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Welfare and Redistribution in Residential Electricity Markets with Solar Power

FABIAN FEGER

University of Bern

NICOLA PAVANINI

Tilburg University and CEPR

and

DOINA RADULESCU

University of Bern, KPM, CESifo and Oeschger Center for Climate Change Research

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An increasing number of households installing solar panels and consuming the energy thus produced raises two challenges for regulators: network financing and vertical equity. We propose alternative tariff and subsidy designs for policymakers to incentivize solar panel adoptions and guarantee that network costs are recovered, while trading off efficiency, equity, and welfare motives. We estimate a structural model of energy demand and solar panel adoption, using a unique matched dataset on energy consumption, prices, income, wealth, solar panel installations, and building characteristics for 165,000 households in Switzerland from 2008 to 2014. Our counterfactuals recommend the optimal solar panel installation cost subsidies and two-part energy tariffs to achieve a solar energy target. We show that, relative to installation cost subsidies, relying on marginal prices to incentivize solar panel adoptions is more cost efficient and progressive across the income distribution, but generates a larger aggregate welfare loss.

Key words: Energy, Photovoltaics, Income distribution, Welfare, RDD, Structural estimation

JEL Codes: D12, D31, L94, L98, Q42, Q52

1. INTRODUCTION

The global challenge of reducing greenhouse gas emissions has become increasingly important in recent years. To meet this goal, policymakers, companies, and individuals worldwide have contributed to the development of renewable energy systems, with a global investment in these new technologies of over \$300 billion in 2019.[1] Solar photovoltaic (PV) is one of the leading

1. *Source:* Renewable Energy Policy Network for the 21st Century (REN21), *Renewables 2020 Global Status Report*.

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technologies among renewables, experiencing a remarkable growth in recent years. Total solar power capacity worldwide grew from around 40 GWp in 2010 to over 627 GWp at the end of 2019, and now 3% of the world's electricity demand is covered by PV.[2] To encourage adoptions of solar panels, regulators have relied on various incentives. First, installation subsidies reduce the upfront investment cost. Second, feed-in tariffs guarantee solar energy producers remuneration above market price for any electricity supplied to the grid. Third, self-consumption policies allow solar energy producers to consume the electricity they produce, saving on the cost of electricity procurement, the marginal grid price, and electricity taxes.[3] Self-consumption policies have gained traction in recent years, as they reduce the financial burden for the government and the grid integration cost of solar panels, incentivizing the timing overlap of electricity consumption and production.

While the widespread adoption of solar panels and self-consumption policies are desirable from an environmental perspective, this trend comes at a cost for utilities worldwide (MIT, 2011; The Economist, 2017). The growing number of PV adoptions poses two main challenges to regulators. First, households with PV installations still require network energy, leaving the fixed grid maintenance costs unchanged, or even increasing operation costs (Joskow, 2012).[4] However, as they produce and consume their own energy, these households contribute less to covering grid costs, because these are mostly paid with revenues from consumption-based marginal prices in a standard two-part tariff. This is likely to make the sustainability of network financing problematic (Borenstein, 2012; Bushnell, 2015), leading to a "death spiral" of rising prices. Second, households that can afford to install a solar panel are usually richer, which can generate a regressive redistributive effect in green energy incentives. This is both because subsidies mostly benefit richer households, and because households without solar panels, which are likelier to be poorer, may end up paying a larger share to finance the distribution grid. In the absence of equity and environmental considerations, efficiency arguments would require recovery of increasing grid costs through a higher fixed access fee instead of via marginal prices, ensuring that solar panel owners fully contribute to grid financing. However, such a change in tariffs would erode incentives to install solar panels and potentially have regressive effects, since it would increase grid expenditure relatively more for low-consumption households. This opens the question of how policymakers should design two-part tariffs and subsidies in order to achieve solar adoption targets, while balancing efficiency and equity, and recovering fixed network costs (Borenstein, 2016).

This article proposes a tariff design that addresses the challenges of network financing and vertical equity, developing a structural framework for households' static electricity demand and dynamic PV adoption, and modelling regulators' optimisation problem when setting two-part tariffs and subsidies. While Feldstein (1972) derived the optimal two-part tariff combining equity and efficiency considerations, we contribute to the literature on public utility pricing by adding a third dimension, namely renewable energy targets to address environmental concerns. Moreover, in contrast to earlier work on solar panel adoption (Burr, 2016; Langer and Lemoine, 2018; De Groote and Verboven, 2019), our article is the first to study optimal design of both two-part

2. *Source:* International Energy Agency, *2020 Snapshot of Global Photovoltaic Markets* (Report IEA-PVPS T1-37:2020).

3. In the US, energy providers commonly employ "net metering," meaning that electricity bills are based on energy consumption net of solar panel production, which corresponds to a self-consumption percentage of 100%.

4. As reported by a study commissioned by the Swiss Federal Office of Energy titled *Energieszenarien für die Schweiz bis 2050* (*Energy Scenarios for Switzerland until 2050*), the Swiss government expects a total CHF 6 billion (equivalent to around USD 6 billion) additional grid costs from 2011 to 2035 from decentralized production of electricity. Borenstein (2008) argues that the costs of adopting the PV technology exceed its market benefits, as solar panels increase the costs of energy transmission and distribution.

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tariff and subsidy in a setting where households can consume the solar energy they produce, and to investigate the distributional effects of policies to stimulate PV adoption.

More specifically, our tariff design involves marginal prices, fixed fees, and installation subsidies. Our model allows us to quantify the trade-offs that these three instruments generate, when the regulator aims to achieve a predefined solar energy target, while guaranteeing the recovery of network costs based on efficiency and equity motives. First, fixed fees can serve to recover grid costs but are regressive and do not encourage PV adoption. Second, marginal prices can instead incentivize solar panel installations, and are also useful to finance the grid in a progressive way, as high-income households tend to consume more electricity and be less price sensitive. Last, installation cost subsidies foster adoptions but must be financed via higher fixed fees or marginal prices. These trade-offs highlight the importance of modelling not only PV installation but also households' electricity consumption, as the latter can serve to measure how changes in fees and marginal prices affect the recovery of network costs and the solar energy target, defined as the ratio of solar energy produced to total electricity consumption.[5] Our findings highlight that relying on marginal prices to finance the energy grid is a cost-efficient and progressive way to incentivize PV adoptions but generates a larger aggregate welfare loss relative to installation cost subsidies.

Similar challenges are common in other markets where the adoption of a new technology helps to achieve environmental targets, but erodes the revenue to finance infrastructure network costs, and is incentivized with government schemes that mainly benefit higher income adopters. For example, the spread of electric vehicles, mostly purchased by wealthy households due to their high prices, and often subject to generous government incentives, contributes to a decline in revenues from fossil fuel taxes used for road maintenance and development (Davis and Sallee, 2020). This calls for a redesign of motoring taxation that, as in the context of our article, incorporates not only environmental objectives, but also distributional effects and the recovery of infrastructure costs.[6] More generally, these challenges also apply to government incentives for building renovations or firms' investments that improve energy efficiency. These are beneficial from an environmental perspective, but mostly target landlords and home or building owners, and can result in lower revenues for electricity and gas utilities that face large fixed network costs.

We use a unique matched panel dataset with yearly information on electricity consumption, prices, income, wealth, solar panel installations, and building characteristics for around 165,000 households in the Canton of Bern (Switzerland) in 2008–14. These data combine information from four different sources. First, the three main energy providers in the Canton gave us data on households' electricity consumption and expenditures, electricity prices, and households' PV adoptions. Having access to household level electricity consumption data is crucial to estimate the elasticity of electricity demand, and to incorporate in our structural framework the impact of marginal prices on electricity consumption, welfare, and grid financing. It also allows to accurately model the impact of marginal prices on solar panel adoption, because the revenue from installing a PV is a function of the share of electricity produced by a solar panel that each individual household can consume. Moreover, it is necessary to measure the distributional effects of alternative tariff designs. Second, the Tax Office of the Canton of Bern gave us yearly information on each household's income, wealth, tax payments, and demographics, including location. To our knowledge, this is the first paper that is able to match households' energy consumption with exact

5. Most regulators set these green energy targets in terms of percentage of electricity consumed coming from renewable sources, such as the EU's Renewable Energy Directive 2008/28/EC.

6. The UK government could lose up to £28 billion revenues from fuel duties if it reaches its target of zero vehicles' net emissions by 2050 (Institute for Fiscal Studies' publication "A road map for motoring taxation" by Adam, Stroud, 4 October 2019).

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income, wealth, and PV ownership data. Third, the Swiss Federal Statistical Office gave us access to cross-sectional information on each household's building characteristics, including number of rooms, house or apartment surface, heating and water systems, and building construction period, all key determinants of households' energy consumption. Last, we have information on installation costs, and a Swiss online advisory platform for solar energy systems simulated for us a novel dataset on potential energy production and self-consumption shares of solar panels on each building in our data, based on the respective building and household characteristics.

We use these data to estimate a structural model of energy demand and PV installation. We let households be forward looking and solve a dynamic problem in their solar panel adoption decision, and estimate the parameters of their energy demand function using a geographical boundary regression discontinuity design. This approach exploits price variation at spatial discontinuities between electricity providers and allows us to address the endogeneity of energy prices and fees. The electricity consumption and PV adoption model allows us to simulate the effects of energy tariffs and subsidies on PV adoption, welfare, and redistribution.

In our counterfactuals, we specify the regulator's constrained optimization problem that allows us to find the optimal combinations of marginal prices, fixed fees, and PV installation cost subsidies to achieve various solar energy targets over a 5-year horizon, while guaranteeing network financing. We find that the cheapest way to reach the solar target relies on raising marginal prices, which simultaneously serve as an incentive to adopt, and as a financing tool for network costs. This has a regressive effect across adopting and non-adopting households, but overall, a stronger progressive effect due to the larger grid contribution of richer non-adopting households. Accounting for equity considerations in the regulator's cost minimization makes grid financing more expensive and relies on small changes in marginal prices and fixed fees to finance the installation subsidies. This strategy uniformly distributes the additional cost of transitioning to more solar energy across household income distribution. On the other hand, a regulator preference for achieving the solar energy target while maximizing households' welfare would require a different approach. This would entail high installation cost subsidies to stimulate PV adoptions; a drastic reduction in marginal prices, as these negatively affect household surpluses; and a high fixed fee to cover network costs. Last, accounting for both welfare and equity motives leads to a less pronounced reduction in marginal prices and a lower subsidy. Overall, our approach can be easily generalized to any household's or firm's technology adoption decision that affects network costs and vertical equity within the system.

Related literature. Our article contributes to various strands in the literature. First, our modelling approach and counterfactuals, together with a rich and unique dataset, bring a novel contribution to the recent literature on the distributional and efficiency effects of environmental policies in energy markets (Borenstein, 2017).[7] Our regulator's tariff design approach is close to Wolak (2016), who focuses on the non-linear price schedule design for water utilities to balance revenue and conservation goals, while preserving vertical equity. Relative to this literature, we are the first to develop a structural model of both electricity consumption and PV installation to quantify the distributional effect of current policies, and to offer alternative tariffs that incentivize adoption while recovering network costs, trading off efficiency, welfare, and vertical equity motives. Our approach could be directly used by policymakers, who generally have access to the same data that we use, to set their tariffs and subsidies. It could also be applied in other settings, such as adoption of electric vehicles, or energy efficient renovations of buildings.

7. Several papers have analysed the distributional consequences of environmental policies (Bento, 2013), ranging from gasoline taxes (Bento *et al.*, 2009), US clean energy tax credits (Borenstein and Davis, 2016), fuel economy standards (Davis and Knittel, 2019), solar panel adoption (Eid *et al.*, 2014), and US energy market (Reguant, 2019).

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Connected to this literature, we rely on various contributions in public finance to motivate the vertical equity concern of a policymaker in the design of energy tariffs. While Atkinson and Stiglitz (1976) argue that redistribution should only be achieved via income tax, Stiglitz (1982) and Naito (1999) support the use of a second instrument to achieve income redistribution, and a number of papers promotes the redistributive role of public utility pricing.[8] This literature on public utility pricing commonly assumes that the regulator is constrained in the design of income taxation, one of the reasons being the political cost of changing income taxes. This provides an argument for vertical equity that is particularly relevant in Switzerland, where direct democracy implies that changes in income tax can only be achieved via national referenda. Based on this principle, Switzerland and other European countries (UK and Italy, for example) have separate budgets for energy vs. other types of government spending, avoiding cross-subsidisation between different areas.[9]

Second, we contribute to the growing literature on structural models of households' solar panel adoption (Hughes and Podolefsky, 2015; Burr, 2016; Langer and Lemoine, 2018; De Groote and Verboven, 2019). While all these papers exclusively model households' dynamic adoption decisions, by focusing on the effect of subsidies and feed-in tariffs, we are able instead to estimate a model that encompasses households' PV installation and electricity consumption decisions, quantifying the extent to which marginal prices can incentivize adoption. This allows us to study two-part tariff and subsidy design under a self-consumption policy, where households directly consume the electricity produced by their solar panel, reducing their energy bills. In addition, we analyse tariff and subsidy design from a regulator's perspective, guaranteeing that the network and subsidy costs are recovered through electricity bills, while also achieving predefined solar energy targets. Finally, our exact income match at the household level and our counterfactual simulations allow us to correctly identify the distributional effects of both tariff and subsidy schemes, a topic that none of the above papers considers. These novel contributions are possible because we are the first to be able to match detailed data on households' electricity consumption, prices, expenditures, incomes, building characteristics, and PV adoption status.

Last, our article is part of a large literature estimating price elasticities of residential electricity demand (Reiss and White, 2005; Ito, 2014).[10] A common feature of these papers, as with others in the literature, is that they can only imperfectly match households' electricity consumption with income census data, using aggregate zip code information. Our dataset has two fundamental advantages compared to the data used by the existing literature. First, it covers almost the whole population of the Canton of Bern, the second-largest canton in Switzerland, as opposed to previous papers only having access to a representative sample of households. Second, it provides an exact match of households' yearly electricity consumption to their annual incomes and wealth, as well as to detailed building characteristics, and potential PV costs and production.

Our article is structured as follows. Section 2 introduces the institutional features of the Swiss energy market and describes the data. In Section 3, we present the model, and in Section 4, we describe the estimation strategy and the identification. Section 5 shows the results, Section 6 presents the counterfactuals, and Section 7 concludes.

8. See, for instance, Feldstein (1972a, 1972b), Munk (1977), and Saez (2002).

9. We explore the adequacy of energy policy for redistribution in detail in a follow-up paper (Feger and Radulescu, 2020).

10. Other relevant papers are Maddock, Castano and Vella (1992), Kamerschen and Porter (2004), and Alberini, Gans and Velez-Lopez (2011).

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2. SWISS ELECTRICITY MARKET AND DATA

Switzerland is a federal state, divided into 26 cantons and roughly 3,000 municipalities. The Swiss electricity market is optimally suited to study a regulator's optimisation problem, because energy providers are local monopolists when it comes to households' electricity provision, and need to follow the requirements of the regulator, ElCom, when setting prices. This also means that residential customers are assigned different energy providers depending on their locations, and cannot choose their preferred suppliers.

Switzerland is a successful example in terms of solar power incentives and adoptions. Between 2006 and 2017, the total capacity of solar panels in Switzerland increased by 66 times, from 29 MW to 1.9 GW (Swissolar, 2017), as reported on the left panel of Figure I.9 in Supplementary Appendix I (in MW), matching the overall global growth presented on the right panel of Figure I.9 in Supplementary Appendix I (figures shown in GW). According to recent reports by the International Energy Agency,[11] in 2019, Switzerland reached 4.2% of PV contribution to national electricity demand, close to the average EU level of 4.9%, and above the 3% world average. Moreover, despite its large share of mountainous terrain, Switzerland has an average sun irradiation index of 950 kWh/kW, at the same level as other European countries that are leading in the PV adoption process, such as Germany and Belgium. Last, when considering installed PV capacity per habitant in 2019, Switzerland reached a level of 242 W, compared to 548 W in Germany, 191 W in the US, and 126 W in China.

A key driver of the growth of solar panels in Switzerland was the introduction in 2008 of the feed-in tariff remuneration system known as "KEV."[12] Households that entered the programme were entitled to a time-invariant feed-in tariff for any electricity produced over the following 25 years. Since 2008, the compensation for new adoptions has been progressively reduced, both because the pre-determined budget could not match the large number of incentive requests, and because of the sharp decline in PV installation costs. In 2014, the Swiss regulator switched from a subsidized feed-in tariff system to a self-consumption-based system. Since then, small panels ($<$10 kW) receive a one-time subsidy amounting to 30% of PV installation cost, instead of a guaranteed feed-in tariff for their production. Simultaneously, the new legislation mandated energy providers to allow households to consume directly the electricity they produced.

Figure 1 illustrates the trade-off that households faced between declining feed-in tariffs and declining installation costs, which motivates our use of a dynamic framework to model households' PV adoption decisions. It summarizes the expected production revenue and the installation costs for households in the Canton of Bern across time and solar panel size in kWp.[13] The left panel depicts production revenue under two different policies: subsidized feed-in tariffs, active between 2008 and 2013; and self-consumption, from 2014 onwards. The subsidized feed-in tariff was well above the electricity market price and was adjusted annually for new adopters, but once a household adopted a solar panel, the tariff was fixed at the installation date and guaranteed for the following 25 years. Since 2014, households instead receive a one-time subsidy that reduces their installation costs. Under this policy, for each kilowatt fed into the grid, households are remunerated by their energy provider at the market price for electricity. However, for each kilowatt of solar production that households directly consume (i.e. self-consumption), they additionally

11. See *Trends in Photovoltaic Applications 2019* (Report IEA PVPS T1-36:2019), and *Snapshot of Global Photovoltaic Markets 2020* (Report IEA PVPS T1-37:2020).

12. An abbreviation for *Kostendeckende Einspeisevergütung* in German, which means cost-covering feed-in remuneration.

13. Installation costs include the cost of the solar panels, as well as the additional materials used during the installation process. We do not have information on labour costs.

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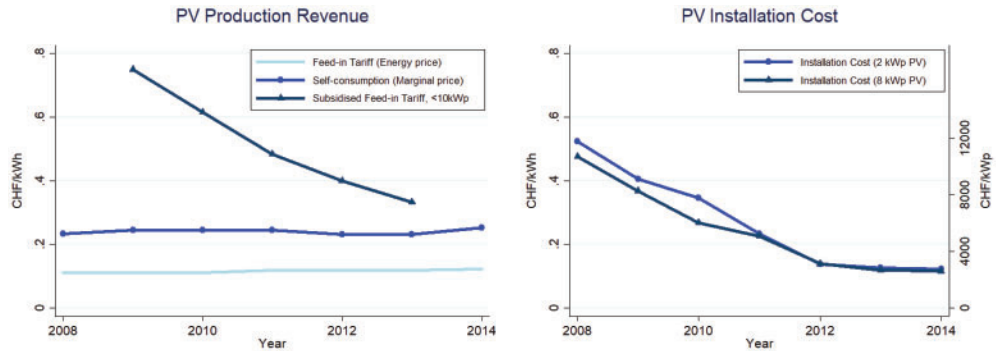

FIGURE 1

Feed-In Remuneration and Average Installation Cost

Notes: The left panel shows remuneration fees for on-roof solar panels in Switzerland. The right panel depicts average installation costs in Switzerland, collected by an annual survey published by the company PhotovoltaikZentrum für Solarmarketing (http://www.photovoltaikzentrum.de/). kWp means kilowatt peak, which is the capacity of a solar panel under standard test conditions. The values corresponding to the left vertical axis of the right panel are calculated as follows: fixed installation costs divided by total production of the panel over 25 years (its life span), where 1 kWp corresponds to slightly less than 1,000 kWh yearly, due to the panel's degrade factor.

save on taxes and the marginal grid price. The right panel of Figure 1 depicts the declining trend in cost, excluding subsidies, of a PV installation in Switzerland from 2008 to 2014.

To address our research questions, we constructed a unique dataset for the Swiss Canton of Bern for the years 2008 to 2014, which combines yearly household level electricity consumption, prices, income, wealth, PV installations, and buildings' characteristics. With an area of around 6,000 km^2 and just over 1 million inhabitants, the Canton of Bern is the second-largest Swiss canton in terms of population. The three main energy providers in the canton are BKW Energie AG (BKW), Energie Wasser Bern (EWB), and Energie Thun (ET).[14] These three main energy providers made available to us their data on household energy consumption, household PV installations, and infrastructure network costs and tariffs (datasets BKW, EWB, and ET). The map in Figure B.2 in Supplementary Appendix B shows the geographical distribution of households and the coverage of the respective energy providers in the Canton of Bern, highlighting the clear spatial discontinuities between providers that we will exploit to identify price elasticities.

As in many other countries, and importantly in the context of our analysis, the energy providers in the Canton of Bern recover the fixed cost of the energy grid partially through marginal grid prices. Table 1 reports the detailed price components for each company. The energy costs are divided into a fixed fee to access the energy grid, and a variable price consisting of four major components. First is a variable energy price defined by each supplier, reflecting the costs of internal production and of procurement of electricity on the market. The procurement cost makes up only 50–60% of the total energy price. Second is a variable price for grid usage, covering the energy distribution network costs and again varying across providers. This is roughly 40% of the total variable price. Third is a uniform surcharge levied by the federal state used to promote renewable energy. Fourth are taxes levied by the communal, cantonal, and federal authorities. As opposed to Californian utilities, which usually resort to increasing marginal prices with the level of consumption (also known as Increasing Block Pricing), Swiss utilities apply a constant price per kWh irrespective of the amount of electricity consumed. However, some of the households in

14. BKW supplies over 7,500 GWh of energy to around 200,000 households in 400 municipalities. EWB supplies energy to around 70,000 households and is mainly responsible for the city of Bern, whereas ET serves only 20,000 households in the city of Thun.

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TABLE 1
Annual energy prices, network tariffs, and taxes

	BKW		EWB		ET	
	Mean	**Std Dev**	**Mean**	**Std Dev**	**Mean**	**Std Dev**
Fixed fee (CHF/year)	139	27	82	47	105	20
Marginal price (Rp./kWh)	21	2.8	17.5	2.3	22.5	1.6
Energy price	10.3	1.2	10	0.8	11.5	.5
Grid price	8.3	1.7	6.4	1.6	8.2	1.8
Municipality tax	1.8	0.3	0.5	0.3	2.3	1.6
KEV tariff	0.5	0.1	0.5	0.2	0.5	0.1

Notes: The table shows average annual prices and standard deviation in the sample. KEV Tariff is the surcharge used to promote renewable energy. Rp (Rappen) is one-hundredth of a Swiss franc (CHF). All prices include the value-added tax.

TABLE 2
Annual energy consumption and expenditure

	N Obs	Mean	Std Dev	5th Perc	Median	95th Perc
Energy consumption (kWh)	872,665	4,136	3,797	812	3,022	11,032
Energy expenditure (CHF)	872,665	928	700	267	738	2,224
Energy price expenditure (CHF)	872,665	409	350	88	313	1,052
Grid expenditure (CHF)	872,665	441	281	157	370	960
Tax expenditure (CHF)	872,665	59	67	2	40	178
KEV expenditure (CHF)	872,665	19	19	3	14	53

Notes: The descriptive statistics are pooled over all companies and years. KEV Expenditure is the surcharge used to promote renewable energy.

our data face a dual tariff scheme, with prices differing between night and day, and with higher daytime price steering consumption to off-peak hours.[15] In the estimation and counterfactuals, we will use a constant variable price and postpone the discussion of dual tariff customers to Section 4.

Households in the Canton of Bern receive their electricity bills once per year. From the energy providers, we have access to the corresponding metre readings and construct household energy expenditures based on the historical price lists. Table 2 presents descriptive statistics of households' energy consumption and annual expenditures , with a breakdown for the different components of the electricity bill. As displayed in the first row of Table 2, the annual household energy consumption is on average 4,136 kWh. Rows 3–6 in Table 2 display summary statistics for the different expenditure components of the electricity bill. Of the average annual bill of CHF 928, roughly 44% consists of energy grid payments, which are a combination of the fixed fee and marginal grid price expenditures.

Detailed yearly data on household income and wealth were provided by the Tax Office of the Canton of Bern (Swiss Federal Statistical Office, 2014).[16] These data are essential to

15. While ET only offers a dual tariff to its customers, BKW and EWB assign either dual or uniform tariffs to each of their clients. Both providers base this tariff assignment on building characteristics and expected consumption patterns. Customers with a dual tariff metre have the option to switch to a uniform tariff, but for almost all households in our dataset, this would result in a higher electricity bill. Switching from a uniform to a dual tariff scheme would instead require the household to install a costly dual tariff metre. For these reasons, we observe in our data only 1.2% of households switching from uniform to dual tariffs, and only 0.8% of households switching from dual to uniform tariffs. We exclude tariff switchers from the analysis. Table I.3 in Supplementary Appendix I reports the full breakdown of prices across uniform and dual tariffs.

16. We describe in detail in Supplementary Appendix A the data-merging process that determined the final sample of around 165,000 households.

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TABLE 3
Annual income, wealth, and tax payments

	N Obs	Mean	Std Dev	5th Perc	Median	95th Perc
Total income (CHF)	872,665	92,492	124,767	13,235	78,255	201,249
Taxable income (CHF)	872,665	71,162	114,591	4,864	60,663	156,040
Total wealth (CHF)	872,665	493,751	2032658	0	195,176	1,570,740
Cantonal tax (CHF)	872,665	7,159	14,003	0	5,358	18,366
Municipal tax (CHF)	872,665	3,683	6,846	0	2,807	9,349
Federal tax (CHF)	872,665	1,654	9,148	0	454	5,845

Notes: The table shows descriptive statistics for the sample pooled over all years. All variables are measured in Swiss francs (CHF). Taxable income is defined as total income (in the form of labour income or income from self-employment) plus rental value of owner-occupied housing, less mortgage interest payments, and commuting and living expenses. Given the federal structure of Switzerland, households are subject to three different income taxes levied by the three different levels of government (cantonal, municipal, and federal).

understand the redistributive impact of the trend in PV adoptions and of different tariff designs. Furthermore, they also provide many household characteristics important in the estimation and the counterfactuals. Table 3 reports summary statistics for different measures of income and household tax payments. Despite Switzerland being one of the richest countries in the world, it is still subject to issues of income and wealth inequality. In particular, while it ranks close to large European countries in terms of Gini coefficient of income inequality,[17] its wealth inequality measured as the share of total wealth owned by the top 1% has been the highest since the 1960s among countries with long time series of wealth data. Among those countries, Switzerland is the only one that has experienced no reduction in wealth inequality over the last century.[18] This evidence makes redistribution an important concern for policymakers in Switzerland when designing energy tariffs and subsidies. Finally, cross-sectional information on building characteristics was obtained from the Swiss Federal Statistical Office.

Our data provide evidence that richer households are more likely to install a solar panel. In fact, the percentage of solar panel owners monotonically increases with income quintiles, as reported in Table A.1 in Supplementary Appendix A, which presents a breakdown of PV adoption, energy consumption, and household characteristics by income quintile. The data also shed light onto how incentives to install a solar panel differ across income categories. First, higher income quintiles are more likely to be homeowners and live in buildings with fewer apartments, both of which tend to be preconditions for installing a solar panel.[19] In fact, among households in the first income quintile, only 17% are home owners, whereas among households in the top income quintile, 72% are home owners. Second, higher income quintiles tend to live in larger apartments with larger roof sizes, which allows them to build larger solar panels and to profit from economies of scale in installation costs. Third, high income quintiles are associated with higher marginal tax rates, and since PV installation costs are tax deductible, richer households can achieve larger tax savings from adopting a PV. Fourth, high-income households are more likely to be able to afford the installation costs. The model we build in the next section will incorporate all of these incentives. Moreover, switching from a feed-in tariff to a self-consumption setting adds an extra channel. Richer households tend to have higher electricity consumption and more electric appliances, making them more likely to effectively match consumption to the production of a PV. In fact, for a given size of solar panel, having 1 kWh higher annual consumption is associated with 0.2

17. *Source*: https://data.oecd.org/inequality/income-inequality.htm.

18. *Sources*: Credit Swiss Global Wealth Report 2017; Data webpage for handbook chapter by Roine and Waldenström (2015).

19. We do not have data on cases where a group of households collectively installs a solar panel.

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TABLE 4
Annual PV energy production and remuneration

Variables	N Obs	Mean	Std Dev	5th Perc	Median	95th Perc
PV inverter capacity (kVA)	3,988	7.7	5.2	2.5	6.5	19.3
PV energy production (kWh)	3,988	7,267	4,872	2,268	6,175	17,778
PV Remuneration (CHF)	3,988	4,095	2,664	1,649	3,332	9,275
Energy consumption (kWh)	3,988	8,668	6,610	1,946	7,382	20,017

Notes: The descriptive statistics are only for BKW and for solar panels installed from 2008 onwards. This is the subsample we use for the estimation and counterfactuals, representing 90% of installations. PV remuneration is constructed as the estimated production multiplied by the remuneration fees of the respective year. The PV inverter capacity is measured in kilo-volt-ampere, a unit of apparent power that is very close to, or slightly lower than, the kilowatt, therefore comparable to the kWp measure used in Table 5.

kWh of higher self-consumption. The higher the level of self-consumption, the more a household saves on marginal grid prices and energy taxes.

In Table 4, we provide additional details on PV installations across the three providers, for which we have information on the size of the solar panel, expected or actual production, and remuneration. In total, 1,544 households in our dataset owned PV systems by the end of the sample period, corresponding to 1.07% of all households.[20] Table 4 shows that households tend to install, on average, 7.7 kilowatt peak of production capacity, which the Swiss regulator categorizes as a "small installation." Each kilowatt peak translates to roughly 1,000 kWh of annual production. On average, PV energy production was remunerated at a rate of 0.39 CHF/kWh. Last, electricity consumption of households owning a PV is on average 8,546 kWh, which is more than double the average consumption across all households as reported in Table 2. While this shows that high electricity consumption households are more likely to adopt a solar panel, most of these installations were built under a feed-in tariff scheme, where the income generated by the solar panel was independent of a household's electricity consumption.

Finally, our analysis requires information on the potential production, revenue, and installation cost of a solar panel for each household in our data. To address this need, we assembled a novel, simulated dataset with the support of Eturnity AG, a Swiss startup company providing an advisory platform for solar energy systems, which has developed software to forecast the potential production of rooftop solar panels, using data on roof surface and local weather as proxies for potential sun exposure (Eturnity). The company used their software to simulate the PV production capacity (in kWp) and energy production (in kWh) for each household in our sample.[21] The company's computations assume that the expected size of an installed solar panel is proportional to the household's building surface, with each square metre of building surface translating into roughly 0.080 kWp of installed solar capacity. In comparison, the effective kWp per square metre for current owners amounts to 0.077, which is very similar in terms of magnitude. The annual production of a solar panel is computed by multiplying each kWp by 1,000 kWh, where the number varies slightly based on geographic location. Finally, given the importance of self-consumption policies within our analysis, Eturnity provided us with an estimate of the share of solar production a household can directly consume based on its electricity consumption, estimated solar production, type of heating, and type of boiler.

20. 1,387 of them are customers of BKW, 118 of EWB, and 39 of Energie Thun.

21. See Supplementary Appendix C for a template of the price and production quotes that Eturnity provides to a household, and Supplementary Appendix D for a description of the formulae, methods, and assumptions that were applied by Eturnity for the simulations provided to us.

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TABLE 5
Simulated annual capacity and energy production

	N Obs	Mean	Std Dev	5th Perc	Median	95th Perc
PV production capacity (kWp)	40,394	9.5	4.7	4.7	8.4	18.9
PV energy production (kWh)	40,394	9,687	5,586	4,708	8,355	19,116
Self-consumption						
% of production	40,381	14.8	10.1	5.1	12.4	33.8
% of consumption	40,394	20.3	8.1	11.8	18.6	33.4
in kWh	40,394	1,223	876	592	990	2,626

Notes: The variables show simulated capacity and potential energy production for homeowners of single or double apartment buildings assigned to BKW. This is the subset of households that, in our PV adoption model, will be allowed to choose whether to install a solar panel or not. Values are simulated based on roof size, appliances, and geographic location. The number of observations equals the number of households. kWp means kilowatt peak, which is the capacity of a solar panel under standard test conditions.

Table 5 summarizes the simulated variables for potential PV adopters, which we classify as homeowners of single or double apartment buildings.[22] The simulated capacity and production are slightly higher than the historical data in Table 4 because the simulations are based on more recent PV technology. Due to the mismatch between time of production and time of consumption, on average only 14.8% of the energy produced can be consumed by a household ("Self-Consumption % of Production" variable), while the rest is fed into the grid. This implies that, on average, 20.3% of a household's total energy demand will be covered by its own solar panel, which corresponds to roughly 1,223 kWh, while the remaining 79.7% will be sourced from the energy provider. With a marginal grid price of approximately 0.1 CHF/kWh, self-consumption translates into CHF 120 annual grid cost savings. Throughout the rest of the paper we will refer to the directly consumed electricity as "self-consumption."

While the simulated self-consumption percentages include households using electric boilers or heating to shift PV energy production across time, they do not include batteries. Batteries allow households to reach an even higher percentage of self-consumption but require additional investments. In Switzerland, installing a 6 kWh lithium battery cost roughly CHF 9,000 in 2016.[23] As a robustness check, we also consider a scenario where batteries allow households to satisfy all of their energy demand through their own PV. Besides providing an upper bound for the impact of self-consumption on grid financing, this scenario also corresponds to "net metering" billing, where households are billed based on the net difference in production and consumption, irrespective of how much of the production they feed in.

3. THE MODEL

We define a framework to model how households respond to fixed and variable energy charges, as well as to subsidies for PV adoption, in their optimal electricity consumption and solar panel installation decisions. We let households be forward-looking and solve a dynamic problem, in the spirit of Hendel and Nevo (2006). Crucially, in contrast to a static model, our dynamic approach allows households to trade off present and future solar panels' costs and revenues, which exhibit substantial variation within our sample period as shown in Figure 1. Estimating the structural

22. Tenants have little incentive to bear the costly upfront investments because most solar panels are integrated into the roof. Buildings with more than two parties are also less likely to install a solar panel, as it would require coordination among parties. While solar panel co-ownerships are becoming increasingly popular, they are beyond the scope of our article, due to lack of data.

23. *Source:* Swisssolar (2016) Merkblatt Photovoltaik Nr. 13.

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parameters of this model allows us to simulate a counterfactual scenario, in which the policymaker finds alternative tariff designs to achieve a renewable energy target, while preserving network financing and trading off efficiency, equity, and welfare motives. We model the supply side as a regulator's constrained optimization problem, in which the model's dynamics allow the regulator to exploit the declining trend in solar panel costs. In the following, we describe the household's problem, and introduce the regulator's problem in Section 6.

In our model, a household $i=1,...,N$ decides every year $t=1,...,\infty$ on the amount of electricity in kWh to consume C_{it}, its consumption of an outside good Q_{it}, and whether to install a solar panel $\mathcal{PV}_{it}=\{0,1\}$. We normalize the price of the outside good to 1. We assume that installing a PV is an absorbing state, so if a household adopts one in year t, it cannot substitute it or install another one in the future.[24] This makes the framework a non-regenerative, optimal stopping problem. We let households' decisions be subject to a budget constraint, which implies that their yearly optimal energy and outside good expenditures should not exceed their yearly net income. To summarize, the solution of the structural model requires each household to make two decisions. First, it chooses electricity consumption conditional on PV adoption status based on a static demand model, and second, it decides on PV adoption in a dynamic model, using the solutions of the static model as inputs.

3.1. *Static energy demand*

In the first step, we assume that households solve a constrained static utility maximization problem to choose their optimal energy consumption. We specify a quasi-linear utility function and a budget constraint[25] that give us the following energy demand function:

$$C_{it}(\Lambda)=P_{ut}^{\beta_i}e^{\alpha+X_{it}'\omega+\nu_{it}}, \tag{1}$$

where P_{ut} is the electricity marginal price charged by energy utility $u\in\{BKW,EWB,ET\}$ in year t, X_{it} are household and building characteristics that are likely to determine energy consumption, such as household size, home ownership, electric and water heating, house surface, and number of rooms. ν_{it} are shocks to energy demand independently distributed across years and households, and $\Lambda=\{\alpha,\beta_i,\omega\}$ are the parameters of the demand function that we want to recover. We allow the price elasticity of demand β_i to vary across the quintiles of the wealth distribution, to capture any heterogeneity in price sensitivity across wealth groups. Since wealth is a stock variable, we view it as a more robust measure than income to capture differences in households' preferences. We use the estimates of the price elasticity of energy consumption $\widehat{\beta_i}$ as well as *observed* consumption C_{it} to compute the indirect utility of each household without a PV in year t:

$$v_{it}(\mathcal{PV}_{it}=0;\widehat{\Lambda})=\tilde{I}_{it}-F_{ut}-\frac{1}{\widehat{\beta_i}+1}P_{ut}C_{it}, \tag{2}$$

where $\tilde{I}_{it}=I_{it}-\mathcal{T}(I_{it})$ is income net of income tax payments, and F_{ut} is the fixed fee charged by energy utility u in year t. A household that has installed a solar panel receives as additional utility the annual revenue generated by its solar panel $\mathcal{R}_{it}$:

$$v_{it}(\mathcal{PV}_{it}=1;\widehat{\Lambda})=\tilde{I}_{it}-F_{ut}-\frac{1}{\widehat{\beta_i}+1}P_{ut}C_{it}+\mathcal{R}_{it}. \tag{3}$$

24. Within our sample period of 7 years, we do not observe any household substituting or installing more than one PV.

25. In Supplementary Appendix E, we show the functional form of the utility function, deriving energy demand and indirect utilities.

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Note that owning a solar panel does not change the consumption level of a household but only enters as an additional income stream. That is, we assume the adoption of a solar panel does not change the marginal price a household faces.[26] The annual revenue from the solar panel depends on the institutional setting, that is, whether production is sold entirely under a feed-in system, or partially sold and partially self-consumed. We formalize these alternative revenues in the next section.

3.1.1. PV revenue. As discussed in Section 2, the Swiss regulator relied on a subsidized feed-in scheme until 2013, but switched to a self-consumption scheme from 2014 onwards. Under a subsidized feed-in tariff scheme, households feed all produced electricity back into the grid and receive remuneration τ_{it} per kW-h. Even if households could potentially have directly consumed part of their production during this period, they would have had no incentive to do so, since the subsidized feed-in tariff was well above the total electricity price. In the Swiss case, the subsidized feed-in tariff was limited to 25 years, and after this period, the household was remunerated as in the self-consumption setting. We now formalize how, within the context of our model, the total expected discounted revenue that a PV generates over its lifetime $\mathcal{R}_{it}$ changes depending on whether there is a feed-in tariff (FT) or a self-consumption (SC) setting.

Under a subsidized feed-in scheme, this would be:

$$\mathcal{R}_{it}^{FT} = \overbrace{\sum_{s=t}^{t+24} \rho^{s-t}(1-\zeta)^{s-t} \cdot \tau_{it} \cdot Y_i +}^{\text{Feed-in period}} \overbrace{\rho^{25}\mathcal{R}_{t+25}^{SC}}^{\text{Post feed-in period}} , \tag{4}$$

where ρ is the discount factor, and ζ is the panel's degrade factor.[27] $\mathcal{R}_{t+25}^{SC}$ is the net present value of all additional PV revenue after the feed-in period. Note that the remuneration rate τ_{it} is set at the time of installation and is fixed for the next 25 years.

In a self-consumption setting, a household has the incentive to directly consume its produced electricity. For each kWh a household directly consumes, it saves on the total electricity price P_{ut}. The remaining produced electricity is fed into the grid and remunerated by the energy utility at electricity procurement price P_{ut}^{e}, which is roughly half the total electricity price, the difference being comprised of the marginal grid price and taxes. Each household can directly consume a fixed share $\mathcal{SC}_i$ of its electricity production Y_i, calculated by Eturnity as a function of the household's average level of electricity consumption, its appliances, and the total production of the PV.[28] The

26. While carefully pinning down the potential impact of installing a PV on electricity consumption is an interesting empirical question, we think it is beyond our analysis, and our data does not allow us to measure it accurately. If PV adoption would indeed cause a reduction in households' electricity consumption—and households would expect this when making their adoption decision—we would be slightly overestimating the revenue that enter the PV adoption decision. However, revenue is not directly a function of consumption, and only weakly increases through a higher self-consumption, which is simulated from Eturnity based on electricity consumption before adoption. As an additional imprecision, it would be slightly easier for the regulator to reach the solar energy target for a given set of tariffs, if the consumption of households were to be lower after adoption. This effect again is minor as PV adoption rates remain low.

27. We set the degrade factor to 3% for the first year and 0.7% for the following years. We take these values from the guidelines of a popular European panel manufacturer at: http://www.kiotosolar.com/de/assets/media/downloads/produktdatenblaetter/strom/power60/KIOTO_SOLAR_DB_POWER60_DE_250416.pdf.

28. This is the variable labelled as "Self-Consumption % of Production" in Table 5. We assume that $\mathcal{SC}_i$ is time-invariant and does not change with actual consumption C_{it} in the counterfactuals, for three reasons. First, as described in Supplementary Appendix D, Eturnity only produced a single cross-section of this self-consumption variable based on each household's heating system, hot water system, and consumption decile. Second, unless households have a battery, it

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total revenue under a self-consumption scenario reads as:

$$\mathcal{R}_{it}^{SC}=\sum_{s=t}^{\infty}\rho^{s-t}(1-\zeta)^{s-t}\cdot Y_i\cdot\left[\mathcal{SC}_i\cdot E[P_{ut}]+(1-\mathcal{SC}_i)\cdot E[P_{ut}^{e}]\right], \tag{5}$$

where the self-consumed part of electricity shows up here as a revenue to cancel out part of the consumption costs incurred in equation (3). This function shows how revenue under a self-consumption scenario is increasing in panel production Y_i and in self-consumption share $\mathcal{SC}_i$. As for a given household $\mathcal{SC}_i$ declines with a larger panel size, equation (5) captures the decline in the marginal value of the subsidy for self-consumption, intended as the difference between saving on a higher P_{ut} when consuming the electricity produced by the panel, and earning a lower P_{ut}^{e} when feeding to the grid the electricity produced by the panel. We let households form expectations over future electricity prices P_{ut}, P_{ut}^{e}, but given the trend of relatively constant prices within our data as reported in Section 5.2, these expectations will result in future expected prices remaining almost constant, which allows us to compute the infinite sum in (5) with a geometric series.

3.2. *Dynamic PV adoption*

In the second step, we define the PV adoption decision as a Bellman equation, using as inputs the static consumption decision of household i in each year t:

$$\mathcal{V}_i(\mathcal{S}_{it})=\max_{\mathcal{PV}_{it}}\left\{\theta_v v_{it}(\mathcal{PV}_{it})+\varepsilon_{it}(\mathcal{PV}_{it})+\mathcal{PV}_{it}\left(\theta_v V_{it}+\theta_{\mathcal{F}i}\mathcal{F}_{it}\right)+(1-\mathcal{PV}_{it})\rho E\left[\mathcal{V}_i(\mathcal{S}_{it+1})|\mathcal{S}_{it}\right]\right\}, \tag{6}$$

where $\mathcal{S}_{it}$ are the state variables of the dynamic problem, namely the total expected discounted value of PV revenue $\mathcal{R}_{it}$ and the installation cost $\mathcal{F}_{it}$, and $\varepsilon_{it}(\mathcal{PV}_{it})$ are independently and identically distributed type 1 extreme value shocks to the solar panel adoption choice, a state variable unobserved by the econometrician. We define $V_{it}=E[\sum_{s=t+1}^{\infty}\rho^{s-t}v_{is}(1)]$ as the present discounted indirect utility under PV adoption for all future years. The parameter $\theta_{\mathcal{F}i}$ measures households' sensitivity to solar panel installation costs $\mathcal{F}_{it}$, and similarly to the energy demand model is heterogenous across households' wealth quintiles, while θ_v scales the indirect utility, allowing for flexibility in the variance of $\varepsilon_{it}(\mathcal{PV}_{it})$.[29] In estimating equation (6), we aim to recover $\Theta=\{\theta_v,\theta_{\mathcal{F}i}\}$, since these capture the relative weight of the indirect utility from electricity consumption and of the fixed installation cost in households' adoption decisions.

The disutility of adopting a PV is a linear function of the fixed installation cost $\mathcal{F}_{it}$. Based on data availability, we construct gross fixed installation cost as:

$$\mathcal{F}_{it}=(1-T_i)\cdot \mathrm{kWp}_i\cdot \mathcal{C}_t^{kWp}, \tag{7}$$

where kWp_i is the size of the solar panel in kWt peak, which Eturnity simulated for us as a function of the roof size of the dwelling, $\mathcal{C}_t^{kwp}$ is the installation cost per kilowatt peak, and T_i is

would be hard to calculate how the percentage of production that can be consumed varies as their consumption changes, because of the mismatch between time of production and time of consumption. Due to this mismatch, explicitly modelling $\mathcal{SC}_i$ would require a more complex consumption model that allows not only for consumption choice, but also for timing of consumption, something we do not observe in our data. Third, the calculation provided by Eturnity for this variable already incorporates an estimated adjustment in consumption caused by the PV adoption.

29. We also experimented with adding a constant term to the function $\theta_v V_{it}+\theta_{\mathcal{F}i}\mathcal{F}_{it}$, to capture any non-monetary disutility from adopting, but the effect is not statistically significant.

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the household's marginal income tax. This tax credit further exacerbates the redistributive issues involved in the adoption of solar panels, as richer households have larger income levels, hence higher marginal taxes and possibly larger homes, such that the amount of tax deduction from which they can benefit is larger than for low-income households. In 2014, the Swiss regulator switched from a subsidized feed-in tariff to a lump sum subsidy equivalent to 30% of the installation cost. This further reduced the fixed installation cost to $\mathcal{F}_{it} = (1-S)(1-T_i) \cdot \text{kWp}_i \cdot \mathcal{C}_t^{kWp}$, where S is the subsidy as share of installation costs. In the estimation, we include the subsidy for all observations in 2014.

Under conditional independence, we can write the following alternative specific expected value functions, describing a non-regenerative optimal stopping problem:

$$E\mathcal{V}_i(\mathcal{S}_{it}, \mathcal{PV}_{it}) = \begin{cases} \theta_v v_{it}(1) + \theta_v V_{it} + \theta_{\mathcal{F}i}\mathcal{F}_{it} & \text{if } \mathcal{PV}_{it} = 1 \\ \theta_v v_{it}(0) + \rho \int_{\mathcal{S}_{it+1}} E\mathcal{V}_i(\mathcal{S}_{it+1}) p_1(\mathcal{S}_{it+1}|\mathcal{S}_{it}; \widehat{\delta}) & \text{if } \mathcal{PV}_{it} = 0, \end{cases} \tag{8}$$

where $p_1(\mathcal{S}_{it+1}|\mathcal{S}_{it}; \widehat{\delta})$ summarizes the transition probabilities of the state variables, described in Section 3.3. We normalize both alternative specific value functions by dropping the indirect utility components that are choice independent, that is, $\tilde{I}_{it} - F_{ut} - \frac{1}{\beta_i+1} P_{ut} C_{it}$. This normalization highlights that we are not allowing for a direct link between consumption C_{it} and adoption $\mathcal{PV}_{it}$, but only a connection between adoption and self-consumption $\mathcal{SC}_i$ in equation (5), and a direct effect of adoption on households' revenue and indirect utility. This leads to the following alternative specific value functions:

$$E\mathcal{V}_i(\mathcal{S}_{it}, \mathcal{PV}_{it}) = \begin{cases} \theta_v \mathcal{R}_{it} + \theta_{\mathcal{F}i}\mathcal{F}_{it} & \text{if } \mathcal{PV}_{it} = 1 \\ \rho \int_{\mathcal{S}_{it+1}} E\mathcal{V}_i(\mathcal{S}_{it+1}) p_1(\mathcal{S}_{it+1}|\mathcal{S}_{it}; \widehat{\delta}) & \text{if } \mathcal{PV}_{it} = 0. \end{cases} \tag{9}$$

Given that ε follows a type 1 extreme value distribution, the probability of installing a solar panel reads:

$$\Pr(\mathcal{PV}_{it} = 1|\mathcal{S}_{it}; \Theta) = \frac{\exp\left[\theta_v \mathcal{R}_{it} + \theta_{\mathcal{F}i}\mathcal{F}_{it}\right]}{\exp\left[\theta_v \mathcal{R}_{it} + \theta_{\mathcal{F}i}\mathcal{F}_{it}\right] + \exp[\rho \int_{\mathcal{S}_{it+1}} E\mathcal{V}_i(\mathcal{S}_{it+1}) p_1(\mathcal{S}_{it+1}|\mathcal{S}_{it}; \widehat{\delta})]}. \tag{10}$$

We assume that households form expectations over the two aggregate variables in equation (9), the total PV revenue $\mathcal{R}_{it}$ and the installation cost $\mathcal{F}_{it}$, as opposed to keeping track of all the variables that determine $\mathcal{R}_{it}$. The advantage of this approach is that it greatly reduces the dimensionality of the state space, making the solution of the model more tractable. In the next section we discuss the transition process of both variables.

3.3. *Transition probabilities*

We define the transition probabilities of the state variables $\mathcal{S}_{it} = \{\mathcal{R}_{it}, \mathcal{F}_{it}\}$ with an autoregressive process of order one for each. We further distinguish between two different processes for $\mathcal{R}_{it}$ depending on the institutional setting in year t, that could be feed-in tariff FT or self-consumption SC. While in the FT setting, the evolution of revenue is driven by the decline in feed-in tariffs, whereas in the SC setting, the evolution of revenue is driven by overall electricity prices. The estimated parameters of the processes $\widehat{\delta} = \{\widehat{\delta}_{FT}, \widehat{\delta}_{SC}, \widehat{\delta}_{\mathcal{F}}\}$ act as inputs to construct the transition matrix for the dynamic part of the model. As is standard in the literature, we assume conditional independence between state variables observed by the econometrician $\mathcal{S}_{it}$ and those unobserved by the econometrician ε_{it}. In practice, we specify the following AR(1) processes:

$$\mathcal{R}_{it}^{FT} = \delta_{FT}\mathcal{R}_{it-1}^{FT} + \eta_{it}^{FT}, \ \mathcal{R}_{it}^{SC} = \delta_{SC}\mathcal{R}_{it-1}^{SC} + \eta_{it}^{SC}, \ \mathcal{F}_{it} = \delta_{\mathcal{F}}\mathcal{F}_{it-1} + \eta_{it}^{\mathcal{F}}, \tag{11}$$

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where $\eta_{it}^{FT} \sim N(0,\sigma_{FT})$, $\eta_{it}^{SC} \sim N(0,\sigma_{SC})$, and $\eta_{it}^{\mathcal{F}} \sim N(0,\sigma_{\mathcal{F}})$ are *IID* error terms. We estimate each of the equations using ordinary least squares. Using the estimated coefficients, we also estimate the standard deviation of the error terms $\sigma_{FT},\sigma_{SC},\sigma_{\mathcal{F}}$ which are used to construct the transition matrix.

3.4. *Model discussion*

We build our framework as a discrete-continuous choice model where the current continuous decision, energy consumption, does not impact any of the state variables that determine the discrete choice, PV adoption. This implies that households solve a static optimization problem when deciding on their optimal energy consumption, but their solar panel installation decision is instead dynamic, depending on their expectations over the evolution of revenues and costs of adoption. While there is a growing literature developing computational methods for solving and estimating dynamic programming models with discrete and continuous choice variables (Bajari, Benkard and Levin, 2007; Iskhakov *et al.*, 2017; Gautam, 2018), we believe that the lack of a relevant dynamic component in the energy consumption decision does not make those approaches the best option for our case. Alternatively, we could simplify our framework by allowing households to make static discrete-continuous decisions, which would reduce the computational complexity and allow us to rely on a well-established literature (Dubin and McFadden, 1984; Hanemann, 1984). Despite its advantages, we think that modelling PV technology adoption as a static decision would omit the benefit to households of waiting for a decline in fixed cost over time, which we view as an important determinant in the adoption of a novel technology, thus biasing one of the key parameters of our model and leading to inaccurate counterfactual predictions.[30]

Both consumption and adoption decisions within our model have an important, albeit different, role in the counterfactuals. The dynamic portion captures how marginal prices and installation cost subsidies shape PV revenue and net installation costs, and thus adoption rates. The static electricity consumption portion captures the impact of tariff design on aggregate consumption, which the regulator needs in order to correctly assess solar energy targets, grid financing, and welfare. As discussed in Sections 3.1.1 and 3.2, in our model, adopting a solar panel generates an extra revenue that increases households' indirect utilities, but does not directly impact their consumption decisions, which means that consumption and adoption unobservables are assumed to be independent. This is reasonable, as a solar panel is mostly a production unit that generates income from selling the electricity it produces, rather than an electric appliance that directly affects a household's consumption as in Dubin and McFadden (1984). Nevertheless, we do link consumption and adoption in the self-consumption setting through an exogenously given household's self-consumption level.[31]

With regard to the size of the installed solar panel, we assume that each household only considers the size of a PV simulated by Eturnity, which is approximately the maximum available size given the rooftop area. Three reasons underly this assumption. First, households have the incentive to install the largest possible solar panel to benefit from economies of scale. Second, allowing households to choose between different sizes would mean that we have to arbitrarily

30. We have experimented with estimating a static PV adoption model, finding an installation cost sensitivity around 30% smaller in absolute value relative to the dynamic one.

31. PV adoption could impact households' consumption via another channel. If the extra revenue from solar energy production substantially increases a household's wealth, this can move it to the next wealth quintile, changing its price elasticity β_i. However, this is unlikely to happen in our sample, as the annual PV revenue is relatively small as compared to the difference in wealth between wealth quintiles.

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decide the minimum size of a PV for each household, which can be hard to approximate. Third, to our knowledge, most households rely on their energy provider or on an energy consulting firm to define the details of the PV installation, in which case they are likely to base their decision to adopt on a standard offer similar to the one we are using for our simulation. Even if households were not actually considering the optimal size as suggested by Eturnity, but instead something smaller, this would simply imply that the regulator needs to provide stronger incentives to reach a given target, relative to our suggested ones.

Last, we omit from the model the possibility of savings. While households could be reducing their electricity consumption to save for the future purchase of a solar panel, such savings would be relatively small compared to PV installation costs in our setting. Hence, the role of savings represents at most a second-order effect, not justifying the additional complexity that including it in the model would generate.

4. ESTIMATION

We estimate the parameters of the energy demand function using a geographical boundary regression discontinuity design, the parameters determining the PV adoption decision by maximum likelihood, and the parameters of the state variables' transition processes with a linear autoregressive model.

4.1. *Energy demand*

The energy demand part of the model is estimated to recover the parameters $\Lambda = \{\alpha, \beta_i, \omega\}$ in equation (1). The limited price variation over time and the small number of utilities in our sample represent a challenge for the identification of the price elasticity of demand β_i, a key parameter to capture the reaction of household consumption to changes in tariffs. Specifically, our data consist of three utilities and 6 years, with the utilities adjusting prices only once per year. For this reason, we refrain from estimating a model with household fixed effects, which would absorb most of the identifying variation in prices, and decide to tailor the estimation approach to exploit the rich cross-sectional variation in our data. We estimate the following regression model:

$$\ln(C_{it}) = \alpha + \beta_i \ln(P_{ut}) + X_{it}'\omega + \underbrace{\mu_t + \bar{\nu}_{it}}_{\nu_{it}}, \tag{12}$$

where X_{it}' are various household characteristics, and μ_t are year fixed effects. The year fixed effects address any upwards bias that can be expected from a positive correlation over time between prices and demand shocks. As an example, severe weather conditions could increase households' energy consumption and lead utilities to import more energy, or increase production through their marginal (more expensive) power plants, driving up prices. However, given the limited variation in prices over time documented in Figure 1, this is a minor concern in our setting. Another potential source of bias we face is systematic differences across households served by different providers. In fact, EWB and ET households are all located in cities, whereas BKW households are mostly in rural areas. Providers serving systematically larger households, or areas with systematically colder weather, will experience higher energy demand and therefore set higher prices, causing an upward bias in price elasticities. The limited times series variation prevents us from including utility-year fixed effects to address this. We instead use our rich set of household and building characteristics to control for any differences across households. Moreover, in our preferred specification, we further address this concern implementing a geographical boundary regression discontinuity design (RDD), in the spirit of Black (1999) and Ito (2014). This restricts

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the estimation sample to all households within 1 km of the city borders and adds border point fixed effects to the estimation.[32] This leads to the following regression equation:

$$\ln(C_{it}) = \alpha + \beta_i \ln(P_{ut}) + X'_{it}\omega + \underbrace{\xi_b + \mu_t + \tilde{\nu}_{it}}_{\nu_{it}}, \quad (13)$$

where ξ_b are fixed effects for each border point b. Potential sorting at the border, which may be problematic with a RDD (Lee and Lemieux 2010), is unlikely to affect our design, as households are not allowed to choose their energy provider, and energy prices are a negligible factor in location choice. For robustness, we provide a statistical test of whether households and houses are similar at the boundary discontinuity, in line with Bayer, Ferreira and McMillan (2007). The last column of Table I.4 in Supplementary Appendix I reports the results of a test of differences for several variables across the two sides of the border. The test is conducted for the sample of households within 1 km from each border point. We regress each variable listed in the first column on a dummy equal to one if the provider is BKW, plus border point and year fixed effects. We find no significant differences in household and house characteristics across the two sides of the border.

One additional challenge we face is understanding the price that households actually respond to. Households in the Canton of Bern face simpler tariff schemes as compared to US examples. In fact, two providers, BKW and EWB, offer uniform tariffs with a single price for any level or timing of consumption. However, all providers also offer a dual tariff, with different marginal prices between day and night time. Dual tariff customers face a non-linear pricing scheme, where the non-linearity lies in the timing of consumption. We assume that these customers respond to a weighted marginal price, where the weights are based on day and night time consumption shares. However, since the households' actual consumption shares might be correlated with the level of consumption, we predict the consumption shares for customers under a dual tariff scheme based on household characteristics, as described in detail in Supplementary Appendix F.

An additional bias potentially arises from BKW and EWB assigning their customers to uniform or dual tariffs based on households' energy consumption and appliances. For example, households having an electric heat pump are assigned to a dual tariff due to their high consumption. Consequently, dual tariff households tend to have a higher rate of energy consumption and pay lower marginal prices. Moreover, all ET customers are billed under the dual tariff scheme, implying that ET households have, on average, a lower energy consumption relative to dual tariff customers of one of the other two companies. We address this by including in our model a dummy variable for dual tariff customers of BKW and EWB, and a separate dummy variable for all ET customers. We do not expect selection bias to be an issue in comparing dual and uniform tariff households, as dual tariff households face lower prices so have no incentive to switch to a uniform tariff, and uniform tariff households need to invest in a costly new meter to access the dual tariff. The data contains only a handful of households that change tariff schemes, mostly after relocating, and we drop them from the sample when estimating elasticities.

Lastly, in contrast to US households, Swiss households receive their final energy bill once a year, which includes their total energy consumption and all variable and fixed tariff components

32. We experimented with alternative distances (e.g. 250 m, 500 m, 1.5 km), finding similar results. The maps in Supplementary Appendix B represent respectively the cities of Bern and Thun and their surroundings, and highlight the border areas illustrative for our geographical RDD design. We identify 19 and 6 border points for Bern and Thun, respectively. Only considering households within 1 km from the border reduces observations of BKW to roughly one-sixth of the full sample, EWB to one-third, and ET to one-fifth.

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(e.g. energy, grid, taxes).[33] We focus on the sum of all variable tariff components as the relevant marginal price, and based on billing time and previous literature, we use lagged prices in the estimation.[34]

4.2. *PV adoption and transition probabilities*

In the dynamic PV adoption part of the model, the parameters of interest $\Theta=\{\theta_v,\theta_{\mathcal{F}i}\}$ describe the impact on PV adoption of the indirect utility from PV revenue and of the fixed installation cost. We recover the parameters that maximize the following log-likelihood function:

$$L(\Theta)=\sum_i\sum_t \log\left[\Pr(\mathcal{PV}_{it}|\mathcal{S}_{it};\Theta)\right]. \quad (14)$$

Following Rust (1987), we discretize the state space to obtain the numerical solution to the Bellman equation through value function iteration. We discretize $\mathcal{R}_{it}$ and $\mathcal{F}_{it}$ around [50, 50] length intervals, corresponding respectively to [9,271, 4,902] CHF, and create the state space as all possible combinations.[35] To define the transition matrix of the discretized state space, we follow Tauchen (1986), who provides a procedure to calculate for each state the probability distribution over all possible states in the next period. Finally, the estimation procedure consists of an inner loop and an outer loop. In the inner loop, given a set of parameters Θ, we use a nested fixed-point algorithm to calculate the expected value of each state, using the value of adoption $\theta_v\mathcal{R}_{it}+\theta_{\mathcal{F}i}\mathcal{F}_{it}$ and the transition matrix as inputs. In the outer loop, we search over the parameters Θ, where we assign to each household the probability to adopt based on its position in the state space and equation (9). Supplementary Appendix H provides additional details on the estimation procedure.

The identification of θ_v and $\theta_{\mathcal{F}i}$ relies on both time series and cross-sectional variation. The aggregate trend in PV adoptions is driven by time series variation, and is induced on the cost side by the decline in installation costs over time, and on the production side by the decline in production revenues over time. Both of these trends are depicted in Figure 1. An interpretation of the coefficients in the dynamic model is that they capture the relative weight of those two trends in the household's decision. Cross-sectional variation identifies the distribution of PV adoptions across household types, along three dimensions. First, differences in available roof space lead to varying economies of scale in installation costs. Second, differences in income determine

33. BKW and ET customers all receive their bill at the end of each year. EWB customers receive their bill yearly but at a customer-specific time, based on when their meter is read by EWB.

34. Similarly to Ito (2014), we test whether households respond to current or lagged prices, including both in our regression model, and find that, while the coefficients of lagged prices are highly statistically significant and of large magnitude, those of current prices are very weakly statistically significant with very small economic magnitude, about 5% the size of the elasticities of lagged prices. We infer from this that households mostly respond to lagged prices. This implies a mild time inconsistency with respect to the model described in Section 3, where we assumed that households respond to current prices in their consumption decisions. However, given the limited time series variation in prices in our sample, this inconsistency is rather innocuous for our results. Hence, for consistency with the model in Section 3, we keep P_{ut} and F_{ut} in our notation, despite actually using the lagged values.

35. We considered using an adaptive grid method to improve the numerical solution of our model, which requires narrower intervals between nodes in the discretization where our state variables' distribution has a higher density, as opposed to the current equally spaced nodes. We did not follow this approach for two reasons. First, even increasing the interval space between equally spaced nodes compared to the current intervals did not affect our estimates. Second, most portions of the state variables' distribution, where intervals between nodes could be less narrow, were the parts where the counterfactual solution would end up, so we opted for keeping equally spaced nodes, both in the estimation and in the counterfactuals.

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different marginal tax rates, and thus different net installation costs. Third, different households' locations imply different sun exposure, affecting electricity production per installed production capacity measure.

Besides this variation, two key modelling choices impact identification. First, we only allow home owners to install a solar panel. Since almost all solar panels are integrated into the roof of a particular house, there is little incentive for tenants to invest in one. The evidence from our data is consistent with this, as roughly 90% of PV owners are also home owners. Home owners are associated with different characteristics than tenants (e.g. are typically richer), which helps to better capture the cross-sectional distribution of PV adoptions. Second, between 2013 and 2014, there was a shift in the institutional setting, where the Swiss regulator switched from a feed-in tariff scheme to an installation cost subsidy with self-consumption.[36] We assume this change was unexpected from a household's perspective.

To create the transition matrix of the state space, we estimate AR(1) processes for the revenue side of the indirect utility from installing (δ_{FT}, δ_{SC}) and the cost side of the indirect utility from installing ($\delta_{\mathcal{F}}$). The identification of these parameters relies on time variation in the installation cost per kWp and the revenue per kWh, where both variables are available only on an annual basis. We estimate these parameters using the full sample of households in the PV estimation.[37] The parameters are the basis to estimate the standard deviation of the error terms $\sigma_{FT}, \sigma_{SC}, \sigma_{\mathcal{F}}$, which are needed to generate the transition matrix.

5. RESULTS

5.1. *Energy demand model*

We report in column (1) of Table 6 the regression results for the full sample, corresponding to equation (12), and in column (2), the results when using the sub-sample of households located at the border between energy utilities, corresponding to equation (13). In both specifications, we control for apartment or building characteristics, such as the number of rooms and the apartment's surface, also including fixed effects for the number of apartments in the building and the building's construction date. We further add fixed effects for whether a household's dwelling uses electricity, a heat pump, or other sources (e.g. oil, gas, wood) for its heating system or for hot water heating. Additionally, we control for household size, the age of the household head, and home ownership.

Table 6 shows that the price elasticity of demand is negative and significant, ranging between −0.06 and −0.22 across all wealth quintiles and specifications. We find that wealthier households are less price elastic, as shown by the positive price interactions increasing across quintiles. We also find that larger households, home owners, and households using electricity for heating or hot water consume more energy. More recent buildings consume less, as these are likely to have more efficient insulation.

Our RDD estimates display lower price elasticities in absolute terms compared to other papers in the literature. For example, Reiss and White (2005) estimate the distribution of electricity price elasticities for a sample of households in California, finding it to be centred at −0.39. There are three main differences between our setting and theirs, as well as with other papers in the field. First, Reiss and White (2005) derive this result for a sample of 1,307 households over two years, whereas our dataset covers around 165,000 households over 7 years, a far larger sample than that of most of the papers estimating energy demand elasticities in the literature. Second,

36. Given this change in institutional setting, we estimated the model without 2014 as robustness check and found similar results.

37. We thereby assume that households have perfect foresight across the sample period.

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TABLE 6
Energy price elasticities

Variables	**(1)**	**(2)**
Price	−0.166***	−0.224***
	(0.014)	(0.030)
Price interactions		
2nd wealth quintile	0.063***	0.072***
	(0.003)	(0.005)
3rd wealth quintile	0.092***	0.099***
	(0.003)	(0.005)
4th wealth quintile	0.103***	0.129***
	(0.003)	(0.006)
5th wealth quintile	0.085***	0.115***
	(0.003)	(0.007)
Double tariff BKW/EWB	0.457***	0.433***
	(0.004)	(0.010)
Double tariff ET	0.155***	0.267***
	(0.005)	(0.019)
Household controls	Yes	Yes
Heating system FE	Yes	Yes
Water system FE	Yes	Yes
Construction period FE	Yes	Yes
Year FE	Yes	Yes
Border FE	No	Yes
N Obs	618,226	132,715
R^2	0.547	0.539

Notes: Standard errors in parentheses are clustered at the household level to account for serial correlation. One star denotes significance at the 10% level, two stars denote significance at the 5% level, and three stars denote significance at the 1% level. Log of total yearly energy consumption is used as a dependent variable. Price is in logs. Household controls include number of rooms, apartment's surface, fixed effects for number of apartments in the building, dummies for energy source of heating and hot water system (e.g. electricity, heat pump, oil, gas, wood), household size, age of household head, and home ownership. Column (2) shows the results for the RDD model. The number of observations for columns (1) is lower than reported in the descriptive statistics in Section 2, mostly because we use lagged prices (i.e. we lose 1 out of 7 years of data).

households in Switzerland face a simpler pricing structure, mostly determined by a uniform or dual tariff and a fixed fee, whereas US households are offered a more complicated Increasing Block Pricing schedule, where marginal prices increase with consumption. Third, because of the more complicated non-linear pricing applied in the US, Reiss and White (2005) need to rely on a more complex estimation method, relative to ours, that takes into account households' selection into different levels of marginal prices. The difference in pricing schemes between the US and Switzerland can also provide an economic interpretation for the difference in price elasticities. In the US setting of Reiss and White (2005), prices are adjusted monthly and are non-linear in terms of the quantity consumed, while in Switzerland, they are adjusted yearly and are linear in terms of the quantity consumed. The more frequent price adjustment and the non-linear variation can generate more price salience for US households, which, according to the literature on price salience, is likely to determine a greater response to price changes (Sexton, 2015; Blake *et al.*, 2021).

5.2. *Transition processes*

In Table 7, we present the estimates of the AR(1) processes of the state variables, which are used to construct the transition matrix. We find that both the revenue in the FT setting and the fixed installation cost are declining over time, however at different rates, as is shown by their coefficients δ_{FT} of 0.873 and $\delta_{\mathcal{F}}$ of 0.774. The revenue under a self-consumption setting evolves

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TABLE 7
AR(1) estimates

	(1)	(2)	(3)
δ_{FT}	0.873***		
	(0.000)		
δ_{SC}		1.016***	
		(0.000)	
$\delta_{\mathcal{F}}$			0.774***
			(0.000)
N Obs	204,979	204,979	204,979
R^2	0.965	0.994	0.950
$\hat{\sigma}$	0.390	0.039	0.444

Notes: The estimations of the parameters of the AR(1) processes are based on the counterfactual sample of potential solar panel adopters, with 204,979 observations. However, the feed-in tariffs that drive variation for δ_{FT}, the energy prices that drive variation for δ_{SC}, and the installation costs that drive variation for $\delta_{\mathcal{F}}$, are only available on a yearly basis and for several installation size categories. The resulting standard errors for these two parameters are thus artificially low. Standard errors are clustered at the household level to account for serial correlation. One star denotes significance at the 10% level, two stars denote significance at the 5% level, and three stars denote significance at the 1% level. The magnitude of $\hat{\sigma}$ reflects the rescaling of the three dependent variables, which have been divided by CHF 10,000, as described in Section 5.3.

with a positive trend, as shown by δ_{SC} of 1.016, which is due to electricity prices slightly increasing over time. The last line of Table 7 summarizes the estimate of the standard deviation of the error term of each AR(1) process, which determines the variability of the transition matrix.

5.3. *PV adoption model*

To estimate the PV adoption portion of the model, we restrict the sample to the main energy provider (BKW), which covers 94% of the solar panels installed,[38] and to single family houses or buildings with at most two apartments, for which it is more likely that a single household is making the installation decision. We calibrate the discount factor to $\rho = 0.8788$, the value estimated by De Groote and Verboven (2019) for PV adoption decisions of Belgian households. Unfortunately, we do not have the same rich time series variation in feed-in tariffs that these authors have to identify the discount factor in our setting, hence we assume that time preferences of Swiss households for PV installation are similar to Belgian ones.[39]

Table 8 reports the results of the coefficients of the indirect utilities and installation costs $\theta_v, \theta_{\mathcal{F}i}$. We provide three alternative specifications. In column (1), we only include fixed installation cost (without heterogeneity across wealth quintiles) and indirect utility from electricity consumption, and find that the former has a negative effect on adoption, while the latter has a positive impact. The underlying variables are measured in CHF 10,000, that is, each CHF 10,000 increases the scale utility by the respective coefficient. The estimated coefficients show that CHF 1 reduction in installation costs weights roughly twice as much as CHF 1 increase in PV revenue. Similarly to the results in Table 6, in column (2) we let households' sensitivity to installation costs vary across wealth quintiles. As expected, top wealth quintiles are the least sensitive to installation costs. In column (3), we include three indicator variables to further improve the goodness of fit of the model. First, we add a dummy for the year 2010, during which there was a bureaucratic delay

38. PV systems are more likely to be adopted in non-urban areas, which are those served by BKW.

39. We conducted robustness checks varying the value of the discount factor between 0.85 and 0.9 for a simplified version of our model, and found that our calibrated value delivers the highest goodness of fit based on the likelihood ratio test statistic.

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TABLE 8
PV adoption results

Parameters	(1)	(2)	(3)
θ_v	0.231***	0.213***	0.214***
	(0.020)	(0.019)	(0.019)
$\theta_{\mathcal{F}}$	−0.452***	−0.569***	−0.702***
	(0.020)	(0.040)	(0.058)
Fixed cost interactions			
2nd wealth quintile		0.067	0.148
		(0.094)	(0.108)
3rd Wealth quintile		0.044	0.125
		(0.068)	(0.082)
4th wealth quintile		0.150***	0.251***
		(0.048)	(0.064)
5th wealth quintile		0.239***	0.357***
		(0.049)	(0.066)
Year 2010			−1.096***
			(0.153)
Mid-age household head			0.310***
			(0.050)
Rural area			0.210***
			(0.053)
N Obs	204,979	204,979	204,979
LR test statistic	263.9	351.6	506.0

Notes: Bootstrapped standard errors in parentheses. One star denotes significance at the 10% level, two stars denote significance at the 5% level, and three stars denote significance at the 1% level. The details of the bootstrapping are summarized in Supplementary Appendix H. The variables used in the estimation are expressed in CHF 10,000s. The null hypothesis for the LR test statistic is that all parameters are equal to zero.

in the allocation of feed-in subsidies that negatively affected installations. Second, we include a dummy for a middle-aged household head, that is between 40 and 65 years of age, which has a positive and significant effect on adoption decision. Third, we add an indicator for rural households, defined as those living in areas with 400 or fewer households within a 500-m radius, who are more likely to adopt.

5.4. *PV doption model fit*

We evaluate the model's predictive performance based on two metrics, both highly relevant for the counterfactuals. First, the model should capture the time trend in PV adoptions, as the counterfactual scenarios provide out of sample predictions for five years beyond the end of our sample period. Second, the model should capture the cross-sectional distribution of PV installations across wealth quintiles in order to infer the correct distributional impact of an increase in PV adoptions.

Hence, in Table 9, we compare our model's predictions with the data along the time series and across wealth quintiles. The left-hand section of the table shows the number of predicted and actual installed solar panels each year, whereas the right-hand section shows by wealth quintile the predicted and actual number of households that adopted a solar panel. The model captures relatively well both the trend in the number of adoptions, as well as the increase in installations across the wealth distribution. We perform a χ^2 test of fit for both the yearly adoptions and the installations across wealth quintiles. While for the full sample period (2008–14) we reject the null hypothesis that the distributions of predicted and actual adoptions across the years are the same, we show that instead, the two distributions are the same for 2010–14. We interpret this as evidence that the first 2 years, with their low number of PV installations, are more challenging to

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TABLE 9
Prediction based on PV adoption model

Year	PV predicted (N)	PV actual (N)	Wealth	PV predicted (N)	PV actual (N)
2008	89	48	1st quintile	169	157
2009	156	114	2nd quintile	91	73
2010	73	74	3rd quintile	202	152
2011	224	220	4th quintile	381	344
2012	329	343	5th quintile	608	651
2013	307	322			
2014	276	256			
Total	1,452	1,377	Total	1,451	1,377
2008–14 χ^2_6	52.61		All quintiles χ^2_4	28.62	
2010–14 χ^2_4	2.92		1st and 5th quintiles χ^2_1	3.76	

Notes: PV predicted, predicted number of solar panels adopted based on the estimated coefficients; PV actual, number of solar panels adopted in the data. The 5% and 1% critical values of the χ^2 distribution for six degrees of freedom are 12.59 and 16.81, for four degrees of freedom are 9.49 and 13.28, and for one degree of freedom are 3.84 and 6.63.

accurately predict. Our test of fit also shows that the model best predicts adoptions for the lowest and highest wealth quintiles.

6. COUNTERFACTUALS

By 2014, Switzerland and most EU countries had introduced self-consumption policies and installation cost subsidies for PV adoption (Pablo-Romero, 2013), allowing households to directly consume any electricity that their solar panel produced. While self-consumption policies incentivize the spread of renewable energy technologies, they also pose financing and distributional challenges for grid tariff design. Under the current tariff scheme, where grid financing is mostly based on marginal grid prices, solar panel owners do not fully bear the cost of their grid access.

In our counterfactuals, we study the optimal tariff and subsidy design for residential electricity markets to address those challenges. We take the stand of a regulator who wants to achieve a solar energy target, following the example of many policies around the world that mandate a certain share of renewable energy in a country's production mix. In our setting, we define the solar energy target as a mandated ratio of total solar production over total electricity consumption. In our model, the regulator relies on the combination of two instruments to stimulate PV adoption and achieve the target. The first is installation cost subsidies. The second, marginal grid prices, indirectly incentivizes PV adoption because households can forego these charges by consuming electricity from their own solar panels. The need to generate sufficient revenues to cover grid investment costs also constrain the regulator. To satisfy this network financing constraint, we allow the regulator to rely on a fixed fee as a third instrument, a grid-access yearly lump-sum payment. This fixed fee does not directly impact the probability of installing a solar panel, as its effect on households' indirect utility is the same regardless of whether they adopt or not.

The optimal combination of a two-part tariff and subsidy requires the regulator to consider various effects. Installation cost subsidies are narrowly targeted to PV adopters and require an additional source of financing. In contrast, a higher marginal grid price not only stimulates PV adoption, but can also generate additional grid revenue, depending on households' price elasticities, and so long as the number of PV owners is sufficiently low. A higher marginal price can also curb total electricity consumption, the denominator in the solar energy target. Subsidies and marginal grid prices can also have distributional consequences by shifting grid expenditures from (high income) PV owners to (low income) non-PV owners. However, while a high marginal

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price shifts grid expenditures from low- to high-consumption households, as the latter are less price sensitive, increasing the fixed fee spreads costs more equally among households. Ultimately, the impact of a given instrument mix on equity depends on how income and wealth affect electricity consumption and PV adoption rates. Our detailed data and structural model allow us to precisely measure these effects and to provide optimal tariff designs.[40]

6.1. *Regulator's constraints*

In what follows, we describe the regulator's constraints when choosing the optimal two-part tariff and subsidy design. For all counterfactual scenarios, we divide the marginal price P into its energy component P_E, its tax component P_T, and its grid component P_G, and only allow the last to vary. Moreover, we allow households with a PV to consume a share $\mathcal{SC}_i$ (self-consumption) of the energy they produce $\widetilde{Y}_{it} = Y_i(1-\zeta)^t$ with their solar panel.[41]

6.1.1. Network financing. The first constraint is the requirement for the regulator to generate sufficient revenue to cover grid costs. We define each household's expected contribution to grid costs as the following grid expenditure GE_{it}:[42]

$$GE_{it}(P_{Gt}, F_t) = F_t + P_{Gt} \cdot [P_t^{\widehat{\beta}_i} e^{X_{it}'\widehat{\omega} + \widehat{\nu}_{it}} - \mathcal{SC}_i \cdot \widetilde{Y}_{it} \cdot \Pr(\mathcal{PV}_{it} = 1 | P_{Gt}, F_t, S)], \tag{15}$$

where $P_t^{\widehat{\beta}_i} e^{X_{it}'\widehat{\omega} + \widehat{\nu}_{it}}$ is the electricity demand of household i, $\mathcal{SC}_i \cdot \widetilde{Y}_{it}$ is the household's potential self-consumption, and $\Pr(\mathcal{PV}_{it} = 1 | P_{Gt}, F_t, S)$ is the probability of installing a solar panel as predicted by our model. Energy providers in our setting are cost-plus regulated, and we assume they recover total grid costs without making any additional profits. Total grid costs are the sum of a fixed component GC_0, representing the annual cost of maintaining the grid, of an additional cost to integrate decentralized renewable energy production, and of the revenues needed to finance installation cost subsidies. We recover GC_0 from BKW at the end of our sample period in 2014.[43] For two reasons, we incorporate an additional grid integration cost for decentralized solar productions. First, solar panels produce intermittently at times of high demand, requiring extra investments to increase the flexibility of the grid.[44] Second, the Swiss regulator has budgeted CHF 6 billion of additional grid costs to accommodate the increase in decentralized production of energy from renewables until 2035, expecting the annual production from solar, wind, and geothermal to increase by over 5,500 GWh.[45] Based on these cost estimates of the Swiss regulator,

40. Policymakers and energy utilities worldwide also fear that the increasing adoption of solar panels is eroding grid revenues, because households with a solar panel do not pay marginal prices when consuming their own electricity. Since subsequent increases in marginal grid prices provide even higher incentives to install solar panels, this has also been characterized as a "death spiral" of rising grid prices. We conduct a simpler benchmark counterfactual in Supplementary Appendix G to quantify the distributional effects of this "death spiral," imposing an exogenous solar panel adoption rate and allowing the regulator to increase marginal grid prices based only on the missing grid revenue in the previous year.

41. Simulated data on self-consumption, with an average self-consumption share of 14.8%, are reported in Table 5.

42. As for the PV adoption model, in the counterfactuals we restrict the sample to the main energy provider (BKW), which covers 94% of the solar panels installed. For this reason, we omit the u subscript from the model.

43. Specifically, $GC_0 = \sum_{i=1}^{N} GE_{i0}(P_{G0}, F_0) = NF_0 + \sum_{i=1}^{N} C_{i0} P_{G0}$, where N is the total number of households, C_{i0} is each household's electricity consumption, and F_0 and P_{G0} are fees and prices in the current tariff scheme.

44. As reported by The Economist (2017), in South Australia the large number of solar panel adoptions has required grid upgrades that have doubled network costs since 2008.

45. Swiss Federal Office of Energy (*Bundesamt für Enegie*): 2017 report on 'Development of network costs in Switzerland in the light of current needs, the ES2050 and the electricity grids strategy' (*Entwicklung der Netzkosten in der Schweiz vor dem Hintergrund des derzeitigen Bedarfs, der ES2050 und der Strategie Stromnetze*); 2017 report on 'Energy scenarios for Switzerland until 2050' (*Energieszenarien für die Schweiz bis 2050*).

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the additional total cost per kWh of decentralized production in 2035 implies an additional grid cost of CHF 0.055 per kWh of PV energy production per year.[46] This leads to the following network financing constraint:

$$\underbrace{\sum_{i=1}^{N} GE_{it}(P_{Gt},F_t)}_{\text{Revenue}} = \underbrace{GC_0}_{\text{Fixed grid cost}} + \underbrace{\sum_{i=1}^{N} \Pr(\mathcal{PV}_{it}=1|P_{Gt},F_t,S)\big(0.055(1-\mathcal{SC}_i)\widetilde{Y}_{it}+S\mathcal{F}_{it}\big)}_{\text{Integration cost decentralized production + Subsidy financing}}. \quad (16)$$

We decided to compute this expected increase in fixed costs on the basis of the Swiss regulator's budget estimates, in order to best approximate how the Swiss idiosyncrasies, such as the large share of mountainous terrain, impact grid investment costs. However, it is important to benchmark these expected extra costs with evidence from the literature in other countries. For example, Gowrisankaran, Reynolds and Samano (2016) compute the cost of additional grid investment to integrate solar energy into the US network to be only \$0.00078 per kWh,[47] but also estimate the gross social costs of solar energy with a 10% penetration to be \$0.1267 per kWh. While our cost estimates mostly relate to the former concept, our higher value can be interpreted as also capturing part of the social costs of PV for which the Swiss regulator is budgeting. Nonetheless, we included as a robustness check an alternative version of our counterfactuals where we assume no grid integration costs.

6.1.2. Solar energy target. The second regulator's constraint is a solar energy target (*SET*), capturing policies set by the EU and other countries to reach a target share of renewable energy by 2050 or earlier. Specifically, the regulator chooses a two-part tariff and subsidy to reach a predefined share *SET*:

$$\frac{\sum_i Y_{iT}\Pr(\mathcal{PV}_{iT}=1|P_{GT},F_T,S)}{\sum_i \widehat{c}_{iT}(\mathcal{PV}_{iT},P_{GT},F_T)} \geq SET, \quad (17)$$

where T is the year when the solar energy target is scheduled to be reached, $Y_{iT}\Pr(\mathcal{PV}_{iT}=1|P_{GT},F_T,S)$ is solar energy production of household i, and $\sum_i \widehat{c}_{iT}(\mathcal{PV}_{iT},P_{GT},F_T)$ is total energy consumption net of self-consumption. Figure 2 provides some intuitive graphical evidence to quantify how marginal grid prices and subsidies can contribute to achieving the solar energy target, based on simulations from our model. The black lines in the left-hand panel denote various solar energy targets (SET), while those in the right-hand panel represent the total amount of solar energy produced in GWh. As these figures show, the share and production of solar energy are increasing in both the subsidy and the marginal grid price, and the instruments seem to complement one another. The flatter lines in the left-hand panel reflect the fact that marginal grid prices also decrease overall electricity consumption, the denominator of the solar energy target.

Perhaps surprisingly, the share of residential solar energy only reaches slightly above 11% of total households' consumption, even with subsidies close to 100% of installation costs and marginal grid prices reaching five times the current levels. There are two reasons for this. First, we only allow home owners in one or two apartment buildings to install a solar panel. Since only

46. Dividing expected additional grid costs by the increase in annual renewable productions amounts to CHF 1.09 per kWh of annual production. This cost is spread equally across the 20 years between 2015 and 2035.

47. The decentralized production of energy may also reduce grid costs if it lowers grid energy demand during peak times. Gowrisankaran *et al.* (2016) model the reduction of line losses as a potential benefit of decentralized production.

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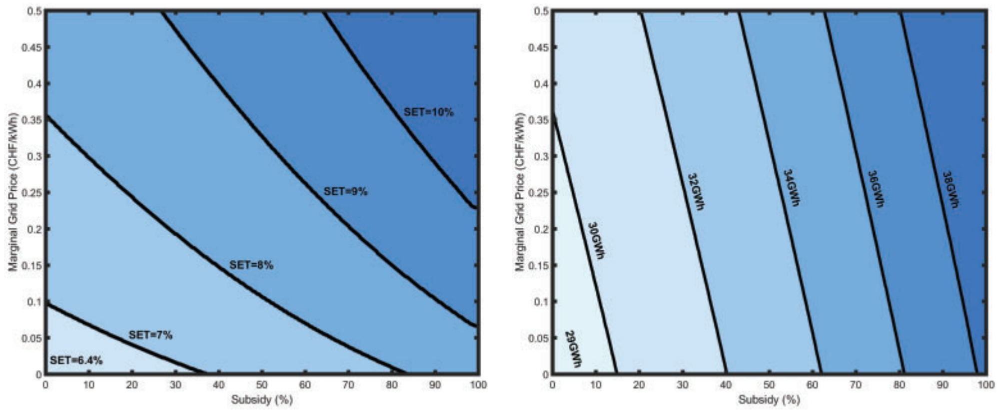

FIGURE 2

Solar energy induced by marginal grid price and subsidy

Notes: The left panel shows how the share of energy consumed from solar panels changes as we vary marginal grid price and subsidy to installation cost. SET, solar energy target in percentages. The right panel shows total solar electricity production in GWh as we vary both instruments.

25% of all households belong to this category of potential adopters, there is a natural limit to the share of households adopting, even if incentives to install are sufficient. If all home owners were to install a solar panel, the upper bound of potential solar energy share would be roughly 70%. Second, even when installation costs net of subsidies are close to zero, a marginal grid price of 0.5 CHF/kWh might still not provide a revenue sufficiently high to compel households to install, as they can benefit from waiting for a larger revenue shock in coming years. This implies that, to stimulate PV adoptions beyond that 11%, increasing prices and subsidies might not be enough, potentially requiring additional policies, such as incentives for solar panels' co-ownership in multi-apartment buildings.

6.2. *Tariff and subsidy designs*

Our counterfactuals quantify the trade-offs that policymakers face when deciding how to achieve a solar energy target. We assume the regulator wants to set a two-part tariff and a subsidy to achieve a solar energy production target, while recovering network costs. We let the regulator solve a constrained optimisation approach, in the spirit of Wolak (2016), to find the corresponding combinations of marginal grid prices P_G, fixed fees F, and subsidies S as a percentage of the installation cost. We use the estimated parameters of the energy demand and PV adoption model, but modify some state variables in the latter component. We assume that the regulator makes a five-year plan and sets the instruments P_G, F, S as constant across these years. This is motivated by our Swiss data evidence on installation cost subsidies being constant at 30% since 2015, and on very limited time series variation in marginal grid prices and fixed fees.

6.2.1. Regulator's problem. We consider four distinct policy goals, varying along two dimensions. First, we let the regulator base its optimisation either on minimizing households' grid *costs* or on maximizing households' *welfare*. Second, we allow the regulator to have a preference for redistribution (*equity*), which implies that it favours reaching the solar energy target by avoiding a regressive effect of the changes in tariffs and subsidies across the income distribution relative to the 2014 tariff level.[48] If instead the regulator has no preference for redistribution, it

48. We define the 2014 level of household grid expenditure as GE_{i0} and of household welfare as v_{i0}.

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assigns an equal welfare weight to all households, optimizing over the aggregate *cost* or *welfare* metric. As common in the policy debate, we let the solar energy target be a medium term goal, allowing the regulator to set tariffs and subsidies to achieve a certain share of solar energy within 5 years.[49]

We define the following regulator's optimization problem, where the regulator sets P_G, F, S subject to the network financing and solar energy target constraints:

Objective functions:

	No equity	Equity
Cost	$\min_{P_G,F,S} \sum_i \sum_{t=1}^5 GE_{it}(P_G,F)$	$\min_{P_G,F,S} \sum_i \frac{\left[\sum_{t=1}^5 (GE_{it}(P_G,F)-GE_{i0})\right]^2}{I_{it}}$
Welfare	$\max_{P_G,F,S} \sum_i \sum_{t=1}^5 v_{it}(P_G,F)$	$\min_{P_G,F,S} \sum_i \frac{\left[\sum_{t=1}^5 (v_{it}(P_G,F)-v_{i0})\right]^2}{I_{it}}$

Constraints:

$$\sum_{t=1}^{5}\sum_{i=1}^{N} GE_{it}(P_G,F)$$

$$= \sum_{t=1}^{5}\left[GC_0 + \sum_{i=1}^{N} \Pr(\mathcal{PV}_{it}^{\text{new}}=1|P_G,F,S)\big(0.055(1-\mathcal{SC}_i)\widetilde{Y}_{it} + S\mathcal{F}_{it}\big)\right] \qquad \text{(network financing)}$$

$$\frac{\sum_i Y_{i5}\Pr(\mathcal{PV}_{i5}=1|P_G,F,S)}{\sum_i \widehat{c}_{i5}(\mathcal{PV}_{i5},P_G,F)} \geq SET \qquad \text{(solar energy target),} \tag{18}$$

where the cells in the top table show the four alternative objective functions that we consider, and $\Pr(\mathcal{PV}_{it}^{\text{new}}=1|P_G,F,S)$ is the adoption probability of a household that has not installed prior to 2014. Note that the *SET* constraint is only focused on the fifth and last year, and requires that the ratio of the total solar energy produced $\sum_i \widetilde{Y}_{i5}\Pr(\mathcal{PV}_{i5}=1|P_G,F,S)$ over the total energy consumed $\sum_i \widehat{c}_{i5}(\mathcal{PV}_{i5},P_G,F)$ must be at or above the target. We only focus on consumers' utility as the relevant welfare metric, because energy providers in our setting are price regulated and supply energy at zero profit. In addition, we only consider households' utility over the regulator's 5-year horizon, and do not include any social benefits of solar energy, assuming that these are already captured by the solar energy target.[50]

When solving for the optimal solutions, the regulator adjusts the three margins of P_G, F, S, balancing its objectives. We let installation costs decline according to the estimated AR(1) process, and keep electricity prices (excluding marginal grid price and fixed fee) and households'

49. This means that we do not allow the policymaker to set the instruments dynamically, trading-off the incentive to have subsidies increase over time to inter-temporally price discriminate, or decrease over time to take advantage of decreasing installation costs. For the analysis of dynamic PV adoption subsidies, we refer to Langer and Lemoine (2018). We differ from their approach, not only because we let the regulator solve a static optimisation problem rather than a dynamic one, but also because we allow marginal prices to incentivize adoptions, we consider potential increases in fixed grid costs with more adoptions, and we focus on the trade-offs between cost, welfare, and equity.

50. This implies an asymmetric treatment of the subsidies, because we fully include the subsidies' cost in the households' energy bill, but only include cost savings from the corresponding increase in adoptions for the first five years. While we do not include social benefits from solar panels, we allow for more solar energy to reduce households' expenditure.

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characteristics fixed at the 2014 level across the 5-year period considered. Note that without any adjustment in tariffs relative to 2014, we predict a share of solar energy of 7.5% in 2019.[51]

6.2.2. Welfare effects. In Table 10, we present the optimal tariff designs for two solar energy targets, where the lower target of 7.5% is the target we predict without any adjustments in tariffs (*Status Quo*), and the higher target of 9% corresponds to the short-term energy target set by the Swiss regulator (*Swiss Regulator*).[52] While we wish we could provide simulations for higher targets, two main constraints prevent us from doing so. First, we are concerned that a prediction that is too much out of sample would not be very reliable. Second, as reported in Figure 2, even for benchmark levels of incentives, our model predicts that, at most, an 11.2% solar energy target can be achieved.

In the top portion of the table, we present the percentage increase in marginal grid price and fixed fee, as well as the share of installation cost that the subsidy should cover in order to achieve each of the targets. We also show the percentage change in marginal price, and the share of households installing a solar panel under each scenario. In the second and third portions of the table, we show by income quintile the average percentage change in households' annual grid expenditures under the new tariff design. The third section of the table depicts expenditure changes by solar panel ownership. The fourth portion calculates the aggregate welfare change under each scenario. Last, the two bottom rows show the grid development costs required to integrate the electricity fed in by solar panels, and the subsidy cost per kWh of solar electricity production.

The results show how tariff designs differ across the four alternative policy goals. We will focus on the *Status Quo* columns, as the results for the *Swiss Regulator* have a similar qualitative interpretation, but requires a larger subsidy to achieve a higher target. If the regulator is mainly concerned with minimizing overall grid expenditures (*Cost* column), the marginal grid price is the most effective instrument to achieve the solar energy target, as it both contributes to grid financing and serves as an incentive to adopt. Moreover, it can be used to finance the subsidy, which is costly and therefore set to the lowest level across the four solutions. In contrast, a regulator with a preference for an equitable grid cost distribution (*Cost/Equity* column) will opt for a small percentage reduction in the marginal grid price, and a slight increase in the fixed fee, accompanied by a higher subsidy compared to the previous case. These small adjustments help to keep grid expenditure close to the status quo for most households, avoiding the large progressive or regressive effects of the other two tariff designs. The welfare maximizing solution (*Welf* column) recommends almost a 70% reduction in the marginal grid price, and therefore more reliance on the subsidy to reach the solar energy target, financing it mainly with an increased fixed fee. This solution relies less on marginal prices because these distort consumption, reducing households' welfare, while the fixed fee financing is welfare-neutral. However, a small marginal price is still desirable, because it lowers aggregate consumption, helping to reach the solar energy target by

51. This prediction matches closely actual data on adoptions up to 2018, following our calculations based on information from the Swiss Federal Office of Energy (*Bundesamt für Enegie*—BFE). The BFE in fact reports a 252% increase between 2013 and 2018 in total PV capacity in Switzerland (both residential and commercial), and if this trend is the same for residential installations in the Canton of Bern, then it would imply a 7.84% share of solar energy for our sample in 2018.

52. According to the most recent Swiss energy law, by 2020 total annual electricity consumption must be reduced by 3% compared to 2000, i.e., to 50,801 GWh compared to 52,373 GWh in 2000 (Swiss Electricity Statistic, 2016). At the same time, the policymaker has set an annual renewable electricity production target of 4,400 GWh to be reached by 2020, excluding hydro energy. Based on these targets, we consider a benchmark scenario of solar panels fully accounting for this increase in renewable production, and households contributing according to their consumption share, which results in a solar energy target of approximately 9%.

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TABLE 10
% change in marginal grid price, fee, subsidy, grid expenditure, welfare

	Solar energy target							
	Status quo (7.5%)				**Swiss regulator (9.0%)**			
	Cost	Cost equity	Welf	Welf equity	Cost	Cost equity	Welf	Welf equity
Instruments								
% Grid price (P_G) change	25.8	−4.4	−69.8	−13.2	34.6	−0.7	−30.8	−10.7
% Fixed fee (f) change	−96.3	10.8	257.3	42.7	−98.5	27.0	138.8	63.9
% subsidy (s) as % F_i	20.8	29.0	50.0	31.5	83.3	91.0	98.3	93.5
% Marginal price change	11.5	−2.0	−31.2	-5.9	15.4	−0.3	−13.8	−4.8
PV adoption (%)	1.8	1.9	2.0	1.9	2.4	2.4	2.5	2.4
Percentage change by income quintile of grid expenditure (GE_i)								
1st quintile	−15.5	4.2	49.6	10.1	−11.0	12.4	33.2	19.3
2nd quintile	−12.0	3.9	40.9	8.7	−7.2	11.7	28.7	17.3
3rd quintile	−7.1	3.5	28.0	6.6	−1.8	10.8	22.1	14.5
4th quintile	−2.9	3.1	17.2	4.9	2.7	10.0	16.6	12.2
5th quintile	1.8	2.6	5.0	2.9	7.8	9.0	10.3	9.4
Percentage change by PV ownership of grid expenditure (GE_i)								
Non-PV HH	2.4	2.9	4.4	3.1	8.5	9.4	10.3	9.7
PV HH	−19.5	−13.7	−0.8	−12.0	−14.9	−7.9	−1.7	−5.8
Agg. welfare change (M CHF)	−12.16	−11.60	−11.02	−11.46	−14.76	−14.21	−13.93	−14.10
Grid integr. cost (M CHF)	2.24	2.34	2.62	2.37	3.29	3.44	3.59	3.49
Subsidy cost (CHF per kWh)	0.09	0.13	0.24	0.15	0.45	0.50	0.55	0.51

Notes: The table illustrates the change in marginal grid price P_G, fixed fee F, subsidy S required to achieve 7.5%, 9% solar energy targets, preserving grid financing and vertical equity. The baseline variable price P_G is CHF 0.089, and the baseline fixed fee F is CHF 128. It also presents the percentage change across scenarios of marginal price, which includes energy price, grid price, and taxes. It then presents the percentage of households adopting a PV across scenarios. It also shows the percentage change in households' annual grid expenditure across income quintiles and across PV owners (PV HH) and non-PV owners (Non-PV HH) for each target. Aggregate welfare changes and grid integration costs are in millions of CHF. The last row shows the average subsidy cost per kWh to stimulate production of renewable energy.

reducing the denominator on the left hand side of the *SET* constraint in equation (18), without requiring the additional grid investment that new solar panels call for. Last, when welfare is the relevant metric and the regulator is also concerned about redistribution (*Welf/Equity* column), we have an intermediate case, where marginal grid prices are lower relative to the cost/equity case, but still higher than in the welfare case without equity concerns. In this situation, the regulator trades off low marginal grid prices to reduce consumption distortion and higher marginal grid prices to reach an equitable distribution of welfare.

As the last two lines of Table 10 show, relying more on the marginal price to reach the solar energy target has two positive effect on total costs. First, since a higher marginal grid price reduces total consumption, less PV energy production is required to reach a given target, and hence grid integration costs are lower. Second, leveraging marginal grid prices to stimulate adoption implies a lower subsidy cost per kWh.

6.2.3. Distributional effects. Our four proposed policy scenarios imply different redistributive and welfare effects. The *Cost* solution benefits low-income quintiles through lower fixed fees, and increases grid expenditure for high-income quintiles due to the rise in marginal prices. Households adopting a PV face the largest reduction in grid expenditure relative to the other solutions. The *Cost/Equity* solution instead uniformly distributes the additional cost across income quintiles and implies a smaller reduction in grid expenditure for PV adopters relative to

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the *Cost* case. The *Welfare* solution generates a regressive effects on grid financing across the income distribution induced by the large increase in fixed fees. However, this reduces the gap between higher grid expenditure across PV adopters and non-adopters. While the *Welfare* solution minimizes households' welfare losses from reaching the target, the *Cost* solution generates the worst welfare effects. Last, the *Welfare/Equity* solution represents an intermediate case in terms of the aforementioned effects.[53]

The impact of these alternative tariff designs on grid expenditure can be quite substantial for some households, especially due to the recurring nature of grid expenditure, and the heterogeneity in electricity consumption within and across income quintiles. This is particularly true for households in the lowest income quintile, for which the welfare solution for the *Status Quo* target implies an additional CHF 755 of grid expenditure over 5 years for the median household, equivalent to 3.3% of their annual income. There is, however, a large degree of variation within that lowest income quintile, as some households face an even larger increase in expenditure of up to CHF 1,278, or 5.5% of annual income, while others face a decrease of a similar amount. On the other hand, for households in the highest income quintile, the welfare solution can lead to up to CHF 2,838 in grid savings over 5 years, which is equivalent to 2.1% of their annual income.[54]

Figure 3 provides graphical evidence of the distributional effects of alternative tariff designs, using as an example all tariff combinations that achieve a 7.5% solar energy target. The left panel quantifies the benefits of PV adoption, measured as the sum of installation cost subsidies and grid expenditure savings for PV owners, across income quintiles. The figure shows that higher income quintiles benefit the most from solar panel incentives, because they can install larger solar systems, on average. The figure also shows that high-income households' benefits increase with higher marginal prices and decrease with higher subsidies, because richer adopters have, on average, higher energy consumption and therefore can save more from self-consumption. The right-hand panel presents instead the share of grid expenditure across income quintiles for all households, showing that the distribution of grid expenditure becomes more progressive when PV adoptions are mostly incentivized via higher marginal grid prices rather than subsidies. This is the result of two competing effects. On the one hand, high-income quintiles consume more electricity and are less price-sensitive, so they will bear a larger share of total grid costs as marginal prices increase. On the other hand, these households are also more likely to install a solar panel and thus forego part of the grid charges through self-consumption. As the right-hand graph shows, the first effect clearly dominates.

53. Note that the effects reported in the second and third panel of Table 10 are in terms of changes in grid expenditure only, which could be caused both by changes in tariffs and changes in consumption. In order to take these two effects into account, Table I.5 in Supplementary Appendix I reports the outcomes of the second and third panel of Table 10 in terms of welfare. In particular, it shows the percentage change by income quintile and PV ownership of household welfare, measured as of equations (2) and (3), net of income. Despite a relatively inelastic electricity demand, we find large differences in the welfare effects both across income quintiles and alternative tariff designs. In particular, we believe that comparing the cost-equity solution (second column of Table Table I.5 in Supplementary Appendix I) to the welfare solution (third column of Table I.5 in Supplementary Appendix I) is the closest comparison to a two-part tariff vs. a lump-sum tariff. The first is in fact very close to the actual two-part tariff we observe in the data, while the second has the largest reduction in the marginal price component and the largest increase in the fixed fee component, making it the closest tariff to a lump-sum among the four we simulate. Our results show that, for all income quintiles other than the top one, the welfare drop in the cost-equity solution is more or less around half that of the welfare solution. This suggests that a lump-sum tariff, relative to a two-part tariff, would imply that policymakers reach the solar energy target with larger reductions in welfare for most income groups and a more regressive effect.

54. These increases and decreases correspond to the 5th percentile and the 95th percentile, respectively, of the distribution expenditure change of households in the lowest income quintile. Annual income corresponds to the median annual income of the quintile, which is CHF 23,063 for the first quintile and CHF 132,893 for the fifth quintile.

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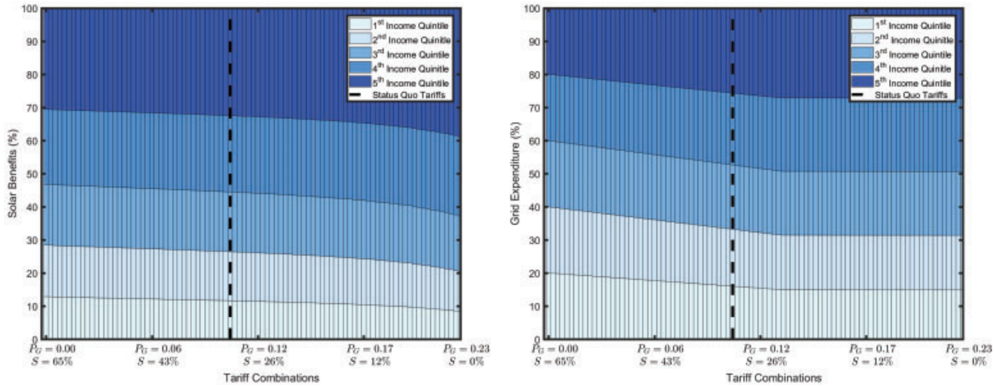

FIGURE 3

Distributional impacts of different tariff designs (7.5% solar energy target)

Notes: The left-hand panel shows the distribution of solar benefits for PV adopters across income quintiles and alternative tariff combinations. Solar benefits are the sum of installation cost subsidies and grid expenditure savings for PV owners. The right-hand panel shows the distribution of grid expenditure for all households across income quintiles for the same tariff combinations.

To summarize, achieving the solar energy target by increasing marginal prices, as in the *Cost* case, represents the most cost-effective and progressive solution, but with a high aggregate welfare loss. On the other hand, reaching the target with a higher installation cost subsidy and fee, as in the *Welfare* case, leads to a more costly and regressive strategy, but with lower aggregate welfare loss. The *Equity* solutions instead mostly recommend small deviations from the baseline tariffs and subsidy, to minimize the distributional effects of the costly transition to the target.

6.2.4. Robustness checks. We perform three robustness checks for these counterfactuals. First, we analyse the impact of lower grid integration cost, assuming that these costs are negligible as in Gowrisankaran *et al.* (2016). We find that this does not change our results much, simply lowering overall grid expenditure, but with no substantial impact on the distributional effects of alternative tariffs. Second, we investigate the importance of the income tax deduction of PV installation costs by eliminating this tax benefit. As expected, we find that in this case, the regulator needs to employ a higher installation cost subsidy to achieve the same energy target. As income-tax deductions increase with the marginal tax rate, which is higher for high income households, we find that the installation cost subsidy tends to be less regressive than an income tax deduction, reducing differences in adoption rates across income groups. Third, we study the potential impact of installing batteries for solar panels, which can allow households to overcome the timing mismatch between PV electricity production and electricity consumption, increasing the self-consumption share, and thus their grid cost savings. We find that with batteries that allow for 100% self-consumption, the regulator should rely more on marginal grid prices to stimulate PV adoptions.

7. CONCLUSION

In this article, we quantify the distributional challenges of environmental policies for residential electricity markets, focusing on the effect of an increasing penetration of PV installations and mostly fixed or increasing network costs. Our analysis is based on a self-consumption setting, where grid tariffs provide incentives for households to invest in solar panels, but the widespread adoption of solar panels erodes the energy providers' revenue to finance the grid. We address this

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challenge by proposing alternative tariff designs, in terms of variable and fixed charges together with PV installation cost subsidies, that a regulator can implement to achieve a minimum solar energy target while guaranteeing network financing. We also consider the option of a regulator being concerned about the regressive effects of these tariff designs. We find the optimal tariff mix and calculate the corresponding distributional impact on grid expenditures across households, as well as the cost per kWh of solar energy for different scenarios.

We base our analysis on a structural model of households' energy demand and PV installation, using a detailed dataset with 165,000 households in the Swiss Canton of Bern for the years 2008–14. We adopt a regression discontinuity design to identify price elasticities, and estimate a structural dynamic model of PV adoption. Our estimates show that the price elasticity of energy demand is low and decreases with wealth. Furthermore, households' PV adoption rate reacts only weakly to changes in subsidies and marginal grid prices. Consequently, even generous subsidies and high marginal prices only induce a share of residential solar energy slightly over 11% of total households' electricity consumption. An important factor that limits the potential of PV adoption policies is that only 25% of all households in our sample are homeowners.

We use the estimates of our model for counterfactual simulations to find the optimal combination of marginal prices, fixed fees, and subsidies to installation costs to achieve a 7.5% or 9% solar energy target within 5 years, while guaranteeing network financing. We show that the cheapest way to achieve the target is to rely on higher marginal grid prices, which simultaneously incentivize PV adoptions and generate extra revenue to finance the grid. In contrast, to achieve the target maximizing households' welfare requires a drastic reduction in marginal prices to reduce consumption distortions, relying on high subsidies to stimulate PV adoptions, and high fixed fees to finance the grid. If the regulator has a preference for redistribution, we show that it should favour marginal grid prices to stimulate PV adoptions. While both marginal prices and installation cost subsidies imply that high-income households enjoy the largest share of solar panel benefits, marginal grid prices help to make the financing of these benefits more progressive. Last, we show that stimulating PV adoptions is costly, ranging from 0.1 to 0.55 CHF per kWh of solar energy, that is up to 2.5 times the marginal price of electricity. However, with declining solar panel installation costs, subsidies to PV installations are bound to decrease.

Our analysis provides important insights for tariff design in high fixed-network-cost markets that are experiencing the introduction of a new technology. While shifting revenue recovery from marginal prices to fixed access fees would guarantee that the adopters of the new technology fully contribute to recovering network costs, we show that relying mostly on marginal prices is a cost-effective way to stimulate the adoption of the new technology, and is more progressive across the income distribution.

Despite our results being constrained by the extent of our institutional setting and available data, they open the door for various other relevant questions that we hope will be addressed in the near future. First, to better characterize the direction towards which various residential electricity markets worldwide are evolving, our model could be adapted to the case of a competitive market for retail and distribution of electricity. Second, through the lens of our model, a regulator interested in maximizing production of solar energy could consider heterogeneous subsidies for PV installation depending on buildings' sun exposure, favouring installations by households with the highest potential "solar power productivity." Last, another potentially useful application of our rich dataset could be to understand how well the regulator can achieve redistribution by observing only households' grid expenditure or both grid expenditure and income, where in the first case grid expenditure can be thought as an imprecise proxy for income. We regard each of these topics as worthy of future research.

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Supplementary Data

Supplementary data are available at *Review of Economic Studies* online. And the replication packages are available at https://dx.doi.org/10.5281/zenodo.5930274.

Data Availability Statement

The code and test data underlying this research are available on Zenodo at https://dx.doi.org/10.5281/zenodo.5930274. The data used in this analysis are confidential. These data offer information on household electricity consumption, ownership of a photovoltaic solar panel, numerous household socio-demographic attributes as well as building and apartment characteristics for 165,000 Households in the Canton of Bern, Switzerland for the years 2008–14. Authors gained access to these data under a number of confidentiality agreements that restrict access. The authors entered into these confidentiality agreements with BKW Energie AG, Energie Thun, Energie Wasser Bern, the Tax Office of the Canton of Bern and the Swiss Federal Statistical Office as part of a larger project funded by the Swiss National Science Foundation (SNF) project number 100018_166386/1. These agreements established the terms under which the authors could access the data, prohibiting them from sharing the data with third parties or publishing the data. These restricted-use data cannot be shared under the terms of the confidentiality agreement contracts. Researchers interested in accessing the different datasets would need to first contact each of the six data providers, write an application describing their research project, ask for the necessary variables and then merge the six datasets.

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