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DISCUSSION PAPER

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How Cost-Effective Were Subsidies for Solar Energy in Germany?

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How Cost-Effective Were Subsidies for Solar Energy in Germany?

By Jakob von Ditfurth and Sebastian Rausch*

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We study Germany's photovoltaic (PV) subsidy program, estimating a dynamic model of new technology adoption which accounts for heterogeneity in residential ownership structures. We find that homeowner and landlord investors heavily discount future benefits, highlighting the suboptimality of the feed-in tariff structure and the inefficient use of government funds. The high administrative costs associated with tenant electricity contracts strongly discourage landlords from investing in new energy technologies. Our analysis suggests that policy design should prioritize upfront investment subsidies over feed-in tariffs to promote renewable energy adoption. Reducing administrative costs associated with tenant electricity programs is key to unlock investments by landlords and expand tenants' access to solar energy, thereby enhancing cost-effectiveness.

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JEL Classification: *C51, D15, Q48, Q58*

Subsidies for new, low-carbon energy technologies are a widely used policy approach to bolster decarbonization—motivated by incomplete carbon pricing and positive externalities in knowledge creation and diffusion (Popp, 2002; Acemoglu et al., 2012; van Benthem, Gillingham and Sweeney, 2008; Bollinger and Gillingham, 2014). The German subsidy program is one of the largest renewable energy policies globally and is widely regarded as a forerunner in establishing and popularizing subsidies to promote the uptake of solar energy.[1] The subsidy is structured as a fixed production subsidy—the feed-in tariff—that guarantees the owner of the PV system a price for 20 years at which they can sell the produced electricity. Em-

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[1] Introduced in 2002, the German model inspired more than 50 countries worldwide to implement similar policy support schemes. Notably, countries such as Japan, China, and Ontario, Canada, have adopted especially large-scale versions. The program's design and outcomes have significantly shaped international renewable energy policy frameworks, demonstrating the potential of feed-in tariffs to drive widespread adoption of wind and solar energy technologies. Appendix B provides a breakdown of key countries that adopted subsidy programs influenced by the German policy.

pirical and theoretical studies (Allcott and Greenstone, 2012; Busse, Knittel and Zettelmeyer, 2013; De Groote and Verboven, 2019; Langer and Lemoine, 2022) have documented that the undervaluation of future benefits from investments in new energy technologies can significantly hinder adoption and undermine the effectiveness of policies, particularly when subsidies target future consumption or output rather than upfront investment costs—as is the case with the German subsidy scheme.

This paper provides novel empirical estimates of the extent to which households discount future benefits from PV investments and employs counterfactual experiments to assess the cost-effectiveness of the German subsidy program, one of the world's largest renewable energy support policies. In doing so, we specifically consider the ownership structures of residential buildings in Germany from 2012 to 2021. The ownership structure is important because the self-consumption of the generated electricity is responsible for about half of the revenues earned from a PV system. Self-consumption is more profitable than feeding electricity into the grid since the feed-in tariff has consistently been several orders of magnitude lower than the retail electricity price for consumers.[2] Consequently, investment incentives differ significantly between homeowners and landlords.

To address this disparity, the German government introduced the tenant electricity model, which allows landlords to sell PV-generated electricity directly to their tenants, thereby capturing the financial benefits of self-consumption. The German government subsidizes such contracts in addition to the regular feed-in tariff, but the high administrative burden associated with these contracts has impeded widespread adoption. Understanding landlords' investment incentives and evaluating the effectiveness of tenant electricity regulations are therefore essential for gaining a comprehensive perspective on PV adoption in Germany.[3]

We estimate a dynamic model of new technology adoption based on De Groote and Verboven (2019). To identify discount factors, we use the feed-in tariff and the tenant contract subsidy as an exogenous shifter that affects the future but not the present utility. In each period, households or landlords can choose to invest or postpone their investment. We estimate the model at both aggregate and state level, using comprehensive administrative data capturing all PV installations that received subsidies from the federal government between 2012 and 2021 and including information on whether the electricity generated is sold to tenants.

Our results suggest that the current feed-in tariff structure is suboptimal. Homeowner investors, or households, assign a value of only 67 cents to each euro of the total discounted future benefits from PV electricity production. Put differently, they apply an implicit real interest rate of 8.6% when assessing these future

[2]The feed-in tariff varies based on the year of construction and system size, declining from 20 cents per kWh in 2012 to approximately 7 cents in 2021. The retail electricity price for consumers during this period was around 30 ct/kWh.

[3]The landlord-tenant problem is a classic principal-agent dilemma, where the agent (tenant) enjoys the benefits (here, the reduced future cost of electricity), while the principal (landlord) bears the initial investment costs. This has been shown to impede the adoption of new energy technologies (Gillingham, Newell and Palmer, 2009; Borenstein, 2015). Recognizing this issue, several countries have adopted programs similar to Germany's tenant electricity model, aiming to enable landlords or housing associations to provide renewable energy directly to tenants or facilitate energy sharing through renewable energy communities. Some recent examples are listed in Appendix C.

benefits—a rate significantly higher than the real market interest rate of 2–3% during the same period.[4] This undervaluation of future benefits is problematic from a public policy perspective: one-time upfront subsidies on the investment costs of a PV installation could have achieved the same level of adoption as continued production subsidies at 36% lower cost, translating to potential government savings of approximately 2.7 billion euros. In addition, as the German feed-in tariff was financed through a levy paid by all electricity consumers[5], the production subsidies not only resulted in unnecessarily high public costs but also shifted the subsidy burden onto consumers who did not directly benefit from the subsidy, as well as onto future households. Such distributional concerns could have been circumvented if upfront investment subsidies had been used instead of production subsidies.

Moreover, landlords are strongly discouraged from investing in PV systems in combination with tenant electricity contracts. We estimate that administrative costs associated with the tenant electricity program account for approximately 22.5% of the total revenue stream, significantly discouraging adoption. In an optimal scenario where landlords face the same incentives as homeowners, the number of potential PV adopters in Germany could more than double, given that 52% of households live in rental properties (Statista, 2025). In turn, this could decrease the necessary subsidies even further while keeping adoption constant, increasing cost-effectiveness.

This paper makes four contributions. First, we add to the empirical intertemporal choice literature, which examines how consumers value future payoffs. A significant portion of this research focuses on the adoption of new technologies that require upfront investment but generate long-term savings. One strand of this literature studies the energy efficiency gap which is the apparent under-adoption of energy-saving technologies despite financial benefits (Jaffe and Stavins, 1994; Allcott and Greenstone, 2012; Hausman and Greenstone, 2015; Gerarden, Newell and Stavins, 2017). We provide novel empirical estimates from one of the world's largest subsidy program to promote investment in new energy technologies. Moreover, much of the literature does not account for rapidly evolving technologies, such as PV systems, which have become significantly cheaper over time. We follow De Groote and Verboven (2019) by incorporating the timing of adoption as a key decision variable, rather than focusing solely on the investment decision. Given the government-set feed-in tariff schedule and the declining cost of PV panels over time, it would be too narrow to attribute every non-purchase decision to a dislike of future payoffs. Instead, some households may delay adoption in anticipation of better purchase conditions. By allowing consumers to postpone their purchase in our model, we can better capture these forward-looking decisions and assess the role of policy incentives more accurately.

[4] While we provide the first estimate for case of Germany, these results are in line with previous literature. De Groote and Verboven (2019) find for the Belgium program subsidizing PV installations between 2006-2012 that consumers are willing to pay only approximately 0.5 euro upfront for 1 euro of discounted benefits from future electricity production.

[5] The *Renewable Energy Surcharge* (*EEG-Umlage*) covered essentially the difference between the market price of electricity and the higher feed-in tariffs. It was paid by electricity consumers until 2022, when it was abolished and replaced with direct government funding from the federal budget.

Second, we contribute to the literature on PV system subsidies and adoption. Several studies, including Burr (2016), Feger, Pavanini and Radulescu (2022), and De Groote and Verboven (2019), demonstrate the effectiveness of upfront subsidies in promoting PV system adoption. Although Burr (2016) and Feger, Pavanini and Radulescu (2022) rely on specific assumptions about time discounting, we adopt the more flexible approach proposed by De Groote and Verboven (2019), in which the discount factor is identified through variation in initial investment costs and future payoffs. In addition, this approach requires minimal assumptions about the future investment opportunities of households. Our findings build on this body of work by estimating how discounting behavior influences adoption and how alternative subsidy structures could improve policy efficiency.

Third, we contribute to the extremely sparse literature on tenant electricity. Kühn et al. (2024) describe the landlord-tenant dilemma, where landlords have little incentive to invest in new technologies, and even when they do, the cost-benefit ratio for tenants is often unfavorable. To address this misalignment of incentives, the German government introduced the tenant electricity framework, which includes subsidies to encourage adoption. However, Moser et al. (2021) document limited tenant electricity uptake after the reform, with only 1% of available subsidies utilized. Their survey-based analysis identifies the restrictive legal framework as the primary barrier to adoption. To our knowledge, we provide the first empirical estimate of the implicit costs of administrative burdens in a tenant electricity framework, quantifying how regulatory complexity affects landlord participation. Our approach assumes that landlords' true discount factor is similar to that of homeowners.[6] By comparing estimated discount factors for homeowners and landlords, we infer the implicit costs of administrative barriers and evaluate how policy reforms could improve adoption rates.

Finally, we contribute by providing the first ex-post assessment of the cost-effectiveness of the German renewable energy subsidy program. Existing studies analyze effectiveness of the German feed-in tariffs in terms of their impacts on the adoption and deployment of renewable energy technologies (Hitaj and Löschel, 2019), reductions in CO_2 emissions (Frondel et al., 2010; Hitaj and Löschel, 2019), electricity price and employments effects Frondel et al. (2010), as well as the innovation effects related to new energy technologies Frondel et al. (2010); Böhringer et al. (2020). Winter and Schlesewsky (2019) conduct an empirical analysis of the distributional effects of the German feed-in tariff across different income groups and regions. Abrell, Streitberger and Rausch (2019) examine the optimal and second-best designs of renewable energy support policies in the presence of a carbon externality using ex-ante analysis and a structural model of the German electricity market. In contrast, we quantify the cost-effectiveness of the German subsidy program ex-post by conducting an econometrically-based counterfactual analysis.

This paper proceeds as follows. Section I provides industry background and describes the data used in our analysis. Section II outlines our dynamic adoption

[6]If landlords discount the future less than homeowners—given their generally higher wealth—our approach would underestimate the negative impact of the restrictive legal framework on landlords' investment behavior.

model, and Section III presents our empirical results and counterfactual simulations and discusses policy implications. Section IV concludes. Appendixes contain additional results from sensitivity analysis and further detail on the policy context.

I. Industry and Policy Background

A. Data

CORE ENERGY MARKET DATA REGISTER.—Our primary dataset, the Core Energy Market Data Register (*Marktstammdatenregister*), provides comprehensive information on all registered PV systems in Germany. Since July 2017, registration has been legally mandated to maintain grid access and eligibility for subsidies.[7] For each installed system, we observe adoption date, location, capacity, ownership type, efficiency, feed-in type, and whether electricity is sold to tenants. We focus on PV systems owned by private households, with system sizes below 15 kW and without battery storage.[8] Systems exceeding 15 kW are typically larger than a standard residential rooftop and fall outside our analysis scope. Similar to De Groote and Verboven (2019), we analyze the data using seven capacity size categories (0-2 kW, 2-4 kW, ..., 12-15 kW) at a monthly frequency.

PV SYSTEM PRICE DATA.—We supplement this dataset with PV system price data from EUPD Research (2024). These prices include not only panel costs but also inverters, mounting structures, electrical equipment, and labor. We have system price data spanning 2012 to 2023 for systems under 100 kW. Additionally, we collect data on solar panel prices from PhotovoltaicXchange (2024), a retailer of solar modules. Their publicly available price index tracks panel prices from 2010 onwards and is published on a monthly basis.

ENERGY PRICES.—We also obtain consumer retail electricity prices from the German Federal Statistical Office (Statistisches Bundesamt, 2024) and crude oil prices from the Federal Reserve Economic Data (2024).We also collect basic electricity supply tariffs from the German Federal Statistical Office (Statistisches Bundesamt, 2024). These tariffs, set by municipal utilities (*Stadtwerke*), serve as a reference for pricing tenant electricity contracts.

SUBSIDIES (FEED-IN TARIFFS).—The primary form of subsidy for PV systems under 100 kW in Germany is provided through feed-in tariffs, as established by the German *Renewable Energy Sources Act* (EEG - *Gesetz für den Ausbau erneuerbarer Energien*) (Federal Ministry of Justice, 2023). These tariffs guarantee a fixed payment to the owners of the PV system for the electricity generated and fed into the grid. The German government sets the feed-in tariff to achieve its renewable energy adoption targets. By adjusting the tariff rate, the government influences the profitability of PV investments, ensuring that adoption aligns with policy goals. From the perspective of the investor, the feed-in tariff is determined on the date of commissioning of each PV system and is guaranteed for 20 years. Generally, the

[7]Owners of PV installations installed before this date were legally required to register retroactively to remain eligible for the subsidy. Consequently, our data captures all PV installations in Germany that received government subsidies during the sample period.

[8]Battery installation and purchase costs are not included in the dataset.

feed-in tariff is lower for larger systems, reflecting the higher installation cost per kW of smaller systems. In addition, the feed-in tariff for new systems decreases over time as installation costs, primarily due to cheaper panels, have also decreased. For our sample period 2012 to 2021, we use the archived remuneration rates for PV installations, including for full and partial feed-in as well as for tenant electricity, published by the Federal Network Agency (2024).[9]

B. *Tenant Electricity*

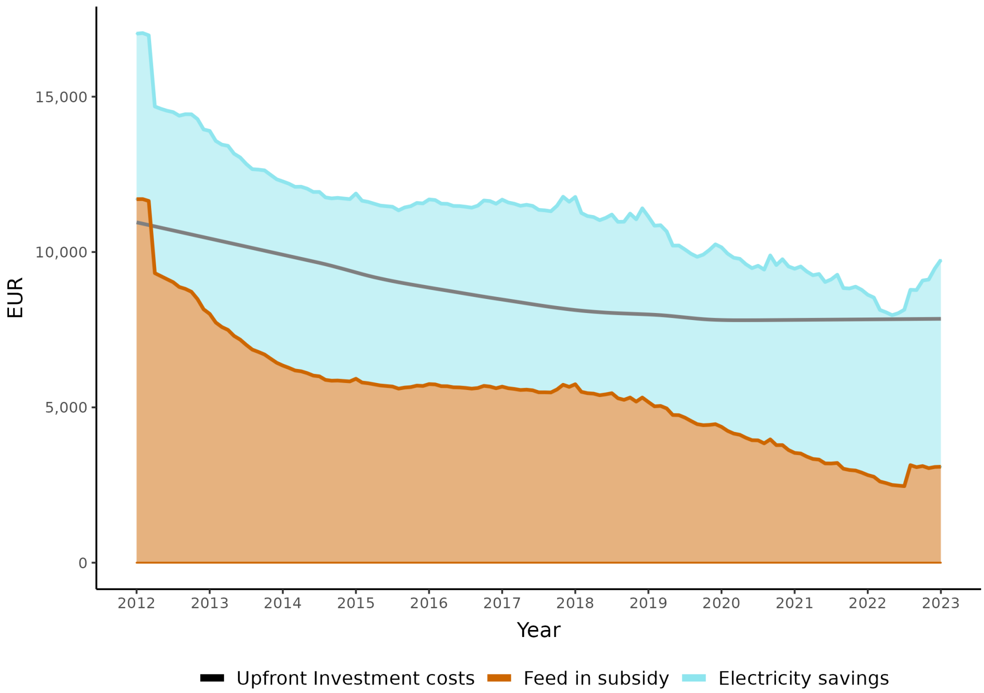
As PV investments gained momentum in 2012, discussions emerged in Germany about the challenges that prevent tenants from accessing solar-generated electricity. After years of debate, the government enacted the *Tenant Electricity Law* in 2017, creating a framework that allowed landlords or energy companies to sell self-generated solar electricity directly to tenants without using the public grid (Federal Government of Germany, 2017). To encourage adoption, the government provided subsidies ranging from 0 to 3 cents per kilowatt hour for electricity sold directly to tenants. However, the system involved significant bureaucratic hurdles for setup and proper integration with the grid. In addition, landlords were required to supply the entire electricity demand of their tenants, further complicating the implementation. Since it was impossible to cover the entire electricity demand of tenants with self-generated solar power, landlords were required to sign contracts with electricity providers to supply the remaining energy needed.

The law mandated that landlords charge the same price for both self-generated and grid-sourced electricity, leading to two key challenges. First, tenants had no incentive to shift their electricity usage to periods of peak solar production. Second, landlords faced increased uncertainty regarding electricity supply costs and the share of PV energy consumed on-site. While the law aimed to address a significant gap in Germany's renewable energy landscape, its impact was hindered by complex regulations and bureaucratic barriers. Some of these restrictions were lifted in 2024, but they remained in effect during our sample period from 2017 to 2021 for tenant electricity.

Tenant electricity contracts are not directly observable, which requires us to make assumptions about typical electricity prices. A survey conducted by the Center for Solar Energy and Hydrogen Research Baden-Württemberg as part of the government's evaluation found that, on average, tenant electricity prices amounted to 85% of the basic supply tariff (German Bundestag, 2019).

[9] We lack comprehensive data on subsidy programs at the communal and state level. Overall, this limitation is not problematic. Failing to account for these programs likely leads to an underestimation of households' reluctance to invest in PV systems, suggesting that households may discount the future more than our estimates indicate. Therefore, our estimated cost savings from an upfront investment subsidy should be interpreted as a lower bound, indicating that the potential savings could be even greater. Subnational programs, which show relatively little variation over time, are controlled by our model with fixed effects at the state level.

Figure 1. **Present value of benefits and costs of a 6kW PV system in EUR 2012**



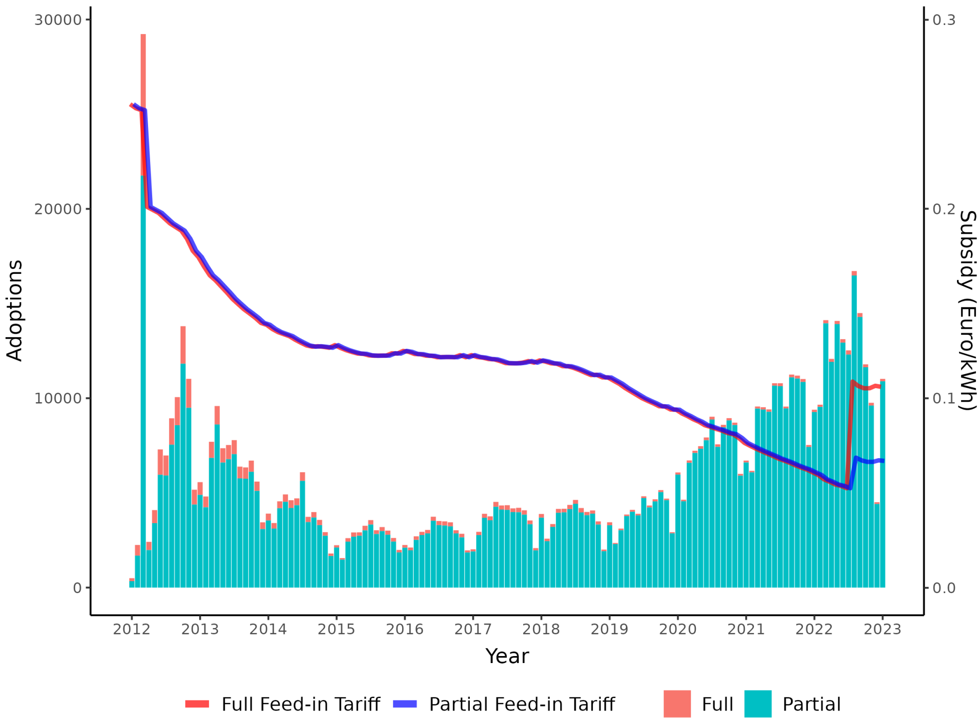
Notes: Areas shown refer to stacked values. Real interest rate used to calculate discounted benefits and costs = 3 percent. Upfront investment costs based on (approximation of) price index from EUPD Research (2024).

C. Evolution of Costs, Benefits and Adoption

To illustrate the financial assessment of a PV system purchase decision, we compare costs and benefits for 6kW partial feed-in systems across time. While the investment cost is incurred at the time of purchase, the benefits of a PV system are realized through its electricity production over its lifetime. The lifetime of PV systems is expected to be 20 years. To convert future benefits in present value terms, we use a real interest rate of 3 percent and convert all prices to 2012 prices.

One difficult question related to partial feed-in PV systems concerns the percentage of electricity that households consume at home. Weniger and Quaschning (2013) derive the own consumption as a function of the capacity of the PV system. They suggest in another paper that this model could be extended to include annual household electricity consumption for greater accuracy. However, since we do not have data on household size or electricity consumption, we will model the percentage of the own consumption solely as a function of the size of the PV system capacity. Based on their calculations, our model assumes own consumption rates of 50% for a 2 kW system, 25% for a 5 kW system and 17% for a 10 kW system. The benefits of own consumption depend on the consumer price of electricity, as PV electricity replaces purchased grid electricity. Using historical consumer electricity

Figure 2. **PV adoption numbers and feed-in rates over time**



Notes: The bars for "Full" and "Partial", referring to the left vertical axis, show the number of monthly adoptions under the full and partial feed-in model, respectively. The two solid lines, referring to the right vertical axis, show the average feed-in tariff (across different capacity sizes) for the two categories.

prices, we estimate a simple trend to account for the changes in electricity prices during the lifetime of the PV system.

Figure 1 summarizes the benefits and costs of a 6kW PV system with partial feed-in. We can see that the benefits outweigh the cost throughout the sample. In 2012, most of the benefits came through feed-in subsidies. This changed during the following decade despite own consumption using only 22% of the electricity produced for 6kW PV systems. Profitability was almost at 0% before the new governments took the higher priority on installations. Finally, the higher electricity prices induced by the war in Ukraine increase the net present value of its electricity savings.

Given the importance of benefits derived from electricity savings, it is not suprising that private households mostly build partial feed-in systems. Figure 2 provides compelling empirical evidence of a strong preference for partial feed-in systems. We can also see that there was a huge spike in adoptions in July 2012. Given the large drop in feed-in subsidies, it hints to the dynamic nature of the household adoption problem. Households decided to invest before the drop rather than after, thus shifting a lot of adoption just before the drop.

Figure 2 thus also makes the point that full feed-in PV systems are extremely unpopular among households. Although some systems were still installed toward the beginning of the sample period, the number of installed full feed-in systems had virtually dropped to zero by the end of the 2010s. Figure A1 in an appendix shows that full feed-in systems are largely unprofitable, even when discounted at the market interest rate. Considering that households may discount the future much higher than the market interest rate, it rationalizes the low adoption rates.

II. Model

In this section, we specify a dynamic adoption model that can be estimated with aggregate data. We closely follow De Groote and Verboven (2019) in model formulation and exposition. We first describe the adoption decision for homeowner and landlord investors which mainly differ in the conditional value of adoption. We then derive our estimating equation and describe our estimation strategy, including the choice of instruments.

A. The Adoption Decision

OVERVIEW.—The adoption decision follows a dynamic framework where investors—either homeowners or landlords—choose whether to adopt a PV system in a given period. If they choose adoption, they must select from different PV system sizes, making an irreversible decision. Alternatively, they may delay adoption, retaining the option for future periods. The decision is influenced by a random taste shock, assumed to follow a type I extreme value distribution. The key component of the model is the conditional value of adoption, which reflects the expected discounted utility of investing in a PV system, factoring in upfront costs, future electricity savings, and revenues from feed-in tariffs or tenant electricity sales.

The conditional value of adoption differs between homeowners and landlords due to variations in expected benefits. Homeowners consider electricity savings based on household electricity prices, while landlords focus on revenue from selling electricity to tenants. The price variable incorporates the investment cost, feed-in tariff revenues, and discounted future savings or revenues, adjusted for factors such as inflation, depreciation of solar panel efficiency, and electricity price trends. The model assumes a 20-year subsidy period, a 1% annual efficiency loss of PV modules, and a 2% inflation rate. Consumption shares for self-used electricity are derived from prior estimates, assuming tenant behavior mirrors that of homeowners.

Investors maximize their expected utility, leading to a set of choice probabilities that determine adoption rates. The conditional value of non-adoption accounts for the flow utility of waiting and the option value of future adoption. Using a logit choice model, the probability of selecting each alternative is derived based on expected utilities. Market shares are estimated following Berry (1994), equating predicted and observed adoption shares. The potential adopter pool is based on the number of homeowners in Germany, adjusting dynamically as adoption occurs. This framework captures how policy changes, electricity prices, and household preferences shape PV system adoption dynamics over time.

SETUP.—In a given period t, an investor i of type h may either choose not to adopt a PV system ($j = 0$) or choose to adopt one of the available PV alternatives ($j = 1, ..., J$) referring to the different available capacity sizes. Adopting one of the alternatives ($j \neq 0$) represents an irreversible, terminating decision, while not adopting ($j = 0$) gives the household the option of adopting in a later period. Investor types comprise homeowners and landlords ($h \in \{Homeowners, Landlords\}$). In each period, an investor experiences a random taste shock $\varepsilon_{i,j,t}$ which is assumed to follow a type I extreme value distribution. Let $\delta_{j,t}$ denote the conditional value of alternative j in period t, i.e. the expected discounted utility from choosing j at t before the realization of the random taste shock $\varepsilon_{i,j,t}$.[10]

We assume that in each period t investors choose the alternative j that maximizes their random utility, given by $\delta_{j,t}+\varepsilon_{i,j,t}$. This decision framework results in a choice probability or an aggregate market share for each alternative in each period. Before deriving these probabilities, we first describe the conditional value of (no) adoption, $\delta_{j,t}$.

CONDITIONAL VALUE OF ADOPTION.—The conditional value of adoption represents a terminating action and can therefore be expressed as the expected discounted utility of adoption:

$$\delta_{j,t} = x_{j,t}\,\gamma - \alpha\, p_{j,t} + \xi_{j,t}\,, \qquad j = 1, \ldots, J\,, \tag{1}$$

where $x_{j,t}$ is a dummy variable for the alternative j at period t, $p_{j,t} = p_{j,t}(\beta^h)$ is the price variable as a function of the monthly discount factor β^h, and $\xi_{j,t}$ is the unobserved quality of alternative j at period t. The price variable is the sum of the upfront investment price, $p_{j,t}^{INV}$ and the discounted future flow benefits from the fixed feed-in tariff, $p_{j,t}^{FIT}$, and electricity cost savings—in the case of homeowners—or revenues from selling electricity directly to tenants—in the case of landlords, $p_{j,t}^{ELE,h}$:

$$p_{j,t} = p_{j,t}(\beta^h) \equiv p_{j,t}^{INV} - \theta_j \frac{1-(\beta^F)^R}{1-\beta^F} p_{j,t}^{FIT} - (1-\theta_j)\frac{1-(\beta^E)^R}{1-\beta^E} p_{j,t}^{ELE,h}\,, \tag{2}$$

where β^F and β^E are monthly adjusted discount factors, specified as

$$\beta^F = (1-\lambda)(1-\pi)\beta^h \tag{3}$$

$$\beta^E = (1-\lambda)(1+\vartheta_h)\beta^h\,, \tag{4}$$

adjusting the monthly discount factor β^h for a depreciation parameter λ, the inflation rate π, and the trend in real electricity prices ϑ_h. $R = 240$ indicates the

[10] Given the lack of household-level information in our data, the conditional value does not include a household-specific component. The drawback of this approach is the assumption that household heterogeneity is uncorrelated over time. In reality, it is likely that investors inclined to adopt today remain inclined to adopt in the future. Additionally, household preferences for PV systems with similar capacity sizes may be correlated. This correlation is plausible, as the physical constraints of a household's roof may limit the feasible PV system size. Both of these aspects stem from data limitations, which prevent a more nuanced modeling of household-specific adoption behavior.

number of months over the fixed 20-year period (after installation) for which subsidies are guaranteed for investors under the German feed-in program.

λ reflects the efficiency loss due to physical degradation of solar panels which is assumed to be 1 percent (Audenaert et al., 2010). We assume a yearly inflation rate of 2 percent. Using data from (Statistisches Bundesamt, 2024) to estimate the trend in real electricity prices, both for the household price of electricity and basic supply tariffs (the latter being relevant for tenant electricity), we find evidence for almost no growth in both price variables in the period 2012-2021. Finally, θ_j represents the share of our own consumption and depends on the size of the PV system. As we do not observe the electricity consumption behavior of tenants, we assume that tenants consume electricity from the PV system the same way that homeowners would, implying that θ_j is assumed to be identical across both the homeowner and landlord investment decisions. We rely on estimates from Weniger and Quaschning (2013) to obtain θ_j.

The conditional value of adoption differs between homeowners and landlords with respect to discounted future benefits from electricity production that is not directly related to the feed-in tariff (i.e., the third term on the right-hand side of (2)). Homeowners take into account electricity cost savings which depend on the price of household electricity purchased from the grid. In contrast, landlords consider the income stream earned from selling electricity to tenants. The variables $p_{j,t}^{FIT}$ and $p_{j,t}^{ELE,h}$ are essentially prices per kW in period t, multiplied by the capacity size k_j of the alternative j and a factor that converts the PV capacity into monthly electricity production. Combining the adjusted monthly discount factors (β^F, β^E) with R months of income generated from the guaranteed feed-in tariff and R months of electricity savings converts the future monthly benefits into present value terms.

Conditional value of no adoption.—The conditional value of not adopting is identical for both homeowners and landlords and is determined by the flow utility in each period t, $u_{0,t}$, plus the option value of waiting:

$$\delta_{0,t} = u_{0,t} + \beta \mathbb{E}_t \bar{\Delta}_{t+1} \,, \tag{5}$$

where $\bar{\Delta}_{t+1}$ is the ex-ante value function, i.e. the continuation value from behaving optimally from period $t+1$ onward. Assuming a type I extreme value distribution for the random taste shocks $\varepsilon_{i,j,t}$, the ex-ante value function $\bar{\Delta}_{t+1}$ has the closed-form logsum expression,

$$\bar{\Delta}_{t+1} = \bar{\mu} + \ln \sum_{j=0}^{J} \exp(\delta_{j,t+1}) \,, \tag{6}$$

where $\bar{\mu} \approx 0.577$ is the mean of the type I extreme value distribution (i.e., the Euler-Mascheroni constant).

Random utility maximization.—With random utility maximization, we obtain the following choice probabilities or the predicted market shares for each alternative

$j = 0, \ldots, J$ at period t:

$$(7) \qquad S_{j,t} = s_{j,t}(\delta_t) \equiv \frac{\exp(\delta_{j,t})}{\sum_{i=0}^{J} \exp(\delta_{i,t})} \, .$$

As in Berry (1994), we can equate the predicted market shares $s_{j,t}(\delta_t)$ to the observed market shares $S_{j,t}$ because of the inclusion of unobserved qualities $\xi_{j,t}$ for every product and period. The market shares of the alternative j are calculated using the number of adopters $q_{j,t}$ over the number of potential adopters in period t, N_t. Since adoption is a terminal action, the number of potential adopters decreases with time. As a starting point, we take the number of households in Germany (about 40 million) and multiply it by the number of home owners (42%).

B. *Estimating Equation*

We closely follow De Groote and Verboven (2019) to address the two main complications involved in solving the aggregate market share equation (7). First, the conditional value for not adopting $\delta_{0,t}$ involves the expected future value term $\mathbb{E}_t(\bar{\Delta}_{t+1})$, which is recursively defined by (6). This can be addressed by deriving an analytic expression for $E_t\bar{\Delta}_{t+1}$. Second, the conditional value for adopting $\delta_{j,t}$ contains the unobservable product quality term $\xi_{j,t}$, which enters nonlinearly into the aggregate market share equation. This can be addressed by inversion of the market share equation.

EXPECTED EX-ANTE VALUE FUNCTION.—The expectation operator in $E_t\bar{\Delta}_{t+1}$ integrates over uncertainty about the next period state variables, that is, $\omega_t = (u_{0,t+1}, \delta_{1,t+1}, \ldots, \delta_{J,t+1})$. Usually, an explicit stochastic process of state transitions is defined. De Groote and Verboven (2019) instead follow Scott (2014) and decompose $E_t\bar{\Delta}_{t+1}$ into the realized ex ante value function $\bar{\Delta}_{t+1}$ and a short run prediction error $\eta_t \equiv \bar{\Delta}_{t+1} - \mathbb{E}_t\bar{\Delta}_{t+1}$. They then write

$$(8) \qquad \delta_{0,t} = u_{0,t} + \beta(\bar{\Delta}_{t+1} - \eta_t) \, ,$$

which bears the advantage of having a flexible prediction and avoids arbitrary assumption on households belief about the evolution of states.

The ex ante value function $\bar{\Delta}_{t+1}$ recursively depends on the future value function. Hotz and Miller (1993) show how to write $\bar{\Delta}_{t+1}$ in terms of conditional choice probabilities (CCP). Taking any terminal action in our setting, that is, any adoption decision, we can rewrite the recursive future value functions as follows for $j = 1$: $s_{j,t+1} \equiv \exp(\delta_{j,t+1}) / \sum_{j=0}^{J} \exp(\delta_{j,t+1})$. Rewriting and taking logs, we get

$$(9) \qquad \ln \sum_{j=0}^{J} \exp(\delta_{j,t+1}) = \delta_{j,t+1} - \ln s_{1,t+1}(\delta_{t+1}) \, ,$$

which yields the following expression after substituting it into (6)

$$\bar{\Delta}_{t+1} = \bar{\mu} + \delta_{1,t+1} - \ln s_{1,t+1}(\delta_{t+1})\,. \tag{10}$$

The ex ante value function is essentially equal to the utility of choosing option $j = 1$ plus the mean of the type I extreme value distribution (that is, being able to get another draw) plus the CCP correction term $-\ln s_{1,t+1}(\delta_{t+1}) \geq 0$. The last term adjusts for the fact that $j = 1$ may not be optimal and thus the expected utility is on average higher (unless $s_{1,t+1}(\delta_{t+1}) = 1$).

Substituting these insights into the decomposed value mean value of not adopting, we get

$$\delta_{0,t} = u_{0,t} + \beta(\bar{\mu} + \delta_{1,t+1} - \ln s_{1,t+1}(\delta_{t+1}) - \eta_t) \tag{11}$$

$$= \beta(\delta_{1,t+1} - \ln S_{1,t+1} - \eta_t)\,, \tag{12}$$

where the second equality follows from normalizing $u_{0,t} + \beta\bar{\mu} = 0$ and from the fact that the CCP at the realized mean utilities is equal to the observed market share ($S_{1,t+1} = s_{1,t+1}(\delta_{t+1})$.

MARKET SHARE INVERSION.—De Groote and Verboven (2019) follow the approach of Berry (1994) to invert the market share equation. We can divide $S_{j,t}$ by $S_{0,t}$ in the market share equation (7) and take logs to obtain

$$\ln(S_{j,t}/S_{0,t}) = \delta_{j,t} - \delta_{0,t}, \quad j = 1, \ldots, J\,. \tag{13}$$

Substituting in our expressions for our conditional values from (1) and (5), we get

$$\ln(S_{j,t}/S_{0,t}) = (x_{j,t} - \beta x_{1,t+1})\gamma - \alpha(p_{j,t} - \beta p_{1,t+1}) + \beta \ln S_{1,t+1} + e_{j,t}\,, \tag{14}$$

where

$$e_{j,t} \equiv \xi_{j,t} - \beta(\xi_{1,t+1} - \eta_t) \tag{15}$$

is the econometric error term. De Groote and Verboven (2019) provide the following intuition for the case of $J = 1$. Then, the equation can be rewritten as

$$\ln(\frac{S_{j,t}/S^{\beta}_{1,t+1}}{S_{0,t}}) = (x_{1,t} - \beta x_{1,t+1})\gamma - \alpha(p_{1,t} - \beta p_{1,t+1}) + e_{1,t}\,, \tag{16}$$

which is essentially a regression for the change in the number of new adopters on the change in price and other characteristics, given β being close to 1. With forward-looking consumers, one may then expect a relatively low number of adopters this period if there is a significant price drop in the next period.

C. Estimation

Given the non-linearity of the unknown parameter β—i.e., its non-linear involvement in the price terms—in the estimating equation (14), we will require a non-linear estimator. The error term $e_{j,t}$ consists of the household prediction error and demand shocks. The household prediction error is, by construction, uncorrelated with variables at time t and therefore does not give rise to endogeneity terms. Instead, the demand shock may be correlated with the price variables. First, this may be due to an increased cost of building a PV system when demand is high. In addition, feed-in tariffs are financed through higher electricity prices, known as the German *Renewable Energy Sources Act* surcharge[11], making them a function of current demand shocks.

De Groote and Verboven (2019) deal with these issues by constructing an instrument vector $z_{j,t}$ that is uncorrelated with the error term, and estimate the model using Generalized Method of Moments with the following moment conditions:

$$\mathbb{E}(z_{j,t}e_{j,t}) = 0\,. \tag{17}$$

We construct the vector of instruments $z_{j,t}$ as follows. First, we use a module price index to proxy for PV modules. It is expected to correlate with the endogenous upfront investment price, and as a cost shifter it arguably does not directly influence demand. This instrument will help identify the price coefficient α. Secondly, we include contractually fixed future benefits from the feed-in subsidy, which varies over alternatives and time. Thus, it is a strong instrument to identify the discount factor β^h. To further strengthen the identification of β^h, we incorporate electricity and oil price instruments, as these affect future benefits by influencing savings from electricity consumption. Finally, we also add exogenous $x_{j,t}$ which in our case are alternative j fixed effects. A second source of identification comes from the dynamics of the model. For example, the feed-in tariff is greatly reduced in 2012, and people reacted by adopting just before the decline in subsidies—as evidenced by the large peak in 2012 in Figure 2. This decrease causes a change in the option value if households choose not to adopt, which in turn depends on the discount factor. We follow De Groote and Verboven (2019) and use an approximation to optimal instruments based on Chamberlain (1987) in the household models. They are difficult to implement in the landlord models due to the low number of adoptions, and thus we do not implement them in those contexts.

III. Results

We first describe the investment decisions of homeowners and landlords, with a focus on the extent to which future benefits from PV investments are undervalued. Next, we quantify the cost-effectiveness of the German solar energy subsidies by comparing the fiscal (budgetary) costs of the subsidy program to a counterfactual policy design for promoting PV installations. Finally, we assess the administrative costs associated with tenant electricity.

[11]This surcharge, known as the "EEG-Umlage" in German, is a levy imposed under the *Erneuerbare-Energien-Gesetz (EEG)* (Renewable Energy Sources Act) to help fund Germany's renewable energy transition.

Table 1. **Summary statistics**

Variable	Mean	SD	Min	Median	Max	N
Number of PV adoptions						
Partial Feed-in	703.75	807.13	5	477.50	5,142	840
Full Feed-in	51.99	123.71	0	22	1,691	840
Tenant Electricity	1.61	1.87	0	1	9	378
Subsidies (ct/kWh)						
Feed-in tariff below 10kW	12.33	3.74	6.23	12.16	25.53	840
Feed-in tariff below 30kW	11.91	3.60	6.05	11.83	25.53	840
Subsidy for tenant electricity	2.51	1.21	0	3.04	3.75	378
Price variable (in 2012 €)						
Investment price	11,274	5,774.05	2,835	10,941	31,672	840
Monthly feed-in revenue	74.23	50.20	5.58	69.57	295.80	840
Monthly electricity savings	39.91	10.45	24.13	38.36	63.58	840
Monthly electricity sales	39.33	10.27	24.37	37.50	62.85	378
Energy and module prices						
Electricity prices (ct/kWh)	29.23	0.86	26.93	29.51	30.42	840
Basic supply electricity prices (ct/kWh)	30.79	0.67	30.25	30.31	31.93	378
Oil prices ($/Barrel)	70.73	27.40	17.31	62.41	129.46	840
Module price (€/Wpeak)	0.40	0.14	0.20	0.44	0.75	840

Notes: Both the household macro sample for partial and full feed-in have $N = 840$ observations, the landlord macro sample has $N = 378$ observations.

A. *Main Findings: Undervaluation of Future Benefits*

SUMMARY STATISTICS.—Table 1 provides summary statistics for the sample (January 2012–December 2021). We observe that the number of adoptions for full feed-in and tenant electricity PV systems is low, with partial feed-in systems accounting for the vast majority of adoptions targeted by the government. The feed-in tariffs are identical for both investor types—households and landlords. The investment price of a PV system has on average been 11,274, with a large standard deviation both because of falling prices over time and large differences depending on the capacity size. The government also subsidizes tenant electricity contracts to encourage landlords to adopt tenant electricity models. These subsidies appear effective, as the monthly electricity savings for households closely match the monthly electricity sales for landlords. However, despite identical investment costs and feed-in revenues, landlords adopt an average of only 1.61 systems for tenant electricity. This strongly suggests the presence of substantial unobserved administrative costs.

HOMEOWNER INVESTMENT DECISIONS.—Table 2 shows the empirical results for homeowners using national-level data for Germany for the period January 2012 to December 2021. We provide estimates derived from a static and dynamic model. The static model simplifies the dynamic adoption model presented in Section II by setting $\beta = 0$ in (14), while keeping β in the price variables, as given by (2)-(4). Effectively, this implies that households cannot delay their investment but still

Table 2. **Empirical results for homeowners (national-level model, partial feed-in)**

	Dynamic		Static	
Price sensitivity in 10^3 Euro (α)	0.4742	(0.2421)	0.5452	(0.2133)
Monthly discount factor (β)	0.9931	(0.0018)	0.9900	(0.0020)
Annual implicit real interest rate in %	8.66	(2.40)	12.82	(2.72)
Alternative-specific constants (γ)				
Common constant	-11.7617	(4.9066)	-8.6638	(0.6485)
2kW	-2.9704	(0.3818)	-3.5503	(0.4119)
4kW	-1.1750	(0.2482)	-1.4760	(0.2638)
8kW	0.1383	(0.2452)	0.4407	(0.2623)
10kW	0.2876	(0.3404)	0.7967	(0.3391)
12kW	-3.2405	(0.5888)	-2.4291	(0.5947)
15kW	-2.4892	(0.8388)	-1.2296	(0.8477)
Number of observations	819		819	

Notes: "Dynamic" refers to estimation results obtained with the dynamic adoption model presented in Section II. "Static" refers to results obtained from a static model, which assumes that investors cannot delay their investment. Consequently, the discount factor β influences only the NPV of future income streams, without affecting the timing of the investment decision. For all models, standard errors are clustered at the monthly level. Both models are estimated using GMM with the optimal weighting matrix obtained from a two-step estimation procedure. [a]Computed as $r = \beta^{-12} - 1$. Sample period from January 2012 until December 2021. Optimal instruments are approximated following the approach by Chamberlain (1987).

consider the discounted future income stream of their investment.[12]

The investment price coefficient (α) is positive, which means that investors react positively to a drop in the investment prices of PV systems. The size of the price sensitivity is comparable to the estimates obtained in De Groote and Verboven (2019). We find that the price coefficients between the static and dynamic models are relatively similar. This difference is more pronounced in De Groote and Verboven (2019) as their data exhibit frequent bunching of PV investments. In contrast, our data display only a single instance of bunching, which occurs in 2012 (see Figure 2).

The estimated real discount factor (β) quantifies the relative valuation of future benefits compared to the initial investment cost. The monthly discount factor for both models differ significantly from 1. The discount factor for the dynamic model is higher than for the static model. However, their confidence intervals overlap, making them non-statistically different. It is instructive to convert the monthly discount factor into an annual implicit real interest rate, calculated as $r = \beta^{-12} - 1$. We find that the implicit interest rate is 8.66% in the dynamic and 12.82% in the static model (with a standard error of 2.4% and 2.27%, respectively). The implicit interest rates are thus several order of magnitudes higher than comparable market interest rates during the sample period 2012-2021. For example, risk-free interest

[12]Static models have frequently been applied in other contexts, such as in analyzing the trade-off between future fuel cost savings and higher upfront purchase prices. For example, Verboven (2002), Busse and Zettelmeyer (2013), and Allcott and Wozny (2014) employ static models in such settings. Including a static model in our analysis, as in De Groote and Verboven (2019), facilitates a direct comparison of estimated discount factors between studies, helping to contextualize our findings within the broader literature.

rate ranged between 0% and 1%, while medium-risk investments yielded around 2%. In addition, the government-owned German development bank KfW provided favorable loans for environmentally friendly investments, which further reduced the effective borrowing costs compared to market conditions. Despite these financing options, households appear to require a significant return premium to carry out investments into new PV technologies.

These estimates add to existing evidence that consumers significantly discount the future benefits of new technologies such as PV installations. An alternative, useful way to interpret these discount factors is to quantify consumers' willingness to pay for each euro of future discounted benefits. Given a future benefits period of $R = 240$ months, the present value of one euro in benefits is calculated as follows:

$$\Gamma(\beta) = \frac{1 - ((1-\lambda)\beta)^R}{1 - (1-\lambda)\beta}\,. \tag{18}$$

Using the empirical estimate for the discount factor from the dynamic model—$\Gamma(0.9931)$—and expressing the benefits relative to benefits obtained at a market discount factor of 3%—$\Gamma(1.03^{-1/12})$—yields: $\Gamma(0.9931)/\Gamma(1.03^{-1/12}) = 0.67$.[13] Thus, homeowner investors are willing to pay only 67 cents for every euro of total discounted future benefits from electricity production.[14] Notably, this means that the same level of German feed-in tariffs would have led to a faster adoption rate if German households placed a higher value on future energy savings—that is, if they were more forward-looking.

We also estimate the model at the state level, which allows us to account for heterogeneity in state-level regulation. Empirical results are shown Table A1 in an appendix. Although the price coefficient differs nominally, it is not statistically different. The discount factor and its standard error are virtually the same as in the main specification.

LANDLORD INVESTMENT DECISIONS.—Table 3 shows the empirical results for landlords obtained from the national-level model for the period July 2017 until December 2021. Due to the limited number of tenant electricity model adoptions in this sample period, price sensitivity is difficult to identify. Additionally, compared to homeowner investment decisions, there is substantially less variation in investment prices.

The discount factor is highly similar between the dynamic and static models, corresponding to an annual implicit real interest rate of 13.72% and 13.16%, respectively. Using the estimates from the dynamic and static model in (18), we find that landlords are willing to pay 51 cents (52 cents) for each euro of total discounted future benefits from electricity production, respectively. First, this sug-

[13]The comparable number obtained from the static model is 53 cents. We continue to rely on the estimate from the dynamic model as our preferred specification.

[14]This is comparable with De Groote and Verboven (2019) who find a slightly lower consumers' willingness to pay 50 cents. It also aligns with the discount rates reported in Allcott and Wozny (2014), where consumers valued future gasoline cost savings at just 76% of the upfront vehicle purchase price. Since market interest rates were higher during their sample period, our results suggest that households in our sample discount future income streams even more heavily than the consumers studied in Allcott and Wozny (2014).

Table 3. **Empirical results for landlords (national-level model, partial feed-in)**

	Dynamic		Static	
Price sensitivity in 10^3 Euro (α)	-0.0001	(0.0000)	-0.0001	(0.0000)
Monthly discount factor (β)	0.9893	(0.0026)	0.9897	(0.0010)
Annual implicit real interest rate (%)	13.78	(3.55)	13.23	(1.32)
Alternative-specific constants (γ)				
Common constant	-0.1716	(0.0415)	-16.0986	(0.0001)
2kW	-0.0831	(0.0001)	-0.0831	(0.0000)
4kW	-0.0415	(0.0001)	-0.0415	(0.0000)
8kW	0.0414	(0.0001)	0.0414	(0.0000)
10kW	0.0830	(0.0001)	0.0830	(0.0000)
12kW	0.1243	(0.0002)	0.1244	(0.0001)
15kW	0.1863	(0.0003)	0.1863	(0.0001)
Number of observations	378		378	

Notes: "Dynamic" refers to estimation results obtained with the dynamic adoption model presented in Section II. "Static" refers to results obtained from a static model, which assumes that investors cannot delay their investment. Consequently, the discount factor β influences only the NPV of future income streams, without affecting the timing of the investment decision. Standard errors are not clustered at the monthly level given the small number of adoptions. Both models are estimated using GMM with the optimal weighting matrix obtained from a two-step estimation procedure. [a]Computed as $r = \beta^{-12} - 1$. Sample period from July 2017 until December 2021.

gests that landlords also appear to require a significantly higher return premium to adopt new technologies such as PV installations. Second, the return premium for landlord investors is even higher than what is required by homeowner investors. We argue in Section III.C, that a large chunk of this may be attributed to costs associated with bureaucracy around the regulation of tenant electricity.

B. Cost-Effectiveness of German PV Subsidies

Our analysis reveals that (homeowner) investors applied an implicit interest rate of approximately 8.6% when deciding to adopt PV installations, despite market interest rates being around 1–2% during the same period. This has an important policy implication: the same level of adoption could have been achieved at a lower budgetary cost by replacing the future production subsidies, providing an income stream over 20 years, with an equivalent upfront subsidy for PV investment costs (paid as a lump-sum subsidy at the time of installation).

To analyze this, we can use equation (2) to calculate the perceived net present value of feed-in tariff revenues over R months for a homeowner investor who adopts a PV system with capacity size j at time t:

$$NPV_{j,t}^{\textit{Perceived by homeowners}} = \frac{1 - [(1-\lambda)(1-\pi)\beta]^R}{1-(1-\lambda)(1-\pi)\beta} p_{j,t}^{FIT}(\beta)\,. \tag{19}$$

Using our estimate (from the dynamic model) from Table 2, $\beta = 0.9931$, yields the upfront subsidy the government would have needed to pay out to an homeowner investor to incentivize the same level of PV adoption. The net present value of the feed-in subsidy payments for the government, spread over the same number of months, is given by:

$$(20) \qquad NPV_{j,t}^{Costs\ for\ government} = \frac{1-[(1-\lambda)(1-\pi)\hat{\beta}]^R}{1-(1-\lambda)(1-\pi)\hat{\beta}} p_{j,t}^{FIT}(\hat{\beta}),$$

where $\hat{\beta}$ denotes the monthly discount factor used by the government. The German government bond interest rate for a 20-year period was approximately 2.5% in 2012 (and 0.2% in 2021). To provide a conservative estimate, we use a discount rate of $r^{gov} = 2\%$. Hence, $\hat{\beta} = [1/(1+r^{gov}]^{(1/12)} = 0.9983$.

The government could have incentivized the same level of PV adoptions with capacity j at time t with paying the amount $NPV_{j,t}^{Perceived\ by\ homeowners}$ as an upfront subsidy, while saving the amount $NPV_{j,t}^{Costs\ for\ government} - NPV_{j,t}^{Perceived\ by\ investors}$. Summing over all adopters[15] and PV capacity sizes during our sample period from 2012 to 2021 provides the total budgetary savings, assuming the effective level of PV installations remains fixed:

$$(21) \qquad \Psi = \underbrace{\sum_j \sum_t NPV_{j,t}^{Costs\ for\ government}}_{\substack{\text{Actual budgetary cost} \\ \text{of feed-in subsidies}}} - \underbrace{\sum_j \sum_t NPV_{j,t}^{Perceived\ by\ homeowners}}_{\substack{\text{Perceived value by investors} \\ \text{(=equivalent upfront lump-sum subsidy)}}}.$$

Put differently, Ψ measures the cost-effectiveness of the feed-in tariff program, i.e. foregone public spending resulting from the use of a sub-optimal subsidy design that fails to account for the undervaluation of future benefits from electricity production by investors. Based on the actual feed-in tariff rates and observed adoption rates, we estimate the actual budgetary cost over our sample period to be 7.5 billion euros. The perceived value of the feed-in subsidies by homeowner investors is estimated at 4.8 billion euros. Therefore, we estimate potential savings of $\Psi = 7.5 - 4.8 = 2.7$ billion euros (or 36% of the amount spent) for the German government, which could have been realized while achieving the same number of PV adoptions.

C. Administrative Costs of Tenant Electricity

We do not explicitly model the bureaucratic requirements that would typically influence the adoption decisions of landlords as an administrative cost (in comparison to homeowners). Instead, by omitting these factors, they are incorporated into the error term, thereby affecting the estimated discount factor. With a fixed level of PV system adoption, underestimating these costs would lead to a higher estimated discount factor. If we assume that landlords and homeowners have the same discount factor but observe a lower estimated discount factor for landlords, the observed difference can be attributed to the additional costs associated with tenant electricity contracts. We argue that this discrepancy reflects the unobserved

[15] Given the low number of PV adoptions by landlords, we only consider homeowner investments when the counterfactual savings obtained from an equivalent upfront investment subsidy.

administrative costs involved in implementing tenant electricity.

We argue that it is reasonable to assume that the discount factor of homeowners provides a lower bound for the discount factor of landlords:

$$\beta^{Landlords} \geq \beta^{Homeowners} \tag{22}$$

as both groups have similar access to lending conditions and financial literacy. This similarity suggests that the discount factors of landlords are likely to be comparable to, or even higher than, those of homeowners. We compare landlords with homeowners because landlords in our sample do not have any other reasonable investment opportunities. We also considered two alternative approaches to modeling a landlord's investment decisions but found them less suitable. First, landlords could theoretically invest in full feed-in systems. However, given the data, these investments are almost never financially viable and would imply a discount factor greater than 1, meaning the investor would incur a loss (see Figure A1 and Table A1 in the appendix). Second, we cannot link ownership of multiple systems to a single individual, making it impossible to determine whether some investors in our sample are both homeowners with photovoltaic systems and landlords. As a result, using the homeowner's discount factor as a lower bound for landlords is, in our view, the most reasonable approach.

Assuming that (22) holds, we can estimate a lower bound for the administrative costs associated with tenant electricity. To do so, we compute the net present value of the benefits from PV investments in tenant electricity, discounting them at the household's discount factor, and compare this to the corresponding value discounted at the landlord's discount factor:

$$\Omega_{j,t} = NPV_{j,t}^{Tenant\ electricity}(\beta^{Landlords}) - NPV_{j,t}^{Tenant\ electricity}(\beta^{Homeowners}) . \tag{23}$$

To compute $NPV_{j,t}^{Tenant\ electricity}(\beta^h)$, we need to account for both the revenue streams from feed-in electricity and from the electricity sales to the tenant

$$\begin{aligned} NPV_{j,t}^{Tenant\ electricity}(\beta^h) = & \frac{1-[(1-\lambda)(1-\pi)\beta^h]^R}{1-(1-\lambda)(1-\pi)\beta^h} p_{j,t}^{FIT} \\ & + \frac{1-[(1-\lambda)(1+\vartheta)\beta^h]^R}{1-(1-\lambda)(1+\vartheta)\beta^h} p_{j,t}^{ELE,Landlords} . \end{aligned}$$

We then use the estimated discount factor from the homeowner ($\beta^{Homeowners}$) and landlord investment decision ($\beta^{Landlords}$) as shown in Table 2 and Table 3, respectively, into (23).

We find that the implicit administrative costs for landlords account for an average of 22.5% of the total benefits of the PV system (95% CI: 21.4%–23.7%), corresponding to approximately 2,240 euros (95% CI: 2,121–2,358 euros). Given the low adoption rate of the tenant electricity program, this result is unsurprising. These findings suggest that administrative costs pose a significant barrier to landlord participation in the tenant electricity program. Policymakers took steps to reduce bureaucratic hurdles in 2021 and again in 2023, but it remains an open question how effective these reforms have been in cutting administrative costs and incentivizing adoption.[16] Here, we provide an estimate of the administrative costs for the period 2012-2021, highlighting the need for measures aimed at reducing these costs.

IV. Conclusion

This paper examines the effectiveness of Germany's PV subsidy scheme, particularly in the context of residential ownership structures and the incentives faced by homeowners and landlords. Our analysis highlights the suboptimality of the feed-in tariff structure, showing that households heavily discount future benefits, leading to an inefficient use of government funds. By estimating a dynamic adoption model, we find that households value each euro of total discounted future benefits at only 67 cents, implying that a lump-sum subsidy paid on upfront investment cost could have achieved the same level of adoption at a 36% lower cost. Our estimates suggest that transitioning from the current feed-in tariff system to an upfront subsidy would have resulted in potential government savings of approximately 2.7 billion euros.

Furthermore, we analyze the investment decisions of landlords within the tenant electricity framework and identify significant barriers to adoption. Despite additional subsidies provided for landlord-tenant electricity contracts, the complexity of administrative regulations has deterred investment. We estimate that administrative costs account for approximately 22.5% of the total benefits of a PV system for landlords, amounting to an additional cost burden of roughly 2,240 euros per investment. These excessive costs have significantly hindered the success of tenant electricity programs, resulting in low adoption rates despite policy incentives. However, the importance of these programs should not be understated. Given the large number of tenants in Germany, the policy has the potential to increase the number of potential adopters in Germany by more than 100%. Since the German government has set an adoption target, facilitating greater landlord participation could have allowed for a reduction in subsidies while still achieving the desired expansion in PV adoption.

Our findings provide important policy implications. First, governments aiming to accelerate renewable energy adoption should prioritize upfront subsidies over long-term feed-in tariffs, ensuring that funds are utilized more effectively. Second, reducing bureaucratic hurdles in the tenant electricity framework is crucial to unlocking the investment potential of landlords and expanding solar energy access for tenants. Although recent regulatory reforms have sought to address these inefficiencies, further research is needed to assess their impact on adoption rates.

[16] Amendments to the German *Tenant Electricity Law (Mieterstromgesetz)* aimed at reducing bureaucratic hurdles and promoting tenant electricity include increased tender volumes for solar projects, segmented tendering with higher compensation for installations on buildings to incentivize landlord participation, the promotion of solar on transport infrastructure, and the relaxation of distance regulations to enable more effective land use.

Third, while many countries (not Germany), have transitioned to auction-based subsidies or other market-driven mechanisms to promote solar energy, the insights gained from a large-scale subsidy program like Germany's are likely to be valuable for designing cost-effective incentives in other public policy areas critical for decarbonization, particularly for the household adoption of electric vehicles and heat pumps.

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Appendix A: Sensitivity Analysis

Table A1. **Empirical results for homeowners (state-level model, partial feed-in)**

	Dynamic		Static	
Price sensitivity in 10^3 Euro (α)	0.6943	(0.1826)	0.7843	(0.2132)
Monthly discount factor (β)	0.9941	(0.0014)	0.9912	(0.0014)
Annual implicit real interest rate in %	0.0732	(0.0181)	0.1118	(0.0190)
Alternative specific constants (γ)				
Common constant	-0.6943	(6.4912)	-6.6194	(0.9332)
2kW	-2.8312	(0.4445)	-3.6812	(0.4940)
4kW	-1.1308	(0.2753)	-1.5675	(0.3094)
8kW	0.0727	(0.2761)	0.5094	(0.3113)
10kW	-0.1520	(0.3986)	0.5992	(0.4178)
12kW	-3.9412	(0.6797)	-2.7474	(0.7170)
15kW	-3.2928	(0.9837)	-1.4388	(1.0409)
Region Dummies	Yes		Yes	
Number of observations	12,285		12,285	

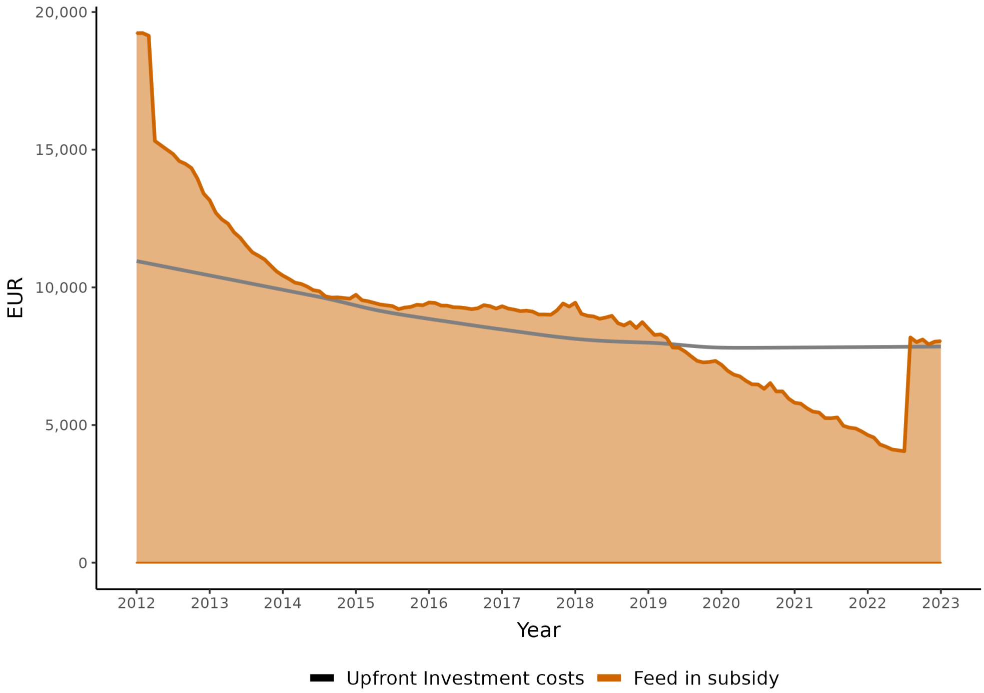
Notes: "Dynamic" refers to estimation results obtained with the dynamic adoption model presented in Section II. "Static" refers to results obtained from a static model, which assumes that investors cannot delay their investment. Consequently, the discount factor β influences only the NPV of future income streams, without affecting the timing of the investment decision. For all models, standard errors are clustered at the monthly level. Both models are estimated using GMM with the optimal weighting matrix obtained from a two-step estimation procedure. [a]Computed as $r = \beta^{-12} - 1$. Sample period from January 2012 until October 2021. Optimal Instruments are approximated using results from Chamberlain (1987).

Table A1. **Empirical results for homeowners (national-level model, full feed-in)**

	Dynamic		Static	
Price sensitivity in 10^3 Euro (α)	-0.0002	(0.0003)	-0.0001	(0.0003)
Monthly discount factor (β)	1.0005	(0.0096)	1.0078	(0.0404)
Annual implicit real interest rate in %	-0.0059	(0.1145)	-0.0889	(0.4379)
Alternative specific constants (γ)				
Common constant	0.0086	(0.1212)	-12.6262	(0.0021)
2kW	-0.0060	(0.0011)	-0.0062	(0.0011)
4kW	-0.0029	(0.0006)	-0.0031	(0.0004)
8kW	0.0029	(0.0006)	0.0031	(0.0012)
10kW	0.0061	(0.0007)	0.0062	(0.0015)
12kW	0.0091	(0.0012)	0.0093	(0.0022)
15kW	0.0136	(0.0019)	0.0139	(0.0033)
Number of observations	497		497	

Notes: "Dynamic" refers to estimation results obtained with the dynamic adoption model presented in Section II. "Static" refers to results obtained from a static model, which assumes that investors cannot delay their investment. Consequently, the discount factor β influences only the NPV of future income streams, without affecting the timing of the investment decision. For all models, standard errors are clustered at the monthly level. Both models are estimated using GMM with the optimal weighting matrix obtained from a two-step estimation procedure. [a]Computed as $r = \beta^{-12} - 1$. Sample period from January 2012 until October 2021.

Figure A1. **Benefits and costs of a 6kW full feed-in PV system.**



Notes: Real interest rate used to calculate discounted benefits and costs = 3 percent. Upfront investment costs based on (approximation of) price index from EUPD Research (2024).

Appendix B: Countries which have adopted feed-in tariff programs following the German program

Germany's feed-in tariff (FiT) program directly influenced more than 50 countries worldwide. Below is a breakdown of some of the key countries that adopted FiT programs inspired by Germany:

Europe

1. Spain (2004): One of the earliest adopters, but its generous FiTs led to an unsustainable solar boom, forcing retroactive cuts.
2. Italy (2005): The Conto Energia program drove rapid solar growth but was later scaled back.
3. France (2006): Introduced high solar FiTs, later revised as costs fell.
4. United Kingdom (2010): Implemented a German-style FiT but later reduced incentives.
5. Portugal (2007): Established a FiT model that helped grow its renewable sector.
6. Greece (2006): Adopted high FiTs, leading to a solar boom.
7. Czech Republic (2005): Implemented generous FiTs, leading to a surge in solar installations.
8. Belgium (2006): Used FiTs alongside green certificates for solar incentives.
9. Austria (2002): Implemented FiTs to drive small-scale renewables.
10. Switzerland (2009): Launched a FiT program called KEV for renewables.
11. Hungary (2016): Launched a German-style FiT program called METÁR.
12. Poland (2016): Introduced FiTs for small-scale solar and wind projects.
13. Romania (2011): Initially used FiTs but later switched to a green certificate system.
14. Turkey (2010): Implemented FiTs to promote local solar manufacturing.

Asia-Pacific

15. Japan (2012): Introduced an aggressive FiT post-Fukushima, leading to a solar boom.

16. China (2011): Adopted FiTs for large-scale solar but later shifted toward auction-based subsidies.
17. South Korea (2006): Implemented FiTs but transitioned to a renewable portfolio standard.
18. Taiwan (2009): Modeled FiTs on Germany's system to boost solar adoption.
19. India (2010): Launched FiTs under the Jawaharlal Nehru National Solar Mission (JNNSM).
20. Thailand (2007): Introduced a FiT program known as the Adder Program.
21. Malaysia (2011): Adopted FiTs to accelerate solar deployment.
22. Australia (2008): State-based FiTs helped drive rooftop solar adoption.
23. Vietnam (2017): Introduced one of Asia's most successful FiT programs for solar growth.
24. Philippines (2012): Adopted FiTs for renewable energy.
25. Indonesia (2016): Launched a FiT system to encourage solar power.

North America
26. Canada (Ontario, 2009): Ontario's FiT program was one of the most ambitious outside Europe, inspired directly by Germany.
27. United States (California, Vermont, Hawaii) – Several states implemented FiTs, though the U.S. focused more on tax credits than nationwide FiTs.

Latin America
28. Brazil (2012): Established FiTs to promote solar energy.
29. Mexico (2013): Adopted a similar incentive mechanism.
30. Chile (2008): Implemented FiTs for small and medium renewable projects.

Middle East & Africa
31. South Africa (2009): Launched a FiT system but later transitioned to competitive auctions.
32. Israel (2008): Introduced FiTs for solar power.
33. Jordan (2012): Implemented a FiT program to promote renewables.

Appendix C: Countries which have implemented programs similar to Germany's tenant electricity model

Several countries have implemented programs similar to Germany's tenant electricity model, aiming to enable landlords or housing associations to provide renewable energy directly to tenants or to facilitate energy sharing through renewable energy communities:

California: The Solar on Multifamily Affordable Housing (SOMAH) program incentivizes the installation of solar energy systems on multifamily affordable housing units. It aims to deliver clean power and direct tenant benefits, reducing energy bills for low-income renters.

Belgium: The ASTER project equips social housing with free solar panels, allowing tenants to consume renewable energy at reduced rates. This initiative not only lowers energy bills but also addresses energy poverty by making clean energy accessible to low-income households.

Italy: Since 2020, Italy has facilitated energy sharing through renewable energy communities. Members connected to the same high-voltage substation can jointly operate renewable energy systems up to a capacity of one megawatt. An incentive system rewards decentralized consumption, providing a premium for shared energy generated and consumed by the community. The City of Magliano Alpi established Italy's first renewable energy community in December 2020, enabling citizens to become energy prosumers by producing energy from sustainable sources like rooftop solar and sharing it with neighboring buildings.

Austria: The Renewables Deployment Act facilitates the creation of energy communities, allowing citizens to participate actively in the energy transition. Members can consume, share, store, and sell their own renewable energy production, promoting autonomy over energy supply.

Spain: Collective self-consumption has been possible since 2015, with significant growth following the abolition of the "sun tax" in 2018. Renewable energy communities, defined in line with EU directives, allow local citizen participation in renewable projects, with various regional programs promoting these initiatives.

Portugal: The legal framework permits shared self-supply from renewable energy sources through the distribution grid. Generation systems and consumers must be connected to the same transformer station, and energy sharing is incentivized with reduced grid usage fees.

France: Energy sharing is facilitated through renewable energy communities, allowing shared self-supply via the distribution grid. In rural areas, a distance of up to 20 kilometers is permitted between generation systems and consumers, promoting decentralized renewable energy consumption. These initiatives demonstrate a growing global effort to integrate tenants into the renewable energy transition, ensuring that the benefits of clean energy reach a broader spectrum of society.

These initiatives demonstrate a growing global effort to integrate tenants into the renewable energy transition, ensuring that the incentives for and benefits from renewable energy investments can be shared among a broader group of market participants.

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