Small-Scale Solar, Large-Scale Change?

The Socio-Psychological Impact Of Plug-In Solar In Germany

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Table of Contents

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List Of Abbreviations

AC - Alternating Current

DC - Direct Current

EU - European Union

kWh - Kilowatt-hour

MW - Megawatt

n - Sample size

NIMBY - Not In My Backyard

PV - Photovoltaic

TPB - Theory of Planned Behavior

UBA - Umweltbundesamt (German Environment Agency)

List Of Figures

List Of Tables

Executive Summary

This thesis investigates the socio-psychological impacts of plug-in solar module ownership in the context of the German energy transition. Plug-in solar, also referred to as balcony photovoltaic, enables households to generate electricity independently with relatively low financial and technical barriers. While technical and regulatory aspects of these systems have received growing attention, their broader implications beyond energy generation remain underexplored, thus societal and behavioral changes.

Grounded in the Theory of Planned Behavior and environmental psychology, this study examines five outcome dimensions: environmental awareness, sustainable energy behavior, individual empowerment, political engagement, and peer effects. A quantitative online survey (n = 294) among German plug-in solar owners was conducted and complemented by national registration data to contextualize trends in adoption, capacity, and regional spread.

Statistical analyses show that plug-in solar ownership is associated with increased environmental awareness, more sustainable energy behavior, strong feelings of empowerment, and moderate increases in political engagement for energy and climate topics. Peer effects, by contrast, were limited, with respondents reporting low perceived visibility and influence. Respondents also tended to overestimate plug-in solar's contribution to total PV capacity, highlighting the role of perceived, rather than purely technical impact.

As one of the first quantitative studies to investigate post-adoption effects of plug-in solar in Germany, this thesis contributes novel insights into how small-scale energy technologies shape public engagement, attitudes, and behavior. The findings have implications for policy and practice, particularly in promoting inclusive participation, enhancing energy literacy, and addressing behavioral dimensions of the energy transition.

Introduction

1. The Urgency of the Energy Transition and Citizen Participation

Mitigating climate change requires the decarbonization of the energy system (IPCC, 2023). This energy transition is a complex, long-term process that will span generations (Smil, 2016). The perception of it as a technical and economic transition is likely insufficient; it also represents a fundamental societal transformation requiring a change in people's behavior, norms, and acceptance (Nyborg et al., 2016; Sovacool, 2014). As Sovacool (2009) argues, "some of the most surreptitious, yet powerful, impediments facing renewable energy and energy efficiency in the United States are more about culture and institutions than engineering and science.". This perspective holds relevance for the broader energy transition: overcoming technical hurdles is necessary, but not sufficient; success also depends on societal engagement.

Energy is often taken for granted, perceived as an unlimited commodity. The Russian invasion of Ukraine in 2022, which triggered sharp increases in electricity prices, briefly disrupted this perception and highlighted the political and economic dimensions of energy systems (Wirth, 2025). As a major contributor to climate change, energy must be understood not only as a commodity but also as a shared responsibility (Agora Energiewende, 2017; Sovacool, 2009).

Despite ambitious policies, the pace of the energy transition remains too slow to meet climate targets. One key challenge is the lack of policy consistency and sustained commitment. Governments and political parties differ in their visions for the energy transition, with ambitions and priorities shifting across electoral cycles. In Germany, for example, opposition parties, including far-right leaders, have lately called for dismantling wind turbines and returning to nuclear energy (Götze & Schlak, 2025), while others advocate for a rapid expansion of renewables. Policy instruments such as feed-in tariffs and subsidies have often favored higher-income households, excluding tenants and lower-income groups from meaningful participation (Expertenrat für Klimafragen, 2025). Recent legislative changes, such as the solar peak law, have reduced feed-in tariffs to alleviate grid congestion, further limiting the financial incentives for decentralized energy generation (Solarspitzengesetz, 2025). Structural barriers, such as political polarization and fragmented policy approaches, hinder a cohesive and equitable transition. Public opposition to local projects, although citizens may generally be in favor of the energy transition, also known as NIMBYism ("Not in my Backyard"), further hinders the implementation of renewable projects (O'Neil, 2021). These dynamics highlight the importance of exploring accessible, low-barrier participation models that can include a broader segment of society.

2. The Rise of Plug-In Solar: A Low-Barrier Entry to Renewable Energy

In recent years, plug-in solar modules have gained popularity in Germany. Often referred to as balcony power plants or mini-PV systems, these small devices can be connected directly to household sockets, allowing users to produce electricity without professional installation. By 2025, over 800,000 plug-in solar modules were registered in Germany, with more than half installed within the previous year (Bundesnetzagentur, 2025). The actual number is likely higher, given incomplete reporting.

Plug-in solar differs technically from conventional rooftop PV systems. While both generate electricity from sunlight, conventional systems typically require professional installation, connection to a dedicated circuit, and integration into the broader grid infrastructure. They are often larger in capacity, involve higher upfront costs, and follow established grid standards and permitting procedures. In contrast, plug-in systems are smaller, more affordable, and designed for simplicity. Mini-PV systems feed power into existing household circuits; see Figure 1 for a simplified visualization. The basic setup consists of a module, an inverter that converts direct current (DC) to alternating current (AC), and a connection to a standard electrical outlet. A bidirectional electricity meter tracks both self-consumed and exported energy (Schuberth, 2024). While compensation for excess energy is rather unusual due to bureaucratic hurdles, the energy generation offsets grid consumption and thus reduces household electricity bills. Other countries do not allow this grid injection, requiring an additional zero-discharge device in Spain or more administration in France (SolarPower Europe, 2025). Typical modules produce up to 800 watts, enough during sunny hours to cover the electricity use of a fridge and a few small devices. They cost between €50 and €1,500, with payback periods ranging from three to six years (Bergner et al., 2022).

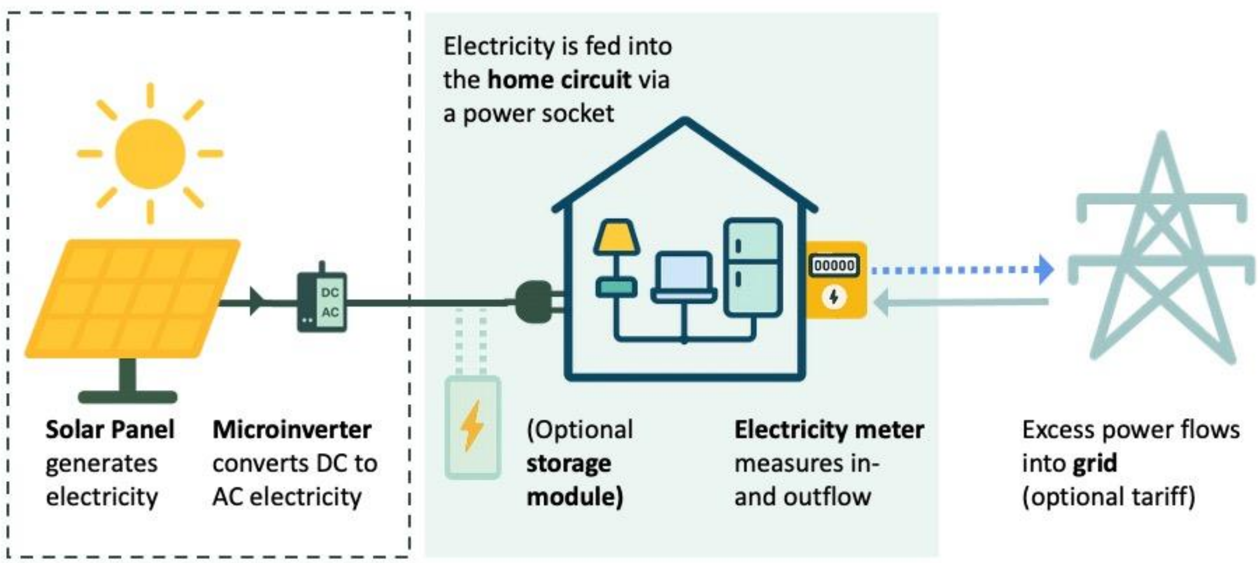

Figure 1. Schematic representation of a plug-in photovoltaic (PV) system integrated into a household energy circuit (own visualization)

Legislative changes have further supported adoption. In 2024, the allowable capacity limit was increased to 800 watts (AC) and 2,000 watts (DC), and registration requirements were simplified. Plug-in solar is now classified as a privileged measure (*privilegierte Maßnahme*) under German law, granting tenants legal rights to install systems even if facing opposition from landlords (Solarpaket I, 2024). However, the technology lacks a standardized product norm that ensures safety in production, installation, and usage, although a European standard is under development (Laukamp et al., 2024). Additionally, plug-in solar modules are like any solar modules and components exempt from value-added tax until the end of 2026 (JStG 2022). While Germany is the largest market, plug-in solar is legal in all EU states, except Sweden and Hungary, and recently legalized in Belgium (SolarPower Europe, 2025).

3. The Societal and Policy Relevance of Plug-In Solar

Plug-in solar has been increasingly framed as a form of societal participation in the energy transition. German Minister for Economic Affairs and Climate Action Robert Habeck described these systems as a low-threshold way for citizens to engage with the energy transition (Habeck, 2024). They offer an opportunity to broaden participation beyond the traditional demographic of homeowners and high-income households, potentially empowering tenants, lower- and middle-income groups, and urban residents (Agora Energiewende, 2017). The CEO of an industry association emphasized that "for us, the acceptance of the energy transition and the activation of as many citizens as possible to participate is central" (Müller, 2025).

Plug-in solar modules, while individually small in output, contribute to the growing complexity of energy system management. Grid operators have raised concerns about technical challenges in an increasingly decentralized system, including voltage fluctuations, bidirectional flows, and network stability (Praetorius & Hoelger, 2021; Siemer, 2024). However, decentralization must be assessed not only by its technical feasibility but also by its social and political value. As such, stakeholders, including policymakers, grid operators, and advocacy groups, have called for clearer strategies that address both the practical challenges of integration and the participatory potential of plug-in solar.

4. Research Gap and Study Contribution

The state of research reflects that plug-in solar is a niche product: only a few studies and data surveys have been carried out to date. Existing market research covers usage, motivations, and barriers (Bergner et al., 2022; Burckhardt & Pehnt, 2017; Praetorius & Hoelger, 2021), with most media reports relying on the report by Bergner et al. The typical user is male, highly educated, relatively affluent, and often a homeowner, highlighting a demographic skew in current adoption patterns (Bergner et al., 2022). Reported barriers include costs, grid operator regulations, installation concerns, and skepticism, especially among tenants (Bergner et al., 2022; Praetorius & Hoelger, 2021).

Technical research has focused on system performance, including power measurements (Gögelein et al., 2024), system integration (Dimara et al., 2023), optimized use with battery storage (Späth et al., 2023), and fire safety risks (Bergner, 2025). Notably, Burckhardt & Pehnt's study, along with others like Orth (2021) on energy analysis, Prinz (2019) on public attitudes, and Vietzke (2011) on market trends, stem from master's theses rather than peer-reviewed publications. A recent industry report has summarized the regulatory landscape in the EU (SolarPower Europe, 2025).

While some studies acknowledge the role of personal values such as participation, democracy, and leading by example in adoption decisions (Bergner et al., 2022; Burckhardt & Pehnt, 2017), there is little evidence on whether these values translate into sustained actions post-adoption. Bergner et al. (2022) identify this as a key research gap, particularly in the socio-psychological aspect of increasing acceptance through visible participation and the direct, measurable generation of solar power. This thesis addresses that gap by asking:

What is the socio-psychological impact of plug-in solar ownership in the German energy transition?

A quantitative survey among German plug-in solar owners (n = 294) investigates self-perceived changes in five outcome dimensions: environmental awareness, energy-related behavior, individual empowerment, political engagement, and peer effects. These dimensions were operationalized using Likert-type constructs. Statistical analyses were conducted to assess whether these changes differed significantly from neutral responses and to determine how they aligned with prior research and theoretical expectations.

The findings suggest that owning a plug-in solar system is associated with meaningful socio-psychological impacts, particularly in fostering empowerment, environmental awareness, and political engagement. Peer effects, by contrast, appear more limited, and the perceived energetic contribution is mostly overestimated.

By investigating the secondary impacts of adoption, which extend beyond energy generation, this study enhances our understanding of how small-scale technologies influence behavior and public engagement. It highlights the psychological and social dimensions of decentralized participation, contributing to debates in environmental psychology, energy justice, and participatory governance. The results can inform policymakers seeking to balance the technical, social, and political dimensions of the transition.

The remainder of this thesis is structured as follows. The next chapter introduces the development of the theoretical framework and five hypotheses, grounded in behavioral science and energy governance literature. The methodology chapter outlines the survey design, construct development, and analytical strategy. This is followed by the results chapter, which presents the analysis of survey and registration data. The discussion interprets these findings in light of theory and societal relevance and reflects on governance implications and avenues for future research. The final chapter concludes with a summary of the study's contributions.

Theoretical Framework

The study builds upon theories from environmental psychology, energy behavior research, social contagion theory, energy transition research, and gaps in plug-in solar research. To operationalize the socio-psychological effects of plug-in solar adoption, five hypotheses are developed within this theoretical context.

1. Theories of Behavior and Energy Transitions

The Theory of Planned Behavior (TPB) (Ajzen, 1991) provides a widely used framework for understanding pro-environmental behavior. According to TPB, behavior follows intentions, which are shaped by attitudes (e.g., environmental concern), subjective norms (e.g., social influence), and perceived behavioral control (e.g., self-efficacy). In the context of solar adoption, TPB suggests that both existing environmental attitudes and the sense of control over one's actions influence behavioral change. Meta-analyses, such as those by Schulte et al., synthesize research on rooftop solar adoption and confirm that psychological factors, especially environmental concern, novelty-seeking, and social norms, are stronger predictors of solar adoption than demographics or economic factors (2022). In Germany, perceived financial and autarky benefits drive purchase intention (Engelken et al., 2018). Wittenberg and Mathies found that German households with PV have a higher environmental motivation than other households (2016). While these studies primarily focus on rooftop solar, it is plausible that similar psychological mechanisms apply to plug-in solar as a more accessible technology. Echoing prior findings from rooftop PV research and environmental psychology (Hondo & Baba, 2010; Keirstead, 2007), it can be expected that plug-in solar owners exhibit higher environmental awareness, reflecting both pre-existing attitudes and potential reinforcement through ownership. This expectation leads to the first hypothesis:

H1: Ownership of a plug-in solar module increases environmental awareness above the German average.

This hypothesis reflects both the expectation that owners differ from the general population and that ownership reinforces awareness through personal energy production. Awareness is operationalized through self-reported changes in energy-related concern, climate conversations, and acceptance of the energy transition.

2. Energy Behavior and the ‘Double Dividend’ Effect

The presence of PV could benefit owners through electricity generated, but also through a long-lasting change in energy behavior, possibly creating a ‘double dividend effect’ as suggested by Keirstead (2007). However, findings on whether PV adoption leads to reduced energy use remain mixed.

The presence of PV and subsequent microgeneration can heighten environmental awareness, encouraging demand management and energy conservation (Keirstead, 2007). In Japan, PV-owning households reported adopting more environmentally friendly behaviors post-installation, with increased family discussions reinforcing this effect (Hondo & Baba, 2010). In the UK, a study estimated that behavioral responses to PV installment reduced overall electricity use by six percent, simultaneous to an increase in general energy awareness, both based on self-reported data (Keirstead, 2007). Gautier et al. show that higher environmental concern correlates with higher self-consumption (2019).

Conversely, it is argued that adapting energy demand to self-generated supply may be more challenging than expected, leading to less sustainable PV use. Wittenberg and Matthies showed that German households that installed PVs did not have lower electricity consumption, but higher environmental motivation compared to other households (2016). Instead, sufficiency attitudes and environmental motivation predicted energy-saving behaviors, resulting in reduced consumption. Similarly, Peters et al. (2019) documented for Dutch PV owners a weakening of the "sustainable PV identity" after installation, with intentions not always translating into actions. Older studies using consumption data found no significant reductions in electricity use post-PV installation in Germany (Erge et al., 2001) and Austria (Haas et al., 1999), although these precede the widespread adoption of smart meters and automation.

Thus, while research on PV household energy use is limited, with small samples, varied methodologies, and differing national contexts, it yields diverse results, making generalizations challenging. Plug-in solar may offer stronger incentives for self-consumption since most systems lack feed-in tariffs, meaning excess energy is effectively donated to the grid. However, it could also serve more as a statement of engagement than a practical energy-saving tool. This study explores whether ownership is associated with changes in energy-related behavior, contributing to the ongoing debate on the behavioral impacts of distributed solar systems:

H2: Ownership of a plug-in solar module leads to more sustainable energy behavior.

This includes self-reported changes in overall consumption, alignment of usage with solar production times, and attention to energy efficiency in purchasing decisions.

3. Autonomy, Empowerment, and Psychological Reward

Deci and Ryan demonstrate that autonomy is a crucial factor in making an activity inherently motivating, such as personal energy production (2008). The concept of 'warm glow' suggests that people derive emotional satisfaction from giving, which extends to environmentally friendly choices (Andreoni, 1990). Individual energy producers engage directly with the energy transition, directly experience the impact of their actions, and gain a deeper understanding of the energy system (Agora Energiewende, 2017). Specified to green energy, consumers may experience moral satisfaction, as their contributions benefit society through climate protection and energy independence. This psychological reward can outweigh financial considerations in decisions such as adopting solar energy (Sun et al., 2020; Wüstenhagen & Bilharz, 2006) and provides a reinforcing mechanism for pro-environmental behavior (Hartmann et al., 2017). These insights suggest that the participatory act of self-generation through plug-in solar may enhance individuals' confidence in their ability to contribute to the energy transition. Previous research on rooftop solar points to intrinsic motivations such as environmental values and the desire to lead by example as key drivers of adoption (Bergner et al., 2022); however, it remains underexplored whether these motivations translate into sustained feelings of empowerment post-adoption. This study investigates whether plug-in solar fosters such feelings of individual agency:

H3: Producing energy with a plug-in solar module enhances individual empowerment.

Empowerment is conceptualized as increased feelings of pride, self-efficacy, and belief in one's ability to contribute to the energy transition.

4. Political Engagement and Spillover Effects

Theories of behavioral spillover suggest that engaging in one pro-environmental action can increase the likelihood of adopting others, either directly such as reducing energy use or indirectly such as civic engagement (Steg et al., 2015; Van Der Werff et al., 2014). While some studies support spillover effects, a recent meta-analysis by Geiger et al. (2021) found generally small or negligible effects on behavior. Spillover is more likely when behaviors are autonomy-supportive, framed in normative terms, and not tied to financial incentives (Truelove et al., 2014). Within Wüstenhagen et al.'s concept of public acceptance, socio-political acceptance of the energy transition is reinforced by visible participation in decentralized energy production (2007). Plug-in solar's affordability and accessibility could empower groups traditionally excluded from renewable energy ownership, expanding the base of support for climate policy and collective action. This study examines whether ownership is associated with higher political engagement, such as discussions, petition signing, or advocacy for the energy transition:

H4: Plug-in solar ownership increases political engagement with the energy transition.

Engagement includes self-reported changes in civic participation, the importance of energy issues in voting, and public discourse.

5. Social Contagion and Peer Effects in Solar Adoption

Visible environmental behaviors foster social contagion, with individuals more likely to adopt behaviors modeled by others (Rogers, 1983; Schultz et al., 2007). Rooftop PV adoption often exhibits strong peer diffusion, with proximity and visibility driving uptake (Baranzini et al., 2017; Barton-Henry et al., 2021; Serra-Coch et al., 2023). The influence of peers increased when they were ascribed positive attitudes and consultation occurred at all decision-making stages (Scheller et al., 2021). Such dynamics have also been observed in related behaviors such as energy conservation and efficiency (Schultz et al., 2007; Wolske et al., 2020). Plug-in solar may foster similar dynamics, as modules on balconies or windows are highly visible in urban settings. At the same time, the technology's affordability and individualistic character may reduce the need for peer consultation or coordinated adoption. This study investigates whether ownership of a plug-in solar module increases social interactions and the perceived prevalence of plug-in solar within one's social environment, including being influenced by others, influencing peers, and engaging in solar-related conversations:

H5: Ownership of a plug-in solar module increases social interactions and perceived prevalence related to plug-in solar.

The hypotheses of this study are grounded in an interdisciplinary theoretical framework integrating insights from behavioral psychology, energy transition research, and gaps in the plug-in solar literature. In particular, the Theory of Planned Behavior (Ajzen, 1991) informs the analysis by linking attitudes, perceived behavioral control, and subjective norms to pro-environmental engagement. Drawing on this literature, five core hypotheses are formulated. Specifically, the study investigates whether producing one's own electricity affects environmental awareness (H1), energy-related behavior (H2), individual empowerment (H3), political engagement (H4), and peer interactions and influence (H5). Each hypothesis reflects a distinct but interrelated dimension of the socio-psychological impact of plug-in solar adoption. These hypotheses are operationalized as constructs that structure the survey design, guide the data analysis, and enable a structured exploration of whether and how plug-in solar contributes to behavioral and attitudinal shifts that extend beyond its immediate energetic function.

Methodology

This chapter outlines the research design, data collection methods, and analytical procedures used in the study. It details the survey design, sampling strategy, data analysis procedures, and the role of registration data as contextual material.

1. Research Design

This study employs a quantitative survey to investigate the socio-psychological impact of plug-in solar module ownership in Germany. The survey investigates self-reported changes in environmental awareness, energy behavior, feelings of empowerment, political engagement, and peer effects since adoption. These five dimensions form the basis for the five core hypotheses (H1-H5). While the survey provides the primary dataset, complementary registration data from the national energy market register (*Marktstammdatenregister*) contextualizes the scale, growth, and geographic spread of plug-in solar adoption. Selected qualitative comments from participants add further interpretive nuance in the discussion.

2. Data Collection and Survey Design

Survey

The online survey was distributed between April 7 and April 25, 2025, targeting German plug-in solar owners through forums (e.g., photovoltaikforum), Facebook groups, snowball sampling, and my personal network. In total, 350 responses were collected, of which 284 were retained after excluding non-owners (n=56) and entries with less than 90 percent item completion (n=10). The threshold aimed to preserve data quality while accommodating typical non-response in open fields and demographic questions. The survey ensured anonymity and neutral wording, characteristics that I fine-tuned through pilot testing.

The survey includes items measuring perceived change since adoption across five main constructs to research the hypotheses: Environmental awareness (H1), energy behavior (H2), individual empowerment (H3), political engagement (H4), and peer effects (H5), as visualized in Table 1. Questions per construct can be found in Appendix B. Each construct consists of 3-7 items measured on a five-point Likert scale from one ("strong decrease") to five ("strong increase"), with three indicating "no change". Constructs were not labeled, and items were presented in random order to discourage patterned responses. For each participant, construct scores were computed as the mean of the corresponding items. Cronbach’s alpha was computed to assess internal consistency.

Table 1. Overview of the constructs, survey questions and corresponding hypotheses

Construct	Questions	Hypothesis
Environmental awareness	A4, A5, A6	H1: Ownership of a plug-in solar module increases environmental awareness above the German average.
Sustainable energy use	B1, B3, B6	H2: Ownership of a plug-in solar module leads to more sustainable energy behavior.
Individual empowerment	D3, D4, D5	H3: Producing energy with a plug-in solar module enhances individual empowerment.
Political engagement	C1, C3, C4	H4: Plug-in solar ownership increases political engagement with the energy transition.
Social influence & visibility	E1, E2, E3, E4, E5, E6, E7	H5: Ownership of a plug-in solar module increases social interactions and perceived prevalence related to plug-in solar.

To enable a meaningful comparison with the general population, three key awareness items (Questions A1, A2, B5) are adapted from a representative study conducted by the German environmental agency (Grothmann et al., 2023). Two additional items on the psychological 'warm glow' were adapted from Sun et al (2020).

Demographic variables collected include age, gender, education, income, and homeownership. Respondents also selected their primary motivation for purchase (economic, idealistic, or other). A full list of survey items is provided in Appendix D.

3. Data analysis

Survey data

Descriptive statistics (means, standard deviations, and frequency distributions) summarized responses for each construct question, see Appendix B. To assess internal consistency, Cronbach's alpha was calculated for each scale. Construct scores were computed as participant-level means across relevant items, forming continuous variables for hypothesis testing.

To test Hypothesis 1, a Chi-square goodness-of-fit test was conducted, comparing the distribution of responses on two environmental awareness items (A1, A2) with nationally representative data from the Umweltbundesamt (Grothmann et al., 2023). The national data were reported as categorical response distributions and used as expected frequencies. This test is appropriate when evaluating whether observed categorical response distributions differ from known population distributions (Agresti, 2002).

Response categories were collapsed where needed to satisfy test assumptions regarding expected cell counts.

For Hypotheses 2 to 5, the goal was to assess whether self-reported changes in behavior or perception differed from a neutral midpoint of 3, which indicates "no change." As all participants were plug-in solar owners, between-group comparisons were not possible. Instead, one-sample tests were used to assess within-group deviation from this defined midpoint. One-sample t-tests are appropriate when testing whether a sample mean differs from a known or expected value, and are widely used in survey-based behavioral research (Bryman, 2016).

Prior to hypothesis testing, the normality of each construct score distribution was assessed using the Shapiro-Wilk test. If the data were normally distributed, a one-sample t-test was applied; otherwise, a non-parametric Wilcoxon signed-rank test was used. This approach follows established recommendations in the social sciences for analyzing Likert-type composite scores, particularly when sample distributions are skewed or assumptions of parametric testing are not met (Field, 2013). All analyses were performed in RStudio, and results are detailed in Appendix C.

Anonymous open-text comments from participants were used in the discussion to illustrate key themes. These were not formally coded but serve to contextualize quantitative findings.

Power Analysis

A power analysis was conducted in G*Power 3.1 (Faul et al., 2007) prior to data collection. Based on medium effect size conventions (Cohen's d = 0.5), $\alpha = 0.05$, and power = 0.80, a minimum of 64 participants was required for one-sample t-tests or Wilcoxon signed-rank tests (H2, H3, H4, H5). For H1, which involves a Chi-square test comparing distributions to national benchmarks, a minimum of 133 participants was required to meet expected count assumptions. Thus, accounting for missing data, the final number of 284 valid survey responses supports both hypothesis testing and subgroup comparisons, providing sufficient power for robust interpretation.

Registration Data

Registration data was sourced from the Federal Network Agency's core energy market register, downloaded on April 4, 2025. Using Python (pandas and geopandas), data were cleaned and analyzed to provide insights into cumulative capacity, installation trends over time, and regional distribution per capita. Rather than being treated as a separate dataset, the registration data were integrated into the descriptive section of the results to provide context for the survey findings. Specifically, they inform comparisons between perceived and actual contribution, illustrate national uptake trends, and situate respondent characteristics within broader patterns. While the registration data might be incomplete due to non-compliance with mandatory reporting, adjusted estimates accounting for underreporting were included based on the survey's self-reported registration rate. To contextualize survey findings, the total registered capacity is compared to participants' self-estimated impact.

Results

This chapter presents the empirical findings from the survey of plug-in solar module owners. First, an overview of respondent demographics and the current installations of plug-in solar provides context for interpreting subsequent results. Second, the core constructs of interest, environmental awareness, energy-related behavior, political engagement, individual empowerment, and peer effects, are analyzed both descriptively and inferentially, each in relation to its associated hypothesis.

1. Sample Characteristics and Installation Context

This section outlines the demographic characteristics and installation contexts of survey respondents and situates them within broader national patterns. It combines survey findings with registration data to clarify who adopts plug-in solar and how adoption has evolved across Germany.

The demographics of respondents are mainly male, with only 10.7 percent female and 5.7 percent diverse or not answering, see Figure 2a. The age range varies from 23 to 99 years, with the majority born between 1960 and 1990, see Figure 2b. Over half hold a university degree (51.3%). Respondents were nearly equally split between living in houses (39.8%) and flats (37.2%), and two-thirds were homeowners.

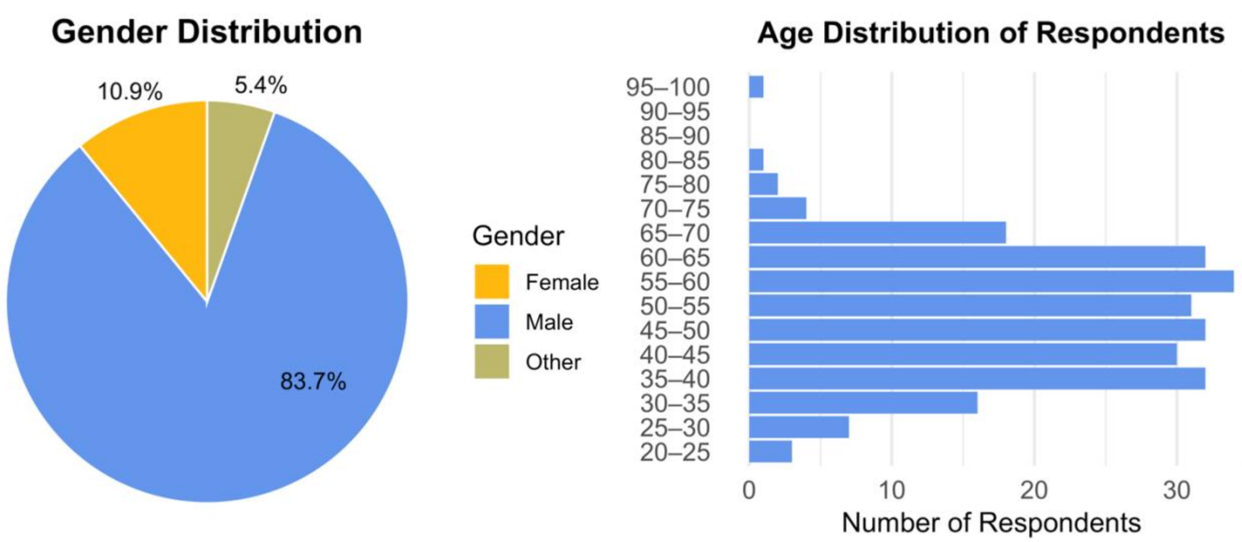

Figure 2. Gender and age distribution of survey respondents

Respondents reported a broad income distribution: A majority of respondents fall into net income brackets above €3,000, with 19.2 percent above €5,000, while ten percent reported to earn below €2,000, see Figure 3a. Most installations occurred in 2023, followed by 2024 and 2022, with a few early adopters before 2020, see Figure 3b.

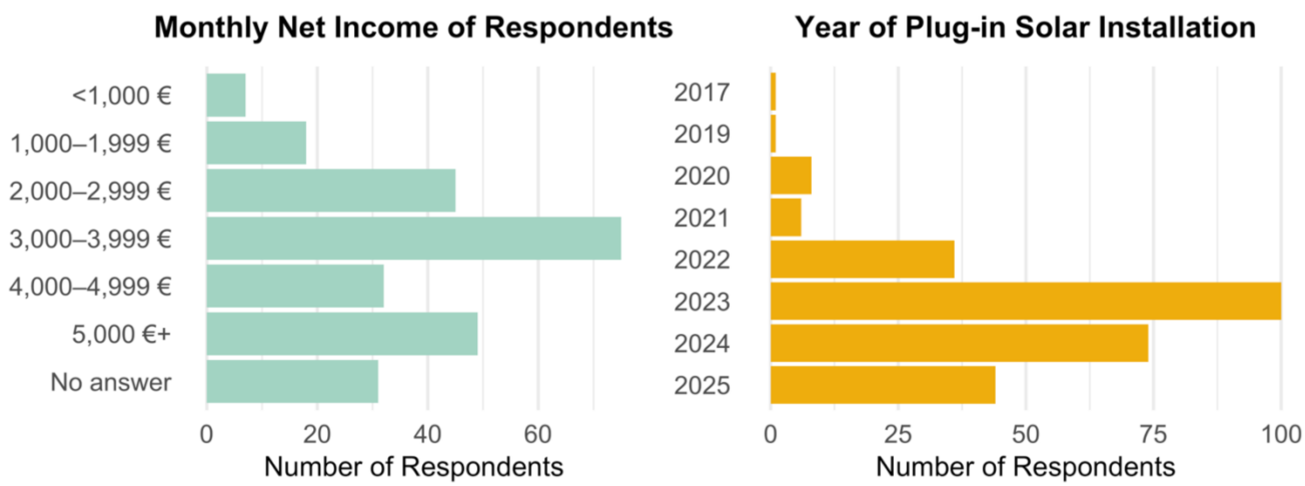

Figure 3. Monthly income and year of plug-in solar installation among survey respondents

Surveyed systems were most frequently installed on the balcony or terrace (43%), followed by roofs (23%), and gardens (14%). Less common placements included garages, garden sheds, and facades, see Figure 4. In 22 percent of cases, respondents had other energy systems in use, such as rooftop PV.

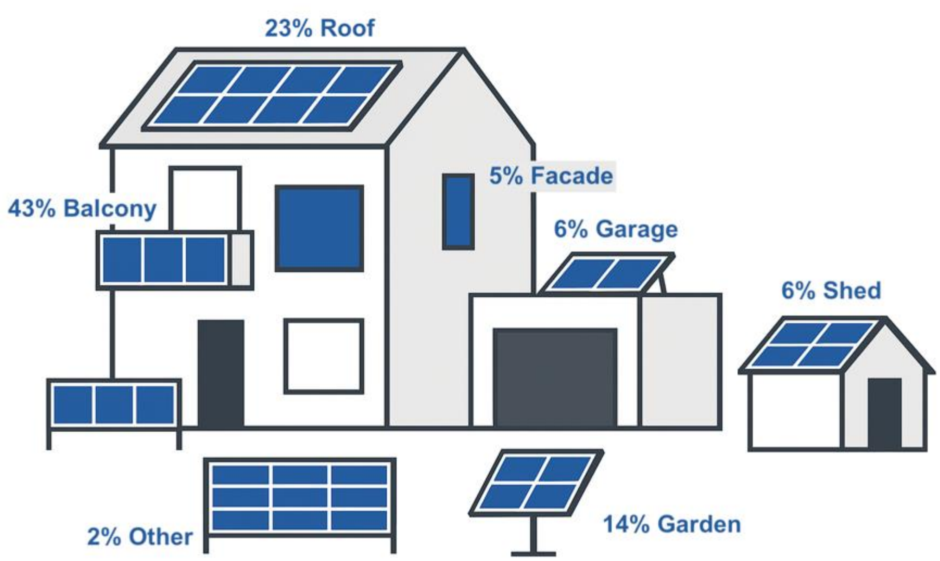

Figure 4. Placement of plug-in solar among survey respondents

The national core energy market register records a steep increase in plug-in solar adoption since 2021, with 912,533 systems officially registered by March 2025. See Figure 5 for an overview. These represent 610.18 MW of cumulative installed capacity. This corresponds to approximately 0.196 percent of Germany's total net electricity generation capacity, 0.332 percent of renewable energy capacity, and 0.655 percent of total installed photovoltaic capacity (Bundesnetzagentur, 2025).

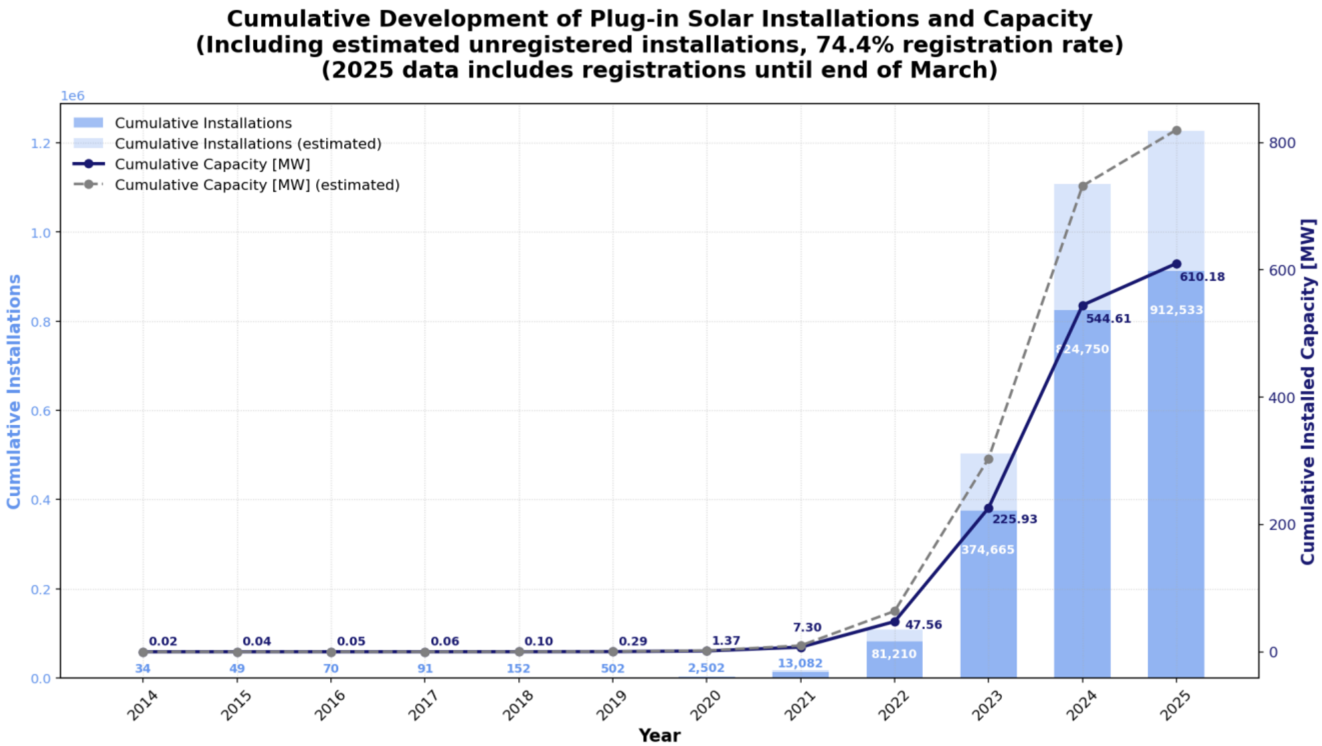

Figure 5. Cumulative development of plug-in solar installations and installed capacity, with extrapolated values based on survey registration rates

Survey data indicate a registration rate of 74.4 percent, suggesting underreporting in the official registry. Adjusted estimates yield approximately 1.23 million units and 820 MW installed capacity by March 2025, as visualized in Figure 5. To contextualize these figures, this capacity is comparable to the annual output of around 55 modern offshore wind turbines[1], or the electricity demand of approximately 213,700 German households[23].

[1] assuming 15 MW rated power such as Siemens Gamesa 14-222 DD or 14-236 DD (Siemens Gamesa, 2025)
[2] assuming the average energy consumption of a 2 person household in Germany in 2021 of 3,470 kWh annually (Statistisches Bundesamt, 2023b)
[3] assuming a capacity factor for solar PV of 10.3% from 2021 (Wirth, 2025, p. 44)

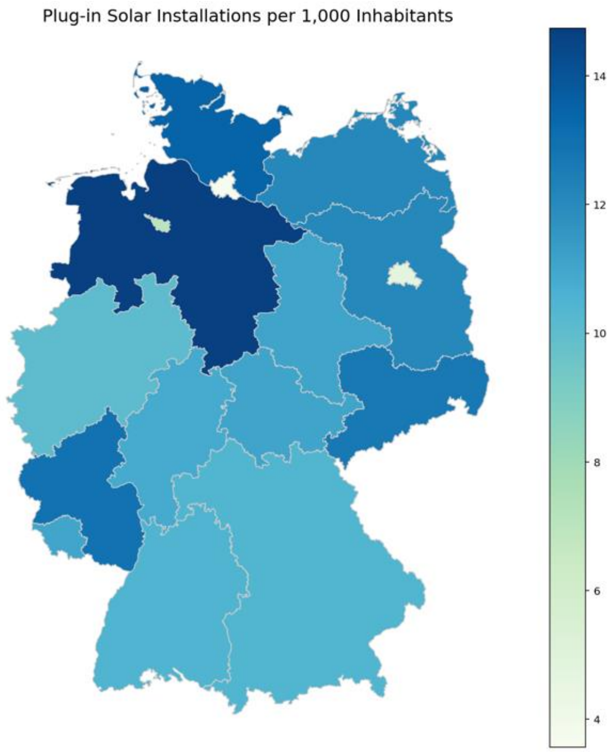

Figure 6. Plug-in solar installations per 1,000 inhabitants across German federal states

Looking across federal states, North Rhine-Westphalia and Bavaria lead in absolute registrations, while Lower Saxony, Schleswig-Holstein, Saxony, and Rhineland-Palatinate lead per capita, as seen in Figure 6. The city states of Bremen, Berlin, and Hamburg exhibit a much lower quota. Across Germany, the average is approximately 11 plug-in solar installations per 1,000 inhabitants, thus on average 1.1 percent of the German population owns a registered plug-in solar device (Statistisches Bundesamt, 2023a).

2. Adoption Motivations and Perceived Contribution

This section presents the motivations for adopting plug-in solar and contrasts user perceptions of system-level contribution with actual energetic figures.

Motivations for Adoption

Respondents could select multiple motivations. The most common were contributing to the energy transition (79%), technological interest (73%), and saving money (72%), followed by curiosity (64%) and environmental concern (61%). When asked for their primary motivation, most cited contributing to the energy transition or saving money, as visualized Figure 7, showing a balance of different motivation categories.

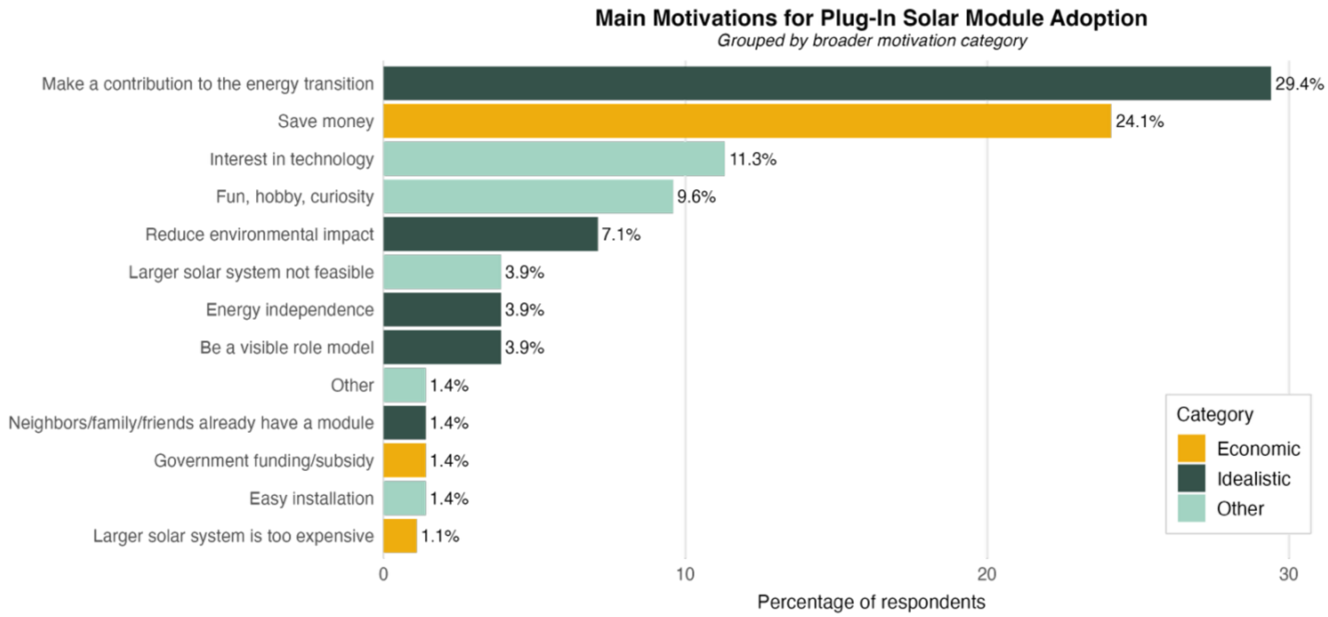

Figure 7. Survey responses on main motivation for plug-in solar adoption (n = 281)

Perceived versus Actual Energetic Contribution

Respondents were asked to estimate the share of Germany's total installed PV capacity attributable to plug-in solar modules. Estimates ranged from 0 to 50 percent, with a median of 2.0 percent and a mean of 4.85 percent, see Figure 8. In reality, the official share is only 0.655 percent, or 0.88 percent when adjusting for unregistered systems. This discrepancy implies that respondents overestimated the energetic contribution by a factor of 25 (official) or 18 (adjusted).

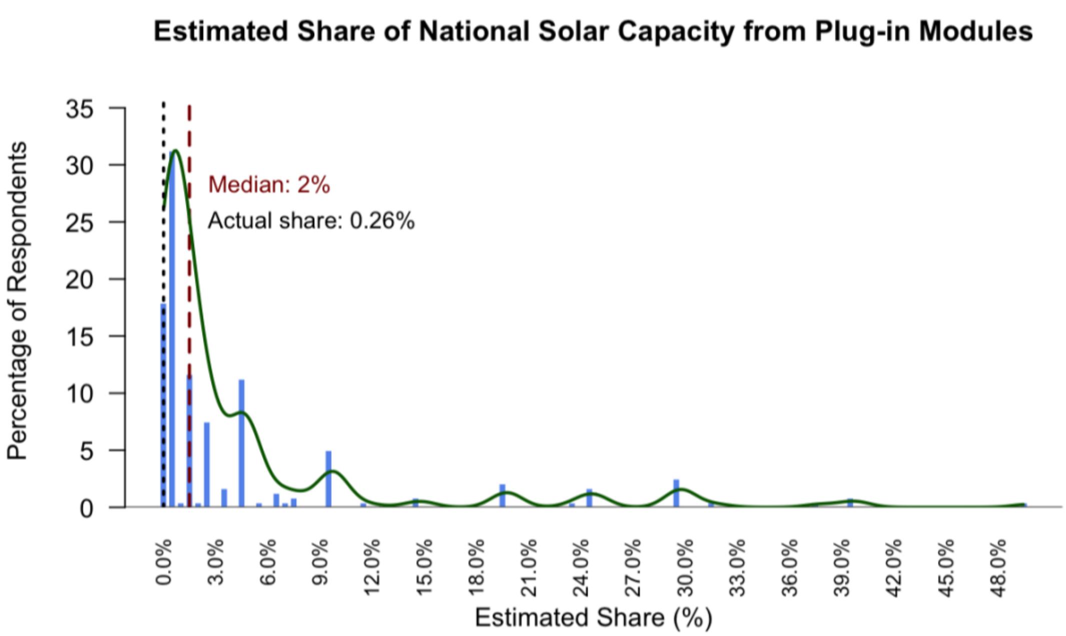

Figure 8. Distribution of survey responses on the estimated energetic contribution of plug-in solar modules

While the actual energetic contribution of plug-in solar remains relatively small, the observed overestimation among respondents suggests that many perceive their systems as more impactful than they are in technical terms. The following section investigates these outcomes in detail by analyzing self-reported changes in environmental awareness, energy-related behavior, empowerment, political engagement, and social influence.

3. Construct-Level Analyses

Environmental Awareness (Hypothesis 1)

The Environmental Awareness construct assesses whether plug-in solar ownership strengthens users' attention to sustainability and climate issues. It includes three items: changes in energy awareness (A4), engagement in climate discussions (A5), and acceptance of the German energy transition (A6). Internal reliability is high (Cronbach's $\alpha = 0.77$), indicating the items consistently capture the intended construct.

Participants reported a moderate increase in environmental awareness ($M = 3.41$, $SD = 0.56$, $n = 261$). Specifically, 42.5 percent reported increased awareness of energy issues (scores 4 or 5), while 56.7 percent reported no change. Similar patterns appeared for discussions on sustainability: 39.1 percent engaged more frequently in such conversations, while the rest reported no change. Acceptance of the German energy transition saw a smaller shift: more than a quarter reported increased acceptance, while two-thirds reported no change. Figure 9 illustrates these patterns across the three items.

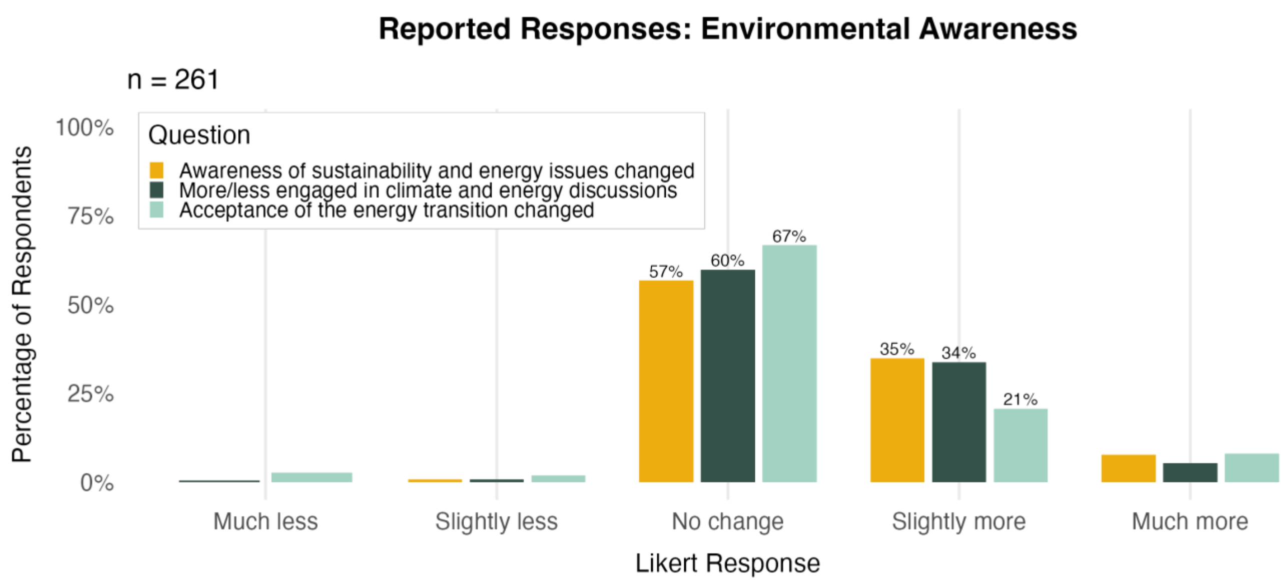

Figure 9. Survey responses on environmental awareness (n=261)

To test the construct, a composite awareness score was evaluated against the neutral midpoint (3). The distribution deviated from normality (Shapiro-Wilk $W = 0.89$, $p < .001$), so a Wilcoxon signed-rank test was conducted. The result showed that awareness scores were significantly above the neutral midpoint of 3 ($Mdn = 3.33$, $V = 11{,}744$, $p < .001$), indicating a perceived increase in environmental awareness following adoption. This supports Hypothesis 1.

To contextualize the findings, two additional items (equivalent to questions A1, A2) from the bi-annual *Environmental Awareness in Germany* survey (UBA) were included for comparison (Grothmann et al., 2023). Results show that 83 percent of respondents believe German citizens are not doing enough for climate protection, compared to 71 percent in the national sample. A Chi-square goodness-of-fit test confirmed this difference ($\chi^2(4, N = 261) = 109.47, p < .001$). Additionally, 93 percent of respondents rated environmental protection as important, slightly above the national average of 89 percent. This difference was also statistically significant ($\chi^2(2, N = 261) = 20.27, p < .001$). Figure 10 presents a visual comparison of these results.

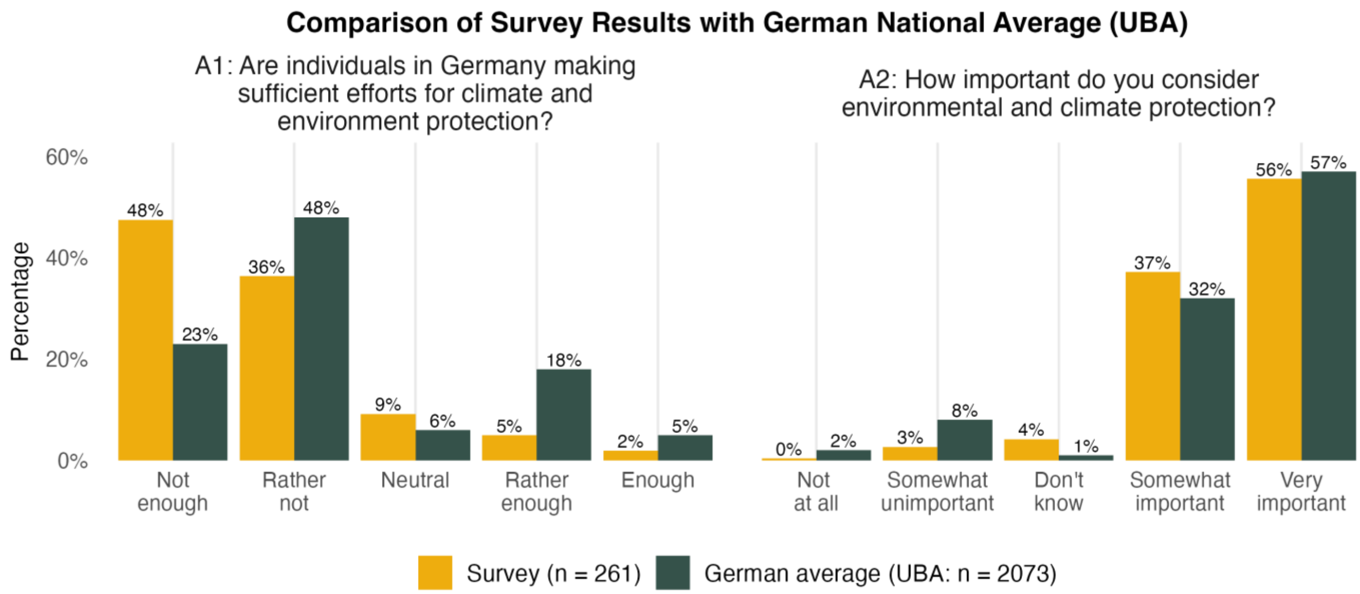

Figure 10. Survey responses and national German average on environmental awareness

Taken together, the construct-level analysis and the comparison with national benchmarks confirm Hypothesis 1. The results indicate that respondents perceive an increase in environmental awareness following the adoption of plug-in solar modules, and expressed greater concern for environmental issues than the general German population.

Energy-related Behavior (Hypothesis 2)

The construct of sustainable energy use examines the change in energy-related behaviors among survey respondents. An index was created by combining three Likert-scale items: self-reported change in total household electricity consumption (B1), change in aligning energy use with solar production times (B3), and change in choosing energy-efficient appliances (B6).

Among respondents, 75 percent reported that they now align their energy use more frequently with solar production times (B3, M = 4.2). A reduction in total energy consumption, meaning overall household use regardless of how much was self-produced or self-consumed, was reported by 55 percent, while 36 percent indicated no change, see Figure 11. Fewer respondents (15%) reported increased consideration for energy efficiency when purchasing appliances (B6, M = 3.2).

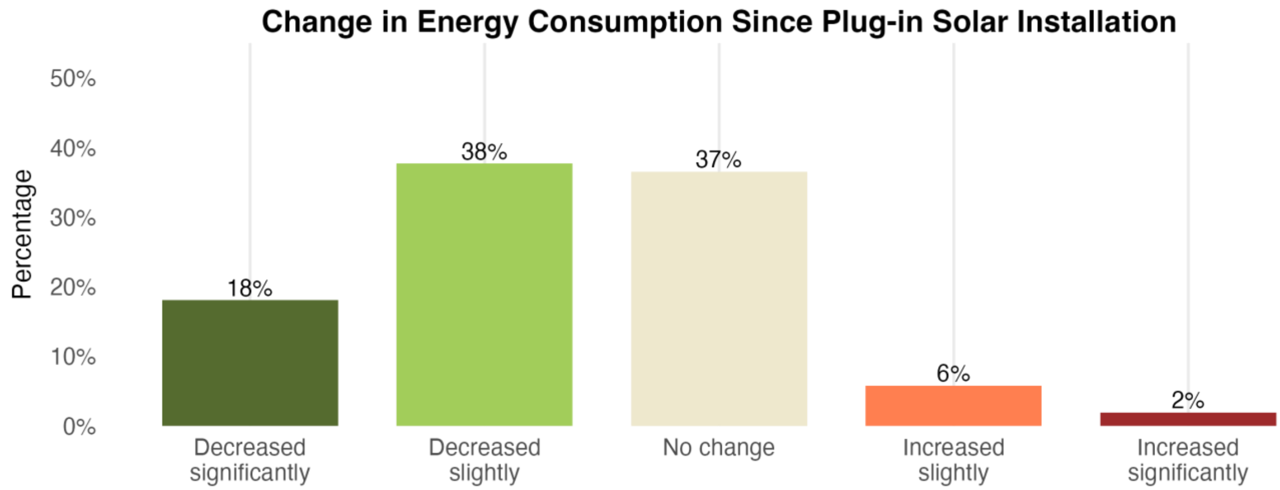

Figure 11. Survey responses on self-reported change in total energy consumption (n = 261)

Half of the respondents reported checking their solar production at least daily, while six percent stated they never check. This behavior was not included in the construct score as it doesn't reflect change but suggests a high level of interest in monitoring electricity production.

Reliability analysis showed low internal consistency among the three items (Cronbach's $\alpha = 0.24$; average inter-item $r = 0.11$), indicating they may represent distinct but related aspects of energy-related behavior. Despite this, the items were retained to capture a broader range of behavioral changes following the adoption of plug-in solar.

To test Hypothesis 2, an energy behavior score was calculated as the individual-level mean across the three items. A Shapiro-Wilk test indicated non-normality ($W = 0.95$, $p < 0.001$), prompting the use of a non-parametric Wilcoxon signed-rank test. The test indicated a significant positive deviation from the neutral midpoint (Mdn = 3.67, V = 25,172, $p < .001$), suggesting a moderate self-reported improvement in sustainable energy behavior. Hypothesis 2 is thus supported, indicating that plug-in solar ownership is associated with a moderate increase in perceived sustainable energy behavior.

Empowerment (Hypothesis 3)

The construct of individual empowerment investigates the psychological effects of plug-in solar adoption on individual agency and pride, including feelings of contributing to sustainability and confidence in the energy transition. It is measured by three Likert-scale items (D3, D4, D5) ranging from "strongly disagree" (1) to "strongly agree" (5). Internal consistency was good (Cronbach's $\alpha = 0.74$), indicating that the items reliably measured the construct.

The results show high levels of agreement across all items. On average, respondents scored 4.38 (SD = 0.67, n = 272), with the vast majority agreeing they feel a sense of pride in generating their own electricity (D3). Similarly, the majority reported that producing their own electricity strengthened their belief in the positive impact of individual action (D4), and also indicated increased confidence in their ability to contribute to the energy transition (D5). The distribution of responses across these items is shown in Figure 12.

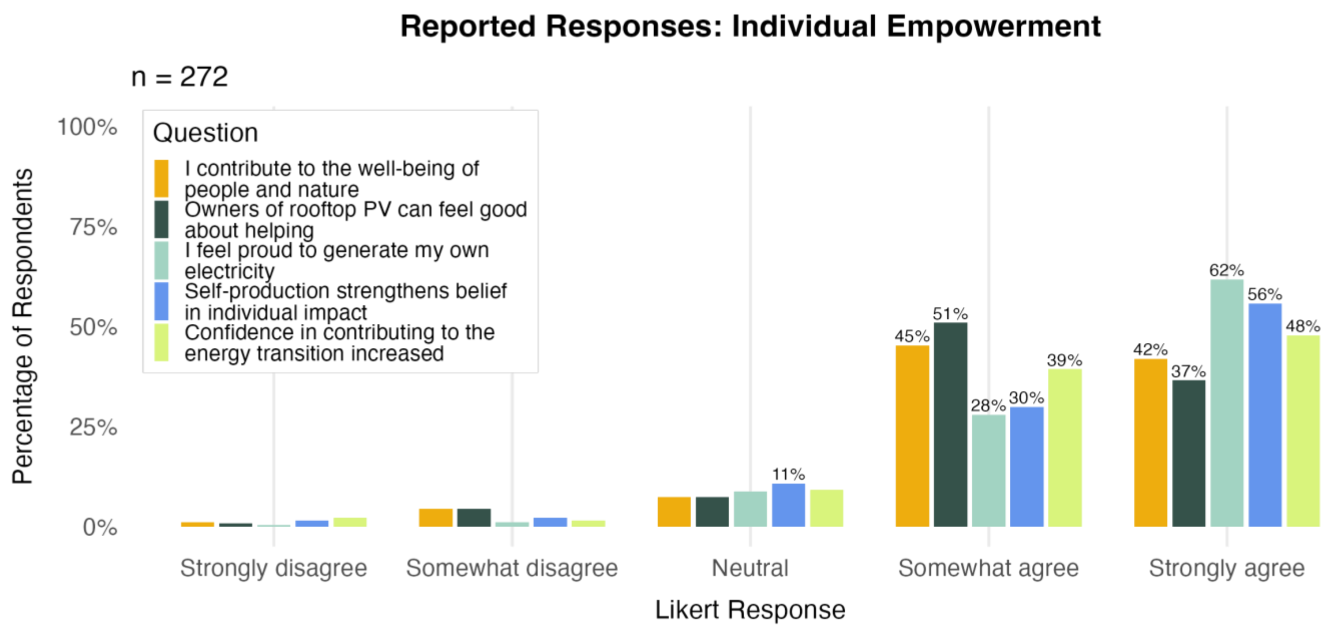

Figure 12. Survey responses on perceived change in individual empowerment

A Wilcoxon signed-rank test confirmed that perceived empowerment significantly exceeded the neutral midpoint (Mdn = 4.67, V = 34,635, $p < .001$), indicating that plug-in solar ownership is associated with strong feelings of personal agency and contribution. This supports Hypothesis 3.

Political Engagement (Hypothesis 4)

The Political Engagement construct captures whether plug-in solar ownership encourages users to engage more with energy and climate politics. It includes three items: general political involvement (C1), the importance of climate policy in voting decisions (C3), and frequency of discussions about the energy transition (C4). The questions asked about an increase or decrease since adopting a plug-in solar module. Internal consistency is acceptable (Cronbach's $\alpha = 0.75$), suggesting the items reliably represent the construct.

The average scores for all three items were around 3.4 on a 1-5 scale, suggesting a moderate increase in engagement, see Figure 13. Specifically, more than half of respondents reported no change in their general political involvement (C1), while slightly more than a third reported increased engagement ("more" or "much more"). For voting behavior (C3), around a third reported that climate and energy policy had become a stronger factor, while two thirds reported no change. Regarding public discourse (C4), almost half of respondents indicated they discussed the energy transition more often since adopting a plug-in solar module, while a small group (1.5%) reported a decrease.

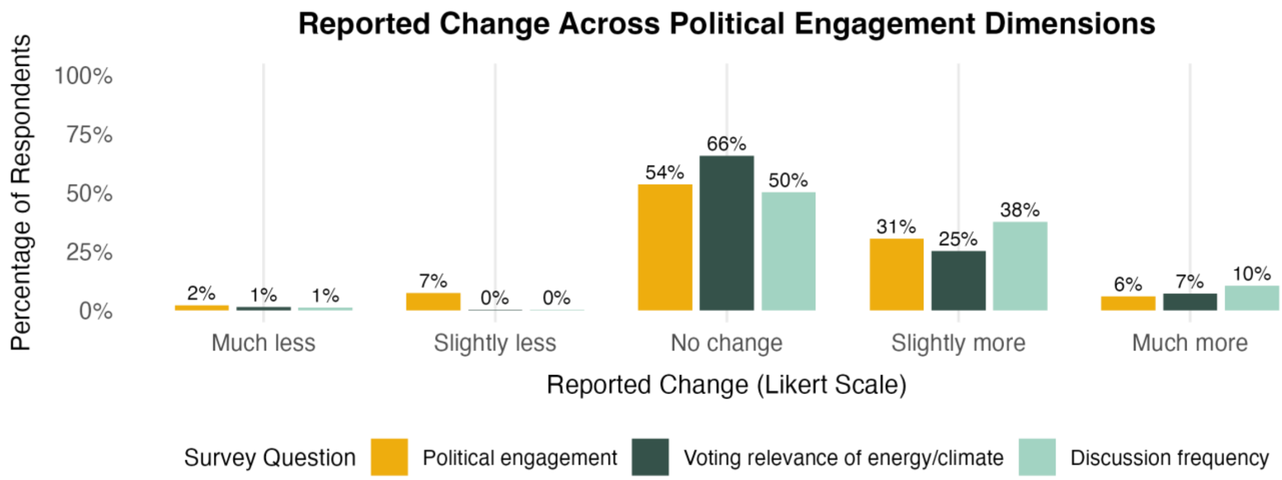

Figure 13. Survey responses on political engagement

To test Hypothesis 4, the composite political engagement score was compared to the neutral midpoint (3). Since the political engagement score deviated from a normal distribution (Shapiro-Wilk $W = 0.92$, $p < .001$), a Wilcoxon signed-rank test was conducted. The test revealed a significant increase in political engagement compared to the neutral midpoint ($Mdn = 3.33$, $V = 14{,}496$, $p < .001$). This suggests that plug-in solar ownership is linked to modest increases in political attentiveness and activity, thereby confirming Hypothesis 4.

Figure 14 shows the specific forms of political engagement reported.

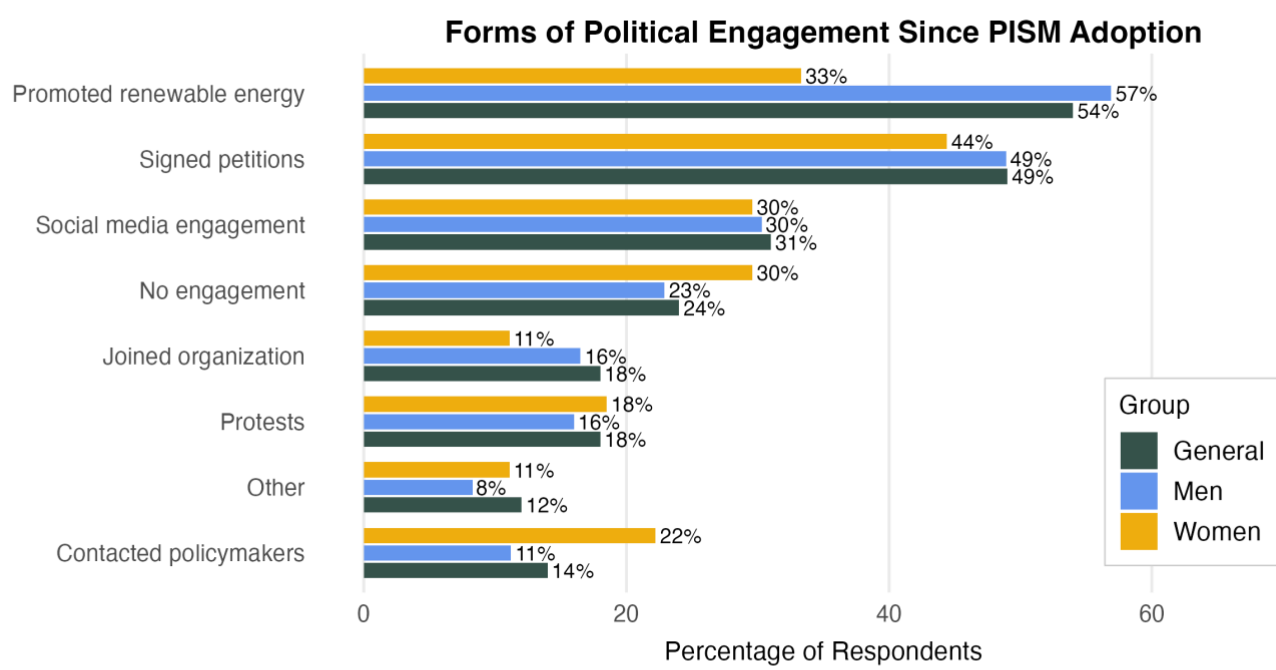

Figure 14. Survey responses on forms of political engagement by respondent groups (general, men, women), multiple selections possible

More than half of respondents indicated they had promoted renewable energy locally, while nearly half had signed petitions on energy policy matters. Other forms of engagement included social media advocacy, joining organizations, participating in protests, and contacting policymakers. Notably, men were more likely to promote renewables in their community, while women were more likely to contact policymakers.

Together, these results support Hypothesis 4, suggesting that plug-in solar owners indicate higher levels of political engagement and increased participation in sustainability-related behaviors since adoption of their PV module.

Peer Effects (Hypothesis 5)

The Peer Effects construct examines whether plug-in solar ownership is associated with increased visibility and social interactions related to plug-in solar within one's social environment. It is grounded in social contagion theory and the subjective norm component of the Theory of Planned Behavior. The construct comprises seven items covering perceived prevalence in one's social environment (E1), influence from and on others (E2, E4), recommendation behavior (E3), unsolicited conversations (E5), questions from peers (E6), and increased trust from others' installations (E7). Internal consistency was acceptable for a construct comprising diverse social dimensions (Cronbach's $\alpha = 0.65$).

Overall, reported peer influence appears limited. The construct mean was 2.65 ($SD = 0.56$, $n = 259$), suggesting a low-to-moderate level of perceived social diffusion. Only 14% of respondents perceived plug-in solar as widespread in their neighborhood (E1: scores 4 or 5), while 61% considered it uncommon (scores 1 or 2). Roughly 24% reported being influenced by someone in their social circle when deciding to adopt (E2).

Post-adoption interactions were somewhat more frequent. A majority (77%) reported recommending the technology at least monthly (E3: scores ≥3), with 25% doing so weekly or daily. Furthermore, 37% stated that others had considered installing solar after seeing their system (E4: scores 3-5), with 12% indicating they had influenced more than three people. Approximately 30% reported that others initiated conversations about their module at least monthly (E5), while 7% reported this happening weekly or daily. 41% agreed that seeing others' plug-in solar modules had increased their trust in renewable energy (E7: scores 4 or 5).

Following confirmed normality, a one-sample t-test revealed that peer effect scores were significantly lower than the neutral midpoint of 3 ($M = 2.65$, $t(258) = -10.02$, $p < .001$). These results suggest that while some interpersonal exchanges do occur, plug-in solar adoption has not (yet) achieved widespread social diffusion or visibility. Hypothesis 5 is therefore not supported.

Construct Overview and Comparison

Figure 15 provides a visual summary of all construct scores, including means, standard deviations, and the neutral midpoint for reference. Empowerment stands out as the highest-rated construct ($M = 4.38$, SD = 0.67, n = 272). Environmental awareness (M = 3.41, SD = 0.56, n = 261) and energy-related behavior (M = 3.67, SD = 0.49, n = 260) are closely aligned, both scoring significantly above the neutral midpoint. Political engagement (M = 3.41, SD = 0.60, n = 275) also exceeded the midpoint, though at a lower level. Peer effects (M = 2.65, SD = 0.56, n = 259) was the only construct scoring below the midpoint.

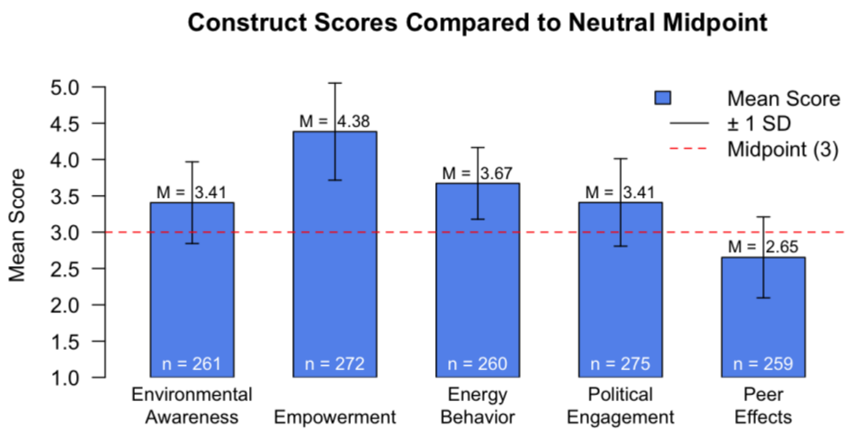

Figure 15. Construct scores compared to the neutral midpoint

Table 2 summarizes the statistical methods used to test each hypothesis and provides an interpretation of the results. Four out of five hypotheses were supported. Constructs related to environmental awareness (H1), energy behavior (H2), empowerment (H3), and political engagement (H4) showed statistically significant increases relative to the neutral midpoint. Hypothesis 5, addressing peer effects, was not supported.

Table 2. Overview of hypotheses, constructs, statistical methods, and outcomes

Hypothesis	Construct	Test	Result
H1	Environmental awareness	Wilcoxon signed-rank test	Supported: scores above midpoint; stronger concern than national average
H2	Sustainable energy use	Wilcoxon signed-rank test	Supported: moderate positive shift reported
H3	Individual empowerment	Wilcoxon signed-rank test	Supported: strong increase in self-efficacy
H4	Political engagement	Wilcoxon signed-rank test	Supported: moderate increase in political engagement
H5	Peer effects	One-sample t-test vs. midpoint	Not supported: scores below midpoint, limited peer visibility and influence reported

Discussion

This discussion reflects on the socio-psychological impacts of plug-in solar adoption in Germany, focusing on effects beyond energy generation. This study explored if ownership relates to shifts in awareness of energy and climate issues (H1), sustainable energy behavior (H2), individual empowerment (H3), political engagement (H4), and peer interactions and visibility (H5). The results supported four of the five hypotheses, with respondents reporting self-perceived increases in awareness, behavior, empowerment, and political engagement, while peer effects remained limited. Drawing on the Theory of Planned Behavior, the findings are interpreted in light of attitudes, perceived behavioral control, and subjective norms. In addition, survey data on perceived impact is compared with national registration data to assess the alignment between perception and actual contribution. The discussion now reflects on the results, integrates theoretical insights, to connect findings to societal and governance perspectives, and identify areas for future research.

Interpretation per Hypothesis

Environmental Awareness

Participants reported significantly higher environmental awareness compared to the national average, supporting H1. This aligns with prior research on visible participation fostering awareness (Wüstenhagen et al., 2007), and may trigger indirect spillover effects (Steg et al., 2015). Many participants reported an increased focus on energy and climate issues post-adoption, suggesting that the act of generating electricity oneself fosters deeper awareness. Interpreted through the Theory of Planned Behavior (TPB), awareness is part of attitude formation, which shapes intention and would predict behavior. However, two narratives were observed in the qualitative comments of the survey, suggesting both pre-existing concern and post-adoption reinforcement. While causality cannot be claimed, the findings support the hypothesis that ownership is associated with high environmental awareness, either already high before or increasing following the installation. This illustrates that decentralized actions can reinforce public acceptance and build environmental acceptance. From a governance perspective, it underscores the importance of supporting awareness with targeted behavioral interventions.

Energy Behavior

Energy-related behaviors showed moderate but significant changes post-adoption, supporting H2. Many respondents reported aligning electricity use with solar production or reducing overall consumption. The results match the mixed findings on energy behavior change reviewed earlier on ‘large’ solar adoption (Schulte et al., 2022), and resonate for part of the respondents with Keirstead’s ‘double dividend’ effect (Keirstead, 2007), which suggests that ownership can foster both electricity production and behavioral change. However, the construct showed a low internal consistency, suggesting these behaviors may represent distinct rather than unified patterns. It shows that producing energy oneself can create new routines, such as checking the production and aligning consumption times. From a theoretical perspective, TPB highlights that even when attitudes, represented in this study by environmental awareness, and perceived behavioral control, reflected through the empowerment construct, are strong, intentions do not necessarily lead to consistent behavior. This phenomenon is commonly referred to as the intention-behavior gap (Bhushan et al., 2021; Peters et al., 2019), where individuals may hold strong pro-environmental attitudes and feel capable of acting, yet still fail to follow through due to situational constraints, competing priorities, or behavioral inertia. It might simply also show a flaw of the research, as one respondent shared: "we did all the other sustainable things first and solar was last on the list".

Beyond individual psychology, these behaviors also carry broader societal significance. Demand-shifting, such as aligning electricity use with periods of solar production, can contribute to balancing supply and demand in a system increasingly reliant on intermittent renewables. Behavioral engagement thus complements the technical side of the energy transition, playing a critical role in enabling flexible, resilient energy systems. The recent legislative change with the solar peak law (*Solarspitzengesetz*) promotes own consumption by pausing feed-in tariffs for large solar PVs during solar peaks. This underscores the importance of household-level flexibility.

These results affirm the potential of plug-in solar to nudge behavioral shifts. Governance interventions should address these gaps by supporting sustained engagement and promoting energy literacy.

Empowerment

Empowerment emerged as the strongest and most consistent effect. Respondents expressed high levels of pride, confidence, and belief in their individual impact, supporting H3. This aligns with Deci and Ryan's (2008) emphasis on autonomy in fostering intrinsic motivation, and with literature on the psychological rewards of environmental action (Andreoni, 1990). Participants reported that generating electricity enhanced their perceived agency and sense of meaningful contribution. In TPB terms, this reflects increased perceived behavioral control, where confidence in one's capacity facilitates action, which supports both intention and action. From a governance perspective, the strength of this psychological outcome underscores the value of plug-in solar as a participatory tool.

Political Engagement

Participants reported moderate increases in political engagement post-adoption, both in attitudes (e.g., voting considerations) and behaviors (e.g., petitions, advocacy). These results support H4 and suggest that ownership may foster not only personal awareness but civic engagement. This aligns with theories of behavioral spillover (Steg et al., 2015) and the notion that decentralized participation can enhance socio-political acceptance (Wüstenhagen et al., 2007). Respondents' comments indicated that plug-in solar served as a catalyst for energy transition discourse within their communities. While these self-reports do not establish causality, they highlight a meaningful link between technological participation and political engagement

These findings highlight a critical tension: while plug-in solar fosters individual engagement, its capacity to drive broader political change remains limited. In the context of growing opposition to the energy transition, including populist backlash and opposition to local projects known as NIMBYism (O'Neil, 2021), small-scale participation can act as a counterforce by normalizing visible engagement. When individuals actively decide to use their backyard (or balcony), they visibly normalize engagement. Especially as nearly half of the respondents reported more frequent discussions of the energy transition, signing petitions, and more than half reported promoting renewable energy locally, although selection bias might have led to an overrepresentation. Yet, without structural support, such engagement risks remaining fragmented and symbolic rather than transformative.

From a governance perspective, this pattern highlights the potential of plug-in solar modules to serve as a democratizing technology: lowering the barriers to participation for those with fewer resources, while also underscoring the limits of participation for those with greater access to alternative forms of climate action. Thus, policy interventions should go beyond technological diffusion by fostering civic engagement and supporting pathways through which small-scale participation can contribute to political agency and collective momentum in the energy transition.

Peer Effects

Hypothesis 5 examined whether plug-in solar adoption increases peer interactions and the perceived prevalence of the technology within one's social environment. The results did not support H5. The construct scored significantly below the neutral midpoint, suggesting limited social diffusion, influence, or visibility. While some respondents reported post-adoption conversations, recommendations, or peer inquiries, only a small minority perceived plug-in solar as widespread in their community or felt they had influenced others.

These findings contrast with literature on rooftop PV, where social contagion plays a significant role in adoption through visibility, proximity, and interpersonal consultation (Baranzini et al., 2017; Barton-Henry et al., 2021). Several explanations are plausible. First, plug-in solar's individualistic nature and low financial threshold may reduce reliance on peer consultation. Second, the relative novelty of the technology may mean that critical mass has not yet been reached for meaningful peer diffusion. Finally, informal exchanges may increasingly take place in digital spaces, such as online forums or social media, rather than through neighborhood interactions, potentially limiting perceived local visibility.

From a TPB perspective, this finding reflects a weak presence of subjective norms: few respondents perceived strong social pressure, modeling, or encouragement related to plug-in solar. While attitudes (environmental concern) and perceived behavioral control (empowerment) were strongly represented, subjective norms appeared to play a lesser role in this form of decentralized energy adoption. From a governance standpoint, this highlights a potential area for policy and communication strategies: encouraging local visibility, showcasing installations in community spaces, and supporting peer exchange may help foster broader diffusion and normalize participation.

Perceived vs Actual Contribution

Registration data confirm that while the total installed capacity of plug-in solar remains modest in energetic terms, the number of installations is high and geographically widespread across Germany. These figures likely underestimate actual adoption. Other sources, such as Bergner (2025), estimate between 1.5 and 4 million devices, depending on assumptions about unregistered systems and market dynamics. The sharp increase in registrations in recent years is likely influenced by the 2024 introduction of mandatory reporting *(Solarpaket I, 2024)*. When asked to estimate the national contribution of plug-in solar, participants' responses varied, with some estimating very low and others markedly higher shares. On average, responses exceeded the actual capacity. This tendency to overestimate may suggest a sense of perceived efficacy. Even when the energetic impact is modest, the act of self-generation can foster a tangible sense of participation. As one respondent put it, "The 'value' of a kilowatt-hour became much more tangible thanks to the plug-in solar devices." These findings illustrate that small-scale energy technologies can shape not only energy flows but also perceptions of agency and relevance, particularly when energy becomes visible and personally meaningful.

Cross-Cutting Themes and Theoretical Reflections

This study extends existing research by demonstrating that values such as participation, democracy, and setting an example, previously identified as important in the adoption decision (Bergner et al., 2022; Burckhardt & Pehnt, 2017), also persist post-adoption. The survey findings suggest that these values are realized both in participants' subjective perceptions, reflected in enhanced feelings of empowerment, and in their concrete actions. These mechanisms align with broader literature on environmental psychology, which highlights the importance of normative motivations in sustaining pro-environmental behavior (Steg et al., 2015). As one participant summarized, "In my opinion, the main contribution of plug-in solar devices to the energy transition is not so much the amount of solar energy that is contributed. Rather, they give people a relatively low-threshold opportunity to participate in the energy transition". Another added: "Balcony power plants make the value of electricity visible and encourage the conscious use of electrical energy."

The Theory of Planned Behavior provides a structured way to interpret these patterns: awareness aligns with attitudes, empowerment with perceived behavioral control, and peer effects with subjective norms. While awareness and empowerment were strongly represented, peer effects were limited, suggesting a relatively weak role for social normative pressure in plug-in solar adoption. The intention-behavior gap observed for energy-related practices illustrates the limits of TPB in predicting action, suggesting the need to integrate situational or contextual factors into behavioral models. As one respondent put it: "Many of the questions assume a certain causality [...]. In reality, a generally higher environmental awareness probably often goes hand in hand with interest in a plug-in solar system.". Another participant echoed this sequencing: "We did all the other sustainable things first and solar was last on the list." This observation underscores a key limitation of the TPB approach: while it provides a valuable lens to examine motivational dynamics, it cannot alone establish causality. Rather, this study aims to move the ball closer to identifying a potential relationship, while acknowledging the need for further longitudinal research to more rigorously establish temporal sequences and causal effects.

The demographic profile of the sample - predominantly male, middle-aged, and highly educated - resembles that of early adopters in previous studies (Bergner et al., 2022). While plug-in solar lowers technical and financial barriers, the survey shows that other factors such as cultural and informational access may still shape participation. While plug-in solar is often framed as a low-cost, accessible technology, the income profile of survey participants reveals limitations to this inclusivity: female and lower-income respondents remain underrepresented, indicating that barriers persist. This pattern is further reflected in regional adoption rates: the per capita spread of plug-in solar was significantly lower in the city states of Berlin, Hamburg, and Bremen compared to other federal states. Urban-specific constraints such as limited installation space, high rental rates, and stricter building regulations may reduce the accessibility in reality. These findings underline that while plug-in solar broadens access, it does not yet ensure equity. Nonetheless, the relatively wide spread of income brackets in the sample, including respondents citing cost or infeasibility of rooftop PV as reasons for their adoption, supports the interpretation that plug-in solar may still serve as a meaningful entry point for some households otherwise excluded from renewable energy participation.

For many respondents, high costs or technical constraints made rooftop solar unattainable, survey data showed that 11 percent cited rooftop system cost, and 33 percent cited feasibility issues as main motivation for adoption. Moreover, 72 percent reported adopting plug-in solar, among other reasons, to save money. Beyond immediate affordability, plug-in solar enables users to reduce their vulnerability to future energy price fluctuations by generating part of their electricity independently. Yet affordability alone is insufficient. Knowledge access remains an important factor: those who understand how to install, optimize, and utilize their systems effectively can maximize energy production, reduce consumption costs, and shorten the payback period. While the survey found limited direct peer exchange, online communities, forums, and interest groups offer important resources for sharing knowledge and providing informal support. This informal peer learning network helps address knowledge barriers and fosters energy literacy among participants, extending the benefits of plug-in solar beyond individual households. One respondent reflected: "Since I bought the system, it has become a real passion and I have told many people about it, shared experiences, and offered personal advice so that even more people get in touch with the topic." Governance strategies should invest in such platforms and promote technical literacy.

Plug-in solar, therefore, not only offers a low-cost entry point into the energy transition but also creates opportunities for individuals to build technical understanding and adopt more sustainable energy practices in their daily lives. This is not just an individual benefit, but address the limited focus in the energy transition on the demand side of the energy system. It increases public understanding of energy flows, raises awareness of the challenges posed by renewable intermittency, and encourages adaptive energy use behaviors.

Rethinking Participation in the Energy Transition

From a broader perspective, plug-in solar can be seen as a case study for low-barrier and small-scale participation in the energy transition. The case adds nuance to the role of perceived significance and emotional rewards of participation. It shows how participation is a multi-dimensional phenomenon, going beyond the generation of energy alone. Its participatory potential supports political framings that emphasize energy democracy (Habeck, 2024). By fostering both feelings of contribution and real behavioral changes, the technology invites a reconsideration of what counts as impactful participation in the energy transition. Plug-in solar adds nuance to the role of perceived significance and emotional rewards of participation, showing how civic engagement extends beyond energetic output.

Implications for Governance and Practice

These results suggest that plug-in solar can serve as a democratizing tool in the energy transition, as one respondent put it: “energy transition from the bottom up!”. Plug-in solar modules can broaden participation for groups traditionally excluded from renewable energy ownership, addressing dimensions of energy justice concerns. However, broader engagement depends not only on access to technology but also on fostering motivation, knowledge, and skills. Governance strategies must go beyond hardware access: they should support energy literacy, communicate the societal value of participation, and pursue targeted outreach to underrepresented groups. Plug-in solar, therefore, is not only a source of energy generation but can play a small role in building societal resilience, empowering citizens, and fostering a culture of climate action. Policies should recognize its function in raising awareness of renewable intermittency, encouraging demand-side participation, and enabling adaptive behavior. Communication strategies should emphasize its role in both enabling action and signaling engagement. Gender-sensitive outreach and peer-learning initiatives can help extend participation across more diverse social groups. To expand participation further, policy should also address the limited role of peer effects observed in this study. Supporting local visibility, community showcases, and informal exchange, especially outside of digital spaces, could strengthen social contagion and normalize adoption beyond early adopter circles.

Limitations & Future Research

These findings offer important insights but are subject to several limitations. First, the sample, primarily recruited through online solar forums and Facebook groups, likely overrepresents individuals who are idealistically motivated and technologically engaged. This may have resulted in an overrepresentation of highly motivated or technologically engaged users. While snowball sampling introduced some diversity, the overall sample remains self-selected. Future research should aim to reach a broader and more diverse sample, potentially through randomized recruitment or population-based sampling. Second, the cross-sectional design limits causal inferences. Although respondents reported changes since adopting plug-in solar, the study lacks a pre-adoption baseline or control group. Longitudinal designs would allow for stronger claims about the directionality and persistence of reported changes. Third, all outcome measures were based on self-report, which may be influenced by social desirability or recall bias., and the risk of misreporting remains. Complementary methods, such as behavioral tracking, interviews, or experimental designs, could help validate and deepen understanding of these findings. Lastly, the use of national registration data was primarily descriptive. Future research could integrate spatial or temporal analyses more systematically, including potential clustering effects or regional policy influences. Comparative studies across different solar technologies and national contexts would also enrich the understanding of decentralized energy participation.

Taken together, these findings show that plug-in solar systems, though modest in energy output, can have notable socio-psychological effects. Across the constructs of environmental awareness, energy-related behavior, empowerment, and political engagement, ownership was associated with self-reported positive change. These findings suggest that even small-scale technologies may reinforce pro-environmental attitudes and actions, enhance perceived agency, and promote engagement with the energy transition. The fifth hypothesis, concerning peer effects, was not supported, indicating that social visibility and interpersonal influence remain limited at this stage. While the technology's low-threshold nature enables participation from individuals otherwise excluded, barriers related to income, gender, and informational access persist. This indicates that affordability and simplicity alone do not guarantee inclusivity. To unlock its full potential, governance strategies must actively support energy literacy, encourage peer exchange, and promote the visibility of decentralized participation. Small-scale technologies such as plug-in solar can thus serve as accessible entry points into meaningful engagement with the energy transition: fostering change that is behavioral, democratic, and socially significant.

Conclusion

This thesis investigated the socio-psychological impacts of plug-in solar adoption in the context of the German energy transition, addressing the question: *What is the socio-psychological impact of plug-in solar ownership in the German energy transition?* The study builds on literature from environmental psychology, energy behavior research, and social contagion theory, exploring whether small-scale, visible participation can foster broader engagement beyond its limited technical contribution. Grounded in the Theory of Planned Behavior, five hypotheses were tested regarding the effects of plug-in solar ownership on environmental awareness (H1), energy-related behavior (H2), individual empowerment (H3), political engagement (H4), and peer effects (H5).

The findings provide support for four out of five the hypotheses. Plug-in solar ownership is associated with higher environmental awareness, modest but positive changes in energy behavior, increased political engagement, and a strong sense of empowerment. These findings indicate that decentralized, small-scale technologies can play a meaningful role in shaping pro-environmental attitudes and behaviors. In contrast, peer effects were limited. Respondents did not perceive plug-in solar to be widespread in their social environment, and few reported being influenced by or influencing others directly.

The comparison between perceived and actual energetic contribution revealed a substantial overestimation of plug-in solar's role in the national energy system. Despite this gap, the technology is seen as a way to participate meaningfully in the energy transition. Many respondents valued the personal experience of producing electricity, reducing costs, and gaining a sense of independence. These perceived benefits may be especially relevant for those excluded from conventional rooftop solar, such as tenants or households with limited financial resources.

The findings underscore the societal relevance of enabling broader participation in the energy transition. Plug-in solar can increase energy literacy, foster awareness of renewable intermittency, and promote adaptive energy practices that support system flexibility. Its affordability and accessibility allow it to function as a democratizing technology, helping lower barriers for a more diverse range of users. However, as the demographic profile of respondents shows, participation remains skewed toward middle-aged, highly educated, and higher-income individuals, indicating that cultural, informational, and economic barriers still persist.

The study contributes to theoretical debates by illustrating how the components of the Theory of Planned Behavior - attitudes (awareness), perceived behavioral control (empowerment), and subjective norms (peer effects) - are reflected in the context of plug-in solar ownership. The strong outcomes for awareness and empowerment suggest that personal experience with decentralized energy can support behavioral and psychological engagement. The limited peer effects, however, point to the need for stronger community-based or policy-supported mechanisms to enhance visibility and social learning.

For policymakers and practitioners, the results emphasize that fostering small-scale participation requires more than technical access or financial incentives. Communication strategies should highlight the societal relevance of participation, while outreach efforts should target underrepresented groups. Investing in peer learning networks, local visibility, and inclusive communication can help realize the broader societal potential of plug-in solar.

Overall, the findings underscore that the energy transition is not solely a matter of infrastructure or economics: it is also shaped by individual perceptions, motivations, and lived experience. By examining plug-in solar - a relatively recent, low-threshold form of decentralized energy participation - this study contributes empirical insight to ongoing debates on individual agency, behavioral spillovers, and participatory governance in energy transitions. It shows that small-scale ownership can foster environmental awareness, perceived control, and political engagement, even in the absence of strong social diffusion. On a societal level, the research underscores the value of enabling accessible, everyday forms of participation that resonate with citizens' sense of agency and identity. Recognizing and supporting the psychological and participatory dimensions of such technologies can help make the energy transition more inclusive, civic-minded, and embedded in daily life.

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Appendices

Appendix A. Reflection on Transdisciplinarity

My curiosity for this topic started with a personal frustration: like many people my age, I care about the energy transition, but often feel powerless to actively take part in it. As a student living abroad without property or long-term stability, most climate-friendly technologies (like heat pumps or electric cars) felt out of reach. Plug-in solar modules seemed like a rare case of accessible, hands-on participation in the energy system, and like a very tangible form of engagement.

From early on, I looked beyond academic literature to understand how this technology is perceived and used in practice. I joined Facebook groups and online forums, where users asked for advice, proudly posted generation statistics, shared frustrations, and even debated misinformation (like whether balcony modules pose fire risks). I reached out to owners of plug-in and larger PV to understand their motivation and perception. These platforms offered insight into the everyday realities and informal knowledge shared within the community. I also engaged with grey literature, including YouTube tutorials, blogs, and podcasts, to better understand the emotional, technical, and political dimensions from the user perspective. In parallel, I had informal conversations with users and family members of users, which helped me better understand how balcony solar is perceived compared to larger rooftop systems.

To get more formal perspectives, I reached out to the *Bundesverband Steckersolar* and *Solar2030*, citizen interest groups lobbying for simpler rules and more political recognition. They expressed strong interest in the results of the research, and in keeping in touch. I also spoke to someone from the Federal Ministry for Economic Affairs and Climate, who expressed concern about the unregulated rise of these devices and their impact on grid stability. This contrast between grassroots enthusiasm and institutional skepticism helped shape the framing of the research.

In the survey, I included an open comment field and 52 respondents used it to share motivations, confusions, technical hurdles, and general reflections. Some of their input even helped me adjust and improve the survey early on. Several respondents and interest group representatives also expressed interest in the results, reinforcing the societal relevance of the topic beyond academia.

Discussions with peers and my own reflections throughout the process highlighted the role of plug-in solar as a low-threshold entry point into the energy transition, especially for those who might otherwise feel excluded. This project was shaped by a range of perspectives: from institutions to citizens, from technical details to lived experience. These inputs were not just background, but actively informed the design, interpretation, and direction of the research.

Appendix B. Overview of constructs and questions statistics

Construct	Questions	Average	Median	sd	n
A) Environmental Awareness	A1 In your opinion, are individuals in Germany making sufficient efforts toward environmental and climate protection? (Likert: Enough - Rather enough - Neutral / In between - Rather not enough - Not enough)	1,77	2	0,94	261
	A2 How important do you consider environmental and climate protection? (Likert: Very important - Somewhat important - Somewhat unimportant - Not at all important - Don't know)	4,45	5	0,74	261
	A4 Since installing my module, my awareness of energy issues and sustainability has changed. (Likert Scale: Less - More)	3,49	3	0,65	261
	A5. Since installing my module, I feel more or less engaged in discussions about climate change and energy policy. (Likert Scale: Less - More)	3,43	3	0,63	261
	A6. My acceptance of the German energy transition has changed. (Likert Scale: Less - More)	3,3	3	0,76	261
B) Sustainable Energy Use	B1 Since adopting your plug-in solar module, has your overall energy consumption changed? (Likert: decreased significantly, decreased somewhat, no change, increased somewhat, increased significantly)	2,36	2	0,91	260
	B3 Compared to before installing your module? (Likert: Less - More)	4,18	4	0,86	261
	B6 Compared to before installing your module? (Likert: Less - More)	3,2	3	0,52	261
C) Political Engagement	C1 Has the introduction of your plug-in solar device influenced your involvement in political discussions or actions in the energy and climate sector? (Likert scale: Much less → Much more)	3,3	3	0,79	275
	C3 Has climate and energy policy become a stronger factor in your voting decisions since adopting a plug-in solar module? (Likert Scale: Less - More)	3,4	3	0,69	275
	C4 How frequently do you discuss energy transition topics compared to before? (Likert Scale: Less - More)	3,6	3	0,73	275
D) Individual Empowerment	D3. I feel a sense of pride in generating my own electricity. (Likert Scale: 1 = Strongly Disagree → 5 = Strongly Agree)	4,5	5	0,73	279

	D4. Producing electricity myself has strengthened my belief that individual actions can have a positive impact. (Likert Scale: 1 = Strongly Disagree → 5 = Strongly Agree)	4,4	5	87	278
	D5. Owning a plug-in solar module has increased my confidence in contributing to the energy transition. (Likert Scale: 1 = Strongly Disagree → 5 = Strongly Agree)	4,3	4	0,86	279
E) Peer effects	E1 How common do you think plug-in solar modules are in your neighborhood or social circle? (Likert scale: Not at all widespread - Rather not widespread - Neutral - Rather widespread - Very widespread)	2,91	3	0,98	259
	E2 Did anyone in your social circle influence your decision to adopt plug-in solar? (Likert scale: Not at all - Rather not - Neutral - Rather yes - Very strongly)	2,24	2	1,24	259
	E3 Since adopting a plug-in solar module, have you recommended it to others? (Likert: Never - Very often)	2,95	3	0,89	259
	E4 Has your installation influenced others to consider installing solar? (Likert scale: Not at all - Rather not - Neutral - Rather yes - Very strongly)	2,88	3	1,17	257
	E5 Have people started a conversation because they saw your module? (Likert: Never - Very often)	1,99	2	0,89	258
	E6 How often do people in your social circle ask you about your plug-in solar module? (Likert: Never - annually - monthly - weekly - daily)	2,19	2	0,92	259
	E7 Has seeing other people's plug-in solar modules increased your trust in renewable energy solutions? (Likert: Less - More)	3,41	3	0,69	259

Appendix C. Statistical Test Results

Construct / Hypothesis	Description	Cronbach's α	Test Type	Test Statistic	p-value	Interpretation
Environmental Awareness (H1)	Awareness of energy/climate issues and acceptance of the energy transition	0.77	Wilcoxon signed rank	V = 11,744	< .001	Significantly above midpoint; confirms H1
Energy-Related Behavior (H3)	Changes in consumption, timing of use, and efficiency awareness	0.24	Wilcoxon signed rank	V = 25,172	< .001	Moderate increase; supports H3
Political Engagement (H4)	Political involvement, voting considerations, and discussions	0.75	Wilcoxon signed rank	V = 14,496	< .001	Significant increase in engagement; confirms H4
Individual Empowerment (H2)	Pride, confidence, and belief in contribution to sustainability	0.74	Wilcoxon signed rank	V = 34,635	< .001	Very high empowerment levels, Significantly above midpoint; confirms H2
Social Diffusion & Peer Effects	Perceived social spread, influence from/to peers, conversations	0.65	One-sample t-test	t = -10.02	< .001	Significantly below midpoint; low perceived diffusion, H5 not supported

Appendix D. Full Survey Questionnaire

(originally distributed in German, translated version)

Hello,

Thank you for clicking on this link. This study is part of my master's thesis and examines how balcony power plants have an effect beyond their energy function - for example on environmental awareness, social commitment, and social dynamics.

Do you have a plug-in solar device/balcony power plant? Then I would be delighted to receive your contribution to my research!

The survey takes about 10 minutes to complete. Participation in the survey is voluntary and your answers will be stored and analyzed anonymously.

Plug-in Solar Device Use

Q0 Plug-in solar devices are often also called mini solar systems, plug & play solar systems, or balcony power plants.
Do you own such a device?
□ Yes
□ No, but I am considering it
□ No, not interested

Module Details

Q1 What is the module output of your plug-in solar device?
□ Up to 400 W
□ 400-600 W
□ 600-800 W
□ > 1000 W

Q2 Location of your module:
□ Balcony/Terrace
□ Facade
□ Roof
□ Garden
□ Other: ______

Q3 Year of installation:
[Open field]

Q4 Other energy generation at home?
□ Yes, classic PV system
□ Yes, other: ______
□ No
□ No, but planned

Q5 Is your device registered in the core energy market register?
(This data is collected and evaluated anonymously.)
□ Yes
□ No
□ I do not wish to specify

Motivations for Adopting Plug-in Solar

Q6 What were your motivations for adopting a plug-in solar module? *(Select all that apply)*
□ Save money
□ Larger solar system is too expensive
□ Larger solar system not feasible
□ Reduce environmental impact
□ Make a contribution to the energy transition
□ Be a visible role model
□ Interest in technology
□ Fun, hobby, curiosity
□ Easy installation
□ Neighbors/family/friends already have a module
□ Government funding/subsidy
□ Energy independence
□ Other: ______

Q7 Which one was the main reason? *(Single choice)*
□ Save money
□ Larger solar system is too expensive
□ Larger solar system not feasible
□ Reduce environmental impact
□ Make a contribution to the energy transition
□ Be a visible role model
□ Interest in technology
□ Fun, hobby, curiosity
□ Easy installation

□ Neighbors/family/friends already have a module
□ Government funding/subsidy
□ Energy independence
□ Other: ______

Perceptions and Personal Impact (Empowerment)

(Likert scale from 1 = Strongly Disagree to 5 = Strongly Agree)

D1 With my plug-in installation, I feel like I contribute to the well-being of humanity and nature.
D2 An owner of rooftop PV can feel good because they help to protect the environment.
D3 I feel a sense of pride in generating my own electricity.
D4 Producing electricity myself has strengthened my belief that individual actions can have a positive impact.
D5 Owning a plug-in solar module has increased my confidence in contributing to the energy transition.

Political Engagement

C1 Has the introduction of your plug-in solar device influenced your involvement in political discussions or actions in the energy and climate sector?
(1 = Much less - 5 = Much more)

C2 If applicable, in what way? *(Select all that apply)*
□ Signed petitions on energy policy
□ Contacted policymakers or representatives about energy issues
□ Participated in demonstrations or protests
□ Joined an energy or climate policy organization
□ Publicly commented on the energy transition or climate issues on social media
□ Promoted or informed about renewable energy in the neighborhood or community
□ Other: ______
□ No engagement

C3 Has climate and energy policy become a stronger factor in your voting decisions since adopting a plug-in solar module?
(1 = Much less - 5 = Much more)

C4 How frequently do you discuss energy transition topics compared to before?
(1 = Much less - 5 = Much more)

Environmental Awareness

A1 In your opinion, are citizens in Germany making sufficient efforts toward environmental and climate protection?
(1 = Not enough - 5 = Enough)

A2 How important do you consider environmental and climate protection?
(1 = Not at all important - 5 = Very important)

A3 Before installing my module, I considered myself very environmentally conscious.
(1 = Strongly Disagree - 5 = Strongly Agree)

A4 Since installing my module, my awareness of energy issues and sustainability has changed.
(1 = Much less - 5 = Much more)

A5 Since installing my module, I feel more or less engaged in discussions about climate change and energy policy.
(1 = Much less - 5 = Much more)

A6 My acceptance of the German energy transition has changed.
(1 = Much less - 5 = Much more)

Behavioral Impact of Plug-in Solar Adoption

B1 Since adopting your plug-in solar module, has your overall energy consumption changed?
□ Decreased significantly
□ Decreased somewhat
□ No change
□ Increased somewhat
□ Increased significantly

B2 How often do you adjust your energy usage to align with solar production times (e.g., running appliances during the day)?
(1 = Never - 5 = Very often)

B3 Compared to before installing your module?
(1 = Much less - 5 = Much more)

B4 How often do you check your solar power production? (e.g. app, smart meter)
□ Never
□ Once a week

□ 2-3 times a week
□ 4-6 times a week
□ Daily

B5 When buying household appliances, I choose appliances with a particularly good energy efficiency class.
(1 = Never - 5 = Always)

B6 Compared to before installing your module?
(1 = Much less - 5 = Much more)

B7 Since adopting a plug-in solar module, have you taken additional sustainability-related actions?
(Select all that apply)
□ Reduced meat consumption
□ Switched to a green energy provider
□ Purchased regional and seasonal food
□ Made energy-saving home upgrades
□ Reduced water consumption (e.g. shorter showers)
□ Used bicycles, public transport or avoided car journeys more often
□ Talked about energy transition issues more often
□ Other: ______

B8 Compared to before installation?
(1 = Much less - 5 = Much more)

Peer Effects

E1 How common do you think plug-in solar modules are in your neighborhood or social circle?
(1 = Not at all widespread - 5 = Very widespread)

E2 Did anyone in your social circle influence your decision to adopt plug-in solar?
(1 = Not at all - 5 = Very strongly)

E3 Since adopting a plug-in solar module, have you recommended it to others?
(1 = Never - 5 = Very often)

E4 Has your installation influenced others to consider installing solar?
(1 = Not at all - 5 = Very strongly)

E5 Have people started a conversation because they saw your module?
(1 = Never - 5 = Very often)

E6 How often do people in your social circle ask you about your plug-in solar module?
□ Never
□ Annually
□ Monthly
□ Weekly
□ Daily

E7 Has seeing other people's plug-in solar modules increased your trust in renewable energy solutions?
(1 = Much less - 5 = Much more)

E8 Do you think small-scale solar solutions like plug-in modules should play a larger role in the energy transition?
□ Yes
□ No

E9 Estimate: How much (%) of Germany's installed energy capacity is from plug-in solar?
[Open field]

General Questions

Q8 Year of birth:
[Open field]

Q9 Gender:
□ Male
□ Female
□ Diverse
□ Not specified

Q10 What is your highest degree?
□ No educational qualification
□ Lower secondary school certificate *(Hauptschulabschluss)*
□ Intermediate secondary school certificate *(Realschulabschluss / Mittlere Reife)*
□ Higher education entrance qualification *(Fachhochschulreife / Abitur)*
□ Vocational training certificate *(Facharbeiter)*
□ Master craftsman qualification *(Meister)*
□ University degree *(Hochschulabschluss)*
□ Prefer not to say

Q11 What is your monthly income?
□ < €1,000
□ €1,001-2,000
□ €2,001-3,000
□ €3,001-4,000
□ €4,001-5,000
□ Over €5,000
□ No answer

Q12 I live in a:
□ Single-family house (*Einfamilienhaus*)
□ Terraced house (*Reihenhaus*)
□ Apartment (*Wohnung*)
□ Not specified

Q13 I live...
□ Owned
□ Rented
□ Not specified

Q14 In which region do you live? Please enter your zip code:
[Open field]

Q15 Would you be open to a brief conversation on these topics?
□ Yes
□ No

Q16 If yes: Please leave an e-mail address to be contacted / phone number to be called:
[Open field]

Q17 Is there anything else you would like to say? Further thoughts, feedback, etc.:
[Open field]

Thank you for taking the time and making a valuable contribution to my research! If you know others who own plug-in solar, feel free to share this survey.

If you have any questions, please do not hesitate to contact me:
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