impact on energy consumption. In addition, intra-day analysis can provide valuable insights into the load shifting throughout the day. This temporal load shifts are relevant to understand the extent in which the SRE alters the dynamics of off-peak loads and midday congestion. Finally, further research on heterogeneity analysis with different datasets can contribute to consolidate inference on these findings.

In conclusion, the SRE exists in the context of Portuguese households as a result of complex interactions that translate into significant heterogeneity. Therefore, all actors of the photovoltaics ecosystem must account for its impacts, and effective public and energetic policy should be carefully designed to mitigate its negative consequences while promoting Renewable Energy Sources.

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