Residential Solar Photovoltaic and Distributional Effects: Net Metering vs. Other Policies

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Abstract

This paper investigates the impact of the net metering policy on residential solar photovoltaic adoption and its distributional effects across different wealth groups. Using Dutch administrative data, the findings show that net metering accounts for 79.21% of residential solar capacity from 2012 to 2022, along with a regressive effect where households in the lowest 20% wealth group contribute a net 11.15% of the total subsidy, while the highest 20% wealth group receives a net 10.38% of subsidy. Replacing the net metering policy with feed-in premiums or the upfront subsidy only improves the redistribution by less than 1%. Moreover, compared to the net metering policy, feed-in premiums encourage larger PV installations, and upfront subsidy promotes smaller capacities. Consequently, feed-in premiums export 13.37% more electricity to the grid, and the average installation cost is 11.93% higher when an upfront subsidy applies. This implies that a simple policy replacement may not address issues such as inequality and rising grid costs with net metering.

Keywords: Photovoltaics, Net metering, Distributional effects, Welfare, Structural estimation.

JEL: D12, D31, D63, Q52, Q58

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1 Introduction

This paper evaluates the net metering policy, which is used to promote residential solar photovoltaic (PV). Under the netting rule, households installing solar PV (henceforth, PV adopters) pay electricity prices and taxes for annual *net consumption*, hence the amount of electricity they draw from the grid (henceforth, grid consumption) minus the amount fed back to the grid (henceforth, feed-in).

While the policy led to the widespread adoption of residential solar PV, it has been criticized for resulting in regressive effects and an excess burden on the electricity grid. The first critique, based on the fact that wealthier households install more solar panels, focuses on two aspects. First, PV adopters paying taxes only on net consumption results in a tax loss. Consequently, the government must increase the current tax rate or create a new tax fund to balance the fiscal budget. Second, energy companies charge the households a fixed retail price regardless of solar PV adoption, while wholesale electricity prices fluctuate: peaking during high grid consumption and dipping during high solar production. As electricity is expensive to store, energy companies purchase electricity at high prices and sell it at low or negative prices, leading to a revenue loss. To break even, energy companies raise the energy price, disproportionately burdening households without solar panels (henceforth, non-adopters) (Johnson et al., 2017; Brown et al., 2015; Costello and Hemphill, 2014; Castaneda et al., 2017).

The second critique is that net metering does not promote self-consumption and increases the burden on the electricity grid. Self-consumption means households directly use part of the electricity produced by their solar panels. There are three ways for households to self-consume solar electricity. First, use electricity when solar panels work. Second, intentionally shift demand to align with peak solar production times. Third, install batteries to store excess electricity for later use. Since net metering offers the same financial benefit for self-consumption and feed-in, households do not have incentives to increase self-consumption. Hence, large amounts of electricity are fed back into the grid during peak solar production times, which strains grid capacity and requires significant investments to expand the grid.

I revisit the two critiques of net metering policy using comprehensive Dutch household-level data from 2019 to 2022.[1] The Netherlands officially introduced the net metering policy in 2004 and decided to abolish it in 2027. Although there has been a lot of discussion on the net metering policy, the households' response to this

[1]The Netherlands provides a perfect setting for evaluating this policy for two reasons. First, net metering is the only incentive policy for small-scale solar systems. Second, net metering is applied with the same rule across the Netherlands.

policy and the distributional effects across different wealth groups remain unclear due to limited micro-level data. This paper intends to fill the gap. Specifically, this article consists of two blocks. First, I build and estimate a structural model to describe households' decisions on PV adoption and predict the adoption outcomes under different renewable incentive policies. Additionally, I evaluate the budgetary costs and distributional impacts of these policies based on adoption outcomes.

A two-level nested logit model is applied to estimate the residential solar PV adoption. The key specification is that households decide not only whether to adopt solar PV but also the PV capacity if they choose to install it. The results indicate that net metering policy accounts for 64.43% of Dutch residential solar PV adoption and 79.21% of residential solar capacity from 2012 to 2022. Furthermore, households are very sensitive to the financial incentive. If only half of the excess electricity fed into the grid is eligible for net metering; the residential solar PV installation in 2022 would reduce by 78.09%. Then, I model the externality of the net metering policy, which is defined as the increase in retail electricity prices under the net metering policy compared to the counterfactual scenario without net metering. The results show that the retail price is €0.038/kWh higher compared to the scenario without net metering in 2022, and the structural model predicts that the externality will increase to €0.082/kWh in 2026, with the expectation of net metering phase-out in 2027.

Next, I present the counterfactual adoption patterns when net metering is replaced by feed-in premiums or upfront subsidies. Because households choose how many panels to install, I can analyze the intensive margin of different policies. The results show that households would opt for different PV capacities. Under the net metering policy, households take advantage of the netting rule up to their electricity consumption, so they adopt the PV capacity aligned with their consumption level. Under feed-in premiums, all electricity feed-in is compensated at a fixed rate on top of the wholesale electricity prices, so the households are incentivized to select larger capacity sizes and mostly utilize their rooftop spaces. An upfront subsidy is a one-time financial payment to reimburse part of solar PV installation costs, and the electricity feed-in is only compensated at wholesale market prices. Hence, households adopt a smaller capacity size. To achieve the same total capacity in 2022, 33.5% of potential adopters installed PV systems under the net metering policy, while it requires a 29% adoption rate under feed-in premiums and 42.36% under upfront subsidy.

The selection of PV capacity provides important insights into installation and grid costs. As module prices have continued to drop in recent years, fixed costs constitute a significant share of solar PV installations. Economies of scale imply that households incur a lower average installation cost when they install more panels. Consequently, given the same capacity target, upfront subsidies require a higher budgetary cost to compensate for installation costs. On the other hand, households contribute to grid costs, which rise rapidly due to increasing residential solar capacity and low self-consumption rates. When households do not adapt electricity consumption behavior, the self-consumption rate under net metering is equal to 0.33, meaning that households directly consume 33% of electricity generated by their solar system. It increases to 42% when households adopt smaller PV with upfront payment and reduces to 23% with feed-in premiums. The comparative analysis indicates that when households are more likely to change solar PV adoption behavior than electricity consumption behavior, compensating feed-in may further strain the grid and increase costs for all households.

Finally, this paper discusses the distributional effect of different policies from 2012 to 2022. I am particularly interested in the scenario when subsidies are collected in the energy sector. Although wealthier households have a higher adoption rate, they also consume more electricity, and a fixed subsidy contribution is most unfair. When a volumetric tariff is used, households in the lowest 20% in wealth distribution contribute 19.12% of the subsidy but receive only 7.97%, hence a net 11.15% contribution under net metering. Moreover, the inequality gap broadens over time when net metering applies. In 2012, households in the lowest 20% wealth group contributed 18%, and this rose to 22.01% in 2022. On the contrary, the contribution from the highest 20% decreased from 25% to 21.27%. Surprisingly, even with a lower level, this regressive effect persists with feed-in premiums or upfront subsidies, where low-income households contribute 18.24% and 18.43%, respectively.

The findings provide new angles on evaluating the net metering policy. While abolishing net metering increases the benefits of self-consumption for existing PV adopters, it significantly reduces incentives for new adoption. Moreover, as electricity demand is very inelastic, potential adopters may reduce PV capacity rather than adjust consumption, so rooftop is not fully utilized. Replacing net metering with feed-in premiums may backfire by encouraging oversized PV systems and excessive grid feed-in. Furthermore, Net metering has a severe regressive effect, which worsens over time, but replacing it with other policies does not resolve this issue. This carries important policy implications: the government should consider financing the subsidies through sectors other than energy consumption to mitigate the regressive effects of renewable energy subsidization. When the subsidy can be financed fairly, net metering provides a good compromise between subsidy and investment costs while also exploring the rooftop potential. Therefore, this paper advocates for a more careful reform of the net metering policy rather than outright replacement.

This paper pertains to two streams of literature. First, it relates to the large amount of literature discussing the role of incentive policies on solar PV installation. For instance, Burr (2016) uses a quasi-experiment in California and shows upfront subsidy encourages more adoption while production subsidy is more efficient, implying adoptions in optimal locations for solar electricity production. There are some papers estimating the price elasticity of upfront subsidies (Hughes and Podolefsky 2015; Gillingham and Tsvetanov 2019; Crago and Chernyakhovskiy 2017). On the other hand, the study by Aldy et al. (2023) on wind farm subsidies gives the opposite result. Comello and Reichelstein (2017) predict PV adoption in three cities of the US when a lower-than-retail overage tariff is paid to solar adopters and find that the adoption will not be affected as long as this tariff is above the levelized cost of electricity. De Groote and Verboven (2019) use monthly data in Belgium and find that feed-in premium stimulates the adoption of solar PV but is too costly compared to investment subsidies as customers heavily discount future benefits. Böning et al. (2023) use variations in incentive schemes across different regions in Belgium and assess the effects of different incentive schemes. They find that feed-in premiums and investment subsidies are at least 60% more effective than net metering in PV adoption. With an input-output model, Eid et al. (2014) calculate the bills in different scenarios and net-metering designs, providing insights into the effect of net-metering policy on cost recovery and inequality. Londo et al. (2020) use the cash-flow model and investigate the effects of alternative policies on pay-back period, government cost, and amount of PV uptake by exogenously given parameters. Masciandaro et al. (2024) show how net metering affects adopters and non-adopters across different regions in the Netherlands. My paper distinguishes itself from previous work by providing the theoretical foundation, utilizing comprehensive micro-level data, and demonstrating the dynamic equilibrium with intensive effects under various policies.

This paper also contributes to the growing literature investigating the welfare effects of renewable energy adoption. Feger et al. (2022) take research on optimal tariff design to incentivize solar PV adoption and avoid an enormous grid cost burden on non-adopters in Switzerland. They argue that consumption-based grid cost is less regressive than fixed grid cost because adopters are more affluent and less price sensitive to electricity price increases. Wolak (2018) uses distribution network price and installation from the three largest utilities in California and finds that residential solar capacity contributed two-thirds of increasing network prices from 2003 to 2016. Dauwalter and Harris (2023) further show that residential solar capacity has unequal environmental benefits, and there is no trade-off between efficiency and equity. Finally, this paper enriches a broad body of literature concerning the inequity of different anti-climate change policies. For instance, Känzig (2023) shows that the poor are more exposed to carbon pricing because they have a higher energy share and face a larger fall in income. Ito et al. (2023) demonstrates that price-elastic consumers are more likely to benefit from dynamic pricing. Holland et al. (2019) examine the distributional effects of local air pollution from electric vehicle adoption in the US.

The rest of the paper is organized as follows. Section 2 describes the institutional background and datasets. Section 3 specifies the structural model for Dutch residential solar PV adoption decisions. Section 4 discusses the empirical results and performs counterfactual analyses. Section 5 builds a styled model to analyze the mechanism of net metering generating externality and discusses its distributional effects. Section 6 compares the different renewable incentive policies. Section 7 concludes.

2 Background and Data

In this section, I describe the market for Dutch residential PV systems. First, I explain the net metering policy and its role in promoting residential solar panels. Next, I briefly introduce the Dutch electricity markets. Then, I describe the available datasets and provide summary statistics on the Dutch household's PV adoption across different wealth groups.

2.1 Net Metering Policy

The net metering policy in the Netherlands was introduced in 2004.[2] Under this policy, households with solar panels can offset their electricity consumption from the grid with the power they feed into the grid, saving money on energy prices and exempt from paying energy tax and VAT on electricity. Residential solar PV that was built from 2008 to 2010 also benefited from feed-in premiums on top of net metering. After 2011, net metering became the only incentive policy. Initially, a maximum of 3000kWh per year of electricity per household could be netted and it was increased to 5000kWh in 2011. As of 2013, the upper limit was abolished, and solar PV adopters could 100% offset their grid consumption with feed-in within a billing period (one year in the Netherlands). For non-adopters, grid consumption is equal to electricity consumption. However, grid consumption is smaller than electricity consumption for PV adopters as they also directly consume a portion of the electricity produced by

[2]Before 2004, there was also unofficial net metering because the discs on the old meters would spin backward when electricity was fed into the grid.

solar panels, the amount of which is called self-consumption. Net consumption is the difference between grid consumption and feed-in, which equals electricity consumption minus solar production.

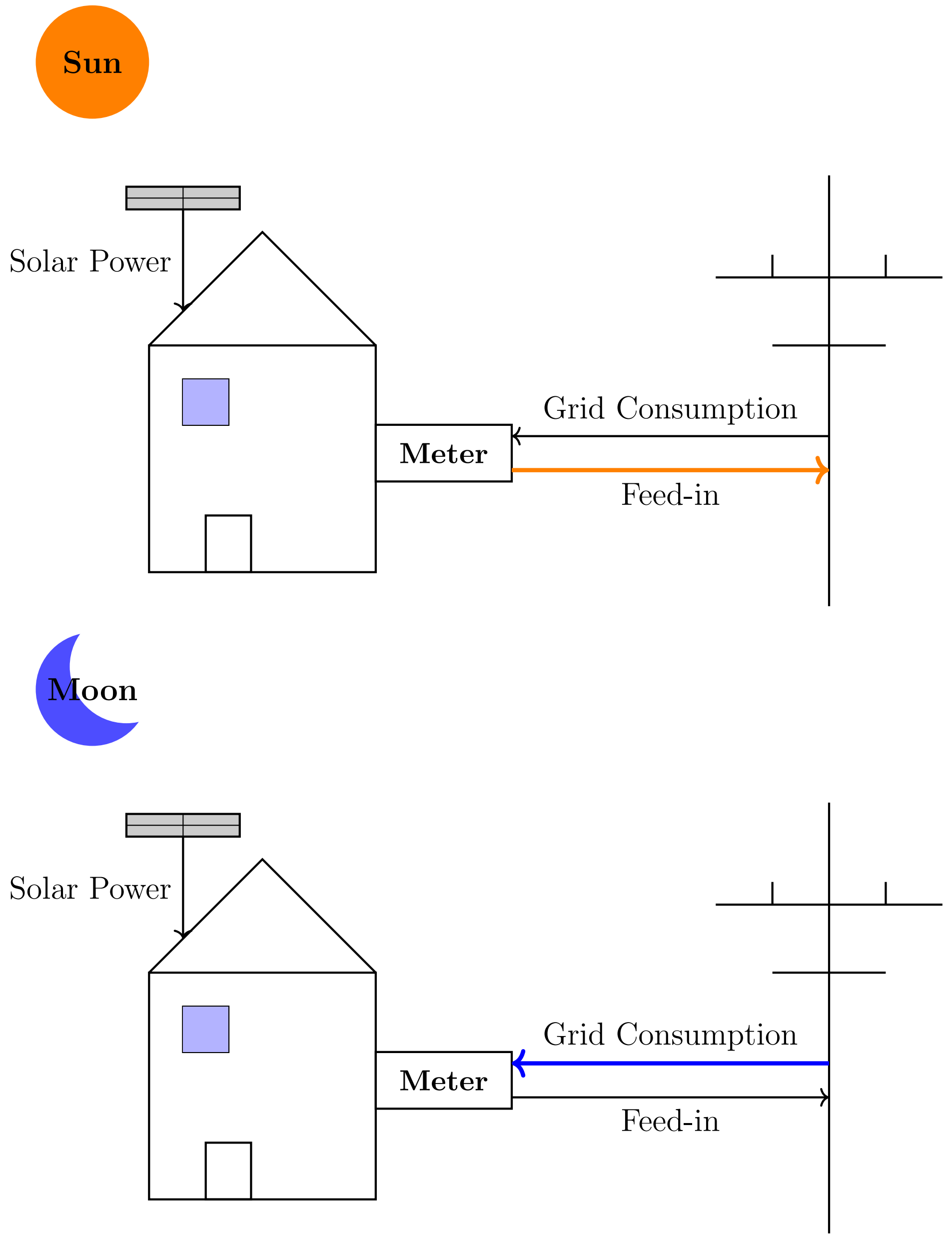


Figure 1: Illustration of Metering

Figure 1 and Table 1 illustrate how net metering works. A household installing solar panels generates electricity during sunny periods, often more than it can consume directly. The excess energy is fed back into the grid. At a time when solar production is low, the household consumes electricity from the grid. The feed-in electricity is deducted from the grid consumption at the end of the year, so the household only

	(1)	(2)	(3)
Grid consumption	3000	3000	3000
Feed-in	2000	3000	4000
Net consumption	1000	0	0
Excess supply	0	0	1000

Table 1: Illustration of Net Metering

pays for net consumption. When the amount of feed-in is greater than grid consumption, the household also receives compensation for excess supply, the rate of which is agreed upon between the household and the energy company, excluding taxes and levies.

As of June 2024, energy companies are allowed to charge a feed-in cost to PV adopters for feeding electricity back into the grid. Additionally, the Dutch government has announced the complete removal of the net metering policy, effective January 1, 2027. From that time onwards, PV adopters will no longer be able to offset the grid consumption with grid feed-in. Alternatively, they pay grid consumption at the retail electricity price and receive a reasonable compensation price for feed-in.

2.2 Dutch Electricity Markets

Electricity activities include production, wholesaling, transmission and distribution, and retailing. Transmission and distribution are not liberalized; therefore, electricity markets typically refer to wholesale and retail markets. Electricity is traded on many wholesale markets, including over-the-counter markets, long-term forward and futures markets, day-ahead markets, intraday markets, and balancing markets. There are also ancillary markets that operate as backups to maintain grid stability and efficiency. The *day-ahead wholesale market* is one of the most important markets for electricity trading in the Netherlands. The day-ahead wholesale market works as follows: at day $d-1$ before noon, electricity sellers and buyers bid price on the volume of electricity they are willing to buy or sell for each hour h of the day d. After the gate closes, the market operator matches the bids in a merit order, meaning that dispatch starts from the cheapest fuel. Then, the market operator determines the market-clearing price for each hour by the marginal cost of the most expensive supply bid needed to meet the demand, and all the selected bids are settled at the same price. Without further explanation, the wholesale electricity price in the rest of the paper refers to the price set in the day-ahead wholesale market. As renewable energy has zero marginal cost, it shifts the supply curve to the right (from blue to red) and lowers the market-clearing price. See Figure 2.

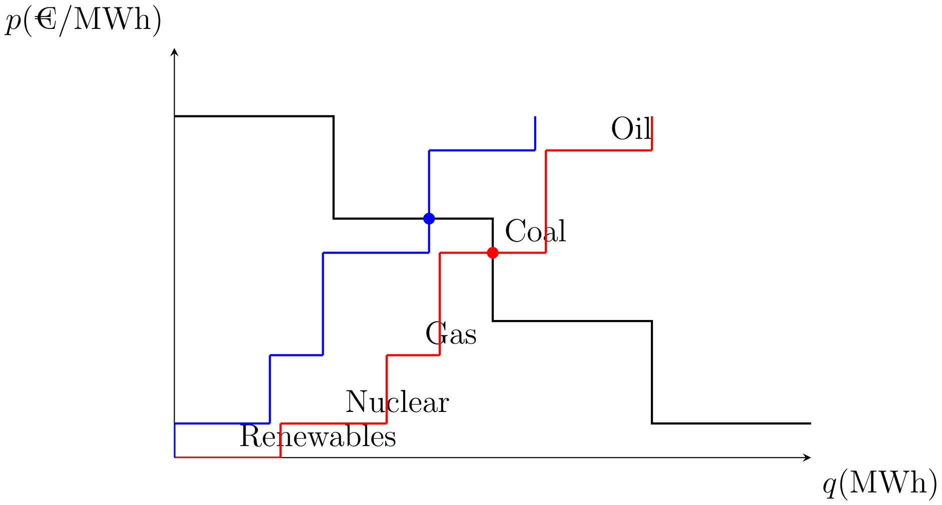


Figure 2: Day-ahead Market Auction

Notes: This figure shows how the day-ahead wholesale electricity price is determined in a blind auction. The operator collects upward supply bids and downward demand bids. The market-clearing price and quantity are determined by the intersection of the supply and demand curves. The figure is illustrative and does not represent the actual market structure in the Netherlands.

Most energy companies are integrated, meaning they engage in both electricity production and retailing. However, in this paper, I assume wholesale and retail activities are independent and focus on retailing. Hence, Retail activity refers to energy companies purchasing electricity from the wholesale markets and reselling it to households, and Energy prices reflect the cost of producing and procuring electricity in wholesale markets. Another explanation is that energy companies consider wholesale electricity prices as the opportunity cost of serving households rather than selling in the wholesale markets.

The retail electricity bill includes not only the energy price but also a fixed grid cost charged by grid operators and taxes paid to the government. The energy price includes fixed delivery costs and volumetric prices based on net electricity consumption. Government taxes are levied on the volume of net electricity consumption, including energy tax and sustainable energy surcharge (ODE-heffing).[3] As energy is a basic need, each household receives a lump-sum tax refund. This refund is the same for

[3]ODE tax was collected to subsidize renewable investment from 2013 and has been canceled as a separate tax and included in the energy tax since 2023.

every household, independent of their electricity consumption, income, house type, and solar PV adoption status. Finally, the electricity bill is subject to a value-added tax (henceforth, VAT) of 21 percent.[4] As fixed costs are independent of the amount of electricity consumption and net metering, from now on, VAT included retail price R only refers to the volumetric retail price (hence energy price r, plus taxes) and excludes fixed delivery and grid costs, and tax refund. Denote τ_e as the sum of energy tax and sustainable energy surcharge per kWh, and τ_v as VAT. The per unit tax on electricity consumption is defined as

$$\tau = r * \tau_v + \tau_e(1 + \tau_v) \tag{1}$$

The retail price per kWh is

$$R = r + \tau \tag{2}$$

Before 2022, 72% of the retail price was taxes and levies. Only 28% was for energy price. In 2022 and 2023, temporarily low taxes and high electricity prices reduced the ratio of taxes to 42%. See Figure 3.

In the Netherlands, the electricity bill is issued annually, while the settled price is determined based on the type of retail contracts. There are three types of retail contracts: fixed, variable,[5] and dynamic. The fixed contract charges a fixed retail price per kWh for a certain period between one to three years, while the variable contract has a variable price per kWh that changes twice to four times a year and can be canceled monthly.[6] The dynamic contract is new in the Netherlands, starting from the second half of the year 2022. It provides a price that changes daily or hourly based on the day-ahead wholesale electricity prices, plus a purchase fee per kWh. By the end of 2023, 27 out of 50 suppliers provide dynamic contracts. In total, 50% of households choose fixed contracts, 47% variable contracts, and only 3% dynamic contracts.

[4]VAT rate was 19% until October 2012 and temporarily reduced to 9% between July and December of 2022 because of the energy crisis.

[5]Model contract is a special variable contract that each energy company is obliged to offer, and the conditions of the model contract are the same across all suppliers so consumers are easy to compare and switch between different suppliers. However, the energy prices could differ. Besides model contracts, energy companies can also choose to offer other variable contracts that have different conditions and rates.

[6]Variable rates were adjusted on Jan 1 and July 1 until the energy crisis, when suppliers could adjust more frequently based on market conditions.

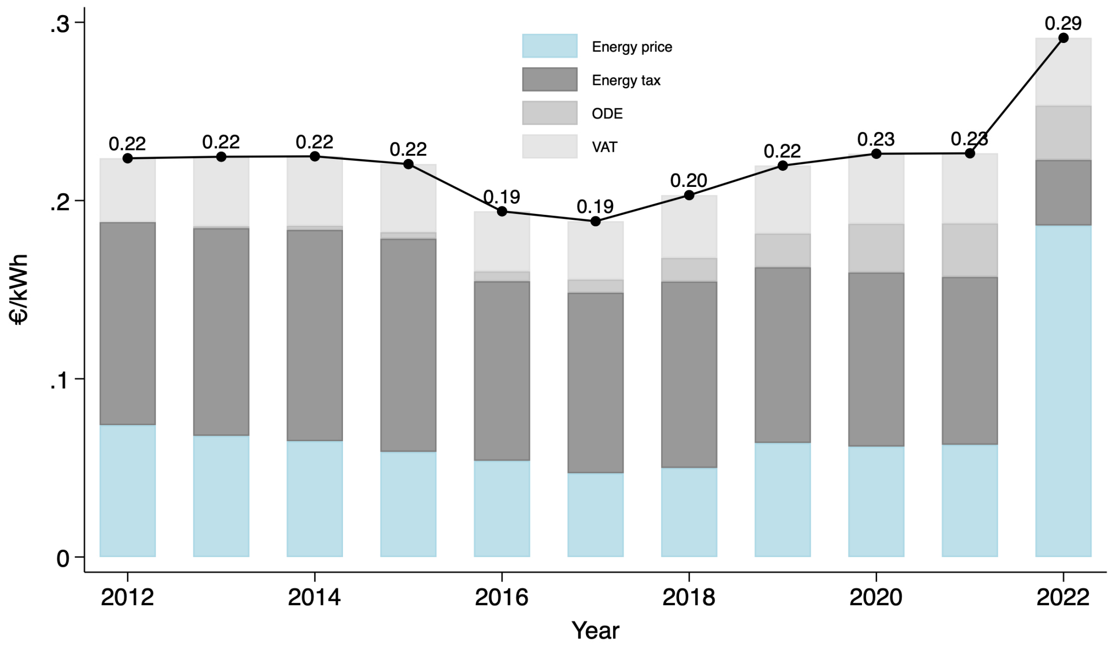


Figure 3: Retail Electricity Price (€/kWh)

Notes: This figure shows the average variable retail price and its breakdown in the Netherlands from 2012 to 2022.

2.3 Data

Several datasets are used for this research. First, I collected Dutch electricity day-ahead hourly wholesale electricity prices from 2015 to 2022. The day-ahead prices are publicly available from SMARD. Second, I obtained the average household grid consumption and feed-in profile from 2020 to 2022 at a 15-minute frequency from MFFBAS. I also have information on solar installation costs and retail electricity prices. Finally, I obtained household data from the Centraal Bureau voor de Statistiek of the Netherlands (henceforth: CBS). These data include household yearly electricity grid consumption, solar PV adoption, and electricity feed-in from 2019-2022. They also offer socio-demographic attributes and dwelling characteristics such as residence type and surface areas.

PV Costs and Adoption Residential solar PV installation costs consist of solar PV module costs, inverter costs, labor costs, and other material and operating costs. Until 2023, households paid VAT of 21% when purchasing solar panels, but this tax could be fully reclaimed. Since 2023, there has been no VAT on solar panels unless someone gets roof-integrated PV panels when buying a newly built house. In this case, solar panels are considered part of the roof and need to be paid VAT. The PV installation costs vary according to the type of PV modules and the roof. For instance, Monocrystalline cells have higher efficiency and are 20-30% more expensive than standard polycrystalline cells. Installing solar panels on a sloping roof is more costly than a flatter one. Furthermore, as module costs have dramatically decreased in the past few years, labor costs take a larger share in the breakdown of installation costs. Since labor costs and operating costs do not linearly increase with PV capacity, residential solar benefits from economies of scale, reducing the cost per unit when installed panels increase. Figure 4 depicts the simple average price per watt-peak (Wp)[7] from 2012-2022.[8] The Netherlands has witnessed a steady growth in residential solar PV adoption. See Figure 5. The soaring electricity prices in 2022 led to a substantial installation surge. Up to 2022, the number of residential solar PV adoption was 2129616, accounting for 26.23% of the total Dutch households.

Grid Consumption and Feed-in Profiles The grid consumption profile measures how much electricity a household draws from the grid over time, and the feed-in profile refers to how much surplus electricity from residential solar is fed back into the grid. I focus on the electricity grid consumption and feed-in profiles provided by MFFBAS for small-scale consumers who have a connection of 3x25 Ampère or lower.[9] The profiles represent 15-minute intervals over an entire year, and separate profiles are available for households with and without solar panels.

MFFBAS collects power flow data every fifteen minutes, so there are 35040 or 35136 samples each year. Then, MFFBAS sums the flow data and publishes the fraction of the total for each quarter hour. Hence, the fraction for each profile sums up to one. Figure 6 aggregates the profiles into hourly and monthly levels. For instance, the feed-in fraction from 1 to 2 p.m. is 0.145, meaning this one hour contributes to 14.5% of the total feed-in. Similarly, the feed-in fraction in June is 0.156, meaning this month accounts for 15.6% of the total feed-in.

The feed-in profile exhibits evident daily and seasonal patterns, peaking in the afternoon and summer. On the other hand, grid consumption is higher in the evening

[7]watt-peak measures the maximum power of a solar panel. For instance, one kWp can generate 1 kWh on an ideally sunny hour. However, depending on local weather conditions and solar panel deterioration, one kWp generates less than 1 kWh in one hour.

[8]Milieu Centraal did the market research once every two years and made a linear regression based on all the data collected in the previous years. After consulting with Milieu Centraal, the mean price between survey years is a good approximation of skipped years. The prices in the years 2013, 2015, 2017, and 2019 are estimated data.

[9]99.42% Residential consumers are in this group.

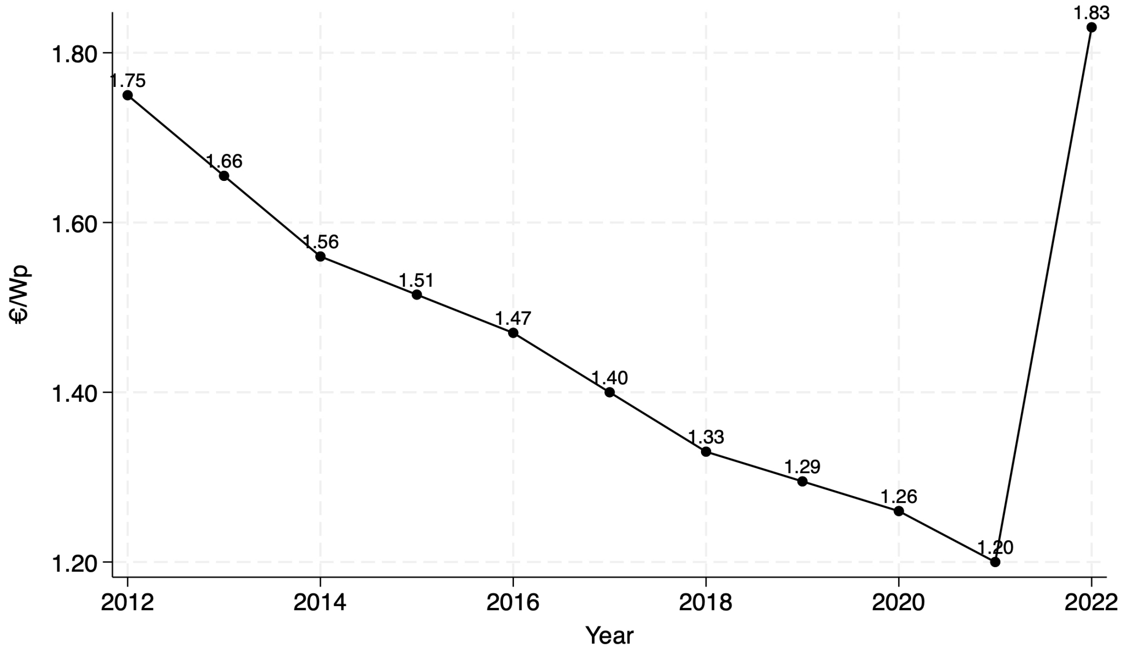


Figure 4: Residential Solar PV Installation Cost (€/watt-peak)

Notes: This figure shows the average price (VAT excluded) of residential solar installation per watt-peak from 2012 to 2022. Data are sourced from Milieu Centraal.

and winter. A typical daily consumption profile has two peaks. One is around 8:00 AM., when people wake up and start to work, while solar electricity takes a small share of total production. The other one is at 7:00 PM., after sunset, and the demand for lighting increases. Furthermore, grid consumption profiles differ between PV adopters and non-adopters because PV adopters can directly use part of the electricity produced by solar panels, resulting in a smaller share during the afternoon and summer.

Household Data A full sample of over 32 million household data is available from 2019 to 2022. It is expressed as unbalanced panel data. To accurately merge the household demographic attributes and energy data, I made a series of sample restrictions. First, I dropped the households that moved within a year. Also, I dropped the households with unverified electricity consumption. Furthermore, households with PV capacity larger than 10kWp were removed to rule out commercial PV systems. Finally, I dropped the households that shared the same dwelling since assigning dwelling-based electricity grid consumption and feed-in to each household was impossible. 21648328 observations remain.

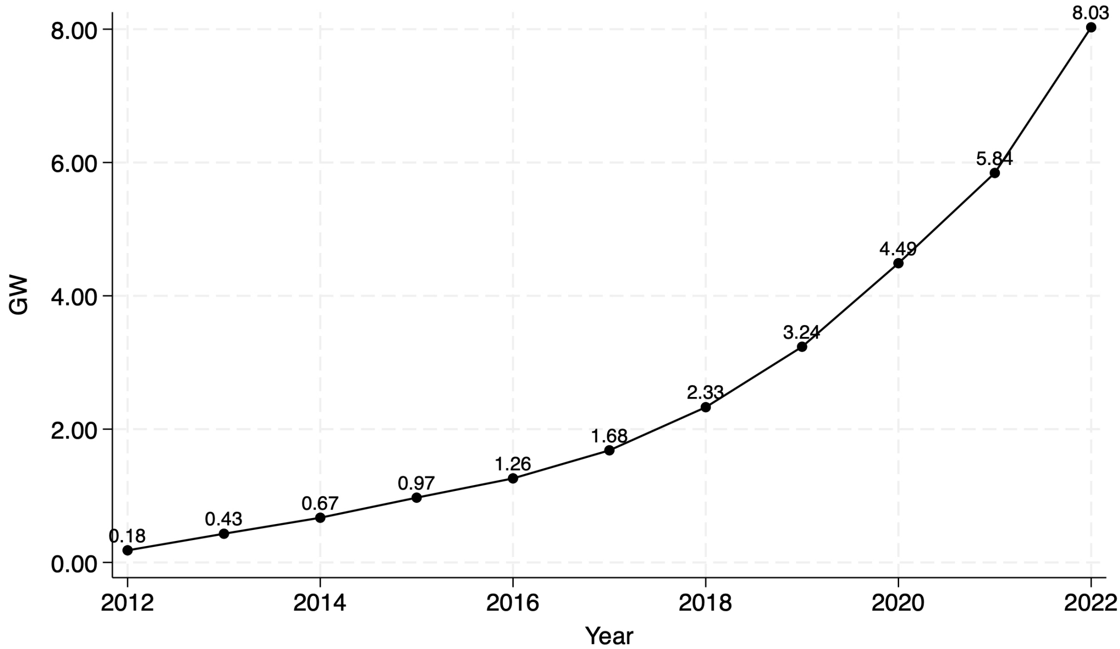
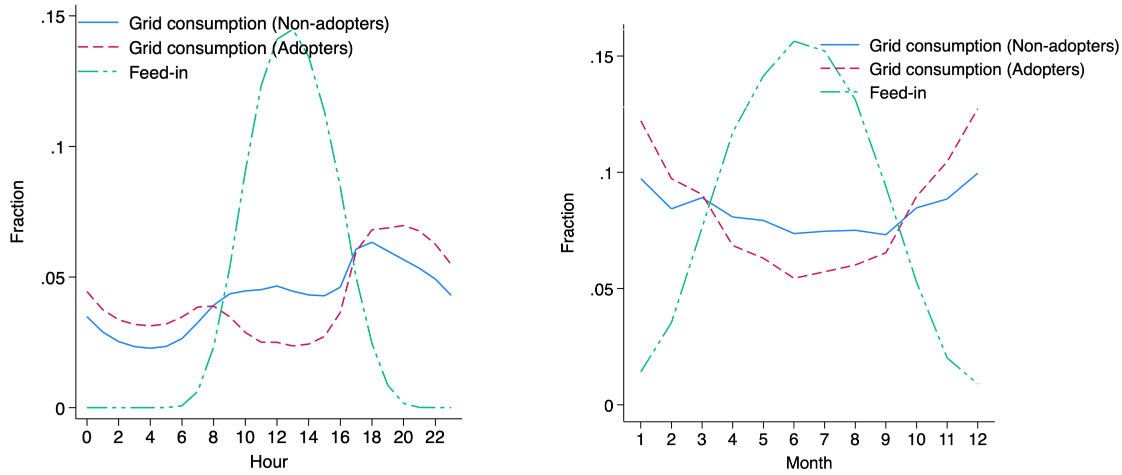


Figure 5: Residential Solar PV Capacity

Notes: This figure shows the total installed residential solar from 2012 to 2022, published by CBS. The number is accumulated capacity at the end of the specified year.

With growing residential solar, the average electricity grid consumption and feed-in have changed over time. Table 2 gives descriptive statistics at the end of 2022. In total, there are 5455953 households in the sample, and 1493037 adopted solar panels. The average electricity grid consumption is 2623kWh per household, while the average electricity feed-in among PV adopters is 1909kWh. All households are classified into five wealth quintiles: the first quintile represents the bottom 20% of households (poorest), while the fifth quintile represents the top 20% (wealthiest). PV Adoption varies significantly across different wealth quintiles. The average adoption rate is 27%,[10] from 15% for the poorest households and 39% for the wealthiest ones. There are two main reasons to explain distinct adoption rates. First, high-income households have fewer financial constraints and can bear high installation costs. Second, homeowners are more likely to install residential solar than tenants. 98% of the wealthiest households are homeowners, while only 4% of households of the first wealth quintile live in their own house.

[10]The adoption rate across the Netherlands is 26.23%. Hence, the sample used in this paper is representative.



(a) Hourly Profile **(b)** Monthly Profile

Figure 6: Grid Consumption and Feed-in Profile

Notes: This figure shows the average electricity grid consumption and feed-in profiles for Dutch households from 2020 to 2022. quarter-hourly data are collected from MFFBAS and summed up at monthly and hourly levels.

3 PV Adoption Model

In this section, I propose a static two-level nested logit model[11] for residential solar PV adoption under the net metering policy.

Each year, a household denoted by i either chooses to install one of the solar panel capacities $j = 1, ..., 5$ or not adopt $j = 0$. Each j only differs in capacity sizes, and there are five types. $j = 1$ refers to capacity less than 2kWp, $j = 2$ includes the capacity between 2 to 4kWp, and for every subsequent category, each represents a 2kWp increment. All solar panel types are classified into *adoption* group, with nesting parameter σ capturing the correlation of utilities that consumers experience among different types in the group. Furthermore, within the adoption group, solar panel types are divided into two subgroups, $g = S, L$. S stands for small capacity subgroup, $G_S = \{1, 2\}$, and large capacity subgroup L includes the remaining sizes $G_L = \{3, 4, 5\}$. There are two reasons for introducing two-level nests. First, PV adoption can be seen as a sequential decision process. Households first decide whether to adopt based on physical feasibility and financial situation. If they choose to adopt, they determine a rough PV capacity considering the rooftop surface and electricity

[11]The results indicate that a static model is sufficient, and a dynamic model does not significantly improve the model. This aligns with the fact that module prices have significantly declined, so the waiting value is low.

Table 2: Summary Statistics

	N Obs	All	< 20%	20 – 40%	40 – 60%	60 – 80%	> 80%
Dispo-income (€)	5,455,953	50581	31,466	32,811	52,408	57,505	71,833
grid consumption (kWh)	5,455,953	2623	2157	1964	2711	2858	3236
Feed-in (kWh)	5,455,953	522	190	224	500	692	883
Surface Area (m^2)	5,455,953	118	84	87	110	129	166
Ownership (%)	5,455,953	62	4	6	80	97	98
Adoption (%)	5,455,953	27	15	17	27	35	39
PV Capacity (kW)	1,493,037	3.62	2.53	2.54	3.63	3.79	4.18
Feed-in (kWh)	1,493,037	1909	1279	1334	1837	2006	2278

Notes: This table gives Dutch households the average PV adoption rate, adopted capacity, disposable income, electricity grid consumption and feed-in for 5 wealth quintiles in 2022.

consumption. After that, they make a precise calculation and select a specific option. Additionally, a two-level nested logit model improves the model fit by allowing more flexible substitution patterns and reducing bias from unobserved correlations. The correlation parameters σ_g captures the dependencies in each subgroup. See Figure 7.

When net metering is applied, solar production up to the total electricity consumption is valued at the retail price, and each household takes full advantage by adopting a capacity size close to its gross electricity consumption. Adopting higher capacity is not profitable, as the compensation rate for surplus electricity is low compared to high installation costs. Data confirm this assumption. Regressing residential solar capacity with respect to lagged consumption gives an estimate that is not significantly different from 1. Therefore, this paper explores electricity consumption as the primary source of variation in identifying the estimates discussed later.

Starting with 21648328 observations, the final sample used for adoption estimation is constructed as follows. First, I only keep households that did not move from 2019 to 2022. I impose this restriction because PV adoption entails a long-term future production and income stream, and residing in the same dwelling helps predictability. Second, I assume the potential PV adopters are only those without solar systems and owning a house. Although some rental houses are also equipped with solar panels, it is difficult to argue whether the decision is made by agencies, landlords, or tenants. Also, Since solar PV adoption is a terminal action, the households installed in year y are removed from the potential market in year $y+1$. Furthermore, based on observed data, households with a consumption of less than 1000kWh are not considered potential PV adopters and are removed from the sample. Finally, identifying PV adoption in 2019

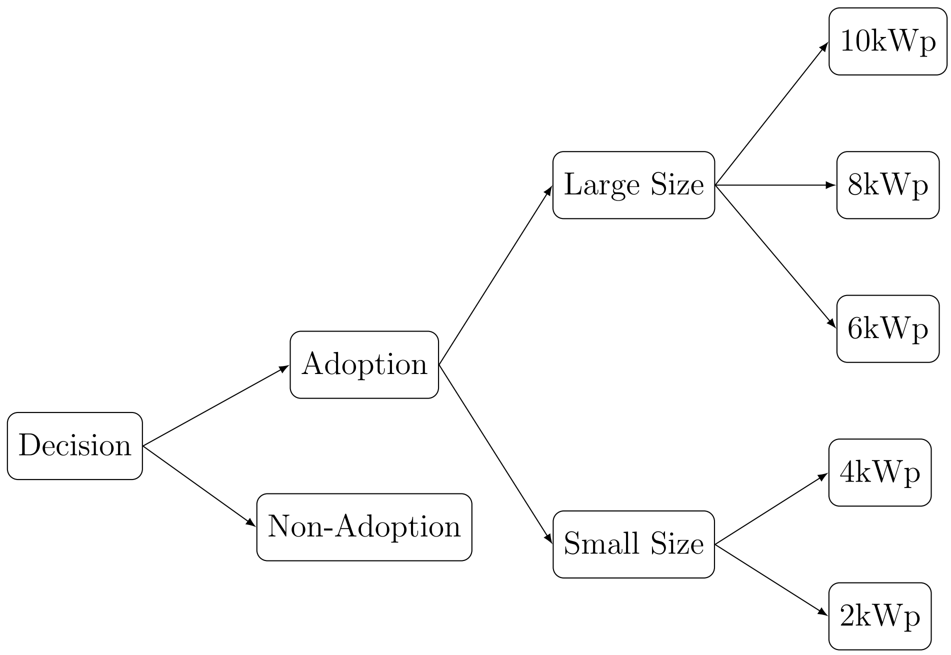


Figure 7: Nested Model Tree Diagram

is impossible as I cannot distinguish whether an adopter installed a solar system in 2019 or before 2019. Therefore, only data from 2020 to 2022 are used for estimation. Applying all the restrictions leaves me with a sample with 3296760 observations.

Although household data are available, estimating a two-level nested logit model through log-likelihood maximization is challenging and highly sensitive to initial values. Hence, I employ Berry's inversion to simplify the estimation process, which needs market shares as variables. Specifically, all households in the sample are divided into $N \times M \times L$ markets. $L = 3$ is the number of years, and each year is denoted by y. There are $N = 5$ electricity consumption categories (1000-2000kWh, 2000-3000kWh, 3000-4000kWh, 4000-5000kWh, >5000kWh). To obtain reliable estimates while preserving variability, I use a spatial variation and $M = 331$ is the number of municipalities.[12] See Figure 8. The consumption category is determined by one-year-lagged electricity consumption and is unlikely to change quickly. Hence, the market segmentation is exogenous. In market m, each household receives an idiosyncratic taste for adoption ζ_{imy}, for the products in subgroup ζ_{igmy}, and random taste shock ε_{ijmy}. ζ_{imy} and ζ_{igmy} follow the unique distribution proposed by Cardell (1997) such that $\zeta_{imy} + (1-\sigma_g)\zeta_{igmy} + (1-\sigma)(1-\sigma_g)\varepsilon_{ijmy}$ and $\zeta_{igmy} + (1-\sigma)(1-\sigma_g)\varepsilon_{ijmy}$ are both type I extreme value random variables. The households within the same market

[12] This approach involves some arbitrary decisions. Alternative methods, such as further subdividing electricity consumption groups, could also be explored.

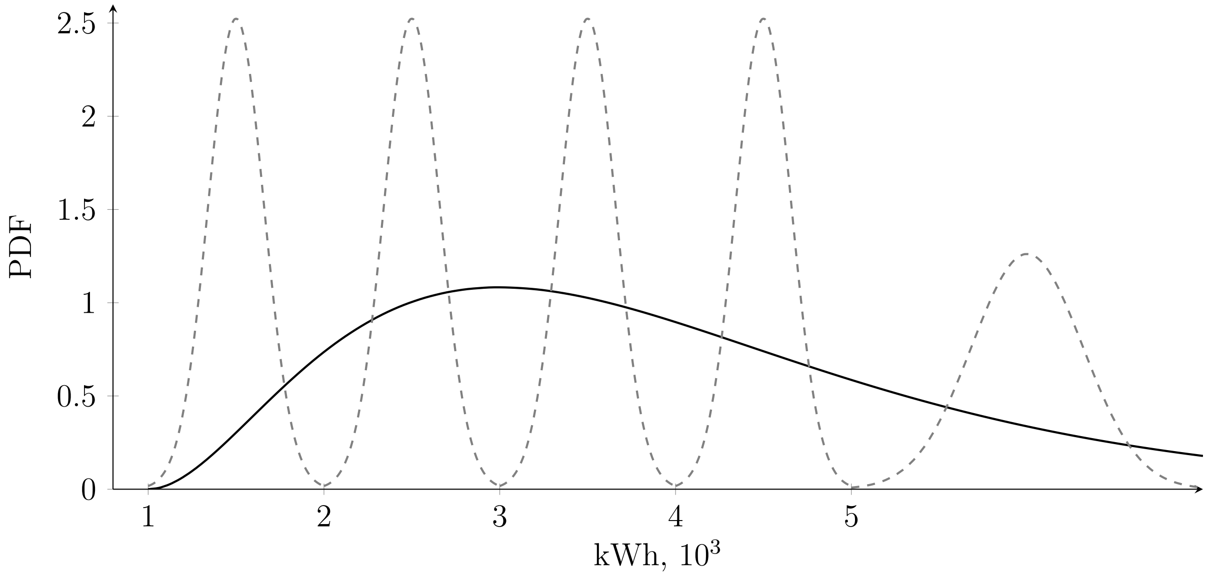


Figure 8: Electricity Consumption Distribution

Notes: The solid line describes electricity consumption distribution by households, which are categorized into five electricity consumption groups. In each group, the dashed line is constructed by municipality-level samples, the variation of which is utilized in the estimation. The figure is illustrative and does not represent the actual distribution.

are homogenous except for the individual shock.

Value of Adoption The utility function of adoption is:

$$u_{ijmy} = \delta_{jmy} + \zeta_{imy} + (1-\sigma_g)\zeta_{igmy} + (1-\sigma)(1-\sigma_g)\varepsilon_{ijmy} \tag{3}$$

The conditional value of household i for capacity type j is:

$$\delta_{jmy} = \boldsymbol{x_{jmy}\gamma} - \beta p_{jmy} + \xi_{jmy} \tag{4}$$

p_{jmy} represents the negative net present value (-NPV), which is equal to the solar panel installation costs, subtracted by the future flow benefits from net metering and excess electricity sale at a low compensation rate p_{cy}, which is exogenously set as 80% of the energy price agreed upon between households and the energy company excluding taxes.

$$p_{jmy} = K_j p_{Iy} - \sum_{k=y}^{y+24} \rho^{k-y}(1-\pi)^{k-y}\left(R_y \min\{C_{m,y-1}, Y_{jky}\} + p_{cy}\max\{Y_{jky} - C_{m,y-1}, 0\}\right) \tag{5}$$

The variation across different markets is explored through electricity consumption discussed before. Since grid consumption rather than total electricity consumption is recorded, I use one-year lagged consumption $C_{m,y-1}$ and assume it will not significantly change over time.[13] Denote p_{Iy} as the installation cost per kWp, and R_y as the yearly average retail price. Solar panel installation costs differ among solar companies and the specific installation time, data of which are not available. Retail electricity prices also depend on the energy company and the month when the energy contract is signed. However, as the solar panel market and the electricity retail market are competitive, the cross-sectional price difference should not raise an issue. Furthermore, even though I do not have rich data on time variation, the yearly adoption, yearly average retail price, and yearly installation show a consistent pattern, and fully exploring the cross-section variation across different markets is sufficient for model estimation. Solar panel installation benefits from economies of scale, reducing the cost per unit as installation capacity increases. I calibrate that, compared to the smallest capacity size, the capacity 2-4 kWp offers a 40% reduction in unit price, to increase capacity to 4-6 kWp offers a 12% reduction in unit price, and the further upgrade of one capacity type leads to a 5% reduction in unit price.

$Y_{jky} = (1-\lambda)^{k-y}\iota K_j$. K_j is taken as the median capacity level of each type j. The life span of solar panels is set as 25 years. ι is solar efficiency that measures how effectively the panel converts solar energy into electricity, expressed as a percentage of the actual power production to its capacity, kWp/Wp. The calibration in Appendix A yields $\iota = 0.91$. Hence, in the Netherlands, 1kWp of PV capacity can, on average, produce 910kWh per year.[14] λ is the solar panel's depreciation factor, which is set to be 3% in the first year and 0.7% afterward, according to Feger et al. (2022). Also, I assume households cannot predict the retail price trends; hence, R_y and p_c are constant. I follow De Groote and Verboven (2019) and set the yearly discount factor $\rho = 0.85$, equivalent to a 7-year payback period. $\pi = 3\%$ is the inflation rate borrowed from a wide range of literature and close to the actual average inflation rate in the Netherlands.[15] See Table 3 for the summary of parameters.

$\boldsymbol{x_{jmy}}$ is a vector of characteristics of PV type j. As all types are different in

[13] Energy efficiency has been a significant topic in recent years and could potentially influence households' consumption levels. However, this complexity is beyond the scope of this paper. Furthermore, this paper assumes that households are unable to predict future changes and that decisions are made based on the current consumption level. This assumption also implies that households' electricity consumption remains unchanged regardless of solar PV adoption.

[14] The solar efficiency typically ranges from 0.85 to 0.95, depending on weather conditions and module efficiency.

[15] The average yearly inflation rate in the Netherlands from 2012 to 2022 is 2.47%. The yearly inflation rates from 2019 to 2022 are 2.67%, 1.11%, 2.82% and 11.62% respectively. The low inflation in 2020 caused by COVID-19 and the exceptionally high inflation in 2022 driven by the energy crisis are unsustainable and unrepresentative.

capacity sizes, I only include the fixed effect of the adoption and the indicator for 2022. And this is sufficient to explain the adoption decision. An interaction term between the year indicators and price, $\mathbf{1}\{y = 2022\} \times p_{jmy}$, is also included to investigate the preference change before and after the energy crisis in 2022. Other fixed effects, such as house size and household size, are highly correlated with electricity consumption $C_{m,y-1}$, and hence not included.

Table 3: Summary of Sources of Parameters

Parameter	Definition	Value	Source
ι	Solar efficiency	0.91	This paper
ρ	Discount factor	0.85	De Groote and Verboven (2019)
λ	Depreciation factor	0.03, 0.007	Feger et al. (2022)
π	Inflation rate	0.03	Literature

Market Share In deriving expressions for the market share of each type $j = 0, 1, ..., 5$, the following equations are useful:

$$I_{gmy} = (1 - \sigma_g) \log \sum_{l \in G_g} \exp \left(\frac{\delta_{jmy}}{1 - \sigma_g} \right) \tag{6}$$

$$I_{my} = (1 - \sigma) \log \sum_{g} \exp \left(\frac{I_{gmy}}{1 - \sigma} \right) \tag{7}$$

I_{gmy} and I_{my} are the inclusive values representing the composite utility of a group of options. Intuitively, I_{gmy} captures the desirability of the subgroup g, and I_{my} evaluates the attractiveness of adopting solar panels. The *predicted market share* of each alternative takes a well-known closed-form expression,

$$s_{jmy}(\delta_{jmy}) \equiv \frac{\exp\left(\frac{\delta_{jmy}}{1-\sigma_g}\right)}{\exp\left(\frac{I_{gmy}}{1-\sigma_g}\right)} \cdot \frac{\exp\left(\frac{I_{gmy}}{1-\sigma}\right)}{\exp\left(\frac{I_{my}}{1-\sigma}\right)} \cdot \frac{\exp(I_{my})}{1 + \exp(I_{my})} \tag{8}$$

The three parts of equation (8) are the share of each type j conditional on subgroup g selected, the share of each subgroup g conditional on adoption, and the share of adoption. The conditional utility of not adopting is normalized to zero, $\delta_{0my} = 0$. Next, I follow the approach of Berry (1994) to equate the predicted market share to the observed market share, $s_{jmy}(\delta_{jmy}) = S_{jmy}$. By the fact that $s_{jmy}(\delta_{jmy})/s_{0my}(0) = S_{jmy}/S_{0my}$ for $j = 1, 2, ..., 5$, to invert the market share and take logs gives the main regression equation,

$$\ln\left(\frac{S_{jmy}}{S_{0mt}}\right) = \boldsymbol{x_{jmy}\gamma} - \beta p_{jmy} + \sigma_g \ln\left(\frac{S_{jmy}}{S_{gmy}}\right) + \sigma \ln\left(\frac{S_{gmy}}{\sum_g S_{gmy}}\right) + \xi_{jmy} \quad (9)$$

Endogeneity and Instruments The investment cost p_{Iy} and retail energy price r_y can relate to unobserved shock ξ_{jmy} and make the price variable p_{jmy} endogenous. To address this issue, I follow De Groote and Verboven (2019) to use the price index of Chinese PV modules on the European market p_{My} to instrument p_{Iy}. Retail energy price is instrumented by lagged wholesale electricity price $p_{s,y-1}$.[16] Furthermore, I construct the discounted future income computed with exogenous variables:

$$w_{jmy} = \sum_{k=y}^{y+24} \rho^{k-y}(1-\pi)^{k-y}\left(\tau_y \min\{C_{m,y-1}, Y_{jky}\} + p_{s,y-1}Y_{jky}\right) \quad (10)$$

If price is endogenous, market shares may also be endogenous. I add the exogenous price deviation from the mean as instruments for within subgroup share S_{jmy}/S_{gmy} and subgroup share conditional on adoption $S_{gmy}/\sum_g S_{gmy}$,

$$Z_{jgmy} = (p_{My} * K_j - w_{jmy}) - \sum_{j\in G_g} \frac{p_{My} * K_j - w_{jmy}}{|G_g|} \quad (11)$$

$$Z_{gmy} = \sum_{j\in G_g} \frac{p_{My} * K_j - w_{jmy}}{|G_g|} - \sum_{j} \frac{p_{My} * K_j - w_{jmy}}{|j|} \quad (12)$$

Hence, the instrument set is $\{p_{My}, p_{s,y-1}, \tau_y, w_{jmy}, Z_{jgmy}, Z_{gmy}\}$.

4 Empirical Results

4.1 Main Findings

Table 4 provides the summary statistics of the main variables used for adoption estimation. There are 4965 markets, with an average of 664 households in each market. Each market has 5 types of capacity sizes, resulting in 24825 observations. The average adoption rate, defined as adoption over potential market size, is 8.91% across all markets. The capacity between 2 to 6 kW is the most popular, accounting for 80.47% of total adoption.

[16] Before the energy crisis, retail contracts are typically signed for half to three years, leading to co-movements between lagged wholesale and retail prices. See Appendix B.

Table 4: Summary of Main Variables

	Notation	N Obs	Mean
Consumption (kWh)	$C_{m,y-1}$	4965	3657
Adoption rate (%)	S_{my}	4965	8.91
0-2kW	S_{2my}	4965	0.3
2-4kW	S_{2my}	4965	3.69
4-6kW	S_{3my}	4965	3.48
6-8kW	S_{4my}	4965	1.09
8-10kW	S_{5my}	4965	0.36

Notes: The total number of observations is 24825 = 4965 market × 5 capacity sizes. $S_{my} = \sum_j S_{jmy}$.

An IV OLS regression is used to estimate the regression equation (9).[17] Table 5 reports the results of the coefficients $-\beta, \sigma, \sigma_g$. The underlying price variable is rescaled in €1000. There are three specifications. In column (1), a standard multinomial logit model is estimated, assuming all capacity types are independent. In column (2), I added a dummy for 2022, when electricity prices were exceptionally high. Moreover, I add an interaction term between the year 2022 and price variable p_{jmy}. In column (3), a two-level nested model is considered. Although all three specifications show a negative result of the adoption price, a nested logit model fits much better. The correlation among five capacity sizes is estimated to be 0.613. The capacities within each subgroup have a higher correlation, indicating consumers are more likely to substitute among closer capacity sizes. The dummy variable year 2022 has a positive fixed effect, showing that consumers find it more valuable to invest in solar systems when shocked by rocketing energy prices in 2022 as they took solar panels to hedge against future increases in electricity prices. However, after controlling the year effect, I do not observe a significant change in price sensitivity in 2022. Finally, the fixed effect of solar PV adoption is negative, suggesting inherent resistance to adoption when the financial benefits are neutral (NPV = 0). There are some potential explanations. For example, people have inertia and tend to stick with existing energy sources rather than proactively adopting new technologies. Also, people are risk-averse and uncertain about future electricity prices and policies. The absence of an intrinsic preference for solar PV adoption highlights the crucial role of financial incentives.

The predicted market shares are calculated by substituting the estimated parameters into equations from (4) to (8). Across all markets and capacity sizes, the model

[17] Zero adoption in some markets is replaced with a very small value.

Table 5: Estimation Results

	(1)	(2)	(3)
Price sensitivity (in 10^3 EUR, $-\beta$)	-1.615***	-1.837***	-0.771***
	(0.118)	(0.171)	(0.121)
Group correlation (σ)			0.613***
			(0.128)
Subgroup correlation (σ_S)			0.741***
			(0.049)
Subgroup correlation (σ_L)			0.678***
			(0.047)
Year 2022		3.183***	1.680***
		(0.359)	(0.221)
Price × Year 2022		0.070	0.017
		(0.107)	(0.087)
Constant	-2.937***	-3.621***	-2.760***
	(0.605)	(0.587)	(0.129)
N Obs	24825	24825	24825
R^2	0.333	0.534	0.920

Notes: For all three specifications, standard errors in parentheses are clustered at the municipality and capacity size level.

predicts the adoption rate from 2020 to 2022 as 5.01%, 5.63%, and 10.85%, while the actual adoption rate is 6.37%, 7.42%, and 11.84%, respectively. On average, the model predicts 83.73% of actual adoptions. The model also predicts the share of subgroup and each capacity size well. See Table 6.

4.2 Counterfactual Adoption Patterns

In this part, I first derive how net metering incentivizes residential solar PV adoption and the substitution effects across different PV capacity. Then, I give counterfactual adoption rates under different scenarios, using the results from Table 5. To start, it

Table 6: Prediction Results (%)

	2020		2021		2022	
	Predict	**Actual**	**Predict**	**Actual**	**Predict**	**Actual**
Adoption Rate	5.01	6.37	5.63	7.42	10.85	11.84
Small Group	2.40	3.82	2.53	3.96	5.57	5.40
0-2kW	0.19	0.33	0.20	0.25	0.17	0.35
2-4kW	2.21	3.49	2.33	3.71	5.40	5.05
Large Group	2.61	2.55	3.10	3.46	5.28	6.44
4-6kW	1.74	2.01	1.97	2.70	3.94	4.59
6-8kW	0.77	0.43	0.98	0.59	1.15	1.37
8-10kW	0.10	0.11	0.15	0.16	0.19	0.49

Notes: This table gives PV adoption rates based on based on the estimated coefficients and actual PV adoption rates in the data. All numbers are in percentage.

is useful to rewrite the negative net present value as

$$\begin{aligned} p_{jmy} = K_j p_{Iy} - R_y \sum_{k=y}^{y+24} \rho^{k-y}(1-\pi)^{k-y} \min\{C_{m,y-1}, [\alpha + (1-\alpha)\eta]Y_{jky}\} \\ - p_{cy} \sum_{k=y}^{y+24} \rho^{k-y}(1-\pi)^{k-y} \max\{Y_{jky} - C_{m,y-1}, (1-\alpha)(1-\eta)Y_{jky}\} \end{aligned} \tag{13}$$

η is the proportion of the feed-in that can offset grid consumption. The current policy is $\eta = 1$. α is the self-consumption rate, which refers to the proportion of electricity produced by a solar panel system that is directly used by the household. The calibration in Appendix A gives $\alpha = 0.33$ under the current net metering policy, suggesting that households, on average, directly use 33% of electricity produced by residential solar systems. Take the derivative with respect to η gives,

$$\frac{\partial p_{jmy}}{\partial \eta} = -\frac{1-(\rho')^T}{1-\rho'}(R_y - p_{cy})(1-\alpha)\zeta K_j < 0 \tag{14}$$

where

$$\rho' = (1-\pi)(1-\lambda)\rho \tag{15}$$

$T \leq 25$ is the year when the sum of self-consumption and the amount of feed-in that can be offset is lower than total electricity consumption, which is determined such that $Y_{j,T,t} < C_{m,y}/[\alpha + (1-\alpha)\eta] < Y_{j,T+1,t}$. When $T = 0$, all solar production can be compensated at retail price, indicating that net metering does not affect the incentive.

A narrower difference between retail and compensation prices, $R_y - p_{cy}$, also reduces the impact of net metering.

Under the current net metering policy, the net present value is independent of the self-consumption rate. That is, $\frac{\partial p_{jmy}}{\partial \alpha} = 0$ if $\eta = 1$. Hence, households have no incentive to proactively increase the self-consumption rate or adopt batteries. When net metering is partially or fully removed, the self-consumption amount retains the benefit of the retail electricity price, while the surplus fed back into the grid is valued only at a compensation rate. Ideally, when PV adopters directly consume all the produced power, $\alpha = 1$, abolishing the net metering policy does not impact the adoption decision, as households receive no benefits from grid "credits".

Finally, a large-capacity solar panel feeds more electricity to the grid and would be affected more by the removal of the net metering policy when feed-in is sold at a low compensation price. Hence, a large capacity becomes less attractive compared to a smaller one. The comparative statics are summarized in corollary 1.

corollary 1. *Comparative statics:*

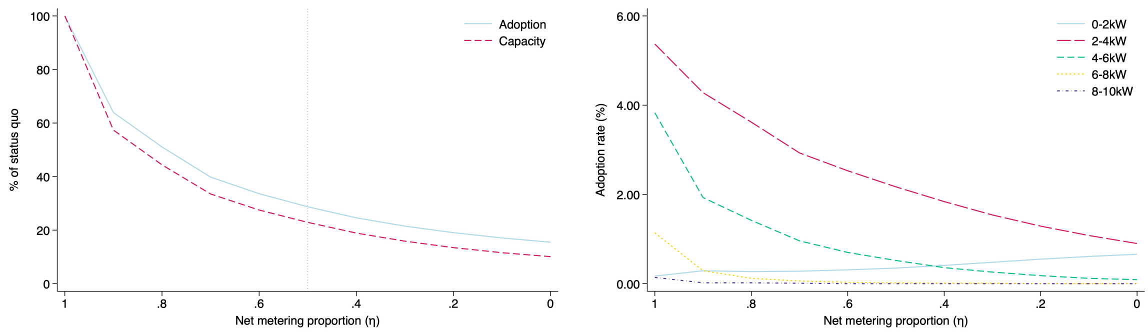
- $T = 0$, $\frac{\partial p_{jmy}}{\partial \eta} = 0$;
- $\frac{\partial p_{jmy}/\partial \eta}{\partial K_j} > 0$
- $\frac{\partial p_{jmy}/\partial \eta}{\partial \alpha} < 0$

The market share of each capacity size changes with η as follows,

$$\frac{\partial s_{jmy}}{\partial \eta} = \frac{-\beta}{1-\sigma_g} s_{jmy} \left(\frac{\partial p_{jmy}}{\partial \eta} - \frac{\sigma_g - \sigma}{1-\sigma} \sum_{l \in G_{g_j}} s_{j|G_{g_j}} \frac{\partial p_{lmy}}{\partial \eta} - (1-\sigma_g) \sum_{l} s_{lmy} \frac{\partial p_{lmy}}{\partial \eta} \right.$$
$$\left. - \frac{1-\sigma_g}{1-\sigma} \sum_{g} s_g \sum_{l \in G_{g_j}} s_{j|G_{g_j}} \frac{\partial p_{lmy}}{\partial \eta} \right) \tag{16}$$

G_{g_j} is the group g to which j belongs. Since each capacity size is a substitute for each other, the change in market share of type j does not only depend on its own price p_{jmy} but also the price of other types, especially those that fall into the same nest. By corollary 1, while reducing the proportion of net metering increases the price for all capacity sizes, larger capacities are more significantly impacted, potentially leading to a larger market share for smaller capacity sizes. See Figure 9b.

Figure 9a shows the counterfactual adoption rate and capacity in 2022 when η decreases from 1 to 0 with a fair compensation rate equal to the wholesale electricity price weight by the feed-in profile. The result is based on a pessimistic scenario where households do not change consumption behavior.[18] Note that retail price R_y is not exogenously given but endogenously determined by the total installed PV capacity and the proportion of net metering. The details will be discussed in Section 5. Compared to the *status quo* of full net metering, completely abolishing the policy reduces the installation rate to 1.65%, and 94.55% of new PV adopters select small-capacity panels rather than those sized to electricity consumption. Consequently, the newly installed capacity decreases by 89.90%. A gradual decrease of η from 1 to 0 shows a nonlinear decline in adoption rates. It significantly hurts incentives in the beginning and then levels off. A 50% compensation proportion predicts an adoption rate of 3.06%, and the installed capacity decreases by 78.09%, suggesting that partial compensation provides little adoption incentive.



(a) Adoption and retail price **(b)** Adoption of different capacity sizes

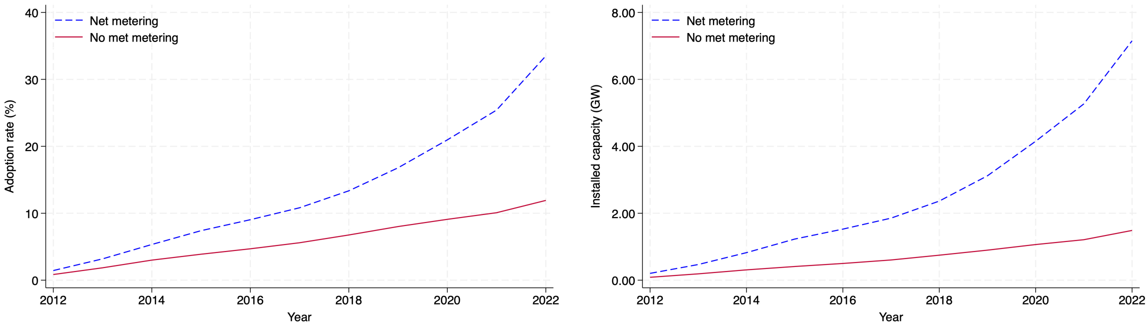
Figure 9: Counterfactual of Net Metering Proportion

Notes: The left panel (9a) illustrates how the solar PV adoption vary with the proportion of net metering η, and the right panel (9b) shows how the five capacity sizes vary with η. Both panels show the counterfactual in 2022.

Figure 10a gives the accumulated adoption rate from 2012 to 2022, with and without a net metering policy. Since household data before 2019 is unavailable, I assume that electricity consumption and wealth distribution in potential markets from 2012 to 2018 are not significantly different from those in 2019, while the market size is scaled.[19] The model shows that 33.5% of the potential market adopts solar panels

[18]It is crucial to fixate the self-consumption ratio over consumption rather than production, as the total electricity consumption remains unchanged regardless of the installed solar PV capacity.

[19]Even if net metering came into effect in 2004, high solar module costs made solar panels unattractive. The installed capacity in 2012 was 182MW and only accounted for 0.95% of total Dutch households. Therefore, starting in 2012 should not raise a concern. Additionally, a feed-in tariff was implemented in parallel until 2012, and ignoring the periods before ensures that the effects of net



(a) Adoption rate **(b)** Installed capacity

Figure 10: Solar PV Adoption With and Without Net Metering

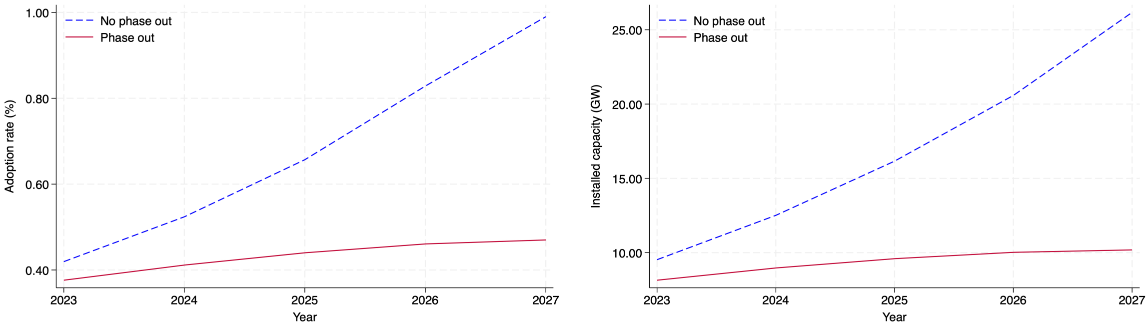
Notes: This figure gives the accumulated residential PV adoption rate and capacity from 2012 to 2022 in the Netherlands, with and without a net metering policy.

under the current net metering policy, which drops to 11.92% in the counterfactual scenario when $\eta = 0$. As discussed earlier, capacity sizes are more significantly impacted, with the net metering policy accounting for 79.21% of the total installed capacity up to 2022.

Figure 11 provides the predicted residential solar adoption rate and capacity, comparing the scenario where net metering continues versus phase-out in 2027. The average solar installation cost is €1.24/Wp and remains constant for five years. Assume that the government determines tax rates and energy companies set energy prices at the beginning of a calendar year based on the installed residential capacity, grid consumption, and feed-in quantity. Wholesale electricity prices in 2022 were unpredictably high and could not be sustained. Hence, I used the wholesale electricity price in 2023 to calculate the energy cost, resulting in the retail electricity price equal to €0.294/kWh in 2023.[20] The installed renewable capacity in 2022 is substantial enough to result in zero or even negative prices during periods of high solar production, and the merit order effect from residential solar is negligible. Hence, I assume wholesale electricity prices are not affected by increased residential solar capacity in the predicted years. Prices during other periods, when solar production is low, are primarily influenced by gas prices, which are challenging to predict. Assuming a stable price pattern simplifies the analysis and allows for a focus on the net metering policy. However, it is worth noting that a sharp increase in gas prices, as seen in

metering are disentangled.

[20] I also used the electricity price in 2021 and the average price from 2015 to 2021. This does not affect the main insight but results in a slower installation path due to lower market prices before 2021.



(a) Adoption rate

(b) Installed capacity

Figure 11: Prediction of Solar PV Adoption

Notes: This figure gives the predicted accumulated residential PV adoption rate and capacity from 2023 to 2027 in the Netherlands, with and without the net metering phaseout in 2027.

2022, would likely drive more solar PV adoption, while lower gas prices could reduce adoption rates. Moreover, expanding storage capacity and other renewable energy sources, such as offshore wind, can affect the results.

The results indicate that if the net metering policy remains unchanged, the Dutch residential market could reach full saturation in 2027, with an expected installed capacity of 26.17 GW. However, since PV adopters require a long future income stream to cover the costs of installation payments, even signaling a phaseout could significantly decrease adoption incentives, lowering the adoption rate by 2027 to 47% and resulting in a substantially reduced capacity of 10.19 GW.

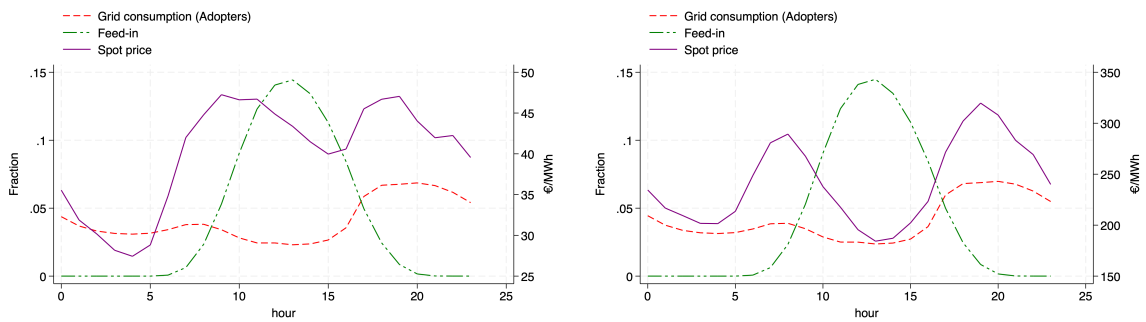
5 Externality and Distributional Effect

Although net metering plays a crucial role in fostering residential solar adoption, it is blamed for driving up retail electricity prices. In this section, I discuss the externality of net metering, defined as the difference in retail electricity price with and without a net metering policy. First, I provide a theoretical foundation for the mechanism through which net metering generates externality for households not adopting solar panels. Then, I estimate the retail price increase attributable to net metering.

5.1 Energy Price

Before discussing the externality of net metering policy, one essential fact to understand is that wholesale electricity prices are positively related to electricity consumption but negatively affected by solar PV production. When fossil fuels mainly produced electricity, wholesale electricity prices were high in the afternoon, and electricity feed-in was sold at a high price. The increasing solar capacity continues to help reduce electricity prices, and the oversupply results in a noticeable price dip in the afternoon. See Figure 12 the price pattern comparison in 2015 and 2022, when residential solar capacity expands tenfold. The same pattern can be found when the profiles are aggregated monthly that consumption is higher in spring and winter when the electricity price is higher, while solar production achieves its peak in summer. Recall that the wholesale electricity price is determined by marginal technology and, hence, is largely affected by gas prices, so seasonal effects are more complicated and less evident than hourly differences.

What mismatches here is that expensive electricity storage forces the energy company to buy electricity at a high price but to sell feed-in volume at a low price. Under net metering, PV adopters only pay for net consumption, so they can exchange their cheap feed-in with expensive grid consumption. In the extreme case when net consumption is equal to zero, a household is exempt from volumetric energy price r and only pays fixed delivery costs. The company has a net cost that cannot be reimbursed by PV adopters. While households with and without solar PV present distinct profiles, they are not price discriminated. Hence, energy companies have to increase energy prices to break even. This is where the externality arises.



(a) 2015 **(b)** 2022

Figure 12: Adopters' Profile and wholesale electricity prices

Notes: This figure shows the PV adopters' grid consumption and feed-in profiles, and the wholesale electricity prices. Quarter-hourly data are collected from MFFBAS and SMARD, and summed up hourly levels.

Now, I formulate the conclusions above. To disentangle the effect of net metering, I assume risk-neutral energy companies and abstract the model from renewable production uncertainty. There are two effects from this simplified model. First, energy companies do not benefit from risk hedging. Second, perfect prediction in the day-ahead market means energy companies do not pay imbalance costs (earn imbalance revenue) for the difference between actual solar production and predicted ones, which may underestimate (overestimate) the total costs. I focus on a one-year fixed retail contract, incorporating daily and monthly effects.[21] I drop the subscript for the year y as the energy price is implicitly calculated annually. Define $p_{d,h}$ the wholesale electricity price at hour h of day d, $X_{d,h}$ and $Z_{d,h}$ is the grid consumption and feed-in for the same time notation. $X = \sum_d \sum_h X_{d,h}, Z = \sum_d \sum_h Z_{d,h}$. $\mathbf{X} = \{X_{d,h}\}$ and $\mathbf{Z} = \{Z_{d,h}\}$ are the vector of grid consumption and feed-in. Under net metering, the weighted average price per kWh is computed as the sum of net consumption times wholesale electricity price across a year, divided by the total net consumption within a year. For brevity, I slightly abuse notation using the expected term to denote the empirical average and remove the subscripts d, h. Hence,

$$p(\text{net}) = \frac{\sum_d \sum_h p_{d,h}(X_{d,h} - Z_{d,h})}{X - Z} = \frac{E[\mathbf{p}(\mathbf{X} - \mathbf{Z})]}{E[\mathbf{X} - \mathbf{Z}]} \tag{17}$$

It is useful to separate the electricity grid consumption for non-adopters and PV adopters, $X = X_0 + X_1$. For the rest of the paper, I use subscript "0" to represent non-adopters and subscript "1" for PV adopters. Hence, X_0 is the grid consumption of non-adopters. X_1 is the grid consumption of PV adopters. X_1' is the net consumption of PV adopters, which is equal to the difference between grid consumption and feed-in, $X_1' = X_1 - Z$. As previously indicated, the bold notation represents the vector. Define $w = \frac{E[\mathbf{X_1'}]}{E[\mathbf{X_0} + \mathbf{X_1'}]}$ as the weight of PV adopters. Given $X_1' > 0$,[22]

$$\begin{aligned}
p(\text{net}) &= \frac{E[\mathbf{p}(\mathbf{X} - \mathbf{Z})]}{E[\mathbf{X} - \mathbf{Z}]} \\
&= \frac{E[\mathbf{p}\mathbf{X_0}]}{E[\mathbf{X_0}]} \frac{E[\mathbf{X_0}]}{E[\mathbf{X_0} + \mathbf{X_1'}]} + \frac{E[\mathbf{p}\mathbf{X_1'}]}{E[\mathbf{X_1'}]} \frac{E[\mathbf{X_1'}]}{E[\mathbf{X_0} + \mathbf{X_1'}]} \\
&= E[\mathbf{p}][1 + Corr(\mathbf{X_0}, \mathbf{p})] \frac{E[\mathbf{X_0}]}{E[\mathbf{X_0} + \mathbf{X_1'}]} + E[\mathbf{p}][1 + Corr(\mathbf{X_1'}, \mathbf{p})] \frac{E[\mathbf{X_1'}]}{E[\mathbf{X_0} + \mathbf{X_1'}]} \\
&= p_0(1 - w) + p_1 w
\end{aligned} \tag{18}$$

$p_0 = E[\mathbf{p}][1 + Corr(\mathbf{X_0}, \mathbf{p})]$ is the "*fair price*" for non-adopters, reflecting their true consumption cost. If electricity demand and wholesale electricity prices are in-

[21] If consumers choose a dynamic contract, they pay wholesale electricity prices and will not be affected by net metering. Consumers with variable contracts can partially circumvent the monthly effect.

[22] Hence, I restrict the case when net consumption to PV adopters is positive. In the Netherlands, even 30% of PV adopters produce more than consumption, the total electricity feed-in only accounts for 64% of the electricity supply for PV adopters. When $X_1' \leq 0$, the externality becomes even larger.

dependent, the fair price equals the average wholesale electricity prices. However, as price and demand are positively correlated, $Corr(\mathbf{X_0}, \mathbf{p}) > 0$, even without any retail margin, the retail energy price should be higher than simple average wholesale electricity prices, $p_0 > E[\mathbf{p}]$. $p_1 = E[\mathbf{p}][1 + Corr(\mathbf{X_1'}, \mathbf{p})]$ is the fair price for PV adopters under the net metering policy. Recall that the correlation between net consumption and wholesale electricity price for PV adopters is higher than that for non-adopters, $Corr(\mathbf{X_1'}, \mathbf{p}) > Corr(\mathbf{X_0}, \mathbf{p})$. Hence $p_1 > p_0$. When retail price discrimination is not allowed, the purchasing cost faced by energy companies is the average between serving PV adopters and non-adopters, weighted by the share of net electricity supply for each type of household.

Proposition 1. *The cost of serving PV adopters is higher than the cost of serving non-adopters. Under net metering policy, PV adopters pay less than their actual costs, while non-adopters pay more,* $p_0 \leq p(net) \leq p_1$.

$p(\text{net})$ can be rewritten as:

$$p(\text{net}) = \underbrace{\frac{E[\mathbf{pX}]}{E[\mathbf{X}]}}_{p(\text{no net})} + \underbrace{\frac{E[\mathbf{p}]E[\mathbf{Z}]}{E[\mathbf{X} - \mathbf{Z}]}[Corr(\mathbf{X}, \mathbf{p}) - Corr(\mathbf{Z}, \mathbf{p})]}_{\text{externality of net metering on energy price}, \phi_e} \tag{19}$$

$p(\text{no net})$ is the average price when net metering does not apply. Wholesale electricity prices positively relate to grid consumption and negatively to feed-in, implying $Corr(\mathbf{X}, \mathbf{p}) - Corr(\mathbf{Z}, \mathbf{p}) > 0$. Hence, net metering creates a negative externality. To clarify, the externality term ϕ_e on the right side of the equation (19) is a positive number, indicating an increase in prices and a decrease in net payoff; therefore, it is termed a negative externality.

Proposition 2. *Retail energy prices are higher under the net metering policy,* $p(net) \geq p(no\ net)$.

The magnitude of externality is determined by two factors. First, it increases with growing solar feed-in and a stronger negative covariance between solar feed-in and wholesale electricity prices. Recall Figure 12. When the installed solar PV capacity was low in 2015, $E[\mathbf{Z}]$ and $Corr(\mathbf{Z}, \mathbf{p})$ were small, and the externality was negligible. In fact, during the early stages of solar installation, solar production coincided with periods of high wholesale electricity prices, and a positive covariance was observed, implying $Corr(\mathbf{Z}, \mathbf{p}) > 0$. Therefore, residential solar produced a positive externality, $p(\text{net}) < p(\text{no net})$. As residential solar capacity grows, oversupply of solar production drives down wholesale electricity prices in the afternoon, leading to an increase in negative externalities, and the marginal externality increases, too.

Second, given the same capacity level, the externality increases alongside the average wholesale electricity price, $E[\mathbf{p}]$. When external shocks, such as the energy crisis in 2022 and 2023, drove up wholesale electricity prices, the net metering policy exacerbated the negative impact on households without solar panels.

Proposition 3. *The externality of net metering policy increases with electricity feed-in and wholesale electricity prices.* $\frac{\partial \phi_e}{\partial Z} > 0, \frac{\partial \phi_e}{\partial E[\mathbf{p}]} > 0$.

The elements in grid consumption and feed-in profiles are formally defined as

$$x_{d,h} = \frac{X_{d,h}}{X}$$
$$z_{d,h} = \frac{Z_{d,h}}{Z}$$

$\sum_d \sum_h x_{d,h} = 1, \sum_d \sum_h z_{d,h} = 1$. The grid consumption profile for PV adopters and non-adopters and the net consumption of non-adopters are defined similarly. Hence,

$$\mathbf{x_0} = \{x^0_{d,h}\}$$
$$\mathbf{x_1} = \{x^1_{d,h}\}$$
$$\mathbf{x_{1'}} = \{x^{1'}_{d,h}\}$$
$$\mathbf{z} = \{z_{d,h}\}$$

Based on wholesale electricity prices, grid consumption profiles, and feed-in profiles, $p_0, p_1, p(\text{net})$ and $p(\text{no net})$ are calculated by equations (17) and (19).[23] Table 7 compares scenarios with and without the net-metering policy, ceteris paribus. The fair prices for non-adopters are independent of the net metering policy since they rely solely on the grid. Even without net metering, a price difference between PV adopters and non-adopters exists because their grid consumptions differ (See Figure 6). Therefore, PV adoption can generate externality even without net metering, but this is relatively small, and this paper focuses on the externalities associated with the net metering policy.

The quantitative results are consistent with the theoretical prediction that solar feed-in and wholesale electricity prices were positively correlated when residential solar was negligible in 2015. The price for PV adopters was €0.035/kWh, lower than that for non-adopters €0.041/kWh, meaning net metering generated a positive externality and reduced the average energy price by 0.17%. In 2022, when residential

[23]Profiles before 2020 are not available and are assumed to be the average profile between 2020 and 2022. This assumption is plausible as electricity consumption and solar production patterns are stable. The profiles from 2020 to 2023 are not significantly distinct, further validating the assumption.

solar took a larger share, the price for PV adopters was 26.34% higher than non-adopters, and as a result, net metering increased the energy price by €0.009/kWh, 3.81% higher than without net metering. Figure 13 overviews the externality change from 2015 to 2022.

Table 7: Cost of Serving PV Adopters and Non-adopters (€/MWh)

	2015			2022		
	Net	No Net	Externality(%)	Net	No Net	Externality(%)
p_0	41.13	41.13	0.00	244.07	244.07	0.00
p_1	34.49	40.34	−14.50	308.36	247.94	24.37
p	41.03	41.10	−0.17	254.79	245.45	3.81

Notes: This table shows the cost of serving PV adopters and non-adopters with and without the net-metering policy in 2015 and 2022, respectively.

5.2 Taxes and Levies

Under the net metering policy, the yearly tax revenue is equal to the per unit tax multiplied by net consumption,

$$\mathcal{T} = \tau(X - Z) \tag{20}$$

Unlike direct subsidies, such as paying for solar energy production or reimbursing installation costs, the net metering policy provides a fiscal incentive that PV adopters do not pay tax for feed-in volume Z and is a tax expenditure. There are two ways to fund subsidy schemes or tax expenditures: general budget or special budget. In the Netherlands, sustainable subsidies, including SDE++ for large-scale businesses and ISDE for households and small-scale businesses, are financed from the proceeds of the specific ODE tax. Hence, the ODE tax rate is determined by allocating a fixed revenue from household net electricity consumption, and a net metering policy would narrow the tax base and increase the tax rate. However, the Dutch government does not explicitly explain how this loss of energy tax revenue from the net metering policy is funded.

I assume that energy tax plus ODE tax τ_e is endogenously determined to balance the government budget in the energy sector.[24] This aligns with the Dutch government's approach to financing direct subsidies and ensures comparability with feed-in

[24]Throughout the paper, the value-added tax $\tau_v = 21\%$ and $\tau_v = 9\%$ in the second half year of 2022 is exogenously given.

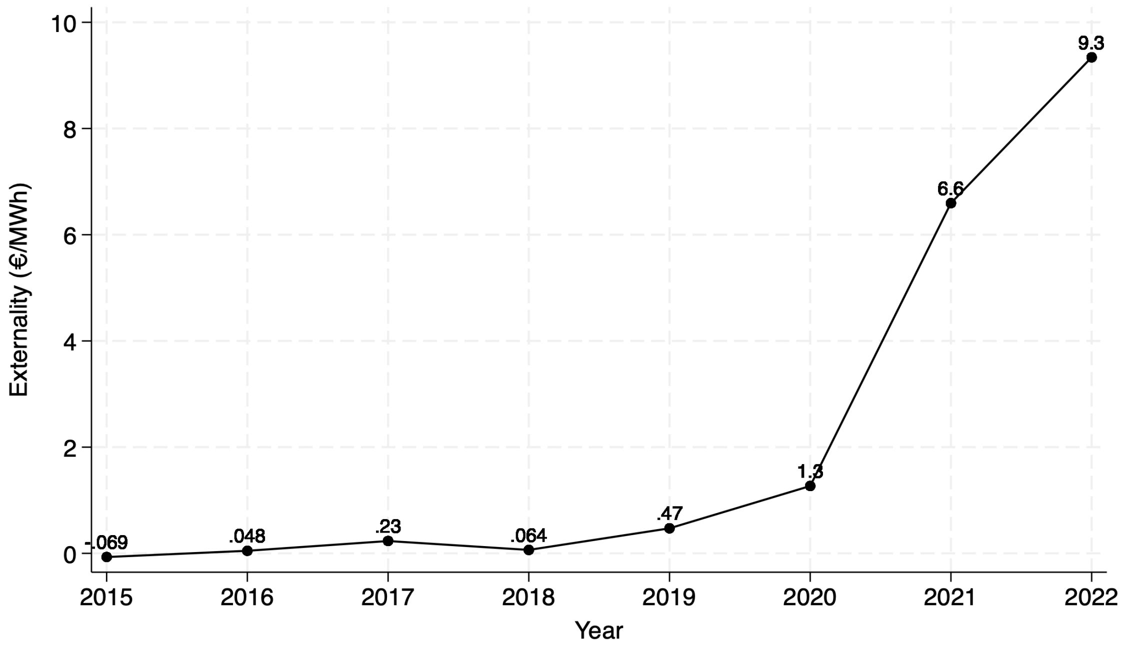


Figure 13: Externality Through Energy Price

Notes: This figure illustrates the externality of net metering policy ϕ_e, from 2015 to 2022.

premiums and upfront subsidies. See Appendix C for an explanation of the Dutch fiscal policy.[25] Hence, the externality on taxes of net metering policy is defined as

$$\phi_\tau = \tau - \frac{\tau(X - Z)}{X} \tag{21}$$

5.3 Externality

The total externality of the net metering policy, reflected as the increase of retail electricity price per kWh, is $\phi = \phi_e + \phi_\tau$. Assume that the pass-through of energy cost is 100%, so energy companies can completely shift the cost to households. I merge the data on grid consumption and feed-in profiles, wholesale electricity prices, and tax rates to calculate the externality from 2015 to 2022. The results are shown in Figure 14. In 2022, the externality $\phi =$€0.038/kWh. Hence, a household without solar systems consuming 3000kWh per year had to pay €114 more because of the net metering policy. As a breakdown, €27 would be paid to the energy company

[25] Also see *Official Report on the Approach to Tax Expenditures.* It explains that tax expenditures indirectly increase the tax burden for others. A decrease in tax expenditures would reduce overall tax rates, and a reduction within the same domain is the obvious choice. https://www.government.nl/documents/reports/2023/09/11/official-report-on-the-approach-to-tax-expenditures.

and €87 to the government. The externality in 2022 would have been higher if the Dutch government did not temporarily half the energy tax or reduce VAT to 9% from July to December. The counterfactual externality without tax reduction would be €0.056/kWh in 2022.

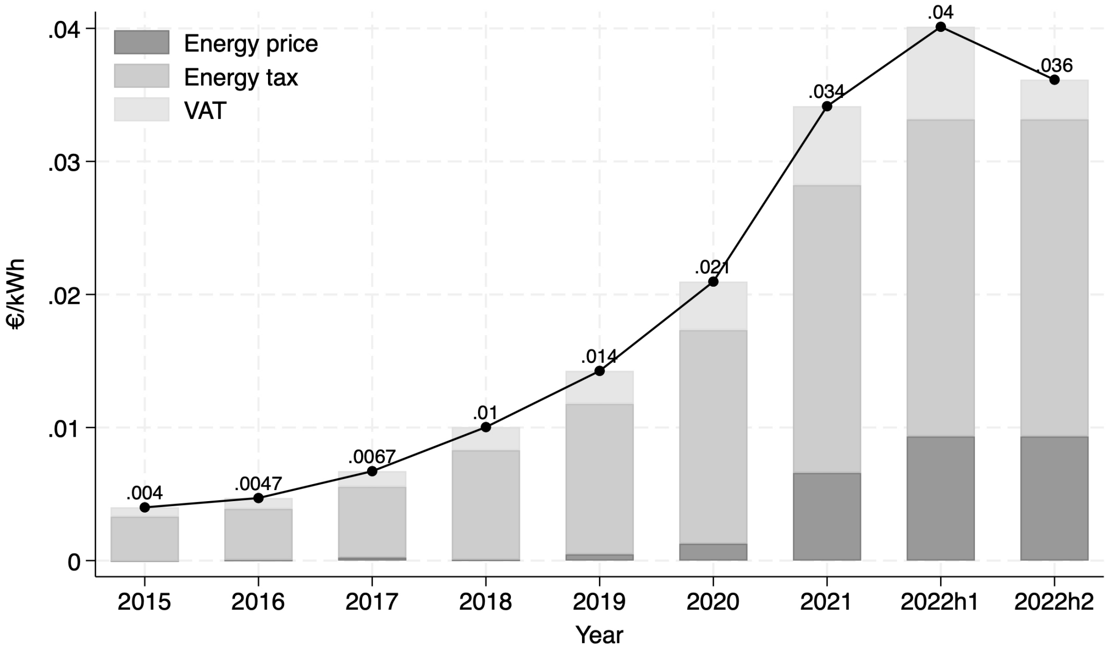


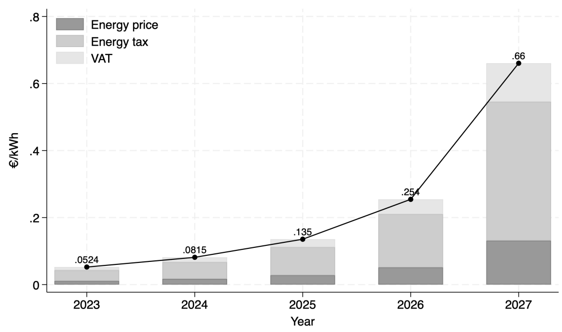
Figure 14: Externality of Net-metering Policy

Notes: This figure shows the retail electricity price increase under the net-metering policy compared to the counterfactual scenario when there is no net-metering policy. The price difference is decomposed into energy price, energy tax (ODE included), and VAT.

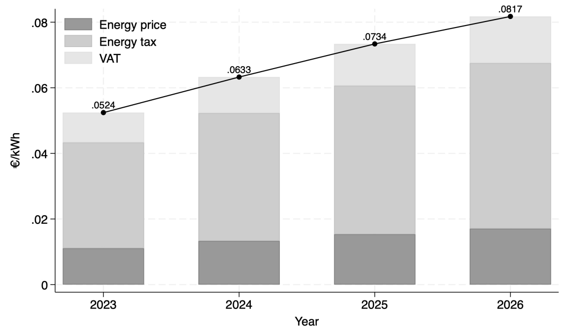
Next, I calculate the predicted externality from 2023 to 2027. The tax target is set at €3 billion, corresponding to an energy tax equal to €0.13/kWh in 2023, and is endogenously computed onwards. As expected, a "death spiral" happens with net metering: retail prices increase fast with growing residential solar capacity, which speeds up residential solar PV adoption and, in turn, further pushes up retail prices. If net metering continues, the retail price will rocket to 0.93/kWh, and the externality will increase to €0.66/kWh, implying that the households not adopting solar PV will have to pay €0.66 per kWh more than their actual consumption cost in 2027.[26] With the net metering phase-out signal, the externality increases relatively slower, achieving

[26]In reality, the government will not allow energy taxes and retail electricity prices to rise to such high levels and will likely explore other solutions to address the issue of high tax expenditures. However, since total fiscal expenditure and revenue must remain balanced, the significant externality is still a big challenge.

€0.082/kWh in 2026, with the average retail price increasing to €0.33/kWh. See Figure 15.



(a) Externality



(b) Externality

Figure 15: Predicted Externality

Notes: The left panel (15) shows the predicted externality evolution from 2023 to 2027 if net metering remains unchanged. The right panel 15b shows the predicted externality evolution from 2023 to 2027, with the phase-out signal.

5.4 Distributional Effect

It has been demonstrated that the net metering policy benefits solar PV adopters at the expense of non-adopters. This won't raise much concern if PV adopters and non-adopters are proportionately allocated to households across the wealth distribution. However, by Table 2, the adoption rate is 39% for the wealthiest households and only 15% for the poorest ones. Therefore, net metering results in a regressive effect that low-income households are more likely to be non-adopters and have a greater welfare loss. In this section, I conduct a quantitative analysis of the distributional effect of net metering across households in different wealth quintiles.

Annual electricity bills across five wealth quintiles can be calculated based on the average yearly household grid consumption and feed-in. Combined with the results in Figure 14, a counterfactual bill without net metering can also be estimated. See Table 8 for the welfare change in 2022. The retail price of €0.403/kWh is average across the new contracts signed in 2022. The total externality €0.038/kWh is calibrated in the previous section. Without net metering, the compensation price of electricity feed-in €0.213/kWh is the wholesale electricity price, weighted by the feed-in profile. Hence, PV adopters receive the *fair* price of solar electricity, and energy companies are unaffected by feed-in.

Table 8: Welfare Change

	All	< 20%	20 − 40%	40 − 60%	60 − 80%	> 80%
Grid consumption (kWh)	2623	2157	1964	2711	2858	3236
Net consumption(kWh)	2101	1968	1740	2211	2166	2353
Bill (Net, €)	846.58	792.62	701.15	890.89	872.81	948.23
Bill (No net, €)	846.15	746.79	669.11	882.94	895.73	993.05
Excess Pay (€)	0.44	45.83	32.04	7.95	-22.92	-44.81
Energy Part	3.03	12.28	9.10	4.75	-1.73	-6.02
Tax Part	-2.59	35.55	22.94	3.20	-21.18	-38.79

Notes: This table shows the electricity bill for 2022 with and without net metering for five wealth quintiles. The retail price is €0.403/kWh. The cost reduction without net metering is calibrated to €0.038/kWh. When net metering does not apply, the reimbursement rate is set to be the weighted average wholesale electricity price, €0.213/kWh. Fixed grid costs, fixed delivery costs, and fixed tax credits are independent of net metering policy and excluded.

On average, in 2022, the electricity bill for each household in the first wealth quintile, excluding fixed payments, increased by €45.83 under the net metering policy, while the wealthiest households benefited €44.81. The negative externality from the energy price side ϕ_e, is €12.28 for the poorest households, accounting for 26.79% of the total externality, while the wealthiest group benefits €6.02, accounting for 13.43% of the total benefit. Hence, most of the distributional effect stems from the tax part.

6 Policy Comparison

By far, I have shown that net metering succeeds in promoting residential solar PV but creates a significant regressive effect. This raises a question: can the same residential solar capacity be achieved with other incentive policies more equitably and cost-effectively?

Specifically, I compare three incentive policies: net metering, feed-in premiums, and upfront subsidy. Under feed-in premiums, PV adopters receive an additional payment on top of wholesale market prices per kWh of electricity feed-in. When an upfront subsidy is applied, PV adopters receive a one-time payment to cover part of the PV installation costs, and the subsidy is expressed as a percentage of upfront costs that can be reimbursed. Net metering benefits PV adopters by offsetting electricity grid consumption with electricity feed-in. For each household, the marginal benefit under net metering is the equilibrium retail price up to total consumption and then a fixed reimbursement rate. However, at the aggregate level, net metering increases the retail price, which does not reflect the true supply cost. Hence, the implied subsidy per kWh is equal to the counterfactual retail price without net metering minus the wholesale market price. Figure 16 shows the equilibrium outcomes from 2012 to 2022. Although all three policies are designed to achieve the same total capacity, they differ in intensive margin.

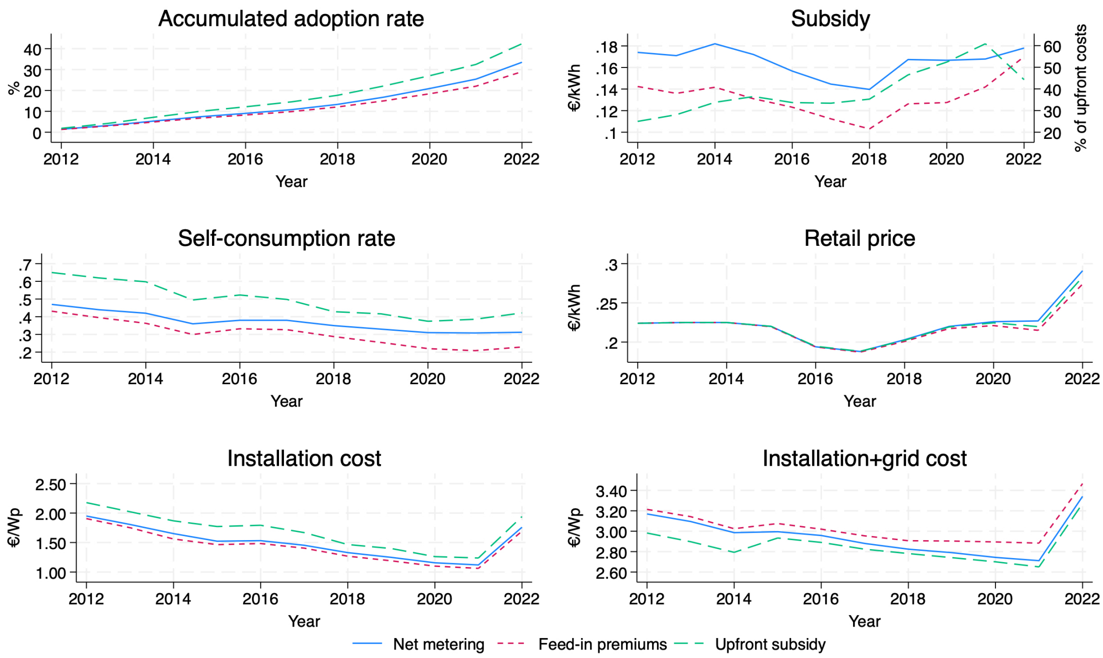


Figure 16: Counterfactual Policy Outcome

Notes: This figure illustrates the adoption outcomes under various policy scenarios from 2012-2022.

First, while net metering aligns solar capacity closely with actual electricity consumption, the upfront subsidy leads to broader adoption but with smaller capacity sizes. As of 2022, 33.5% of the potential market has adopted solar panels under the net metering policy, while the counterfactual adoption rate increases to 42.36% under upfront subsidy.[27] Large capacity under an upfront subsidy is not attractive because PV adopters receive partial upfront costs and benefit from self-consumption, with feed-in being compensated only at the wholesale market price. On the other hand, households tend to install more panels under the feed-in premiums, where all electricity feed-in is compensated at a high price, and an adoption rate of 29% would

[27]Hence, rooftops are not fully utilized. This is not necessarily a drawback of the policy. However, determining the optimal residential solar PV size is beyond the scope of this paper.

achieve the same capacity target.

Due to economies of scale, the average installation cost is highest with the upfront subsidy and lowest with feed-in premiums. For instance, in 2022, the average cost for one watt-peak is €1.76 under the net metering policy, €1.68 under feed-in premiums, and €1.97 under upfront subsidy. Another direct consequence of preferences regarding PV capacity under different policies is that households consume different proportions of solar electricity. In 2022, the self-consumption rate is estimated at 0.39 when installation costs are reimbursed and drops to 0.22 under feed-in premiums. Moreover, the self-consumption rate declined over time because when solar module costs were high, households found it more profitable to install a smaller capacity.

A higher self-consumption rate reduces the burden on distribution networks, leading to grid cost savings. I use feed-in volume to calculate the grid cost. Compared to the net metering policy, feed-in premiums demand 13.37% more grid investment, while it requires 10.78% less under the upfront subsidy. According to Tennet, 2.3 billion euros must be invested to accommodate 1GW of offshore wind capacity. Assuming the power injection from offshore wind has the same grid requirement as solar panels, 1 Wp residential solar under net metering requires a grid investment of €1.59. Upfront subsidies reduce this cost by €0.17, whereas feed-in premiums increase it by €0.21, given the estimated self-consumption rate for each policy in 2022. As a result, the high grid costs offset the low installation costs associated with feed-in premiums, resulting in the most expensive total investment cost, which is equal to the sum of installation cost and grid cost. Between 2012 and 2022, the total investment cost under the net metering policy amounts to €23.8 billion. The counterfactual cost rises to €24.76 billion under feed-in premiums and decreases to €23.25 billion with an upfront subsidy.

In the Netherlands, each household pays a fixed amount to cover grid costs, regardless of PV adoption or incentive policies. Therefore, the subsidy in this context refers specifically to the payments made to PV adopters under different policies. The electricity feed-in is paid a higher subsidy under net metering than feed-in premiums because PV installation is more costly. However, the higher self-consumption rate under net metering narrows the subsidy difference. Using a 15% discount rate and summing over all years from 2012 to 2022, to achieve a capacity equal to 7.15GW in 2022 needs €5.12 billion under net metering and €4.78 billion under feed-in premiums. Alternatively, the upfront subsidy requires €5.65 billion to compensate for high installation costs. Therefore, the upfront subsidy is the cheapest in terms of total investment but requires the highest subsidy, whereas feed-in premiums are the most costly overall but require the lowest subsidy.[28] See Panel A of Table 9.

Table 9: Policy Comparison

Panel A: total value	Net metering	Feed-in premiums	Upfront subsidy
Investment costs (€, billion)	23.8	24.76	23.25
Subsidy (€, billion)	5.12	4.78	5.65

Panel B: distribution	$< 20\%$	$20 - 40\%$	$40 - 60\%$	$60 - 80\%$	$> 80\%$
Subsidy paid (%)					
Net metering	19.12	15.86	19.58	21.48	23.95
Feed-in premiums	18.24	15.33	19.68	21.97	24.77
Upfront subsidy	18.43	15.44	19.65	21.85	24.63
Subsidy received (%)	7.97	9.04	20.95	27.71	34.33

Notes: Panel A gives total investment costs and subsidies under various policy scenarios from 2012 to 2022. Panel B shows the average percentage of subsidy paid and received by each wealth quintile, assuming volumetric pricing.

Finally, I go to the distributional effect of each policy. As in the previous sections, households are categorized into five wealth quintiles. The average percentage of subsidy paid and received for each wealth quintile is presented in Panel B of Table 9. The wealthier households benefit more as they install more solar panels. Overall, the wealthiest quintile receives 34.33% of the total subsidy, and the poorest group receives only 7.97%. A fixed subsidy contribution, in which each quintile bears 20% of the total subsidy, is more regressive since the wealthier quintile consumes more electricity. Volumetric pricing, which means that subsidy is paid based on electricity consumption, performs better but still results in a regressive effect. Under all three policies, poorer households contribute more in subsidies than they receive, with the effect being most pronounced under net metering. However, the difference spanning 10 years is small.

[28] 15% is the discount rate used for future benefits in the structural estimation. De Groote and Verboven (2019) argue that households significantly undervalued the future benefits of the new technology. Hence, subsidies from net metering and feed-in premiums are much more expensive than upfront subsidies, which can be financed with a much lower interest rate. However, this discussion is beyond the scope of this paper. To ensure comparability among different policies, I distribute the upfront subsidy over time using the same discount rate of 15%.

Figure 17 illustrates the distributional effect of the three policies over time. For brevity, I only plot the first and fifth wealth quintiles. The left panels represent the first wealth quintile, while the right panels depict the fifth quintile. The figure indicates that the subsidy burden for the poorest households increases over time while it decreases for the wealthiest. In 2012, all three policies showed similar subsidy allocation, but the inequity problem escalated faster under net metering. The poorest households contributed 18% of the total subsidy in 2012, rising to 22.01% in 2022, whereas the proportion paid by the wealthiest households decreased from 25% to 21.27%. In monetary terms, a household in the first quintile pays €111.58 in subsidies but receives only €38.40, while a household in the fifth quintile pays €107.83 yet receives €165.36 under net metering in 2022.

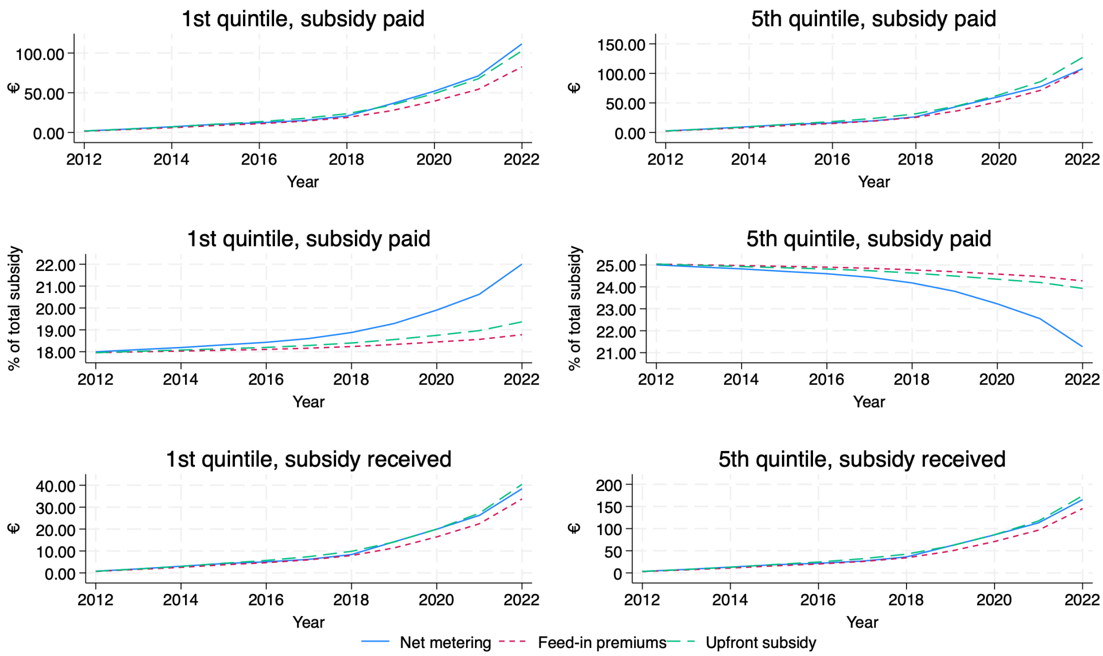


Figure 17: Subsidy between Wealth Groups

Notes: This figure illustrates the subsidy paid and received by the first and fifth wealth quintiles under various policy scenarios from 2012-2022.

Grid costs have been a major driver of the energy bill increase in recent years. Among the three policies, feed-in premiums require the least subsidy and are the least unfair while being expensive in grid investments. From 2012 to 2022, given the same installation capacity, a household in the first quintile pays an additional grid investment cost of €287.54 million under the feed-in premiums policy compared to net metering but benefits from a €38.43 million reduction in installation costs and a

€79.08 million reduction in subsidy transfer. In contrast, the upfront subsidy reduces grid costs for the poorest households by €370.52 million but increases investment costs by €103.51 million and results in €20.38 million more in subsidy redistribution losses compared to net metering.

To sum up, I compare the three policies in three dimensions: cost minimization, capacity maximization, and equity. See Table 10. The upfront subsidy is the most cost-effective option but requires a higher subsidy. For poor households, although they pay more subsidies, they save a lot on grid contribution. However, the upfront subsidy is a one-off payment, requiring the government to finance a large amount of funds in advance. Feed-in premiums incentivize larger PV capacity and are the most equitable, but they come at the cost of significant grid investments. The current net metering policy induces the highest inequality but compromises cost efficiency and rooftop utilization.

Table 10: Policy Selection

	Net metering	**Feed-in premiums**	**Upfront subsidy**
Cost min			✓
Equity		✓	
Capacity max		✓	
Cost min + capacity max	✓		

Notes: This table presents the choices among various policy scenarios, evaluated across different objectives.

7 Conclusion

Using Dutch household-level data from 2019 to 2022 and 15-minute frequency data on aggregate household electricity grid consumption and feed-in profile, this article examines the incentives and distributional challenges of net metering policy for residential solar PV installations. Under net metering policies, households adopting solar panels can offset their electricity usage with electricity production and be exempt from energy taxes and levies, eroding the energy companies' revenue and increasing tax expenditure. To recoup electricity purchase and production costs, energy companies have to increase electricity prices, generating a negative externality for households without solar panels. This externality becomes larger when tax expenditure is also internalized. Since wealthier households adopt more solar panels, the regressive effect occurs that low-income households cross-subsidize high-income ones. Moreover, the net metering policy is criticized for being overly generous, discouraging battery adoption, and increasing the burden on the power grid. Driven by these concerns, the Dutch government approved the phaseout of the net metering policy in 2027, planning to replace it with a feed-in premium.

The structural estimation and counterfactual results highlight the crucial role net metering plays in residential solar PV adoption. While self-consumption and decreasing solar module costs contribute, high residential solar adoption would not have been realized without the net metering policy, which accounted for 79.21% of residential solar capacity from 2012 to 2022. Moreover, the phaseout signal would reduce the new adoption from 2023 to 2027 by 79.39%.

I also compare the equilibrium results of net metering and two other popular policies: feed-in premiums and upfront subsidies. The result shows that the regressive effect of net metering remains when it is replaced with upfront subsidies or feed-in premiums but at a lower level. Furthermore, this paper finds that intensive margin is important in evaluating incentive policies. Given the total installed capacity, compared to net metering policies, households tend to install smaller solar panels under upfront subsidies and larger sizes under feed-in premiums. There are two main consequences; first, due to large size benefits from economies of scale, the installation costs under feed-in premiums are lower. Second, a larger capacity size results in a lower self-consumption rate, thereby increasing the burden on the grid. The selection of policies depends on the objective. Upfront subsidies should be considered if the government wants to minimize the total installation and grid costs. On the other hand, if the government wants to utilize the potential of rooftops to maximize the residential solar capacity and cares about equity, feed-in premiums are best.

This paper has important implications for the energy contract choice. If households without solar panels choose dynamic contracts rather than fixed contracts, they circumvent the externality of net metering on energy companies' commodities cost and hence only pay the wholesale electricity prices, which are independent of the net metering policy. Also, when energy companies are allowed to charge a feed-in penalty on adopters' supply, the price distortion is resolved. However, as solar panel installation is highly sensitive to monetary incentives, the government has to balance between the redistribution effects and adoption targets.

My analysis also provides insights into subsidy finance. I argue that net metering is the most inequitable if the subsidy is funded within the residential energy sector. The assumption is based on the fact that the Dutch government collects volumetric prices based on electricity consumption to subsidize large-scale renewables and small-scale renewables for business, and the total taxes collected are stable over the years.

In reality, net metering is not a direct subsidy, and the energy tax is amended by the government without further explanation. Despite the results being constrained by this opacity, it indicates that charging additional taxes by either fixed or variable tariff is regressive in encountering tax expenditure, no matter which incentive policy is used. The regulator should consider financing the subsidies through other sectors, such as adjusting income or wealth taxes.

This article does not judge the net metering policy and the decision to phase it out but provides some new viewpoints. Beyond concerns about low new adoption, a simple policy replacement may not address current issues such as inequality and rapidly rising grid costs. Therefore, the policy requires further investigation and careful design.

Appendix

A Solar Efficiency and Self-consumption

This section describes the calibration method for solar efficiency and self-consumption rate, which are used for structural estimation and policy discussions.

Self-consumption Define Y as the total annual solar production, $Y = \sum_d \sum_h Y_{d,h}$. $\mathbf{y} = \{\frac{Y_{d,h}}{Y}\}$ is the production profile. Self-consumption rate is

$$\alpha = \frac{Y - Z}{Y} \tag{22}$$

αY is the total self-consumption, so the total consumption of PV adopters equals grid consumption plus self-consumption, $X_1 + \alpha Y$.

There are no official data on the self-consumption rate, which is estimated to be between 20-40% in the Netherlands (Londo et al., 2020). In this paper, I estimate the self-consumption rate rather than arbitrarily choosing a number for two reasons. First, the data, assumptions, and estimation methods explained later are transparent, ensuring traceable estimates. Second, the self-consumption rate is indispensable to estimate solar efficiency, which is essential to evaluate the profitability of solar systems and affect the adoption decision of households estimated in Section 3. Finally, this is useful when understanding the adoption patterns in Section 4 and welfare implications among different incentive policies in Section 6. Hence, a self-evident estimate guarantees consistency throughout the paper.

The data used for estimating the self-consumption rate are grid consumption and feed-in profiles for households with and without solar panels. Hence, $\mathbf{x_0}$ =

$\{x^0_{d,h}\}, \mathbf{x_1} = \{x^1_{d,h}\}, \mathbf{z} = \{z_{d,h}\}$. The main assumption to estimate α is that the electricity consumption profile does not change with PV adoption. In other words, there is no significant difference between the consumption profile of PV adopters and non-adopters, defined as $\mathbf{c_1} = \{c^1_{d,h}\}$ and $\mathbf{c_0} = \{c^0_{d,h}\}$, respectively. The assumption means

$$\mathbf{c_0} = \mathbf{c_1} \tag{23}$$

This is a strong assumption, but it is reasonable when net metering applies, as the surplus electricity returned to the grid can 100% offset the electricity supplied from the grid at a retail price. Hence, there is no incentive to shift demand. One concern is that consumers may adapt their consumption behavior to retail price structure: consumers shift demand to the period when the price is lower. However, the data does not support this argument, showing that consumers who are charged single, double, or night fare do not behave differently. Another concern is that consumers use more electricity when they have independent producers. I do not rule out the possibility that total consumption changes with adoption, but I restrict consumption to unaffected profiles.[29] Solar production $Y_{d,h}$ is unobservable, meaning I cannot calculate each element in consumption profiles of PV adopters $\mathbf{c_1}$. To address this issue, I use the fact that solar panels do not work at night, so consumption during those periods is only supplied from the grid.[30]

$$c^1_{d,h} = \frac{X^1_{d,h}}{X_1 + \alpha Y} = \frac{X^1_{d,h}}{X_1 + \frac{\alpha}{1-\alpha} Z} = \frac{x^1_{d,h}}{1 + \frac{\alpha}{1-\alpha} \cdot \frac{Z}{X_1}}, \tag{24}$$

Z/X_1 is the total feed-in over the total grid consumption for PV adopters, which is calculated as 0.64. For non-adopters, grid consumption is equal to total electricity consumption. Hence, $\mathbf{c_0} = \mathbf{x_0}$. The OLS regression implied by equation (23) and (24) is

$$x^0_{d,h} = \frac{x^1_{d,h}}{1 + 0.64 \cdot \alpha/(1-\alpha)} + \epsilon_{d,h}, \quad d,h \in \{d,h | z_{d,h} = 0\} \tag{25}$$

Even though α enters equation (25) in a non-linear way, $\frac{1}{1+0.64\cdot\alpha/(1-\alpha)}$ can be estimated by a simple OLS regression, and the estimated self-consumption rate $\hat{\alpha}$ is uniquely determined. The result is $\hat{\alpha} = 0.33$, suggesting that households, on average, directly use 33% of electricity produced by residential solar systems. The number aligns with the range suggested by Londo et al. (2020), hence a reasonable estimate.

[29] The violation of this assumption may overestimate the self-consumption rate as consumption is more likely to increase in the daytime when solar produces.

[30] Due to high investment costs and the net metering policy, household energy storage is uncommon in the Netherlands and is therefore not considered in this paper.

Solar Efficiency CBS provides data on households' solar PV adoption status, capacity, and yearly electricity grid consumption and feed-in from 2019 to 2022. I do not observe the specific installation time. To estimate yearly solar production, I identify households installing PV in 2020 and track their electricity feed-ins in 2021. Similarly, for PV installed in 2021, I track the feed-ins in 2022. All other observations are dropped.

Let i index household and y index year. Denote K_i the solar installed capacity. By definition, $\iota = Y_{i,y}/K_i$, and $Y_{i,y} = Z_{i,y}/(1-\alpha)$. Hence,

$$\iota = \frac{Z_{i,y}}{(1-\alpha)K_i} \tag{26}$$

Hence, the OLS regression is

$$Z_{i,y} = \iota(1-\alpha)K_i + \mathcal{E}_{i,y} \tag{27}$$

$\widehat{\iota(1-\alpha)}$ is estimated to be 0.61, indicating that one additional kWp in PV capacity would, on average, result in an additional 610 kWh feed-in to the grid per year. Using the self-consumption rate $\hat{\alpha} = 0.33$ estimated in equation (25), a simple calculation yields $\hat{\iota} = 0.91$.[31] Hence, in the Netherlands, 1kWp of PV capacity can, on average, produce 910kWh per year. Households directly consume 33% of generated electricity, and the remaining 67% is returned to the grid.

[31] Self-consumption rate can be estimated by data from 2020 to 2023, while the necessary data to estimate solar efficiency only span from 2021 to 2022. For consistency, I only use data in 2021 and 2022. The self-consumption rate is solved to be $\alpha = 0.35$ in 2021, and $\alpha = 0.32$ in 2022. The total feed-in is 59% of installed capacity in 2021 and 62% in 2022. The simple regression of grid-in volume over installed capacity can explain over 90% of the total variation.

B Energy Price and Lagged Wholesale Price

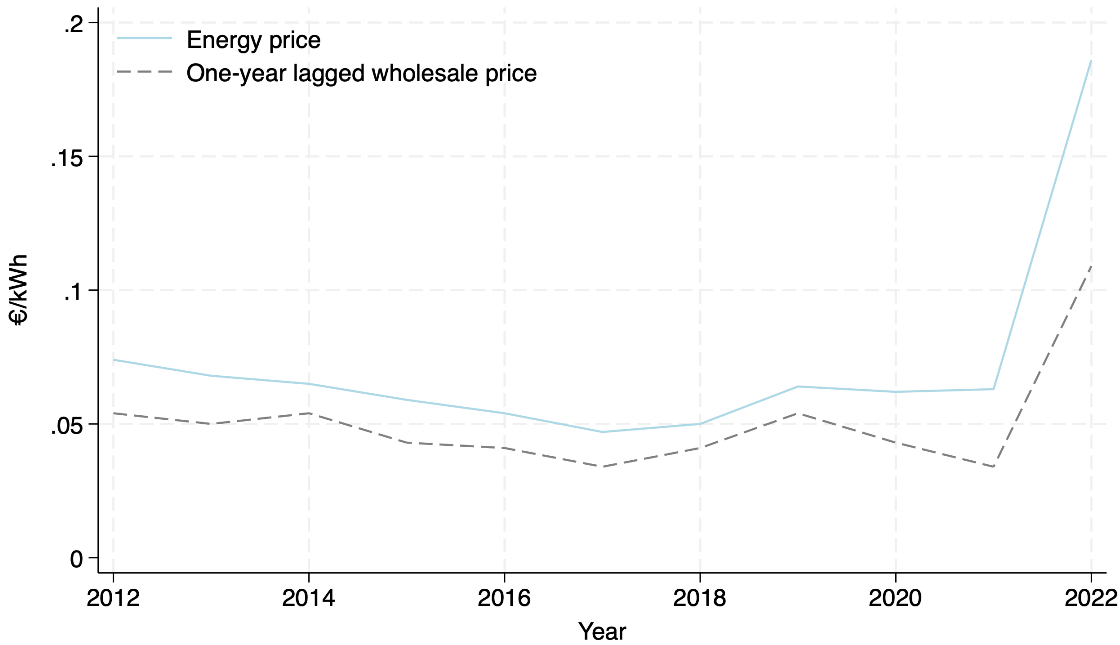


Figure 18: Energy Price and Lagged Wholesale Price

Notes: This figure depicts the retail energy price and one-year lagged wholesale price from 2012 to 2022.

C Dutch Fiscal Policy

The Netherlands has conducted a trend-based fiscal policy since 1994. It means a fixed expenditure and revenue framework and allows tax revenues to move with the economic cycle.

At the start of the government's term, an expenditure framework is set. This framework sets an annual ceiling for real government spending that may not be exceeded. A revenue framework is also agreed on, which sets out the taxes and contributions the government will levy each year. The government lays down these frameworks in its Budget Memorandum. Policy revenue and expenditure changes must be offset within the frameworks during the government term. This involves separating income and expenditure.

Each spring, there is one main decision-making moment when the cabinet decides on spending for the following year. Also, every year in August, the cabinet decides on the taxes and social insurance contributions for the following year. Tax rates are adjusted accordingly.

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