



Distributional effects of the Dutch net-metering scheme for residential solar panels

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ABSTRACT

The adoption of solar panels by households is pivotal in the transition to an energy system based on renewable sources. A common policy to incentivize this is net metering, under which the electricity costs for households with solar panels are based on the difference between the electricity consumed and that generated by them. Although effective, this policy may have unintended distributional effects for households differing in location, housing type, and solar panel ownership. This paper quantifies these effects for the net-metering scheme in place in The Netherlands since 2004. Using our simulation model and data from 2021, we find that net metering increases the electricity bills of households without solar panels by 14% on average, while it reduces those of households with solar panels by 74% on average, leading the latter to save almost three times as much as needed to break even with their investment in solar panels. We also observe heterogeneous effects across the Dutch provinces and different housing types. Moreover, we show that the distributional effects of net metering can be mitigated through fiscal policy measures. Furthermore, we show that replacing net metering with a net billing scheme that compensates returned generation at around 25% of the average wholesale price of electricity results in a more equitable distribution of effects while maintaining the attractiveness of investing in residential solar. Overall, we provide novel results that contribute to the socially relevant and timely debate on policy designs to foster an equal and just energy transition.

1. Introduction

Solar panels are crucial in the transition from a fossil-based to a renewables-based energy system. A widespread policy to foster their adoption by households is net metering (Duke et al., 2005; Dufo-López and Bernal-Agustín, 2015; Gautier and Jacquemin, 2019). Under the latter, the electricity costs for the households are based on the difference between consumption and own generation. This policy has been shown to be one of the most cost-effective (Darghouth et al., 2011; Ramírez et al., 2017; Londo et al., 2020) and easiest to implement (Duke et al., 2005) measures to incentivize residential solar-panel adoption. However, this policy may affect households that have solar panels (henceforth, PV households) and those that do not (non-PV households) differently and it may have heterogeneous effects for households living in different regions or housing types.

Recent literature has investigated some distributional concerns of net metering. Indeed, this scheme has been shown to lead to cross-subsidies, with non-PV households facing higher retail prices to offset reduced revenues from PV users (Eid et al., 2014; Castaneda et al., 2017; Clastres et al., 2019; Iglesias and Vilaça, 2022; Kim et al., 2023).

Moreover, most common grid-tariff designs are found to be distortionary when combined with net metering and to be likely to distribute the burden of grid costs more heavily on non-PV households than on PV households (Picciariello et al., 2015; Schittekatte et al., 2018), especially as residential solar capacity grows (Gupta et al., 2021a,b). Further evidence suggests that net metering disproportionately favors wealthier and better-situated households (Borenstein, 2017; Kraaijvanger et al., 2023), increasing the cost burden for lower-income groups (Burger et al., 2020). Despite existing studies, a comprehensive evaluation of the distributional effects of net metering under a uniform policy and setting is lacking.

This paper contributes to the literature by quantifying the effects of net metering on the electricity bills of households differing in terms of solar panel ownership, location, and housing type in the same country, the Netherlands. We also contribute to this literature by decomposing these effects explicitly paying attention to the retail costs, the grid costs, and the electricity bill taxes. Moreover, we compare the distributional effects of net metering to those of alternative billing mechanisms such as net billing. Furthermore, we also explore possible

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avenues for the government to reduce the distributional effects of net metering through fiscal policy. Overall, we provide novel insights on the channels through which the distributional consequences of net metering occur and discuss potential strategies to mitigate them.

We focus on the Dutch net-metering scheme (*Salderingsregeling*), which was initially implemented in 2004 and, after some changes, has remained unchanged since 2014 (Milieu Centraal, 2024b; Dutch Ministry of General Affairs, 2024a). However, amidst evolving energy policies, discussions arose regarding the phase-out of the net-metering scheme. Such a phase-out was motivated by the low investment costs in residential solar panels, the large government revenue losses associated with net metering, and the scheme's lack of incentives for home batteries and self-consumption (Londo et al., 2020; ACM, 2023). A gradual phase-out plan beginning in 2025, with full implementation by 2031, was backed by the House of Representatives but rejected by the Senate in 2024 due to equity concerns. As of June 2024, the new Cabinet proposes abolishing the scheme by 2027 (Dutch Ministry of General Affairs, 2024b), making a thorough distributional analysis of the effects of net metering particularly timely for the Netherlands. Moreover, net metering is applied with similar designs in several other countries, which would also benefit from our analysis of the distributional consequences of this scheme.

We analyze the distributional effects of the net-metering scheme both directly and indirectly through the increase in installed residential solar capacity. To achieve this, we develop a framework to assess how the scheme affects each component of the household electricity bill and use it to derive a simulation model, which we calibrate using 2021 data for households with and without solar panels across the twelve Dutch provinces, in five different housing types. Our results suggest that households without solar panels, on average, face a 14% increase in electricity bills under net metering compared to a situation in which no residential solar capacity is installed. In contrast, households with solar panels obtain large bill savings under net metering compared to a scenario with no residential solar, almost three times the amount of yearly savings they need to break even with their investment in solar panels. Remarkably, we find visibly heterogeneous effects for households in different provinces and housing types, which we attribute to their differing solar irradiance and ability to install solar panels. Furthermore, we consider possible alternative billing mechanisms and find that a net billing scheme where returned generation is compensated at 25% of the yearly average electricity price on the wholesale market barely affects households without solar panels, while still keeping the investment in residential solar attractive. Furthermore, we show that maintaining the net-metering scheme while adapting the fiscal policy design around it may reduce the distributional effects of the scheme, albeit with some potential changes to the energy tax's objective. Our sensitivity analysis shows that our results are quite robust to loosening several of our assumptions. For instance, using a different grid tariff design and accounting for the rebound effect of solar panels only slightly changes our estimates of the distributional effects of net metering, not affecting our conclusions. Overall, our findings contribute to both the academic literature and the social debate on the distributional effects of net metering, suggesting that the scheme might need to be redesigned or replaced to support a more equal and just energy transition.

The rest of this paper is structured as follows. The next section discusses the current literature on the net-metering scheme for residential solar energy and its effects on households. Then, we develop our conceptual framework and discuss the operational model used to evaluate it. The following section presents the numerical analysis, describing the data and assumptions used. Section 6 discusses the results, proposes alternative billing mechanisms and fiscal policies, and presents a sensitivity analysis on the results. Lastly, we conclude and offer some implications for policymakers.

2. Literature review

Households with grid-connected solar panels may inject surplus electricity into the grid or withdraw when generation is insufficient. There are two main approaches to settling these exchanges between households and the electricity grid: gross metering (or net purchasing or net billing), where injected and withdrawn electricity are priced separately,¹ and net metering (or net-energy metering), where the electricity exchanges between households and the grid are priced together, as the difference between the consumption and generation over a period of time (Yamamoto, 2012; Dufo-López and Bernal-Agustín, 2015; Gautier and Jacqmin, 2019). Under the latter, if the net amount is negative, households would then receive a feed-in tariff for that net amount only.

Net metering gained popularity in Europe and the US in the early 2000s due to climate commitments and the need to correct environmental pricing distortions (Duke et al., 2005). Its simplicity, large social welfare consequences, and cost-effectiveness made it a favored policy option (Yamamoto, 2012; Dufo-López and Bernal-Agustín, 2015; Ramírez et al., 2017). While net-metering schemes have been very effective in increasing the adoption of solar panels by households (Gautier and Jacqmin, 2019), many countries have or are in the process of phasing them out due to their caveats (Londo et al., 2020; Ansarin et al., 2022). Indeed, because of net metering, households do not respond to the marginal value of electricity and the marginal value of grid capacity. This implies that households do not have an incentive to use as much of their self-generated electricity as possible. In a situation where the electricity grid is congested, such as the one in the Netherlands, this can be problematic. Moreover, net metering usually implies that utility bill taxes are also based on the net amount of electricity consumed by the household, which results in significantly lower revenues for the government or higher tax rates for other households (Ziras et al., 2021).

Net-metering schemes may also result in unequal distributional effects. Although no previous study comprehensively evaluated the distributional consequences of net metering on households' electricity bills, various distributional aspects of this scheme have been considered by the previous literature. One such aspect is the possibility of cross-subsidies through retail rates due to the net-metering scheme. This cross-subsidy effect occurs if households without solar panels inadvertently subsidize electricity consumption of households with solar panels. This effect is found in diverse policy contexts, including South Korea (Kim et al., 2023), Brazil (Iglesias and Vilaça, 2022), Colombia (Castaneda et al., 2017), France (Clastres et al., 2019), and Spain Eid et al. (2014).

Another distributional aspect of the net-metering scheme concerns the electricity grid costs. Indeed, net metering is associated with an increase in the installed residential solar capacity, which may result in higher costs for the grid operator. Using the case study of Switzerland, both (Gupta et al., 2021a) and Gupta et al. (2021b) find evidence for this positive relationship between residential PV capacity and grid costs. Moreover, this increase in grid costs may lead to cross-subsidies from non-PV to PV households under the grid tariff designs commonly used for residential consumers. Indeed, Picciariello et al. (2015) show that net metering combined with a volumetric grid tariff results in cross-subsidies using the case study of six US States. Schittekatte

¹ Note that pricing the electricity injected into the grid separately from the electricity withdrawn from it is only possible if the household has (a) two one-directional meters, or (b) one smart meter. At the moment, almost 90% of Dutch households have smart meters (MAX Vandaag, 2024), yet those that do not more commonly have one bi-directional meter. The latter basically runs forward as the household withdraws electricity and runs backward as the household injects electricity into the grid. If the latter is installed, there is no way to measure generation and consumption separately. In this case, a pricing scheme that does not distinguish between the two, such as net metering, is necessary.

Table 1
Summary of the relevant literature and positioning of this study.

Study	Retail Bill Effects	Grid Operator Effects	Government Revenue Effects	Explicit Cross-Subsidy Focus	Spatial Distribution	Housing Type Variation
(Darghouth et al., 2011, 2014) (Mills et al., 2008)	✓	×	×	×	×	×
Gupta et al. (2021a,b)	×	✓	×	×	×	×
(Castaneda et al., 2017); (Clastres et al., 2019); (Eid et al., 2014); (Iglesias and Vilaça, 2022)	×	✓	×	✓	×	×
(Picciariello et al., 2015); (Schittekatte et al., 2018)	×	✓	×	✓	✓(rural–urban)	×
(Sergici et al., 2019); (Kim et al., 2023); (Koumparou et al., 2017)	✓	✓	×	✓	×	×
(Londo et al., 2020); (Ziras et al., 2021)	×	×	✓	×	×	×
(Borenstein, 2017); (Collier et al., 2023); (Sovacool et al., 2022); (Kraaijvanger et al., 2023)	×	×	×	×	✓	✓
This Study	✓	✓(disaggregated: grid vs. retail)	✓(explicit tax revenue effects)	✓	✓(across provinces)	✓

et al. (2018) argue that capacity-based grid tariffs, combined with net metering, can also be distortionary and lead to equity issues.

Another area of distributional relevance concerns the effects of net metering on government revenues. Indeed, Londo et al. (2020) estimate that maintaining the Dutch net metering policy could cost the government up to €7 billion by 2030, while (Ziras et al., 2021) show that government revenue losses in Denmark vary significantly depending on the credit timeframes allowed for excess solar production.

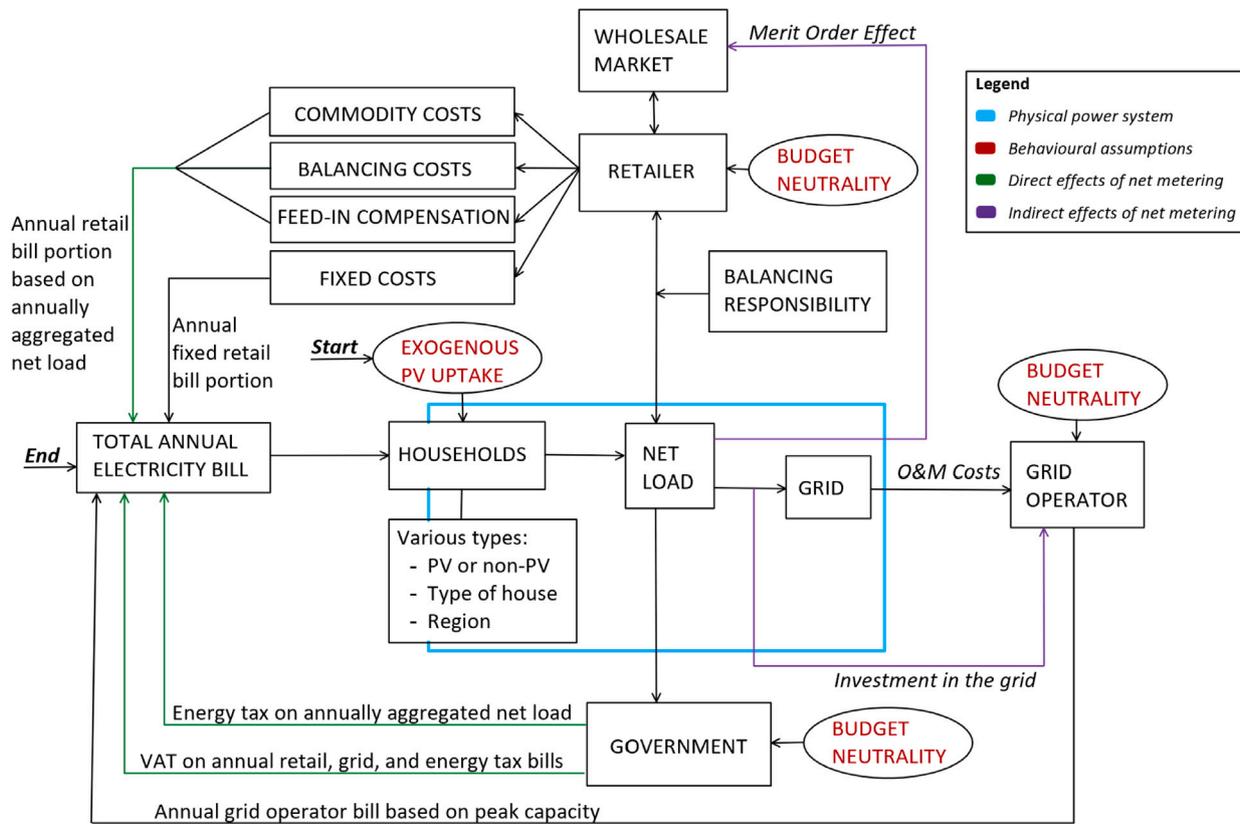
Net metering effects may also vary across spatial locations and economic conditions given the uneven socio-spatial distribution of solar panel adoption. In The Hague, areas with lower rates of home ownership, higher shares of apartment buildings, and more non-native residents exhibit lower PV adoption (Kraaijvanger et al., 2023). Similar disparities are seen in California (Borenstein, 2017) and the UK (Sovacool et al., 2022; Collier et al., 2023). Low-income households are also more exposed to tariff increases due to lower PV uptake and consumption levels, especially under fixed recovery charges (Burger et al., 2020).

Table 1 summarizes the findings of the previous literature and highlights the contribution of this study. Indeed, we contribute to the literature by comprehensively quantifying the distributional effects of net metering through the channels of the retail costs, the grid costs, and the tax component. We also disaggregate the effects on each of these channels. Moreover, we analyze some of the socio-spatial heterogeneity

in these effects. Furthermore, we compare net metering to alternative billing mechanisms and discuss their respective distributional impact. Lastly, we also investigate the fiscal policy implications and potential alternatives to reduce the distributional effects of net metering via energy taxes.

3. Conceptual framework

We assess how households are affected by the net-metering scheme by investigating how the scheme impacts each component of the household electricity bill. We do so within the following conceptual framework, which is based on a stylized depiction of the organization of the retail electricity system in the Netherlands and on the related energy economics literature (Castaneda et al., 2017; Ansarin et al., 2022; Mulder, 2023). Notably, while the previous literature has conceptualized individual aspects discussed in this section, we contribute with a unified framework that encompasses multiple agents and that showcases both the direct and the indirect channels through which net metering may affect households. Our conceptual framework, which is graphically presented in Fig. 1, first characterizes households and then discusses the three components of the household electricity bill: the retail component, the grid operator component, and the electricity taxes.



Notes

- Feed-in compensation refers to the compensation to households for their excess generation after netting their consumption.
- O&M costs refer to operation and maintenance costs.
- VAT refers to Value Added Tax.

Fig. 1. Graphical representation of the conceptual framework.

Households have various characteristics, such as type of house and location, and they have a physical connection to the grid. A crucial distinction in our framework is between households that have installed solar panels (PV households) and those that lack such installations (non-PV households). The decision of households to install solar panels is exogenous to our model. All households consume electricity, that is they have a load, while PV households also generate electricity through their solar panels. Consequently, at any given moment in time, all households have a net load, defined as the difference between their load and generation. The net load can be either positive or negative. In the latter case, the net load is then fed into the electricity grid.

The net load of households is economically handled by retailers. In the Netherlands, retailers operate in a competitive market,² which we simplify here to a perfectly competitive market where retail prices are closely related to the marginal costs. Hence, we refer to a single retailer acting under budget neutrality, which means that it passes all its costs onto its customers. The retailer buys or sells the households' net load amount of electricity on the wholesale market, incurring so-called commodity costs. Additionally, the retailer faces the responsibility of balancing its retail portfolio, incurring balancing costs in the process. Lastly, the retailer incurs some fixed costs, such as administrative and overhead costs.

² The Dutch Authority for Markets and Consumers (ACM) currently licenses about fifty energy suppliers that compete with each other (ACM, 2024). Moreover, Mulder and Willems (2019) analyze the Dutch retail electricity market and find it to be competitive and mature, with consumers easily able to switch between suppliers.

The costs of the retailer are affected directly and indirectly by the net-metering scheme. The retailer's commodity costs are indirectly affected through the wholesale market price. Indeed, the merit order effect (which is further discussed in Appendix A.1) implies that the lower the net load of households the lower the equilibrium electricity price on the wholesale market, which has a downward effect on the sourcing costs of the retailer. Moreover, the commodity costs are also directly affected by the net-metering scheme through a volume and timing effect, as PV households consume electricity only in certain hours and supply electricity to the grid and retailer in other hours. The retailer's balancing costs are also affected by net metering, as increased solar panel generation increases uncertainty, making predictions more challenging and, consequently, leading to higher balancing costs.³ Lastly, under net metering, the retailer compensates PV households that have a negative annual net load with a feed-in fee for their excess generation.

The net load of households is physically handled by the grid operator. Regarding the regulation of the grid tariffs, we assume that the grid operator also operates under budget neutrality and, hence,

³ Currently, in the Netherlands, some retailers are passing (part of) their higher commodity and balancing costs onto PV households through a fee based on the amount of electricity households return to the system. This fee is usually termed return fee, but it is sometimes incorrectly referred to as return fine. It is, however, not a fine but rather a compensation from PV households for the additional costs retailers incur for these households under net metering. We do not include this return fee in our analysis but rather assume that the higher retail costs are passed onto all households, as we aim to analyze the full potential distributional effects of the scheme. Yet, if retailers charge a return fee, the distributional effects of net metering are partly mitigated.

passes the operation and maintenance costs on to its net users (Mulder, 2023). Based on the current situation in the Netherlands, we let the grid operator pass these costs on to consumers based on the consumers' peak capacity. For households, this can be simplified to a fixed grid tariff equal for all households,⁴ as most households have the same standard peak capacity. Regarding the effect of net metering, the higher uptake of solar panels by households increases the need for grid capacity and may lead to congestion problems.⁵ We adopt a long-term perspective in which the grid operator makes additional investments in the grid in order to avoid these congestion issues. Thus, we expect net metering to indirectly increase the grid operator costs and, hence, result in higher grid tariffs.

The net load of households is generally taxed by the government in two ways. Firstly, the government imposes a so-called energy tax to incentivize consumers to increase the efficiency of electricity consumption and raise revenues. Secondly, the government also imposes a value-added tax (henceforth, VAT) on households' annual retail, grid operator, and energy tax bills. The government revenues earned by these taxes are affected by net metering. The revenues from the energy tax decrease because PV households have smaller net loads, which implies a smaller tax base for the energy tax. This also implies that the revenues from the VAT on the energy tax bill decrease. Moreover, the revenues from the VAT on retail bills are also negatively affected by net metering as PV households have smaller retail bills on which the VAT is imposed. On the contrary, the revenues from the VAT on the grid operator bill increase, as the VAT is imposed on a higher grid tariff. We assume that the government acts under budget neutrality,⁶

⁴ While assuming a fixed grid tariff is realistic for the case of the Netherlands, it is not for several other countries. Thus, we will explore the effect of different grid tariff designs in our sensitivity analysis in Section 6.8.

⁵ In countries, such as the Netherlands, where the peaks in electricity load do not coincide with hours in which solar panels have high generation, a larger solar-power generation is generally associated with oversupply and grid congestion. In other regions where the load and the solar generation peaks are better aligned, due to, for instance, high usage of air conditioning, higher solar-power generation may even reduce grid congestion issues (though likely not extensively, see e.g. Ovaere et al., 2025). Our framework is based on the situation in the Netherlands and countries with similar climate and energy consumption patterns (e.g. North-Western and Central Europe). Thus, a larger residential solar panel uptake can worsen grid congestion and related issues in our framework (as also evaluated by Vendrik et al., 2024). One such related issue concerns the inverters of solar panels switching off when there is oversupply to avoid damage to the low-voltage grid. This entails a large cost for households with solar panels who cannot generate electricity neither for their own use nor to sell it to their supplier. Moreover, transporting more electricity than cables are designed for results in the cables and the transformers aging more quickly and needing to be replaced more often, which increases costs for the grid operator and, ultimately, for households. Furthermore, there is an increased risk of outages and disruptions, such as lights flickering and appliances not working properly.

⁶ The government budget neutrality assumption is, arguably, quite strong. However, we have several reasons to motivate it. Firstly, the tax revenue losses associated with the net metering scheme have been one of the main reasons for its abolition (Londo et al., 2020; PwC Advisory, 2016). This suggests that the energy tax is not seen as a Pigouvian tax in the Netherlands. Indeed, if the energy tax were Pigouvian and in place to reduce electricity consumption from fossil fuels, the decrease in tax revenues would be seen as a logical consequence of the greening of the energy mix due to increased solar panel adoption. Secondly, on a more general level, the common fiscal policy of the Dutch government enforces that reduced revenues in one policy domain should be compensated in that same domain. Thus, our assumption that revenue losses from utility bill taxes must be compensated within the domain of utility bill taxes is in line with the Dutch government's budget approach. Thirdly, assuming that the government sets a constant budget to be raised from these taxes and computing the energy tax rate increase makes the effect of net metering on taxes very explicit. Alternatively, we could also assume that the tax rates are identical in the two scenarios and compute

which means that the total government revenues from both taxes have to remain the same with or without net metering. Hence, given that the VAT is hard to adapt, this implies a higher energy tax rate for all households.

This conceptual framework allows us to formulate the following hypotheses regarding the effects of the net-metering scheme on the total annual household electricity bill. We expect PV households to pay a much smaller bill under net metering as their retail and tax bills are based on a smaller net load. Next, we hypothesize that non-PV households are negatively affected by the scheme, as the increases in the retailer's balancing costs, the grid tariff, and the tax rate are larger than the decrease in commodity costs brought about by the merit order effect. Lastly, we expect the two hypothesized effects to differ across households living in different regions and housing types based on their available solar radiation and ability to install solar panels. In the remainder of this paper, we will test these hypotheses by translating the above analytical framework into an operational model. Specifically, to evaluate the effects of interest, we compare the situation in which the net-metering scheme is in place to a counterfactual situation in which no solar capacity is installed. The choice of such a counterfactual is motivated by our interest in analyzing both direct effects of net metering and indirect effects through the increase in residential solar capacity.⁷ We, then, conduct a numerical analysis based on this conceptual framework and operational model using real data for the Netherlands in 2021, as this is the most recent year with available data.

4. Operational model

We operationalize our conceptual framework into a tractable simulation model. To achieve this, we use insights from the standard microeconomic literature and the frameworks used in the related literature (Picciariello et al., 2015; Castaneda et al., 2017; Schittekatte et al., 2018). While the individual components of our operational model are based on standard knowledge in this literature, we contribute by providing one unified, simple, and coherent model that encompasses multiple agents and that is tractable. The derived operational model is on an hourly basis, due to the fact that retailers can adapt their electricity market portfolio every hour. In this model, i denotes an individual household and N denotes the total number of households; h denotes an individual hour and H denotes the total number of hours in a year. We index yearly variables with y . We denote the scenario in which net metering is in place as NM and the counterfactual scenario in which no household has solar panels as CS . When no superscript is present, the calculation is the same in both scenarios. Table 2 provides a summary of all the abbreviations used in this section, in the order in which they appear in the text.

4.1. Characterization of households

We let $L_{h,i}$ and $G_{h,i}$ be the load and the generation of household i at time h . In the counterfactual scenario, all households have a generation of zero. In the net-metering scenario, PV households net

the government revenue losses, yet this approach makes the distributional effects less straightforward. Nevertheless, we use this alternative approach as a sensitivity analysis and present the estimated government revenue losses in Section 6.8.

⁷ Our implicit assumption that the increase in residential solar capacity is caused by the net metering scheme is based on the literature on the effectiveness of net metering in incentivizing solar panel adoption (Duke et al., 2005; Dufo-López and Bernal-Agustín, 2015; Ramírez et al., 2017; Gautier and Jacquemin, 2019) and on the actual situation in the Netherlands, where solar panels would not have been an economically viable option for households were net metering not in place until recently (PwC Advisory, 2016).

Table 2
Explanation of the acronyms used in Section 4.

	Description (Unit)
<i>CS</i>	Counterfactual scenario
<i>NM</i>	Net metering scenario
<i>i</i>	Household identifier
<i>h</i>	Hour (time identifier)
<i>H</i>	Total number of hours in a year
<i>y</i>	Year
<i>L</i>	Load (kW)
<i>G</i>	Generation (kW)
<i>Ln</i>	Net load (kW)
<i>Ge</i>	Excess generation (kW)
<i>N</i>	Total number of households in the country
<i>N_{PV}</i>	Number of PV households in the country
<i>N_{nonPV}</i>	Number of non-PV households in the country
<i>P</i>	Electricity price in the wholesale market (€/MWh)
<i>MOE</i>	Merit order effect from residential solar panels (€)
<i>CC</i>	Retailer's commodity costs (€)
<i>BC</i>	Retailer's balancing costs (€)
<i>b</i>	Balancing cost parameter (€)
<i>a</i>	Parameter for the change in balancing costs
<i>FC</i>	Retailer's feed-in fee compensation costs (€)
<i>f</i>	Feed-in fee (€)
<i>RC</i>	Total costs for the retailer (€)
<i>r</i>	Retail tariff imposed by the retailer on households (€/kWh)
<i>GC</i>	Grid operator's costs (€)
<i>x</i>	Fixed grid tariff imposed by the grid operator on households (€)
<i>γ</i>	Parameter for the change in grid costs
<i>c</i>	Residential solar installed capacity (kW)
<i>GR</i>	Government revenues (€)
<i>t</i>	Energy tax rate imposed by the government on the net load (€/kWh)
<i>v</i>	VAT rate imposed by the government on the retail bill (%)
<i>Bill</i>	Total annual household electricity bill (€)

their annual load against their annual generation. Hence, let the net load of household *i* in year *y* be:

$$Ln_{y,i} = \begin{cases} (\sum_{h=1}^H L_{h,i}) - (\sum_{h=1}^H G_{h,i}) & \text{if } (\sum_{h=1}^H L_{h,i}) - (\sum_{h=1}^H G_{h,i}) > 0 \\ 0 & \text{if } (\sum_{h=1}^H L_{h,i}) - (\sum_{h=1}^H G_{h,i}) \leq 0, \end{cases} \quad (1)$$

and define a negative net load as excess generation, the calculation of which is the inverse of the above:

$$Ge_{y,i} = \begin{cases} (\sum_{h=1}^H G_{h,i}) - (\sum_{h=1}^H L_{h,i}) & \text{if } (\sum_{h=1}^H G_{h,i}) - (\sum_{h=1}^H L_{h,i}) > 0 \\ 0 & \text{if } (\sum_{h=1}^H G_{h,i}) - (\sum_{h=1}^H L_{h,i}) \leq 0. \end{cases} \quad (2)$$

Moreover, we let *N*, the total number of households in the country, be the same for both the counterfactual and the net-metering scenario. Yet, in the net-metering scenario, *N* is also the sum of the number of PV households (*N_{PV}*) and the number of non-PV households (*N_{nonPV}*) in the country.

4.2. Retail component of the annual electricity bill

The retail component of the annual electricity bill consists of four items: commodity costs, balancing costs, feed-in fee compensation, and fixed costs. The latter is unaffected by the net-metering scheme and the increase in residential solar capacity and, hence, it can be ignored in our analysis.

4.2.1. Retailer's commodity costs

The commodity costs (*CC_y*) refer to the costs faced by the retailer when trading electricity on the wholesale market. In the counterfactual scenario, these are computed as the sum of the product of wholesale prices and load:

$$CC_y^{CS} = \sum_{h=1}^H (P_h^{CS} * \sum_{i=1}^N L_{h,i}). \quad (3)$$

In the net-metering scenario, the commodity costs are the sum of the costs of procuring electricity to meet the demand of non-PV households and the costs or revenues of trading the hourly net load of PV households.

$$CC_y^{NM} = \left[\sum_{h=1}^H (P_h^{NM} * \sum_{i=1}^{N_{nonPV}} L_{h,i}) \right] + \left[\sum_{h=1}^H (P_h^{NM} * \sum_{i=1}^{N_{PV}} (L_{h,i} - G_{h,i})) \right], \quad (4)$$

where the second term can be either positive or negative. Specifically, it is positive when PV households consume more than they generate, implying that the retailer faces costs to procure electricity to meet their net demand. On the contrary, it is negative when PV households consume less than they generate, which implies that the retailer sells the net generation on the market, thereby earning revenues from this transaction (provided a positive electricity price).

Note that the electricity price P_h^{NM} is lower than it would be in the counterfactual scenario due to the merit order effect from residential solar panels⁸:

$$P_h^{NM} = P_h^{CS} + \Delta P_{MOE,h}, \quad (5)$$

where the negative term $\Delta P_{MOE,h}$ is the change in the electricity price due to the merit order effect. This is given by:

$$\Delta P_{MOE,h} = \begin{cases} \beta_1 * \sum_{i=1}^{N_{PV}} (G_{h,i} - L_{h,i}) & \text{if } \sum_{i=1}^{N_{PV}} (G_{h,i} - L_{h,i}) > 0 \\ 0 & \text{if } \sum_{i=1}^{N_{PV}} (G_{h,i} - L_{h,i}) \leq 0, \end{cases} \quad (6)$$

where the negative parameter β_1 captures the impact of households' net load on the electricity price and is estimated in [Appendix A.1](#).

⁸ The merit order effect usually refers to the change in the electricity price in response to generation from all low-marginal cost renewable sources. However, we are interested in the (indirect) effects of net metering and, hence, we focus on the merit order effect from exclusively residential solar panels.

4.2.2. Retailer's balancing costs

The retailer also faces balancing costs. We assume the latter to be a linear function of the load. In the counterfactual scenario, this implies that the balancing costs are:

$$BC_y^{CS} = \sum_{i=1}^N \left(b^{CS} * \sum_{h=1}^H L_{h,i} \right), \quad (7)$$

where the balancing cost parameter b^{CS} is exogenous. However, in the net-metering scenario, these balancing costs increase as rising residential solar capacity makes predictions more difficult. To capture this, we let the balancing cost parameter increase linearly with the amount of electricity returned to the system by PV households.

$$b^{NM} = \begin{cases} b^{CS} + \alpha * \sum_{i=1}^{N_{PV}} \sum_{h=1}^H (G_{h,i} - L_{h,i}) & \text{if } \sum_{i=1}^{N_{PV}} \sum_{h=1}^H (G_{h,i} - L_{h,i}) > 0 \\ b^{CS} & \text{if } \sum_{i=1}^{N_{PV}} \sum_{h=1}^H (G_{h,i} - L_{h,i}) \leq 0, \end{cases} \quad (8)$$

where α is the parameter for the change in balancing costs associated with a change in solar electricity returned to the system. Hence, the balancing costs faced by the retailer in the net-metering scenario are:

$$BC_y^{NM} = \left[\sum_{i=1}^{N_{nonPV}} (b^{NM} * \sum_{h=1}^H L_{h,i}) \right] + \left[\sum_{i=1}^{N_{PV}} (b^{NM} * L_{n_{y,i}}) \right]. \quad (9)$$

4.2.3. Retailer's feed-in fee compensation

In the net-metering scenario, the retailer must compensate households for their excess generation if their annual net load is negative. Hence, the retailer determines a feed-in fee f^{NM} , which is exogenous to our model, and faces the following feed-in compensation:

$$FC_y^{NM} = \sum_{i=1}^{N_{PV}} (f^{NM} * Ge_{y,i}). \quad (10)$$

4.2.4. Retailer's bill and retail price determination

The total costs for the retailer (RC_y) are the sum of the three components discussed, such that:

$$RC_y^{CS} = CC_y^{CS} + BC_y^{CS}, \quad (11)$$

and

$$RC_y^{NM} = CC_y^{NM} + BC_y^{NM} + FC_y^{NM}. \quad (12)$$

Under our assumption of budget neutrality, the retailer passes these costs on to its customers. Hence, the retail price that the retailer charges households is a function of its total costs and the total net load. That is:

$$r^{CS} = \frac{RC_y^{CS}}{\sum_{i=1}^N \sum_{h=1}^H L_{h,i}}, \quad (13)$$

in the counterfactual scenario, and

$$r^{NM} = \frac{RC_y^{NM}}{\sum_{i=1}^{N_{nonPV}} \sum_{h=1}^H L_{h,i} + \sum_{i=1}^{N_{PV}} L_{n_{y,i}}}, \quad (14)$$

in the net-metering scenario.

4.3. Grid component of the annual electricity bill

The grid costs (GC_y) faced by the grid operator are exogenous to our model and we assume, based on the Dutch tariff regulation, that they are retrieved by charging an annual fixed grid tariff (x_y) to all households. In the counterfactual scenario, these grid costs are:

$$GC_y^{CS} = x_y^{CS} * N. \quad (15)$$

In the net-metering scenario, the grid operator faces an increase in costs, which is assumed to depend linearly on the installed capacity of residential solar in the country in the given year:

$$GC_y^{NM} = x_y^{CS} * N + \gamma \sum_{i=1}^{N_{PV}} c_{y,i}, \quad (16)$$

where $c_{y,i}$ is the installed capacity of household i in year y . Then, the grid operator charges the following fixed grid tariff to each household:

$$x_y^{NM} = x_y^{CS} + \frac{\gamma \sum_{i=1}^{N_{PV}} c_{y,i}}{N}. \quad (17)$$

4.4. Annual electricity bill taxes

We let the government have an exogenous amount of revenues (GR_y) to be raised from household electricity bill taxes, that is, both the energy tax and the VAT.⁹ Moreover, we assume that the VAT rate v is exogenous and constant. Indeed, this rate is applied to most goods in the economy and, hence, it is hard for the government to adapt it only in response to a change in revenues from the electricity consumption. On the contrary, the energy tax rate t is different between the two scenarios, and it is determined by setting the government revenues in the net-metering scenario (GR_y^{NM}) equal to the government revenues in the counterfactual scenario (GR_y^{CS}). The government revenues are determined as:

$$GR_y^{CS} = [(1 + v) * t^{CS} + v * r^{CS}] * \sum_{i=1}^N \sum_{h=1}^H L_{h,i} + (v * x_y^{CS} * N), \quad (18)$$

in the counterfactual scenario, and

$$GR_y^{NM} = [(1 + v) * t^{NM} + v * r^{NM}] * \left(\sum_{i=1}^{N_{nonPV}} \sum_{h=1}^H L_{h,i} + \sum_{i=1}^{N_{PV}} L_{n_{y,i}} \right) + (v * x_y^{NM} * N), \quad (19)$$

in the net-metering scenario.

Therefore, the energy tax rate imposed by the government in the counterfactual scenario is:

$$t^{CS} = \frac{GR_y - (v * r^{CS} * \sum_{i=1}^N \sum_{h=1}^H L_{h,i}) - (v * x_y^{CS} * N)}{(1 + v) * \sum_{i=1}^N \sum_{h=1}^H L_{h,i}}. \quad (20)$$

Under our budget neutrality assumption (that is, $GR_y^{CS} = GR_y^{NM}$), the energy tax rate in the net-metering scenario becomes:

$$t^{NM} = \frac{GR_y - [v * r^{NM} * (\sum_{i=1}^{N_{nonPV}} \sum_{h=1}^H L_{h,i} + \sum_{i=1}^{N_{PV}} L_{n_{y,i}})] - (v * x_y^{NM} * N)}{(1 + v) * (\sum_{i=1}^{N_{nonPV}} \sum_{h=1}^H L_{h,i} + \sum_{i=1}^{N_{PV}} L_{n_{y,i}})}. \quad (21)$$

4.5. Total annual household electricity bill

The total annual electricity bill of a household in the counterfactual scenario is:

$$Bill_{y,i}^{CS} = \left[(1 + v) * (r^{CS} + t^{CS}) * \sum_{h=1}^H L_{h,i} \right] + \left[(1 + v) * x_y^{CS} \right]. \quad (22)$$

In the net-metering scenario, the total annual electricity bill of a non-PV household is:

$$Bill_{y,i,nonPV}^{NM} = \left[(1 + v) * (r^{NM} + t^{NM}) * \sum_{h=1}^H L_{h,i} \right] + \left[(1 + v) * x_y^{NM} \right]. \quad (23)$$

⁹ We refer the reader to for a complete discussion of this assumption.

On the other hand, the total annual electricity bill of a PV household is:

$$Bill_{y,i}^{NM} = [(1 + v) * (r^{NM} + t^{NM}) * Ln_{y,i}] + [(1 + v) * x_y^{NM}] - (f^{NM} * Ge_{y,i}), \quad (24)$$

The latter equation implies that, when the annual net load of a PV household is positive, its electricity bill is the sum of positive retail, tax, and grid components. When the annual net load is negative, the electricity bill is the difference between the grid tariff payable and the feed-in compensation receivable.¹⁰

5. Numerical analysis

We would, ideally, conduct a numerical analysis to assess the distributional effects of net metering for all households in the Netherlands. However, this is not possible due to a lack of data. Hence, we conduct this analysis for different types of households in the various Dutch regions. Specifically, households are identified by their location (twelve Dutch provinces), their housing type (2-under-1 roof, apartment, corner house, detached house, terraced house), and their solar-panel ownership (i.e., whether they have installed solar panels or not). We conduct this analysis for the year 2021, as it is the most recent year for which data is available. Therefore, all prices are also expressed in euros of 2021. The following subsections discuss the sources and computations used for the variables of interest, while Appendix A.4 presents descriptives for the inputs of our numerical analysis.

5.1. Characterization of households

5.1.1. Number of households

We are interested in the number of households with and without solar panels for each province in the Netherlands across the five housing types considered for 2021. However, this data is not readily available. Hence, we first approximate the total number of households per province and housing type with the number of houses per province and housing type. We obtain data on the latter from CBS (2023).

Then, we estimate the number of households with solar panels per province and housing type, as data on this is not available. We obtain data on the total number of residential solar panel installations by year and province from CBS (2023) and use this as our proxy for the number of households with solar panels per province. Regarding the distribution of PV households over the five housing types considered, we rely on an assumed distribution that we believe to hold nationally and to be constant within the year 2021. We assume that for every 100 households with solar panels in any given province, one of these households lives in an apartment, twenty-nine of these households live in a terraced house, thirty of these households live in a corner house, five of these households live in a 2-under-1-roof house, and thirty-five of these households live in a detached house. Therefore, the product of these shares and the provincial number of PV households provides us with a reasonable approximation of the number of PV households per province and housing type.

Lastly, we calculate the number of households without solar panels as the difference per province and housing type between the total number of households and the number of PV households.

5.1.2. Load

We are interested in the load, that is, the consumption of electricity at every hour, of households by province and housing type. To obtain this, we gather data on the average yearly household electricity consumption by province and housing type from CBS (2023). Then, we

¹⁰ We assume that the feed-in compensation earned by households when they have excess generation is not subject to VAT.

assume a load pattern for all households, based on Trotta et al. (2020). Such a pattern refers to the share of the yearly electricity consumption that each household consumes at any given hour. We show the assumed load pattern in Fig. 2. Since the seasonal variation is the most relevant for the interaction with solar PV, we assume that the load pattern only varies seasonally and we ignore the volatility within seasons. Then, we compute the household load as the product of the yearly electricity consumption and the load pattern.

5.1.3. Generation

We compute the generation from residential solar panels based on Eq. (25) shown in Box I, a commonly used formula in the engineering literature on solar panels' output (Choi et al., 2010; Habib Khan et al., 2022). The term $Capacity_i$ refers to the capacity of solar panels installed by the given household. To estimate this, we gather data on the total installed residential solar capacity per province in 2021 from CBS (2023) and compute the installed PV capacity per household as the quotient of the provincial PV capacity and the number of PV households per province and housing type. The term $Sunshine_{h,i}$ is the hourly solar irradiance at the chosen location. We obtain data on this from the Global Solar Atlas (2023) in the form of average hourly profiles per month and location.¹¹ The terms $Std Irradiance$ and $Crt Irradiance$ are the standard solar irradiance and the certain irradiance point at the chosen location. The latter two values are usually set at 1,000 W/m² and 120 W/m², respectively, for European countries (Choi et al., 2010; Habib Khan et al., 2022).

5.2. Retail component of the annual electricity bill

We require data on the price at which retailers trade electricity to estimate the retailer's commodity costs. Generally, retailers buy electricity through long-term contracts, and, in theory, long-term prices reflect the expected short-term prices. Hence, the day-ahead electricity price can be seen as a good proxy for the price faced by the retailer in our model. We obtain data on the hourly day-ahead electricity price for the bidding zone of the Netherlands from the ENTSO-E Transparency platform (2023).

Additionally, we rely on the prices used by the Dutch retailer Tibber (2023) to derive the parameters needed to estimate the balancing costs. This retailer charges 0.002 €/kWh per household for the balancing costs incurred. Then, we assume that $b^{CS} = 0.001$ €/kWh and we derive α as the quotient of 0.001 €/kWh and the total electricity returned to the grid by households in 2021, such that $\alpha = 2.984 * 10^{-10}$ €/kWh.

Lastly, we assume that the feed-in fee with which the retailer compensates PV households for their excess generation (f^{NM}) is the average day-ahead electricity price over the year of 2021.

5.3. Grid component of the annual electricity bill

Regarding the parameters in the operational model for the grid component of the annual electricity bill, we need an estimate of the grid tariff imposed on households when no residential solar capacity was installed as well as an estimate of the parameter with which grid costs increase in response to larger residential solar capacity being installed. For the former, we estimate that $x_y^{CS} = 190$ €/year based on the fact that the fixed delivery rate for residential consumers was 197.60 €/year in 2018 (the earliest year available) (CBS, 2023) and that the uptake of residential solar panels was already quite high at that time in the Netherlands.

¹¹ This is an indicative average of the amount of sunshine that occurs in a given hour for any day in a given month, implying that the variable we use for sunshine differs per hour and month but does not vary across days within a month.

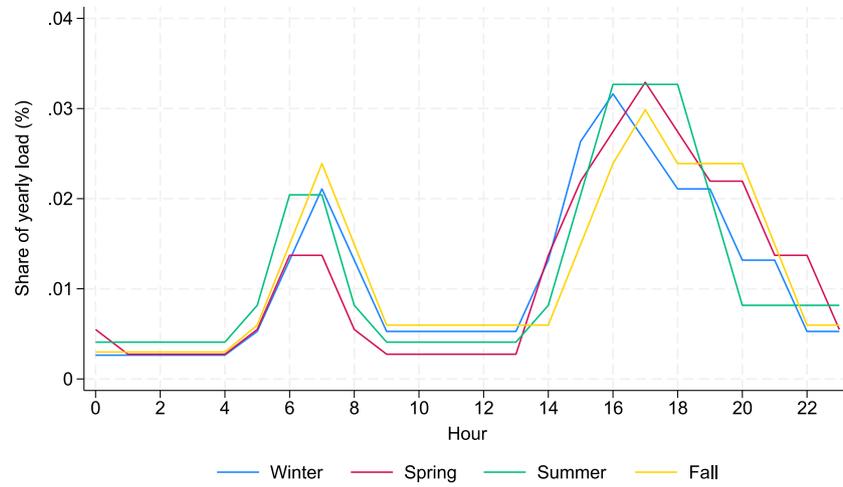


Fig. 2. Daily load pattern per season per household (own assumptions based on Trota et al., 2020).

$$G_{h,i} = \begin{cases} \text{Capacity}_i & \text{if Sunshine}_{h,i} > \text{Std Irradiance} \\ \text{Capacity}_i * \frac{\text{Sunshine}_{h,i}}{\text{Std Irradiance}} & \text{if Crt Irradiance} \leq \text{Sunshine}_{h,i} \leq \text{Std Irradiance} \\ \text{Capacity}_i * \frac{\text{Sunshine}_{h,i}^2}{\text{Std Irradiance} * \text{Crt Irradiance}} & \text{if Sunshine}_{h,i} < \text{Crt Irradiance}. \end{cases} \quad (25)$$

Box I. Equation for the computation of residential solar generation (Choi et al., 2010; Habib Khan et al., 2022).

For the rate at which grid costs increase due to residential solar panels, γ , we rely on Gupta et al. (2021a). They estimate that, in Switzerland, one additional kW of residential solar capacity is associated with an increase in the grid operator's investment and maintenance costs of about 213 CHF, which is equivalent to about 219.33 € at the main exchange rate as of July 2024. We assume that this estimate is applicable to the Netherlands, as the two countries are both small Western European countries with similar electricity systems and ambitious goals for green energy production. Then, we annualize this total cost by assuming a lifetime of 25 years for this grid investment and straight-line depreciation, obtaining a $\gamma = 8.77$ €/kW.

5.4. Annual electricity bill taxes

Regarding the taxes imposed by the government on the electricity bills of households, we are interested in both the VAT rate and the energy tax rate. For the former, the VAT has been 21% in the Netherlands since 2012 (Belastingdienst, 2024), hence, this is the value we use in our analysis. Moreover, we require the energy tax rate that would be imposed when no residential solar capacity was installed. While such a tax rate is not directly obtainable, we estimate that $t^{CS} = 0.08$ €/kWh based on the following. We observe that in 2018 (the earliest available year), the Dutch government¹² charged an energy tax of 0.10458 €/kWh. Since residential solar panels were widespread in the Netherlands that year, we believe that 0.08 €/kWh is a fair approximation for the tax rate in the counterfactual scenario.

¹² At the time, the Dutch government also charged an environmental charge related to the ODE scheme, which was aimed at raising funds to provide subsidies to renewable energy technologies within this scheme. This charge was of a negligible amount (0.01320 €/kWh, CBS, 2023) and, thus, we ignore it.

6. Results and discussion

6.1. Retail component of the annual electricity bill

Table 3 reports that the retailer faces slightly higher total costs to supply non-PV households under net metering than to supply households in the counterfactual scenario where no residential solar capacity is installed. As visible in Table 3, the increase is mainly due to the higher balancing costs, while the commodity costs (which are further explained and decomposed in the next paragraph) decrease due to the MOE. For PV households, the retailer faces much lower costs compared to the counterfactual scenario. These costs are much lower, even if the retailer incurs about 51€ to compensate the average PV household for its excess solar generation. Despite the fact that the total retail costs are lower under net metering compared to the counterfactual scenario, the retail tariff increases from 0.11 to 0.12 €/kWh. This is because PV households are able to net their total annual consumption against their total annual generation, resulting in smaller net loads over which the retailer can spread its costs. Hence, non-PV households essentially subsidize retail costs for PV households under net metering. We estimate that this so-called subsidy increases the retail costs faced by the average non-PV household by about 20€ per year. An alternative way to see this is to compute the extra costs of netting from the perspective of the retailer for each unit demanded by PV households. That is, the costs faced by the retailer for the average PV household are about 98€ while this household only contributes with about 25€. This difference per unit of electricity demanded by the average PV household is the additional cost of netting, which we estimate to be about 0.04 €/kWh.

The effects of net metering on the retailer's costs are complex, especially concerning the commodity cost component. Indeed, the commodity costs of the retailer are affected by net metering both directly through a volume and timing effect and indirectly through the merit order effect, as outlined in our conceptual framework. As shown in

Table 3

Retailer's total annual costs components and tariff revenues for one household in the Counterfactual Scenario (CS) in which there is no residential solar capacity installed and for a non-PV and a PV household in the Net-Metering Scenario (NM).

Average per year	Unit	CS	NM	NM
		One Household	Non-PV Household	PV Household
Total net commodity costs	€	335.76	333.74	46.74
Balancing costs	€	3.02	6.05	0.42
Feed-in compensation costs	€	.	.	51.03
Total retailer's costs caused by household category	€	338.79	339.79	98.19
Retail tariff imposed on households	€/kWh	0.1121	0.1194	0.1194
Retail bill to be paid by household category	€	338.79	360.95	25.03

The values are approximations to the closest second or fourth decimal.
The total net commodity costs include the MOE from residential solar generation.

Table 4

Composition of the commodity costs faced by the retailer for one household in the Counterfactual Scenario (CS) in which there is no residential solar capacity installed and for a non-PV and a PV household in the Net-Metering Scenario (NM).

Average per year (formula with row numbers)	Unit	CS	NM	NM
		One Household	Non-PV Household	PV Household
1 Weighted price to buy demanded electricity	€/kWh	0.1111	0.1104	0.1230
2 Weighted price to sell supplied electricity	€/kWh	.	.	0.0858
3 Volume of demanded electricity	kWh	3023	3023	1910
4 Volume of supplied electricity	kWh	.	.	2196
5 Cost of buying demanded electricity (1 * 3)	€	335.7654	333.7434	235.6709
6 Cost of selling supplied electricity (2 * 4)	€	.	.	188.9281
7 Total net commodity costs (5 - 6)	€	335.7654	333.7434	46.7428

The values are approximated, thus, using the formulas shown with these values may provide slightly different results.
The prices in the NM scenario include the MOE from residential solar generation.
Without this MOE, the prices in €/kWh would be: 0.1111 (non-PV), 0.1230 (PV, buy), 0.0878 (PV, sell).

Table 4, the retailer buys the electricity demanded by the average non-PV household at a volume-weighted price of about 0.11 €/kWh and the electricity demanded by the average PV household at about 0.12 €/kWh regardless of the merit order effect, as PV households demand electricity from the grid in hours of higher demand and low renewables supply in the market. This latter reasoning also explains the relatively low price at which the retailer is able to sell the excess generation of PV households, which we estimate to amount to about 0.086 €/kWh. On top of this timing effect, the merit order effect from residential solar panels lowers the price of buying the electricity demanded by the average non-PV household by about a euro per MWh and lowers the price of selling the electricity supplied by the average PV household by about two euros per MWh. In terms of volumes, we find that, on average, PV households have an overall negative total net load as the amount of electricity they return to the grid exceeds the amount they demand from the grid.¹³ In total, the retailer faces about 334€ a year for the average non-PV household and about 47€ a year for the average PV household in net commodity costs. Both of these costs are lower than the net commodity costs the retailer would face in a scenario without any residential solar capacity installed.

6.2. Grid component of the annual electricity bill

We take a long-term perspective to analyze the effect of net metering on grid costs, as we estimate the investment needed to ensure the proper functioning of the grid.¹⁴ We find that the increase in

residential solar capacity is associated with an additional 51 million euros of investment and maintenance costs for the grid operator. As discussed in Section 5.3, we assume that the grid operator annualizes these additional costs over 25 years. For the year considered, this implies an increase in grid costs of about 3%. Under our assumption of budget neutrality for the grid operator, this cost increase implies that every household pays about six additional euros per year due to the increase in solar panels brought about by net metering. Specifically, we estimate that the yearly grid tariff increases from 190€ in the counterfactual scenario to 196.42€ in the net-metering scenario. Notably, all households face the same increase in the grid component of their electricity bill even though PV households are the main contributors to the increase in costs for the grid operator. These findings are dependent on our assumption that all households face the same fixed grid tariff, which is reflective of the situation in the Netherlands. However, we also conduct a sensitivity analysis to this assumption in Section 6.8 and show that a fixed grid tariff equal for all households leads to the smallest distributional effects compared to other tariff designs.

6.3. Annual electricity bill taxes

The taxes imposed on the electricity bill of households include the VAT on the retail price and the energy tax, as visible in **Table 5**. We show that the government revenues from the VAT on the retail bill and the energy tax decrease substantially as a result of net metering since PV households have a smaller net load. The revenues from the VAT on the grid operator bill increase only slightly, as the grid tariff increases. Hence, we estimate that the government raises the energy tax rate by about 37% under net metering in order to maintain the same government budget as in the counterfactual scenario. This increase strongly negatively affects non-PV households, who pay about 78€ extra in energy taxes alone on average compared to the counterfactual scenario. This also implies a redistribution of the contributions to the total government revenues by PV and non-PV households. Indeed, in

¹³ This is further discussed in [Appendix A.4](#).

¹⁴ Holding a short-term perspective in which the grid operator does not or cannot make these additional investments implies that the households would not face the estimated increase in the grid component of their electricity bill. However, households would still face costs related to congestion as discussed in [Section 3](#).

Table 5

Tax rates and tax revenues earned by the government from one household in the Counterfactual Scenario (CS) in which there is no residential solar capacity installed and from a non-PV and a PV household in the Net-Metering scenario (NM).

	Unit	CS	NM	NM
		One Household	Non-PV Household	PV Household
<i>Tax rates</i>				
VAT	%	0.21	0.21	0.21
Energy tax	€/kWh	0.08	0.11	0.11
<i>Government revenues from</i>				
VAT on retail bill	€/year	71.15	75.80	5.26
VAT on grid operator bill	€/year	39.90	41.25	41.25
VAT on energy tax	€/year	50.79	67.18	4.66
Energy tax	€/year	241.85	319.91	22.18

The values are approximations to the closest second decimal.

Table 6

Total annual electricity bill for the average household and percentage change of the bill faced by the average household with and without PV in the Net-Metering scenario (NM) compared to the bill they would face in the Counterfactual Scenario (CS) with no residential solar capacity installed.

	CS	NM		NM	
	One Household €/year	Non-PV Household €/year	% Change	PV Household €/year	% Change
Retail Component	339	361	7	25	-93
Grid Component	190	196	3	196	3
<i>Tax component</i>					
Energy Tax	242	320	32	22	-91
VAT on retail bill	71	76	7	5	-93
VAT on grid bill	40	41	3	41	3
VAT on energy tax	51	67	32	5	-91
Feed-in Compensation	.	.	.	-51	.
Total	932	1061	14	244	-74

The values are approximated to the closest integer.

the counterfactual, about 76% of government revenues were raised by non-PV households and 24% by PV households.¹⁵ Under the assumption of a constant exogenous government budget, we observe that this distribution shifts due to net metering, with non-PV households contributing to about 95% of total revenues under net metering.

6.4. Total annual household electricity bill

The net-metering scheme is associated with an increase in the electricity bill faced by the average non-PV household of about 14% and with a decrease in the electricity bill of the average PV household of about 74% compared to a counterfactual scenario in which no residential solar capacity is installed. As shown in Table 6, the average non-PV household faces a 7% higher retail component of the bill, as a result of the increase in the retail tariff discussed in Section 6.1. Additionally, the average non-PV household faces a 3% higher grid tariff and about 20% larger electricity bill taxes, including both the energy tax and VAT. For the average PV household, the components of the electricity bill that are directly affected by netting visibly decrease compared to the counterfactual. The retail component of the electricity bill decreases by about 93% and the electricity bill taxes decrease by about 85%. However, the grid tariff, which is independent of the household's net load, increases for all households including PV households by 3%. These results are averages and Fig. 3 shows that there is quite some heterogeneity across household types within the PV and non-PV household groups. We further explore this heterogeneity in Section 6.5.

Our results show that, on average, non-PV households are negatively affected by the net-metering scheme while PV households face a lower electricity bill. However, this latter result does not necessarily

¹⁵ There are no PV households in the counterfactual scenario, but we estimate the contribution in the counterfactual scenario by the group of households that have solar panels in the net-metering scenario.

imply a benefit for PV households, as they also incur costs for investing in solar panels. Table 7 provides some rough investment cost approximations to assess the total effect of net metering on PV households. We find that, given the average household installed capacity from our data and cost estimates by the Milieu Centraal (2024b), the average PV household invests about 4,572€ to buy, install, and maintain solar panels. Moreover, the Netherlands offers a discount to households installing solar panels by waiving the 21% VAT on investment that is applied to non-residential investors (Belastingdienst, 2024). Given this discount and assuming a 5% discount rate on the investment and a 25-year lifespan for the solar panels, we find that the average PV household requires an annual saving on the electricity bill of 256€ to break even. This is much smaller than the average bill savings that we estimate. Indeed, we find that PV households recoup their investment in five to seven years with the average estimated bill savings of 688€. Hence, our results suggest that PV households benefit from the net-metering scheme.

6.5. Heterogeneity across regions and housing types

The effects of net metering on households vary significantly across provinces and housing types. As visible in Fig. 4, non-PV households in Friesland and Zeeland are the least negatively affected by net metering, while those in Zuid-Holland are the most negatively affected. This disparity is primarily due to differences in household electricity consumption, with Friesland and Zeeland having the lowest and Zuid-Holland the highest consumption levels (Appendix A.4). For PV households, those in Noord-Brabant and Limburg enjoy the highest electricity bill savings, while those in Groningen and Utrecht see the smallest savings. The substantial savings in Noord-Brabant and Limburg can be attributed to the highest annual solar generation in the country, driven by a combination of high solar irradiance and high installed capacity per household (Fig. A.3). In contrast, Groningen and Utrecht have the lowest solar generation. Differences in net metering effects

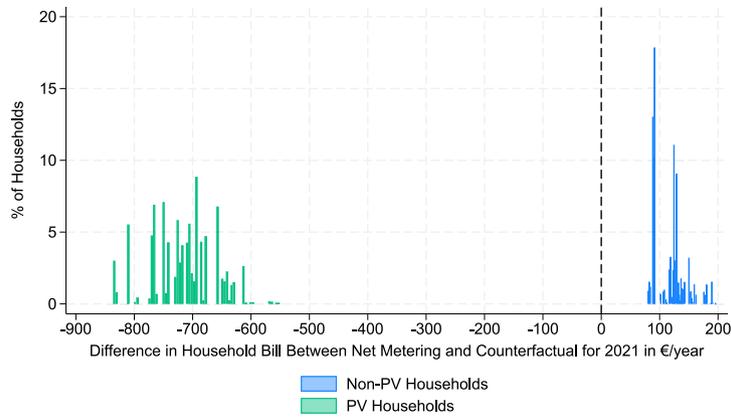


Fig. 3. Distribution of households according to the difference between their electricity bill in the Net-Metering (NM) scenario and that in the Counterfactual Scenario (CS).

Table 7

Calculations of the necessary electricity bill savings for one PV household to recoup their investment in solar panels and of the payback time for their investment with our estimated electricity bill savings.

		Formula with row numbers	Value	Unit	Source
1	Total capacity per household		3600	W	Own data
2	Capacity per solar panel		400	W	Milieu Centraal (2024a)
3	Number of solar panels per household	1/2	9	Number	
4	Cost per panel		508	€	Milieu Centraal (2024a)
5	Value Added Tax (VAT) rate		0.21	Rate	Belastingdienst (2024)
6	Total investment cost, excluding VAT discount	3 * 4	4572	€	
7	Total investment cost, including VAT discount	6 * (1.0 - 5)	3612	€	
8	Lifetime		25	Years	Milieu Centraal (2024a)
9	Discount rate		0.05	Rate	Assumption
10	Needed bill savings to breakeven	$6 * \frac{9}{1.0 - (1.0 + 9)^{-25}}$	324	€/year	
11	Needed bill savings to breakeven with VAT discount	$7 * \frac{9}{1.0 - (1.0 + 9)^{-25}}$	256	€/year	
12	Average electricity bill savings		688	€/year	Our results
13	Payback time, excluding VAT discount	6/12	6.6	Years	
14	Payback time, including VAT discount	7/12	5.2	Years	

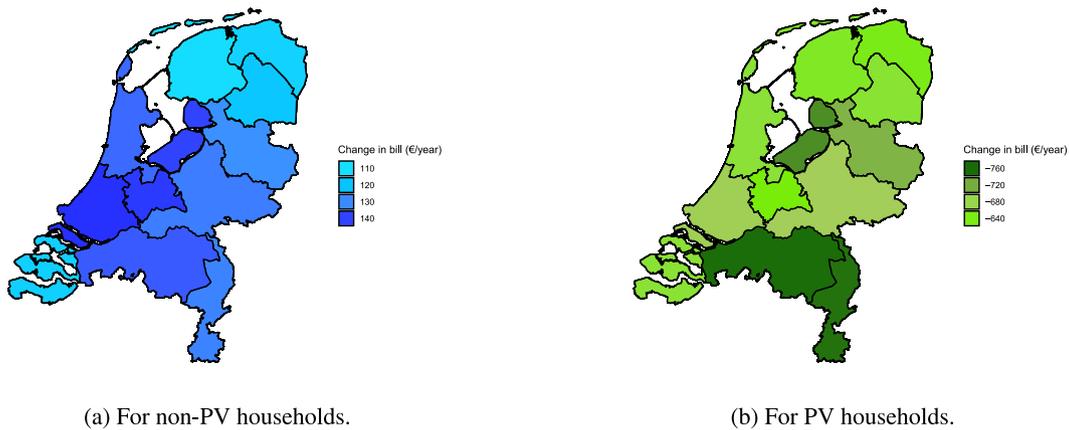


Fig. 4. Change in the electricity bill of the average PV and non-PV household per province in the Net-Metering scenario (NM) compared to the Counterfactual Scenario (CS) in which no residential solar capacity is installed.

are also evident across housing types. Non-PV households in detached houses experience the largest increase in their electricity bills, while PV households in semi-detached houses (2-under-1-roof) experience the largest savings.

6.6. Alternative billing mechanisms

In this subsection, we present the results of an additional analysis that compares households' electricity bills under alternative billing

mechanisms. Indeed, several net metering schemes around the world have been replaced by net-billing schemes,¹⁶ where the price for the electricity demanded from the grid and that for the electricity returned to the grid are different. We explore three possible alternative billing

¹⁶ This has occurred, among others, in the State of Louisiana (USA) in 2020, in Poland in 2022, in the State of California (USA) in 2023, and in Greece in 2024. See also our discussion on net metering and net billing in Section 2.

Table 8

Estimated electricity bills under different billing schemes for the average non-PV and PV households, and difference in bill savings compared to the amount needed to break even with the investment in solar panels (256 €/year).

	Bill for non-PV household	Difference from CS	Bill for PV household	Difference from CS	Difference from break-even amount
	€/year	% change	€/year	% change	€/year
Counterfactual Scenario (CS)	932	.	932	.	.
Net Metering (NM)	1061	14	244	-74	+432
Net Billing, returned generation is compensated at 50% of yearly avg. price	944	1	547	-41	+ 129
Net Billing, returned generation is compensated at 25% of yearly avg. price	941	1	614	-34	+ 62
No compensation for returned generation	938	1	680	-27	- 4

schemes: two net-billing schemes where the electricity returned to the grid is compensated at 50% and at 25% of the yearly average price of electricity on the day-ahead market, and a scheme where no compensation is offered for the electricity returned to the grid. Compensating returned generation at a lower-than-market price not only incentivizes the maximization of self-consumption by households but it also has an economic rationale in the so-called market-value effect (Hirth, 2013). This effect entails that renewable electricity producers earn a price that is lower than the hourly weighted average price in a year, since these producers generate electricity in hours where the price is lower.¹⁷

As visible in Table 8, we find that all three alternative mechanisms have minimal impact on the electricity bill of non-PV households. Specifically, we find that the small increases are tied to a small increase in the energy tax rate, resulting from our government budget-balancing assumption and the smaller tax base associated with PV households compared to the counterfactual scenario. On the contrary, we observe that the bill savings by PV households change significantly depending on the billing scheme adopted. To understand whether solar panels would still be profitable under these alternative billing mechanisms, we compare the bill savings under each scenario with the 256 €/year in bill savings needed to break even (including VAT discount), as presented in Table 7. While limited by some simplifying assumptions, these results suggest that solar panels are a profitable investment for households under both net-billing schemes considered (savings of 385 and 318 €/year), yet they are not profitable under the no compensation for returned generation scheme (savings of 252 €/year).

6.7. Alternative tax policy

Our analysis assumes that the government sets a fixed budget and estimates the increase in the energy tax rate.¹⁸ In this subsection, we relax this assumption and explore different fiscal policy alternatives. Firstly, we can estimate the government revenue losses associated with the net-metering scheme given fixed VAT and energy tax rates. In this case, the government has a revenue loss of about 546 million € for

¹⁷ This is due to the merit order effect of renewables, see also our discussion on this in Appendix A.1.

¹⁸ We refer the reader to for a more in-depth discussion of the fixed government budget assumption.

the year 2021, which is an 18% decrease in revenues compared to the counterfactual scenario. Out of this 546 million € of revenue losses, about 14% is due to the loss of VAT revenues and the remaining 86% is due to the loss of energy tax revenues as a result of the net-metering scheme. Under this scenario with fixed tax rates, we find that the electricity bill for non-PV households due to net metering increases by 4% (rather than 14% under the fixed budget assumption). In contrast, the decrease for PV households is 75% (rather than 74%). However, the government may wish to implement a fiscal policy solution to recoup these losses.

An alternative measure that would ensure no revenue losses for the government is to transform the energy tax rate from a volumetric (i.e., per-kWh) tax to a fixed per-household tax. This would, essentially, result in electricity bills where only the retail component is directly affected by net metering. However, the energy tax is usually imposed with the objective of disincentivizing electricity consumption for households. Thus, the per-household fixed tax rate would effectively change this tax's objective, favoring redistribution and raising government revenues. As visible in Table 9, we find that implementing this new fixed per-household tax results in an increase in the electricity bill of non-PV households by 2% (rather than 14% in our main analysis), due to net metering. In contrast, PV households under this taxation scheme see their electricity bill decrease by 47% (rather than 74%) due to net metering. Hence, this alternative tax measure can be effective in reducing the inequalities associated with net metering without compromising government revenues or the simplicity of the tax.¹⁹

Other solutions are also possible to reduce the distributional impact of net metering through tax policy. Indeed, the government may prefer to use income and wealth fiscal policy to recoup the losses discussed in the first alternative measure or to recoup the losses from completely removing the electricity bill tax. Given the potentially exacerbated income and wealth inequalities associated with the adoption of greener

¹⁹ In the Netherlands, energy bill taxes already have a per household (or more precisely "per aansluiting") component. Indeed, currently, the household energy bill includes a tax refund per household, termed "belastingvermindering per elektriciteitaansluiting" (Belastingdienst, 2025). The latter reduces the tax component of the energy bill by a fixed amount for all households. Thus, reducing this refund while also reducing the electricity tax rate would bring the Dutch energy tax system to the proposed alternative tax measure.

Table 9

Estimated electricity bills under different government budget balancing assumptions and tax designs for the average non-PV and PV households, and government revenue losses for each scenario.

	Bill for non-PV household €/year	Difference from CS % change	Bill for PV household €/year	Difference from CS % change	Government revenue losses million €/year
Counterfactual Scenario	932	.	932	.	.
Net Metering Scenario	1061	14	244	-74	0
No budget balancing assumption	967	4	237	-75	546
Budget balancing but fixed energy tax	955	2	498	-47	0

Table 10

Summary of the sensitivity analyses conducted and their effects on the results.

Parameter	Assumption	Sensitivity	Discussion of Sensitivity	Effect on Results
Electricity price	Day-ahead price of 2021	Day-ahead prices of 2016, 2019, and 2023	Appendix A.5.1	Earlier years with lower volatility and lower prices resulted in smaller distributional effects
Share of households with PV	Share of 2021	2, 3, and 4 times the share of 2021 with the same total population	Appendix A.5.2	More households with PV results in strongly larger bills for non-PV households and slightly larger bills for PV households
Balancing cost parameter	α (Tibber, 2023)	2 and 10 times α	Appendix A.5.3	Strongly larger parameter leads to slightly larger distributional effects
Feed-in compensation	Average electricity price of 2021	Average electricity price of 2016, 2019, 2023, and no compensation	Appendix A.5.4	Bills of PV households are visibly affected, bills of non-PV households are barely affected
Grid tariff design	Same tariff for all households	Fixed additional grid tariff for PV households and two-part volumetric tariff for PV households	Appendix A.5.5	Alternative designs result in lower distributional effects
Load of PV households	Same in both scenarios	Solar rebound effect of 7, 18, and 28%	Appendix A.5.6	The increase in load of PV households as a result of solar panels imply slightly smaller distributional effects

technologies and with net metering specifically, the government may decide to recoup the revenue losses by raising the income tax on the richest percentiles of the population. A similar alternative could be imposing a wealth tax or raising the capital gains tax. Yet another measure that has long been suggested to reduce inequalities is (more strongly) taxing inheritances. While these are interesting possible policies, we cannot test how such alternative measures affect the distributional effects of net metering within our model, given that we do not have income or wealth data. Moreover, although these alternatives would ensure the recouping of government revenue losses associated with net metering, they have different objectives than the tax on electricity consumption. Overall, we acknowledge that fiscal policy can be an effective tool to reduce the distributional effects of net metering, yet we recognize that most alternatives involve different objectives, the choice of which is inherently political.

6.8. Sensitivity analysis

We conduct a sensitivity analysis to assess to which extent our results are sensitive to the assumptions and inputs used. [Table 10](#) presents the parameters for which the analyses are conducted, the parameters or assumptions used in the sensitivity tests, and the summary of the results of these tests. A detailed discussion of each sensitivity test is presented

in [Appendix A.5](#). Overall, our results are quite robust to these sensitivity analyses.

7. Conclusions and policy implications

This paper examines the distributional effects of the net-metering scheme in the Netherlands for households with and without solar panels across regions and housing types. The previous literature on net metering has examined individual distributional aspects of this scheme, such as the effects on the grid operator (Eid et al., 2014; Castaneda et al., 2017; Clastres et al., 2019) or on retail bills (Mills et al., 2008; Darghouth et al., 2014; Kim et al., 2023), yet it lacks a comprehensive quantitative analysis of these effects disaggregated by electricity bill component affected. Additionally, we explicitly include a socio-spatial heterogeneity element in our study. Unlike recent literature, we also compare the distributional effects of net metering to those of alternative billing scheme and discuss the redistribution potential of fiscal policy in this setting. Our results show that net metering is effective in incentivizing the uptake of solar panels for households as it reduces the annual electricity bill of households that install solar panels on average by about 74% (around 244€ in 2021 euros). We show that this decrease results in a payback time for the investment in solar panels of 5 to 7 years. While the benefits of the net-metering scheme are

enjoyed by PV households, the costs are mainly borne by households that do not install solar panels. Indeed, we show that net metering is associated with an average increase of about 14% (around 130€ in 2021 euros) in the annual electricity bill of households without PV. Moreover, we show that there is heterogeneity in these effects across regions and housing types, depending on the solar irradiance and the ability of households to install solar panels. Furthermore, we compare the distributional effects of net metering to those of alternative billing mechanisms, showing that net billing can provide a more equal distribution than net metering without compromising the attractiveness of investing in residential solar. Lastly, we discuss how net metering coupled with a different fiscal policy design may also lead to more equal and sustainable outcomes.

Our analysis is constrained by some limitations, especially concerning data availability. To circumvent this, we derive a tractable simulation model and calibrate it with Dutch provincial and house-type level data for 2021. Future research could use microdata to investigate more deeply how household heterogeneity influences the distributional effects of net metering. Moreover, while our study is specific to the situation of the Netherlands, future research could recalibrate our model by adapting our numerical analysis to other countries that also implement this scheme. Furthermore, we had to make a few assumptions in this study, however we show that our results are quite robust to the sensitivity analyses conducted in Section 6.8. Among these, we assume that the retail market is perfectly competitive. We show that this is relatively realistic for the Netherlands based on ACM (2024). Yet, if this were not the case, the distributional effects would likely be smaller than those we estimate, as retailers would be charging more than their marginal costs in the counterfactual scenario and, hence, they would not pass all of their additional costs associated with the net metering scheme onto households. Moreover, we take the uptake of solar panels by households as exogenous in our model. Future research could extend our model to include households' choices of whether to adopt solar panels and of the amount of solar capacity to adopt. Such an extension would make the incentives to install solar panels provided by net metering explicit. In a similar manner, future research could extend our framework to consider the non-financial effects associated with the scheme, for instance by accounting for the cleaner energy mix that non-PV households benefit from thanks to PV households. These extensions would grant an even deeper understanding of the distributional consequences of the net metering scheme.

Our study offers some policy implications. Net metering can be an effective policy to incentivize the adoption of solar panels by households; however, with the rising shares of PV households, net metering results in unequal redistributions that negatively affect households without solar panels. This is especially problematic as households without solar panels are more likely to be in areas with lower solar irradiance, in housing types that do not allow for solar panels, or are lower-income households unable to afford the initial investment in solar panels even under net metering. Hence, it may be advisable to replace the net-metering scheme with policies that lead to more equal outcomes without becoming less effective. We show that two possibilities for this are maintaining net metering but redesigning the energy tax, or imposing a net billing scheme where returned generation is compensated at least 25% of the yearly average wholesale electricity price. The latter would also incentivize self-consumption, which could reduce the current grid congestion problems and may potentially lead to smaller increases in grid costs than those we estimate.

CRedit authorship contribution statement

Carlotta Masciandaro: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Machiël Mulder:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Michaela Kesina:** Supervision, Software.

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Appendix A

A.1. Estimation of the merit order effect

The merit order effect (MOE) refers to the change in the electricity price in response to a change within the supply curve, which is the so-called merit order. Commonly, the MOE specifically refers to a decrease in the equilibrium electricity price when renewable energy sources, such as wind and solar, are producing, as they have zero marginal costs. The mechanism behind this effect is graphically shown in Fig. A.1.

We are interested in estimating the size of the merit order effect due to exclusively residential solar energy production to assess the indirect effect of net metering on households' electricity bills through the retailer's commodity costs. Note that the market is unable to distinguish the sources of solar electricity (residential or not), hence, we estimate the per unit effect of solar generation on the market price based on the total solar generation in the country, and then we use this parameter to compute the merit order effect from exclusively residential solar generation. Thus, we estimate the following reduced-form equation:

$$P_h^{NM} = \beta_0 + \beta_1 * G_h^{PV} + \beta_2 * G_h^{RESnon-PV} + \beta_3 * G_h^{RES.Neighbor} + \beta_4 * P_h^{Gas} + \beta_5 * L_h + \beta_6 * P_{h,d-1,m,y} + Hour_h + Day_d + Month_m + Year_y + \epsilon_h, \quad (A.1)$$

where P_h^{NM} is the hourly day-ahead wholesale price of electricity, G_h^{PV} is the national solar energy generation, $G_h^{RESnon-PV}$ is the national total generation from renewables excluding solar, $G_h^{RES.Neighbor}$ is the generation from renewables by neighboring countries with which there are sizable cross-border trades (for the Netherlands, these are Denmark and Germany). Moreover, we control for the marginal cost of the technology that is most commonly price-setting in the countries of interest using the hourly price of natural gas, P_h^{Gas} . Additionally, we control for demand using the national load profile L_h and for the dependency over time of the dependent variable by including the day-ahead electricity price at the same time on the previous day. Lastly, we account for the unobservable heterogeneity within and across years using time dummies for the hour, the day, the month, and the year. Then, we use our estimated coefficient $\hat{\beta}_1$ in Eq. (6).

For the estimation of Eq. (A.1), we obtain national data on the hourly day-ahead spot price, the hourly load, and the hourly electricity generation from solar panels and windmills from the ENTSO-E Transparency platform (2023). Note that load and electricity generation are recorded every fifteen minutes and, hence, we sum them up to obtain hourly data. The solar and wind generation are the day-ahead forecast due to a lack of data on the actual realized generation. Moreover, we obtain the day-ahead forecast for solar and wind generation in Denmark and Germany from (ENTSO-E, 2023). For Denmark, we only use the DK1 bidding zone as this is the one having a physical connection to the Dutch grid. For Germany, we use the DE-AT-LU or DE-LU bidding zone, which has been redefined not to include Austria since October 1st, 2018. Lastly, we use the Title Transfer Facility (TTF) natural gas day-ahead price, which we obtain from the Eikon Reuters Database (2023). We choose the TTF price as this is the reference natural gas price for the Netherlands and has established itself as the European benchmark

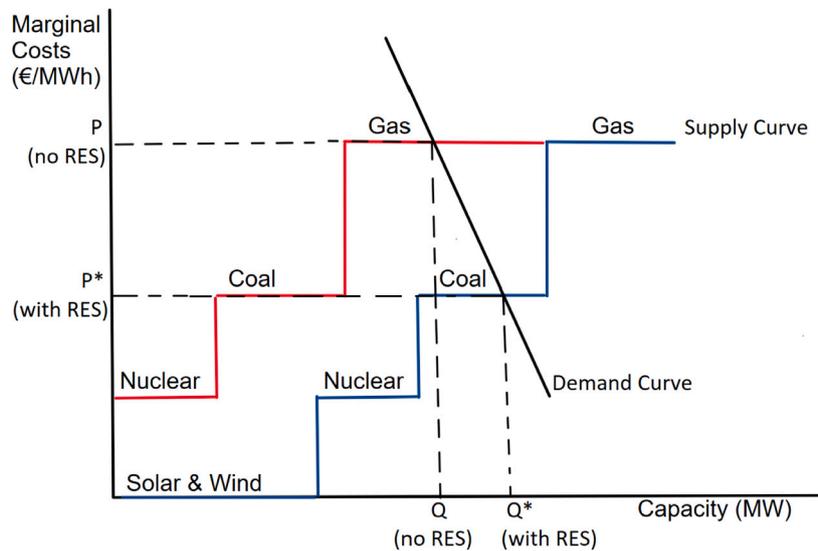


Fig. A.1. Stylized graph of the merit order of electricity when renewable energy sources (RES) are producing and when they are not.

Table A.1

Descriptive statistics on the sample used for the merit order effect analysis. Data for the period 2015–2023.

VARIABLES	Observations	Mean	SD	Unit	Source
Day-ahead Price NL	51,192	78.59	90.53	€/MWh	ENTSO-E (2023)
Load NL	51,192	51,440	8,947	MW	ENTSO-E (2023)
Solar Generation NL	51,192	2,047	4,021	MWh	ENTSO-E (2023)
Wind Generation NL	51,192	5,345	5,092	MWh	ENTSO-E (2023)
Solar Generation DK	51,192	81.89	149.1	MWh	ENTSO-E (2023)
Wind Generation DK	51,192	1,362	1,005	MWh	ENTSO-E (2023)
Solar Generation DE	51,192	19,710	30,554	MWh	ENTSO-E (2023)
Wind Generation DE	51,192	53,134	45,226	MWh	ENTSO-E (2023)
TTF Gas Price	51,192	33.97	41.88	€/MWh	Eikon (2023)

NL refers to the Netherlands, DK to Denmark (only bidding zone DK1), and DE to Germany.

Table A.2

Regression results for the merit order effect, with Newey–West heteroskedasticity and autocorrelation (up to a 15-h lag) consistent standard errors.

	Day-ahead Price NL
Solar Generation NL	-0.00123*** (0.000197)
Wind Generation NL	-0.00256*** (0.000139)
Solar Generation DK	-0.0137** (0.00567)
Wind Generation DK	-0.00241*** (0.000374)
Solar Generation DE	-0.000230*** (0.0000247)
Wind Generation DE	0.00000710 (0.0000105)
Load NL	0.000796*** (0.0000985)
TTF Gas Price	1.845*** (0.0352)
Constant	-35.07*** (4.512)
Observations	51,192

Newey–West standard errors (with 15-h lag) in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.010$

Hour, day, month, and year dummies are omitted from the table.

gas price as well. Table A.1 shows summary statistics for the data used to estimate the merit order effect regression.

We estimate Eq. (A.1) and correct for first-order autoregressive disturbances using Newey–West heteroskedasticity and autocorrelation (up to a 15-h lag) robust standard errors. As visible in Table A.2, we find that renewable energy generation, both national and of neighboring countries (with the exception of Danish solar generation), is associated with a significant decrease in the electricity price, thus, we find evidence for the MOE in the Netherlands. Moreover, as expected, demand for electricity, or load, has a positive effect on the electricity price. The natural gas price also positively affects the electricity price, which is expected as the electricity price depends on the marginal cost of natural gas power plants when the latter are price-setting. This marginal cost strongly depends on the gas power plants' main input, that is, on the natural gas price. Moreover, the electricity price at a given hour today is strongly related to the electricity price at that same hour in the previous day (yet, this significant coefficient is omitted from Table A.2). Regarding the MOE, we find that one MWh increase in the solar generation in the Netherlands is associated with a decrease in the electricity price by 0.123 euro cents per MWh, on average *ceteris paribus*. This implies that at the mean Dutch solar generation of about 2,047 MWh (Table A.1), the merit order effect from solar electricity amounts to about 2.52€. The following subsections present some descriptive plots and some robustness checks for the estimation of Eq. (A.1).

A.2. Time-series plots for the sample used for the estimation of the merit order effect

See Fig. A.2.

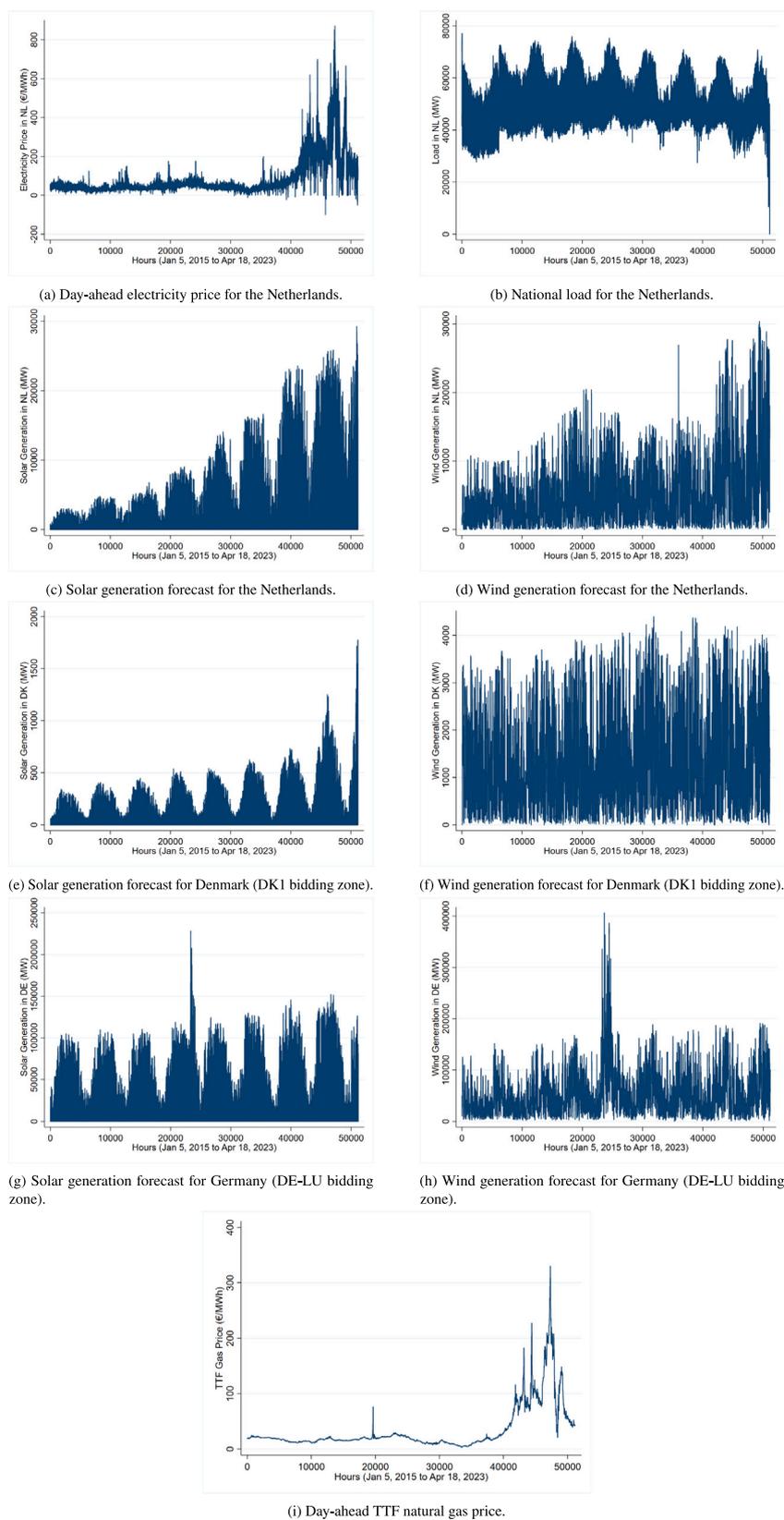


Fig. A.2. Evolution of the variables of interest from 2015 to 2023 (ENTSO-E, 2023; Thomson Reuters, 2023).

Table A.3

Results of the Dickey–Fuller tests for stationarity (the null hypothesis is that a unit root exists). The lags are chosen using the *varsoc* command in Stata, which reports the optimal lag according to the final prediction error (FPE), Akaike’s information criterion (AIC), Schwarz’s Bayesian information criterion (SBIC), and the Hannan and Quinn information criterion (HQIC) lag-order selection statistics. When the trend option is included, the null hypothesis allows for the possibility of a drift in the random walk.

VARIABLES	Lags	Trend	Test Statistic	P-Value	N
Day-ahead Price	0	No	−20.541	0.00	51,191
Day-ahead Price	0	Yes	−24.945	0.00	51,191
Day-ahead Price	80	No	−4.324	0.00	51,111
Day-ahead Price	80	Yes	−5.394	0.00	51,111
Solar Generation NL	0	No	−32.287	0.00	51,191
Solar Generation NL	0	Yes	−34.231	0.00	51,191
Solar Generation NL	79	No	−7.235	0.00	51,112
Solar Generation NL	79	Yes	−9.942	0.00	51,112
Wind Generation NL	0	No	−16.501	0.00	51,191
Wind Generation NL	0	Yes	−17.590	0.00	51,191
Wind Generation NL	77	No	−14.429	0.00	51,114
Wind Generation NL	77	Yes	−16.309	0.00	51,114
Solar Generation DK	0	No	−31.655	0.00	51,191
Solar Generation DK	0	Yes	−32.212	0.00	51,191
Solar Generation DK	75	No	−6.576	0.00	51,116
Solar Generation DK	75	Yes	−7.388	0.00	51,116
Wind Generation DK	0	No	−18.496	0.00	51,191
Wind Generation DK	0	Yes	−18.664	0.00	51,191
Wind Generation DK	0	No	−17.522	0.00	51,111
Wind Generation DK	0	Yes	−17.938	0.00	51,111
Solar Generation DE	0	No	−33.924	0.00	51,191
Solar Generation DE	0	Yes	−33.996	0.00	51,191
Solar Generation DE	77	No	−7.355	0.00	51,114
Solar Generation DE	77	Yes	−7.440	0.00	51,114
Wind Generation DE	0	No	−12.764	0.00	51,191
Wind Generation DE	0	Yes	−12.942	0.00	51,191
Wind Generation DE	77	No	−14.041	0.00	51,114
Wind Generation DE	77	Yes	−14.364	0.00	51,114
Load NL	0	No	−34.394	0.00	51,191
Load NL	0	Yes	−34.599	0.00	51,191
Load NL	80	No	−4.226	0.00	51,111
Load NL	80	Yes	−4.453	0.00	51,111
TTF Gas Price	0	No	−2.967	0.04	51,191
TTF Gas Price	0	Yes	−3.542	0.03	51,191
TTF Gas Price	49	No	−2.990	0.04	51,142
TTF Gas Price	49	Yes	−3.575	0.03	51,142

A.3. Robustness checks for the estimation of the merit order effect

A.3.1. Tests for stationarity

Table A.3 presents the results of the Dickey–Fuller test for stationarity for all variables of interest. We reject the null hypothesis that there is a unit root for all variables, with and without lags, both when accounting for the possibility of a drift and when not. Thus, we conclude that there are no problems related to non-stationarity in our sample.

A.3.2. Tests for heteroskedasticity

We test for heteroskedasticity in our merit order effect analysis sample using the Breusch–Pagan/Cook–Weisberg test and we reject the null hypothesis of homoskedasticity at the 1% significance level.

A.3.3. Tests for autocorrelation

We test for first-order autocorrelation in our time series using the Durbin–Watson test. We reject the null hypothesis of no autocorrelation as we find a test statistic of 0.28, which is below the 5% bound of its distribution (0.997). Moreover, we test for higher-order serial correlation using the Breusch–Godfrey Lagrange Multiplier test. The null hypothesis of no autocorrelation is rejected at the 1% significance level if 24, 48, and 72-h lags are included.

A.3.4. Imperfect multicollinearity

We check imperfect multicollinearity between the variables included in the merit order effect regression using the Variance Inflation

Factor (VIF) and the pairwise correlation. Table A.4 shows that all variables have a VIF below 10, which is considered the threshold for problematic multicollinearity (Wooldridge, 2012). We also present the correlation table for all variables included in the regression model in Table A.5. Generally, a correlation coefficient between two predictors larger than 0.7 is considered concerning for multicollinearity (Wooldridge, 2012). We find that wind and solar generation are highly correlated in the same country and across countries, which is expected given that they are affected by similar weather conditions. Since omitting any of these variables is likely to cause Omitted Variable Bias, we include them all in our regression model, noting that we are likely to find inflated standard errors.

A.3.5. Alternative specifications for the newey–west correction

Table A.6 shows that using a different number of lags for the Newey–West correction of the standard errors does not change the significance of our results. The first column assumes that all higher-order autocorrelation may be ignored, which is not in line with the tests discussed in Appendix A.3.3. The remaining columns present the results with standard errors that are consistent under autocorrelation up to a 24-h, 48-h, and 72-h lag.

A.4. Descriptive statistics for the main sample

This section presents some descriptives for the inputs of our numerical analysis. Fig. A.3(a) shows the variation in average sunshine

Table A.4

Variance Inflation Factor (VIF) for all variables of interest, computed based on a linear regression on the day-ahead electricity price.

VARIABLES	VIF	1/VIF
Solar Generation NL	4.71	0.212262
Wind Generation NL	2.45	0.408203
Solar Generation DK	4.53	0.220992
Wind Generation DK	1.71	0.585835
Solar Generation DE	6.04	0.165426
Wind Generation DE	2.92	0.342268
Load NL	8.78	0.113905
TTF Gas Price	4.00	0.249820

Table A.5

Correlation table for the variables included in the merit order effect analysis.

	Day-ahead Price NL	Solar Gen. NL	Wind Gen. NL	Solar Gen. DK	Wind Gen. DK	Solar Gen. DE	Wind Gen. DE	Load NL	TTF Gas Price
Day-ahead Price NL	1.0000								
Solar Gen. NL	0.2051	1.0000							
Wind Gen. NL	0.0813	-0.0275	1.0000						
Solar Gen. DK	0.1057	0.7925	-0.0938	1.0000					
Wind Gen. DK	-0.0250	-0.0170	0.4697	-0.0702	1.0000				
Solar Gen. DE	0.0264	0.7482	-0.1123	0.8262	-0.0464	1.0000			
Wind Gen. DE	-0.0672	-0.1157	0.6904	-0.1649	0.6055	-0.1636	1.0000		
Load NL	-0.0144	-0.1499	0.0493	-0.0865	0.0889	0.0380	0.1485	1.0000	
TTF Gas Price	0.9259	0.2597	0.1799	0.1469	0.0331	0.0652	-0.0068	-0.1576	1.0000

Table A.6

Regression results for the merit order effect, with Newey–West heteroskedasticity and autocorrelation consistent standard errors when accounting for autocorrelation up to the 0, 24, 48, and 72-h lag.

	0-h lag Day-ahead Price NL	24-h lag Day-ahead Price NL	48-h lag Day-ahead Price NL	72-h lag Day-ahead Price NL
Solar Generation NL	-0.00123*** (0.0000978)	-0.00123*** (0.000203)	-0.00123*** (0.000248)	-0.00123*** (0.000277)
Wind Generation NL	-0.00256*** (0.0000525)	-0.00256*** (0.000155)	-0.00256*** (0.000184)	-0.00256*** (0.000201)
Solar Generation DK	-0.0137*** (0.00256)	-0.0137** (0.00588)	-0.0137** (0.00664)	-0.0137* (0.00703)
Wind Generation DK	-0.00241*** (0.000152)	-0.00241*** (0.000411)	-0.00241*** (0.000467)	-0.00241*** (0.000496)
Solar Generation DE	-0.000230*** (0.0000113)	-0.000230*** (0.0000259)	-0.000230*** (0.0000308)	-0.000230*** (0.0000341)
Wind Generation DE	0.00000710* (0.00000411)	0.00000710 (0.0000115)	0.00000710 (0.0000131)	0.00000710 (0.0000139)
Load NL	0.000796*** (0.0000421)	0.000796*** (0.000107)	0.000796*** (0.000127)	0.000796*** (0.000141)
TTF Gas Price	1.845*** (0.0143)	1.845*** (0.0398)	1.845*** (0.0489)	1.845*** (0.0541)
Constant	-35.07*** (1.946)	-35.07*** (4.892)	-35.07*** (5.772)	-35.07*** (6.355)
Observations	51,192	51,192	51,192	51,192

Newey–West standard errors (with 0, 24, 48, or 72-h lag) in parentheses

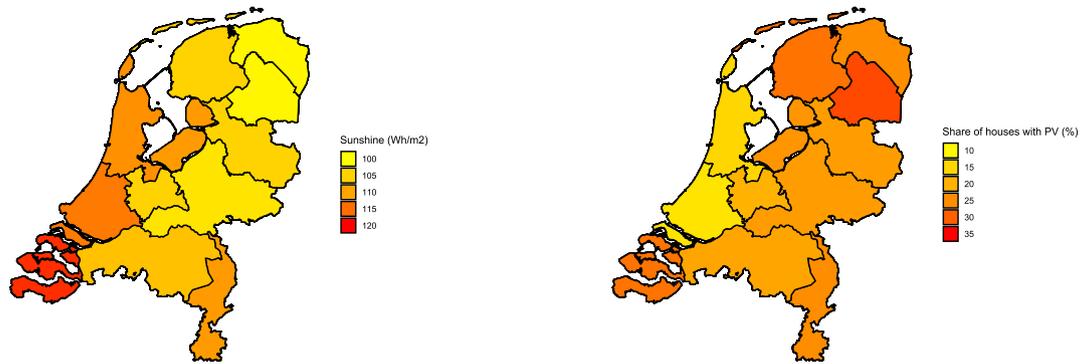
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.010$

Hour, day, month, and year dummies are omitted from the table.

across Dutch provinces, and Fig. A.3(b) shows the variation in the share of households with solar panels across Dutch provinces. Interestingly, we observe that there is a discrepancy between the provinces with the highest solar irradiance and those with the most residential solar panels. This is likely related to the population density and the available housing types. For instance, the fewer solar panels in Zuid-Holland can be explained by the higher share of apartment buildings, which are less suitable for solar panel installation, but are common given the high population density in the province.

Additionally, we plot the load and the generation by household in Figs. A.4(a) and A.4(b). The graphs show the differences in the profiles of these two variables across winter and summer, with important differences in the amount of electricity generated. The box plots also

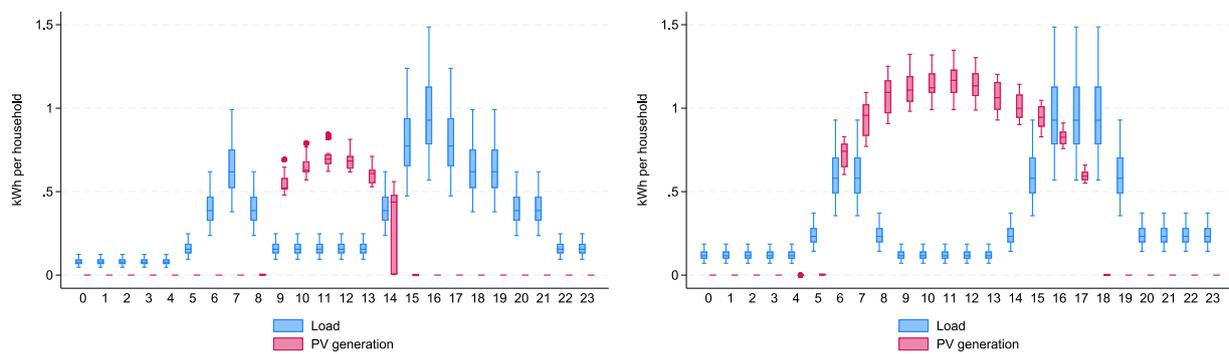
highlight that load and, even more, generation vary quite sizably across groups of households and days within the same month and year, as visible by the length of the boxes and the whiskers. Interestingly, we observe that a large part of PV households generate more electricity than they consume on a yearly basis, with some heterogeneity visible in Fig. A.5. This overinvestment in solar capacity by some households can be explained by three main reasons. Firstly, households maximize their financial benefits under the net metering scheme, also considering the feed-in fee that the retailer uses to compensate PV households for their excess generation (Darghouth et al., 2011). Moreover, households base their investment decisions on their expectations regarding their long-term energy needs. For instance, they may plan to acquire an electric vehicle or install an electric heat pump, both of which would increase



(a) Solar irradiation (The World Bank, 2023)

(b) Households with PV as a share of total (CBS, 2023)

Fig. A.3. Provincial distribution of solar irradiation and the share of households with solar panels in 2021.



(a) January 2021.

(b) August 2021.

Fig. A.4. Distribution of the load and generation of households for various regions and housing types over the hours in a day for the months of January and August 2021 (own calculations).

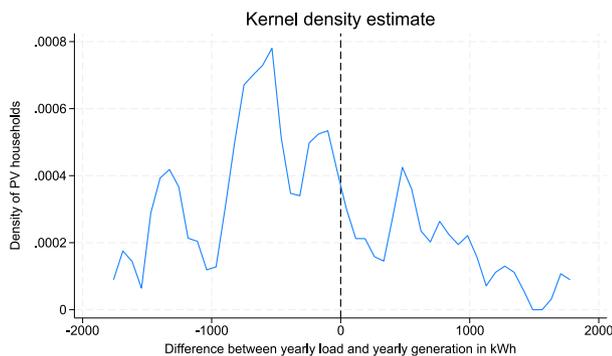


Fig. A.5. Distribution of the difference between load and generation on a yearly basis (own calculations).

their electricity consumption (Rai et al., 2016). Lastly, there is evidence that households install the capacity recommended by their installer rather than estimating the optimal amount of capacity themselves, given the difficulty of doing so (Shimada and Honda, 2022).

Additionally, we provide a further check that the estimated computed generation is realistic in size by calculating the provincial capacity factors. The capacity factor for rooftop solar panels, calculated

as their electricity output in a year over their theoretical maximum output (i.e., their peak capacity), is generally estimated to be around ten percent in Europe (IEA, 2019). We calculate the capacity factors for residential solar panels across the Netherlands to be between 9.5 and 11.5%, which is in line with most estimates for this. Moreover, we observe a strict correlation between provinces with higher capacity factors and provinces with higher solar irradiation (Fig. A.3(a)), as expected.

Lastly, Table A.7 presents the summary statistics and sources of the data used, and Tables A.8, A.9, A.10, and A.11 show some additional descriptives per province and housing type.

A.5. Sensitivity analysis

A.5.1. Sensitivity to the electricity price

The choice of the reference year for the electricity price used in our analysis may influence the estimates of the effects of net metering on households. In 2021, which was chosen as the reference year given complete data for all other variables used, Europe experienced an energy crisis that led to extraordinary price patterns. A price duration curve, which displays the distribution of prices over a year by ranking them from highest to lowest, illustrates these patterns. Fig. A.6 shows that 2021 and 2023 had many more hours with very high prices as well as many hours with zero or negative prices compared to 2016 and 2019.

Table A.7
Sources, units, and descriptives for the raw data used.

VARIABLES	Source	Time	Space	House Type	Unit	Mean	SD
		Dimension	Dimension	Dimension			
Electricity Price	ENTSO-E (2023)	Hourly	National	No	EUR/MWh	103	75
Sunshine	Global Solar Atlas (2023)	Hourly	Province	No	Wh/m2	108	129
Electricity Consumption	CBS (2023)	Yearly	Province	Yes	kWh	3,023	770
No. households	CBS (2023)	Yearly	Province	Yes	Number	132,729	155,162
No. PV households	CBS (2023)	Yearly	Province	No	Number	132,444	70,293
Provincial PV capacity	CBS (2023)	Yearly	Province	No	kW	485,696	266,475

Table A.8
Number of non-PV households per province and house type for the year 2021, in thousands.

	2-under-1-roof	Apartment	Corner House	Detached House	Terraced House
Gelderland	98.10	237.34	75.39	87.34	209.40
Drenthe	36.97	41.11	6.62	40.39	28.38
Groningen	30.63	98.64	5.95	42.71	34.93
Noord Holland	55.74	684.96	80.15	20.31	316.35
Friesland	44.28	58.73	13.66	59.35	43.92
Flevoland	8.06	37.51	15.01	3.18	68.26
Limburg	68.65	145.87	35.89	40.59	108.75
Zeeland	20.28	35.97	13.24	26.07	40.96
Noord Brabant	103.44	285.84	95.21	98.90	315.36
Zuid Holland	48.68	880.19	112.55	4.55	437.83
Utrecht	38.04	220.54	41.03	2.15	172.03
Overijssel	65.69	127.93	41.10	53.58	110.13

Table A.9
Number of PV households per province and house type for the year 2021, in thousands.

	2-under-1-roof	Apartment	Corner House	Detached House	Terraced House
Gelderland	10.74	2.15	64.42	75.16	62.28
Drenthe	3.55	0.71	21.31	24.86	20.60
Groningen	3.61	0.72	21.64	25.25	20.92
Noord Holland	10.09	2.02	60.53	70.62	58.51
Friesland	4.22	0.84	25.32	29.54	24.48
Flevoland	2.13	0.43	12.77	14.90	12.35
Limburg	6.84	1.37	41.02	47.85	39.65
Zeeland	2.60	0.52	15.58	18.17	15.06
Noord Brabant	12.61	2.52	75.66	88.27	73.13
Zuid Holland	11.28	2.26	67.66	78.94	65.41
Utrecht	5.99	1.20	35.97	41.96	34.77
Overijssel	5.82	1.16	34.93	40.75	33.76

Table A.10
Total load by one non-PV household for the year 2021, in kWh.

	2-under-1-roof	Apartment	Corner House	Detached House	Terraced House
Gelderland	3,379.91	2,059.94	2,909.92	4,319.88	2,759.92
Drenthe	3,019.92	1,899.95	2,609.93	3,849.89	2,489.93
Groningen	2,819.92	1,839.95	2,589.93	3,569.90	2,489.93
Noord Holland	3,629.90	1,999.95	3,079.92	4,269.88	2,919.92
Friesland	2,739.92	1,799.95	2,459.93	3,569.90	2,349.94
Flevoland	3,709.90	2,069.94	3,179.91	4,499.88	3,039.92
Limburg	3,249.91	2,009.94	3,019.92	4,229.88	2,879.92
Zeeland	2,939.92	1,879.95	2,569.93	3,649.90	2,449.93
Noord Brabant	3,549.90	2,049.94	3,089.92	4,519.88	2,919.92
Zuid Holland	3,789.90	2,099.94	3,199.91	4,579.87	3,039.92
Utrecht	3,779.90	2,069.94	3,129.91	4,699.87	2,929.92
Overijssel	3,289.91	2,029.94	2,879.92	4,189.89	2,739.92

We assess whether using prices from different years affects the commodity costs faced by the retailer and the total bill for households and present our findings in Table A.12. We find that the results change very slightly when using the prices from 2023 (keeping everything else constant). However, when using the prices from 2016 or 2019, we observe significantly different outcomes. Indeed, there is a much smaller increase in the electricity bill for the average non-PV household and smaller savings for the average PV household. These differences can be partly explained by the smaller price differential between the hours when the retailer buys electricity to satisfy household demand and the hours when it sells the excess generation from PV households.

Additionally, the low volatility and generally lower but non-negative prices observed in 2016 and 2019 contribute to these results.

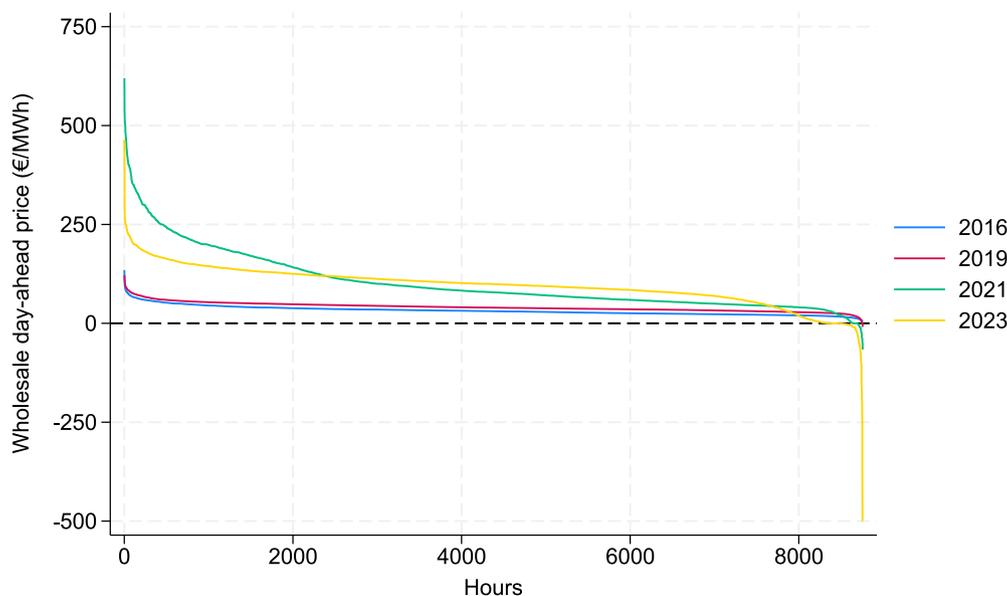
A.5.2. Sensitivity to the share of PV households

Another sensitivity analysis of our results concerns how they are affected by a growing share of households installing solar panels. Such an increase has both direct and indirect distributional effects as mentioned in our conceptual framework. Indeed, an increased number of PV households as a share of the same total strengthens the merit order effect on the wholesale electricity price. This is visible in Fig. A.7, where the cheapest hours exhibit more negative prices due to more

Table A.11

Total annual net load, as computed for the annual electricity bill, by one PV household for the year 2021, in kWh.

	2-under-1-roof	Apartment	Corner House	Detached House	Terraced House
Gelderland	53.36	0.00	0.00	993.33	0.00
Drenthe	0.00	0.00	0.00	664.44	0.00
Groningen	0.00	0.00	0.00	460.52	0.00
Noord Holland	555.52	0.00	5.53	1,195.50	0.00
Friesland	0.00	0.00	0.00	339.75	0.00
Flevoland	206.98	0.00	0.00	996.96	0.00
Limburg	0.00	0.00	0.00	509.52	0.00
Zeeland	0.00	0.00	0.00	427.22	0.00
Noord Brabant	0.00	0.00	0.00	851.69	0.00
Zuid Holland	549.75	0.00	0.00	1,339.73	0.00
Utrecht	808.08	0.00	158.09	1,728.05	0.00
Overijssel	0.00	0.00	0.00	733.01	0.00

**Fig. A.6.** Electricity price duration curves for the four years considered (based on [ENTSO-E, 2023](#)).**Table A.12**

Sensitivity to the electricity price of different years of the estimated net commodity costs faced by the retailer (including the MOE) and the estimated household electricity bill for the average PV and non-PV household.

Day-ahead price of	Retailer's net commodity costs (€/year)		Average household bill (€/year)	
	Non-PV Household	PV Household	Non-PV Household	PV Household
2021	334	47	1061	244
2016	104	-6	750	257
2019	131	-4	786	255
2023	314	46	1036	246

The day-ahead price of 2021 is the one used in the main analysis. All values are approximations to the closest integer.

generation from residential solar panels. Apart from the merit order effect, the costs of the retailer and the grid operator, and the tax rate imposed by the government, all increase as a result of the larger share of PV households. As visible in [Fig. A.8](#), the electricity bill of non-PV households strongly increases as more households adopt solar panels. In contrast, the bill savings for PV households becomes smaller, yet only slightly.

A.5.3. Sensitivity to the balancing costs parameter

In our numerical analysis, we rely on the prices used by the Dutch retailer Tibber [2023](#) to approximate the value of the parameter α . This parameter captures how the balancing costs faced by the retailer change in response to a change in the amount of electricity returned to the grid by PV households. [Table A.13](#) shows that using an estimate for this parameter that is twice the value used in the main analysis does not visibly affect the results. In a more extreme scenario in which

the estimate for the parameter is ten times larger than the one used in the main analysis, the electricity bill of the average non-PV household increases by 28€ while that of the average PV household increases by 2€.

A.5.4. Sensitivity to the feed-in compensation

PV households that have a negative annual net load receive a compensation for the excess generation they have returned to the grid. This compensation is determined by the retailer within some minimum set by the national regulation. In our numerical analysis, we assume the retailer compensates the household with excess generation at the average electricity price of 2021. [Table A.14](#) shows how the results would change if a different compensation were chosen. We observe that the bill of the average PV household is visibly affected, while that of the average non-PV household is barely affected.

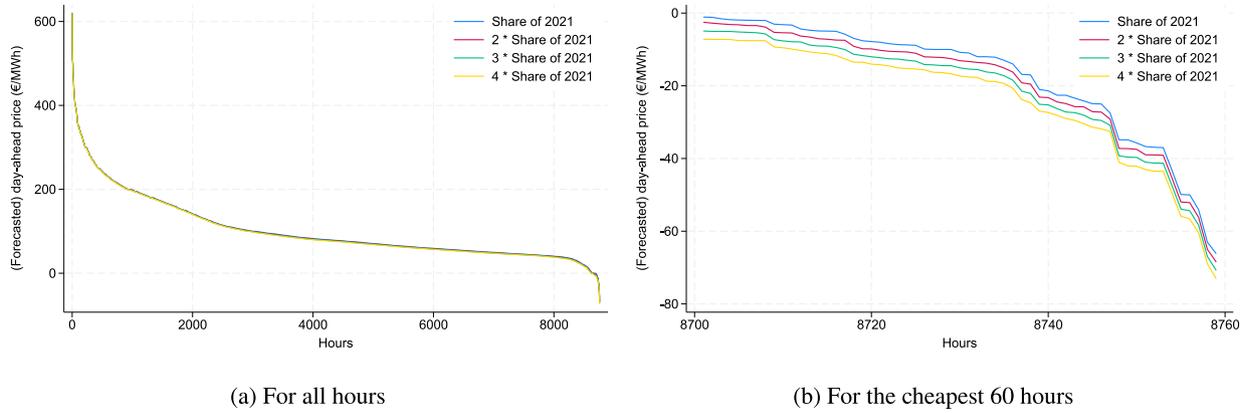


Fig. A.7. Price duration curves showing how price responds to an increase in the share of PV households due to the merit order effect.

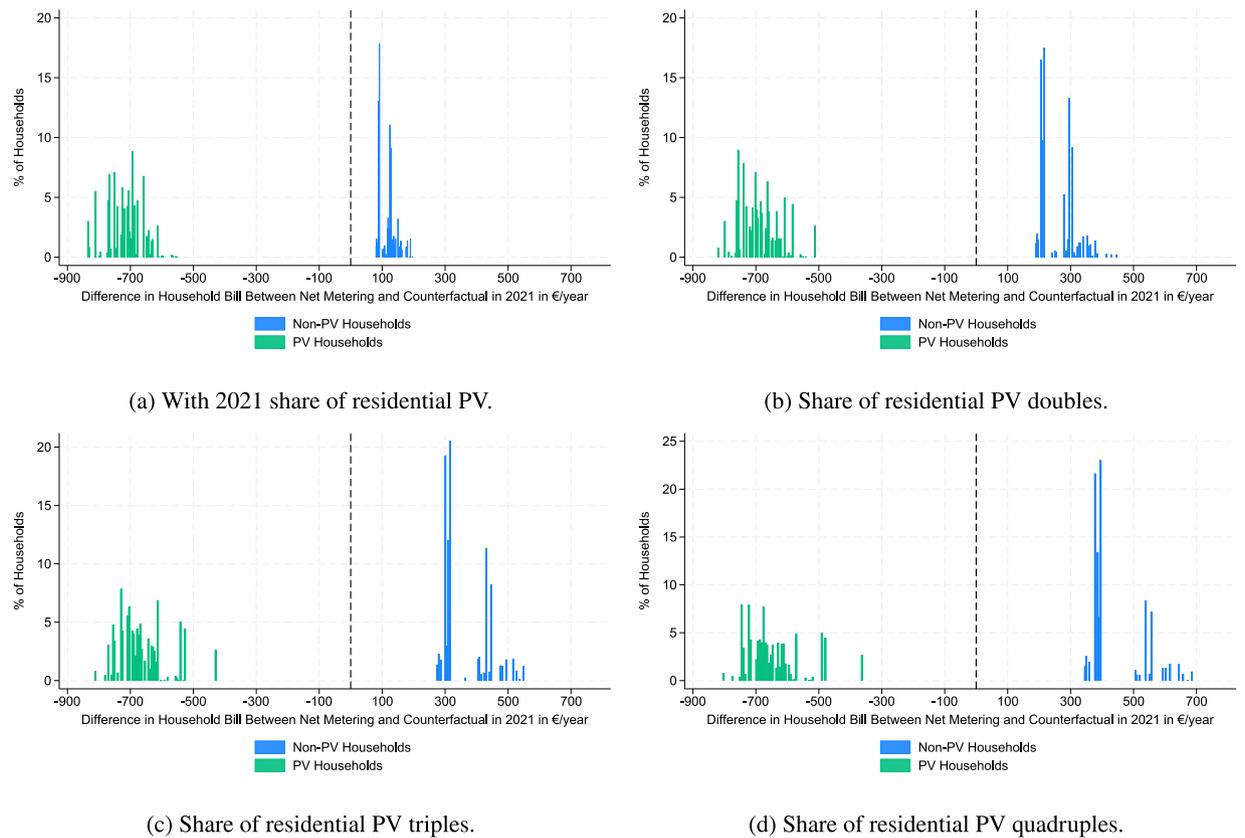


Fig. A.8. Sensitivity to the share of households with PV of the distribution of households according to the difference between their electricity bill in the Net-Metering (NM) scenario and that in the Counterfactual Scenario (CS).

Table A.13

Sensitivity to the balancing cost parameter of the estimated balancing costs faced by the retailer and the estimated household electricity bill for the average PV and non-PV household.

Parameter for the change in balancing costs	Retailer's Balancing Costs (€/year)		Average Bill (€/year)	
	Non-PV Household	PV Household	Non-PV Household	PV Household
α	6	0	1061	244
$\alpha * 2$	9	1	1065	244
$\alpha * 10$	33	2	1089	246

The parameter α is the one used in the main analysis. All values are approximations to the closest integer.

Table A.14

Sensitivity to the feed-in compensation rate of the estimated average feed-in compensation paid by the retailer to one PV household and the estimated household electricity bill of the average PV and non-PV household.

Feed-in compensation rate	Feed-in fee compensation paid by the retailer to one PV household (€/year)	Average Bill (€/year)	
		Non-PV Household	PV Household
Average price of 2021	51	1061	244
Average price of 2016	16	1056	278
Average price of 2019	20	1057	274
Average price of 2023	47	1061	247
No compensation	0	1054	294

Table A.15

Sensitivity to the grid tariff design of the grid tariff and the estimated household electricity bill for the average PV and non-PV household.

Design of the grid tariff	Grid tariff (€/year)		Average Bill (€/year)	
	Non-PV Household	PV Household	Non-PV Household	PV Household
All households pay the same tariff	196	196	1061	244
The increase in grid costs is paid by PV households only	190	222	1054	275
Two-part volumetric tariff depending on installed capacity	190	218–226	1054	275

In the main analysis, all households pay the same grid tariff. All values are approximations to the closest integer.

A.5.5. Sensitivity to the grid tariff design

We assume that all households pay the same grid tariff based on the current situation in the Netherlands. However, the increase in grid costs associated with net metering could also be charged to PV households exclusively. This could be done either in a fixed manner, that is, all PV households pay the same fee, or in a volumetric manner, that is, PV households pay the increase based on their installed capacity. [Table A.15](#) shows that PV households pay on average about 26€ more per year for the grid tariff if either of these alternative designs is implemented. Yet, the distributional effects differ between the two alternative designs, given that the latter design is based on the installed capacity, which differs per group of households.

A.5.6. Sensitivity to the load of PV households across scenarios

The assumption that the electricity consumption of a given household does not change if the household installs solar panels may not necessarily be appropriate. Indeed, there is evidence that households consume more electricity after installing solar panels, the so-called solar rebound effect ([Havas et al., 2015](#); [Deng and Newton, 2017](#); [Qiu et al., 2019](#); [Toroghi and Oliver, 2019](#); [Beppler et al., 2021](#); [Aydn et al., 2023](#); [Nguyen et al., 2024](#)). This effect can be defined as the ratio of the absolute increase in household electricity consumption to the absolute increase in household electricity generation from solar panels. Generally, the solar rebound effect is expressed as the relative increase in daily consumption as a percentage of daily generation. [Oliver et al. \(2024\)](#) find that this rebound effect is especially likely to occur under net metering, though its magnitude varies strongly with the specific net metering design in place.

For the net metering design we focus on in this paper, households with solar panels experience an income effect as their electricity consumption is cheaper up to the volume at which their annual consumption equals their annual generation. While this income effect entails an incentive to consume more electricity, higher consumption implies an opportunity cost as the electricity generated but not consumed is compensated at the feed-in fee. Furthermore, households with solar panels may shift their consumption from hours with less sunshine to those with more sunshine. Under the net metering scheme of interest in this paper, there would be no economic reason to do so, yet households may be motivated by environmental concerns or they may be aware of the grid congestion issues caused by over generation from solar panels and may even fear curtailment (which would actually economically affect the household bill through lower generation to net against). This interplay of drivers makes the estimation of the solar rebound effect a complex and data-intensive process, but we can

nevertheless distinguish two types of effects within the rebound effect: a net income effect and a load-shifting effect.

While we lack access to the granular historical data needed to estimate the rebound effect for our sample, we use findings from the current literature on this effect to estimate the electricity consumption of PV households before they installed solar panels (that is, in the counterfactual scenario). Specifically, the literature finds that the daily increase in electricity consumption due to the rebound effect ranges from about 7% of daily generation, as estimated by [Aydn et al. \(2023\)](#) for the island of Texel in the Netherlands, to about 28%, as found by [Beppler et al. \(2021\)](#) for the eastern United States. Moreover, [Qiu et al. \(2019\)](#) find the solar rebound effect to be around 18% in Arizona (USA), and [Deng and Newton \(2017\)](#) estimate it to be about 16%–20% for Sydney in Australia. These studies also highlight that most of the increased electricity consumption occurs during sunny hours, which indicates that both types of the above-mentioned effects appear to be relevant.

We construct the load profile of PV households in the counterfactual scenario by subtracting the hourly increase in load due to the rebound effect from their load in the net-metering scenario, as this is the scenario on which we have actual data. To do so, we compute the daily increase in load using the rebound effect levels obtained from the literature and the daily household generation from solar panels. Rather than allocating this daily increase evenly over the hours of the day, we let the hours in which solar panels generate have a three times larger weight than the hours in which solar panels do not generate, in line with the literature's finding that the rebound effect is more pronounced during sunny hours. In terms of rebound effect levels, we believe that the increase in daily load of 7% of daily generation estimated by [Aydn et al. \(2023\)](#) is the most realistic for our sample given that it is based on the same country, yet we also compute the results using the levels of 18% ([Deng and Newton, 2017](#); [Qiu et al., 2019](#)), 28% ([Beppler et al., 2021](#)) as a sensitivity analysis. We compare the results using these four levels to the results of our main analysis, which assumes no rebound effect (that is, a level of 0%).

Using this approach, we obtain the hourly load profiles presented in [Fig. A.9](#). As is visible, higher rebound effects imply lower loads for PV households in the counterfactual scenario, and this effect is more pronounced in sunny hours. As in our main analysis, the effect of net metering can be understood as the change in household utility bill between the net-metering and the counterfactual scenario. The lower load profile of PV households in the counterfactual scenario necessarily implies a smaller size of utility bill savings for this type of households compared to the results of our main analysis. This is visible in [Table A.16](#), where the change in the yearly bill for the average PV

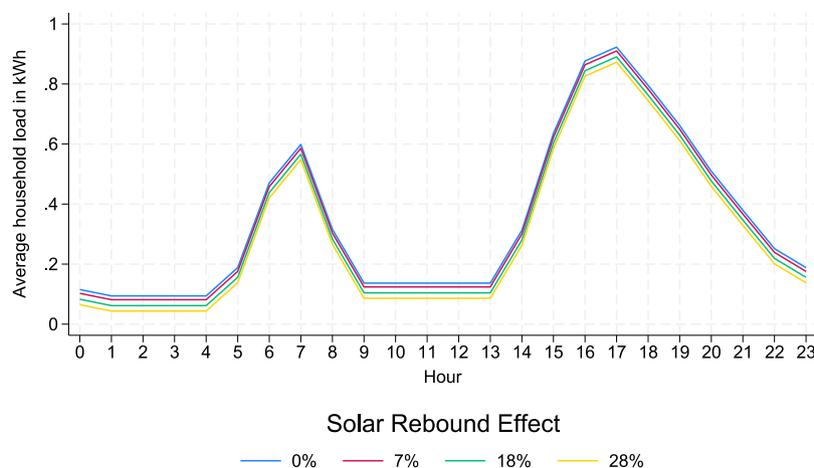


Fig. A.9. Average hourly household load for PV households in the counterfactual scenario at different levels of the solar rebound effect. The latter refers to the increase in electricity consumption by households in response to installing solar panels. This effect is expressed as the relative increase in daily consumption as a percentage of daily generation.

Table A.16

Percentage change in the total yearly bill faced by the average household with and without PV in the Net-Metering scenario (NM) compared to the bill they would face in the Counterfactual Scenario (CS) with no residential solar capacity installed at different levels of the solar rebound effect, expressed as the relative increase in daily consumption as a percentage of daily generation.

Rebound Effect (%)	0	7	18	28
Non-PV Household: % change in yearly bill between NM and CS scenarios				
Retail Component	7	6	6	5
Grid Component	3	3	3	3
<i>Tax Component</i>				
Energy Tax	32	30	26	22
VAT on retail bill	7	6	6	5
VAT on grid bill	3	3	3	3
VAT on energy tax	32	30	26	22
Total	14	13	11	10
PV Household: % change in yearly bill between NM and CS scenarios				
Retail Component	-93	-92	-91	-90
Grid Component	3	3	3	3
<i>Tax Component</i>				
Energy Tax	-91	-90	-89	-88
VAT on retail bill	-93	-92	-91	-90
VAT on grid bill	3	3	3	3
VAT on energy tax	-91	-90	-89	-88
Total	-74	-72	-70	-66

The values are approximated to the closest integer.

household decreases from 74% under no rebound effect to 66% under the higher rebound effect considered (28%). Notably, the lower load of PV households in the counterfactual scenario also implies a smaller increase in the utility bill of non-PV households. This effect arises from the lower increase in retail costs, which implies a lower retail tariff imposed on all households, and a lower constant government budget, resulting in a smaller increase in the energy tax. As shown in Table A.16, the change in the total utility bill of the average non-PV household decreases from 14% under no rebound effect to 10% under the 28% rebound effect. Overall, the results of this sensitivity analysis imply that the distributional impact of net metering becomes less pronounced under higher rebound effect assumptions. However, this effect is quite small, accounting for a one to two percentage points reduction in the change in the electricity bills due to net metering under the most relevant estimate for our context (7%, from the Dutch study by Aydin et al.).

Appendix B. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.eneco.2025.108891>.

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