Who Pays, Who Adopts?
Efficiency and Equity of Residential Solar Policy

Dongchen He*

December 31, 2025

Latest Version Here

Abstract

This paper studies diverse residential solar subsidies within a nested discrete choice framework, introducing endogenous capacity choice and heterogeneous household preferences. Solar subsidies have an intensive margin effect. Households install small solar panels when subsidies reimburse upfront investment costs, creating a high fiscal cost to achieve the capacity target. Furthermore, households respond heterogeneously to subsidies: switching from a subsidy based on future production to one that reduces upfront investment costs shifts solar photovoltaics adoption toward lower-income households. There is no single dominant policy in both cost-efficiency and equity. I propose a novel policy screening that is the most cost-efficient, but at the expense of equity. The method of raising subsidies also shapes distributional outcomes. These findings highlight the importance of subsidy policy design.

Keywords: Photovoltaics, Renewable subsidy, Distributional effects, Policy design, Structural estimation. **JEL:** D12, D31, D63, Q52, Q58

*Dongchen He is at the School of Economics and Management, Tilburg University. d.he@tilburguniversity.edu. I appreciate the big support of my supervisors, Bert Willems and Ronald Huisman. I am grateful to my Ph.D. committee members Jan Boone, Natalia Fabra, Machiel Mulder, and Nicola Pavanini for their constructive suggestions. I am thankful to Stefan Ambec, Olivier De Groote, Reyer Gerlagh, Tobias Klein, Stefan Lamp, Mathias Reynaert, François Salanié, and Herman Vollebergh for their helpful feedback. I also thank participants at IAEE International 2025 (Paris) and EEA 2025 (Bordeaux), and seminars at Tilburg University and Toulouse School of Economics. I acknowledge Centraal Bureau voor de Statistiek for providing me with the Dutch administrative data. Finally, I thank CentER and the economics department at Tilburg University for financial support. The author declares that she has no relevant or material financial interests that relate to the research described in this paper. All errors are my own.

1 Introduction

Residential solar photovoltaic (PV) is widely viewed as a crucial part of tackling climate change. Various subsidies are used to accelerate PV adoption. Although they share the same objective, the choice of subsidies affects which households adopt and how much capacity is installed. These endogenous consequences are not sufficiently studied but are important in two respects. First, subsidies change PV size in ways that may carry substantial grid and fiscal costs. Second, subsidies may disproportionately benefit higher-income households, resulting in regressive effects. This raises a key question for policymakers: Can a better residential solar subsidy design address these unintended outcomes while achieving the goals of the energy transition?

To disentangle the effect of subsidy design on households' adoption decisions, I develop a nested discrete choice framework that models the decision based on the installation cost of solar panels, the expectations about future revenues of adopting solar PV, the electricity consumption, rooftop area constraints, and, importantly, the structure of the subsidy. There are two key specifications. First, households decide not only whether to adopt but also the PV size once they adopt. Second, households across income quintiles have heterogeneous preferences regarding installation costs and future revenues. This structural framework is flexible for investigating different policy designs and circumvents the reduced-form econometric challenge of requiring randomized control and treatment groups for all policies.

The model is estimated using Dutch administrative data from 2019 to 2022. The dataset covers the population of Dutch households, and the cleaned sample gives an unbalanced panel with more than 21 million observations. It provides information on household solar PV adoption status, installed capacity, and rich socio-demographic characteristics. The Netherlands operates a fully liberalized and mature electricity wholesale and retail market, like the US and other European countries. By 2022, the residential PV adoption rate in the Netherlands reached 26%, making it one of the highest in Europe and providing rich variation for model estimation. The main subsidy in the Netherlands is called net metering, which offsets household electricity consumption from the public grid (henceforth, grid consumption) with electricity fed into the grid (henceforth, electricity feed-in) at the current retail price. Net metering was also widely used in 45 U.S. states at its peak, as well as in Canada and several European countries such as Belgium.

With the estimation results, I conduct counterfactual analyses by changing the policy design. In addition to net metering, I consider three other subsidies. The first is a lump-sum transfer that pays households once they adopt, regardless of the PV size. Although less common in practice, the lump-sum transfers provide a meaningful benchmark because they do not affect households' capacity choices. Then, I consider a proportional investment subsidy that provides a one-time payment to reimburse part of the installation cost and is independent of future electricity production. This investment subsidy has been widely implemented, especially in the United States. The last subsidy is the feed-in tariff, which was popular in Europe and reimburses each kilowatt-hour (kWh) of electricity feed-in at a fixed price. Despite variations in implementation details, these four policies are broadly representative and capture the main mechanisms this paper aims to study. Beyond the single-policy design, I also investigate policy combinations and policy menus that enable differentiated policy choices. In the rest of the paper, the lump-sum transfer and proportional investment subsidy are referred to as *investment-based* subsidy, and the feed-in tariff and net metering are referred to as *production-based* subsidy.

The first finding is that, given the total PV capacity target, the subsidy structure has an intensive margin effect. Specifically, the results show that compared with lump-sum transfers, investment subsidies, on average, increase PV capacity by 0.6 kilowatts (kW) per household adoption. Net metering creates a kink in the incentives and bunches capacity at the household consumption level, increasing the average capacity by 0.8 kW. Feed-in tariffs reward additional capacity with a high, constant price, resulting in capacity that is usually restricted by rooftop area, and increasing PV capacity by 1.2 kW for an adopted household. These intensive margins matter in two ways. First, they determine installation costs through economies of scale and grid costs based on the amount of feed-in. A small installed capacity has a higher average installation cost while lowering the grid burden through higher self-consumption, meaning less electricity is exported to the public grid. The countervailing cost effects make the total social cost associated with different policies modest.

However, the intensive margin has important implications for the fiscal budget. In particular, investment-based subsidies tend to induce smaller PV installations, requiring the government to raise the subsidy level and achieve the same capacity target as production-based subsidies through higher adoption rates. The increase in the extensive margin makes investment-based subsidies very costly, as both marginal and inframarginal households installing solar PV receive a higher subsidy. This finding complements De Groote and Verboven (2019), who argue that investment-based subsidies are more cost-efficient because production-based subsidies are heavily discounted. Using the same discount factor of 0.85, I find that an investment-based subsidy can save approximately €70 million in fiscal expenditure per gigawatt (GW) of PV capacity. However, this difference is considerably smaller than that reported by De Groote and Verboven (2019), who do not account for the intensive margin, and the cost difference would vanish when the discount factor increases slightly to 0.87.

The second finding is that households respond heterogeneously to different subsidies, depending on whether the policy reimburses future electricity production or current installation costs. Specifically, low-income households are much more sensitive to immediate cost reductions than to future benefits, whereas higher-income households are relatively indifferent between the two subsidy types. These heterogeneous preferences imply that switching from a production-based subsidy to an investment-based subsidy shifts adoption toward lower-income households. For example, under net metering, the yearly conditional adoption rate, defined as the number of new adoptions out of the potential adoption market, rises by 1.2% for the first (bottom) income quintile, and by 3.7% for the fifth (top) quintile compared with the no subsidy scenario. Switching to a lump-sum transfer increases adoption by 4.5% for the bottom quintile and 3.9% for the top quintile. Nevertheless, higher-income households are less price-sensitive overall and more likely to cross the adoption threshold regardless of the subsidy type. As a result, their adoption rate is always higher than that of lower-income households under all policy designs.

The distributional effect also depends on the method of raising the subsidy. By studying the intersection between subsidy design and the taxation mechanism used to finance subsidies, I show that lump-sum taxes are regressive across all subsidy instruments. Surcharges on electricity consumption are less regressive at the early stage of solar PV adoption. However, when the adoption rate reaches 32%, net metering combined with a surcharge becomes even more regressive than when the subsidy is financed through a lump-sum tax, whereas other instruments under a surcharge still outperform the lump-sum tax. An income tax is progressive, no matter which subsidy is used.

The results change when households are grouped in different ways. For instance, when comparing welfare redistribution between households that adopt solar panels (henceforth, PV adopters) and those that do not (henceforth, non-adopters), PV adopters obtain substantial welfare gains under all types of subsidies and financing schemes. Among the financing methods, the surcharge on electricity consumption is the most regressive, as PV adopters pay less taxes through self-consumption. To the contrary, the lump-sum tax is the least regressive, as all households pay the same amount of tax regardless of solar PV adoption. However, when considering home ownership or dwelling type, the lump-sum tax becomes most regressive again. Therefore, no policy can achieve fairness across all dimensions, and the policy choice depends on the specific distributional objective.

Finally, the finding of heterogeneous household preferences suggests the potential for policy screening. While a combination of policies cannot outperform a single policy in any single objective, such as cost efficiency or equity, a menu of policies can. Specifically, designing a policy menu that includes both a feed-in tariff and an investment subsidy, and allowing households to self-select the option that best fits their preferences, can reduce total fiscal expenditure by about 18% relative to the optimal single policy. However, this policy screening is more regressive than an investment-based subsidy.

This paper comprehensively discusses residential solar policies within a unified structural framework of household decision-making by twisting the endogenous capacity choice and heterogeneous household preferences together. The closest paper by Bollinger et al. (2025) calibrates heterogeneous discount factors for low-income and high-income households, and also suggests reimbursing upfront costs to reduce regressivity. My paper differs by allowing households to choose installation capacity within the structural model, and explicitly capturing the intensive margins and associated welfare changes under diverse policy designs, which provide the countervailing cost effects that, to my best knowledge, have not been identified in previous studies.

There is a growing body of literature discussing the role of subsidies on solar PV installation. For instance, Burr (2016) uses a quasi-experiment in California and shows that the investment subsidy encourages more adoption, while the production subsidy is more efficient as it encourages adoption in optimal locations for solar electricity production. There are some other papers estimating the price elasticity of investment subsidies (Hughes and Podolefsky 2015; Gillingham and Tsvetanov 2019; Crago and Chernyakhovskiy 2017). On the other hand, Aldy et al. (2023) study wind farm subsidies and give the opposite result. Comello and Reichelstein (2017) predict PV adoption in three cities in the US when a lower-than-retail tariff is paid to solar adopters and find that the adoption will not be affected as long as this tariff is above the levelized cost of electricity. With an input-output model, Eid et al. (2014) calculate the bills in different scenarios and net-metering designs, providing insights into the effect of net-metering policy on cost recovery and inequality. Londo et al. (2020) use the cash-flow model and investigate the effects of alternative policies on pay-back period, government cost, and amount of PV uptake by exogenously given parameters. Masciandaro et al. (2025) show how net metering affects adopters and non-adopters across different regions in the Netherlands. Böning et al. (2025) assess the effects of different incentive schemes with a reduced form estimation using regional data in Belgium. My paper contributes by using structural estimation with a large administrative dataset, and by conducting comprehensive and comparable counterfactual analyses within this framework.

This paper also contributes to the literature on the welfare effects of residential solar PV adoption, with a particular focus on its subsidy policies. Closely enough, Feger et al. (2022) investigate an optimal tariff design to incentivize residential solar PV adoption and avoid an enormous grid cost burden on non-adopters in Switzerland. They argue that consumption-based grid cost is less regressive than fixed grid cost because adopters are more affluent and less price sensitive to electricity price increases. Wolak (2018) uses distribution network price and installation from the three largest utilities in California and finds that residential solar capacity contributed two-thirds of increasing network prices from 2003 to 2016. Dauwalter and Harris (2023) further show that residential solar capacity has unequal environmental benefits, and there is no trade-off between efficiency and equity. Rather than documenting the unequal outcomes, this paper contributes by identifying the underlying mechanisms of inequalities and proposing a subsidy design that would improve this issue.

Last, this paper enriches the discussion on the inequity of environmental policies. For instance, Holland et al. (2019) examine the distributional effects of local air pollution from electric vehicle adoption in the US. Ito et al. (2023) demonstrate that price-elastic consumers are more likely to benefit from dynamic pricing. Känzig (2023) shows that the poor are more exposed to carbon pricing because they have a higher energy share and face a larger fall in income. This paper shows that residential solar subsidies have regressive effects similar to those of other environmental policies.

References

Aldy, J. E., Gerarden, T. D., and Sweeney, R. L. (2023). Investment versus Output Subsidies: Implications of Alternative Incentives for Wind Energy. *Journal of the Association of Environmental and Resource Economists*, 10(4):981–1018.

Bollinger, B., Gillingham, K., and Kirkpatrick, A. J. (2025). Valuing Solar Subsidies. Technical Report w33368, National Bureau of Economic Research.

Böning, J., Bruninx, K., Ovaere, M., Pepermans, G., and Delarue, E. (2025). The effectiveness of future financial benefits on PV adoption — Evidence from Belgium. *Energy Economics*, 142:108141.

Burr, C. (2016). Subsidies and Investments in the Solar Power Market.

Comello, S. and Reichelstein, S. (2017). Cost competitiveness of residential solar PV: The impact of net metering restrictions. *Renewable and Sustainable Energy Reviews*, 75:46–57.

Crago, C. L. and Chernyakhovskiy, I. (2017). Are policy incentives for solar power effective? Evidence from residential installations in the Northeast. *Journal of Environmental Economics and Management*, 81:132–151.

Dauwalter, T. E. and Harris, R. I. (2023). Distributional Benefits of Rooftop Solar Capacity. *Journal of the Association of Environmental and Resource Economists*, 10(2):487–523.

De Groote, O. and Verboven, F. (2019). Subsidies and Time Discounting in New Technology Adoption: Evidence from Solar Photovoltaic Systems. *American Economic Review*, 109(6):2137–2172.

Eid, C., Reneses Guillén, J., Frías Marín, P., and Hakvoort, R. (2014). The economic effect of electricity net-metering with solar PV: Consequences for network cost recovery, cross subsidies and policy objectives. *Energy Policy*, 75:244–254.

Feger, F., Pavanini, N., and Radulescu, D. (2022). Welfare and Redistribution in Residential Electricity Markets with Solar Power. *The Review of Economic Studies*, 89(6):3267–3302.

Gillingham, K. and Tsvetanov, T. (2019). Hurdles and steps: Estimating demand for solar photovoltaics. *Quantitative Economics*, 10(1):275–310.

Holland, S. P., Mansur, E. T., Muller, N. Z., and Yates, A. J. (2019). Distributional Effects of Air Pollution from Electric Vehicle Adoption. *Journal of the Association of Environmental and Resource Economists*, 6(S1):S65–S94.

Hughes, J. E. and Podolefsky, M. (2015). Getting Green with Solar Subsidies: Evidence from the California Solar Initiative. *Journal of the Association of Environmental and Resource Economists*, 2(2):235–275.

Ito, K., Ida, T., and Tanaka, M. (2023). Selection on Welfare Gains: Experimental Evidence from Electricity Plan Choice. *American Economic Review*, 113(11):2937–2973.

Känzig, D. R. (2023). The Unequal Economic Consequences of Carbon Pricing. *National Bureau of Economic Research.*, No. w31221.

Londo, M., Matton, R., Usmani, O., van Klaveren, M., Tigchelaar, C., and Brunsting, S. (2020). Alternatives for current net metering policy for solar PV in the Netherlands: A comparison of impacts on business case and purchasing behaviour of private homeowners, and on governmental costs. *Renewable Energy*, 147:903–915.

Masciandaro, C., Mulder, M., and Kesina, M. (2025). Distributional effects of the Dutch net-metering scheme for residential solar panels. *Energy Economics*, 151:108891.

Wolak, F. (2018). The Evidence from California on the Economic Impact of Inefficient Distribution Network Pricing. Technical Report w25087, National Bureau of Economic Research, Cambridge, MA.