PV Laggard or Leader? How Electricity Prices and Feed-In Tariffs Impact Photovoltaic Installations across Switzerland*

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Abstract

This paper examines the impact of electricity prices and feed-in tariffs on the expansion of photovoltaic (PV) systems in municipalities in Switzerland. Using a fixed effects model with panel data on 1,771 municipalities from 2017 to 2023, we find that higher feed-in tariffs have a positive effect on the adoption of PV technology in Swiss municipalities. However, the effect of higher electricity prices on the expansion of PV systems is mixed. Our models reveal varying responsiveness to electricity prices, with households living in single-family homes showing greater sensitivity compared to households living in apartments.

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1 Introduction

Climate change presents a pressing global challenge, manifesting in declining precipitation, global warming, and melting ice, issues not exempting Switzerland. To address these challenges, Switzerland has committed to achieving net-zero emissions by 2050 (SFOE, 2023). To meet the objectives of Switzerland's Energy Strategy 2050, a substantial and swift transformation of the country's electricity supply is imperative (Trutnevyte et al., 2024). Currently, Switzerland relies heavily on imported non-renewable energy sources, including oil, fuels, natural gas, and electricity generated from coal-fired power plants (Admin.ch, 2023a). Conversely, domestic energy production primarily stems from CO2-neutral energy sources such as hydro-power plants (62%), nuclear power plants (29%), and other renewable energy sources (9%) (Admin.ch, 2023b).

To achieve net-zero emissions by 2050, Switzerland must significantly expand its renewable electricity generation, particularly emphasizing photovoltaic (PV) installations (Schmidt et al., 2023). The Swiss Federal Office of Energy (2023) has estimated that to reach this goal, the current photovoltaic (PV) production of 2 terawatt-hours (TWh) must be increased to 34 TWh over the next three decades. Indeed, PV energy production is anticipated to emerge as the predominant technology driving Switzerland's energy transition (Soubelet et al., 2024). Despite the urgent need to expand renewable energy production, Switzerland currently only generates 3.5 terawatt-hours (TWh) per year with photovoltaic (PV) systems (Uvek, 2024). This is considerably less than the potential output of PV energy production in Switerland: The utilization of suitable roofs and building facades has the potential to generate 67 TWh of electricity per year, which exceeds the combined output of hydropower and nuclear power plants (SFOE, 2024c).

The question thus arises as to why Switzerland is failing to exploit its potential in the field of solar energy, despite the considerable resources at its disposal. Several policies have been implemented at various levels of government with the aim of enhancing the economic feasibility of photovoltaic installations for households, such as subsididies for PV installations, feed-in tariffs, and tax benefits (Schmidt et al., 2023). These incentives have undergone periodic revisions and exhibit significant variation across cantons and municipalities. In addition, the profitability of PV installations is contingent upon a number of other variables, including electricity prices and installation costs. It is reasonable to assume that all of the aforementioned factors influence households' decisions to install PV systems.

This paper thus aims to investigate how financial incentives impact the expansion of PV systems across municipalities in Switzerland. However, including all of the aforementioned financial incentives would go beyond the scope of this paper. Hence, we focus on the effect of electricity prices and feed-in tariffs on the expansion of photovoltaic (PV) systems in Switzerland.

We contribute to the existing literature by analyzing the impact of electricity prices and feed-in tariffs on the expansion of PV systems over a seven-year period. To the best of our knowledge, no study has yet investigated a study period of such length in the context of Switzerland. Using a fixed effects model with panel data on 1,771 municipalities from 2017 to 2023, we find that higher feed-in tariffs have a positive effect on the adoption of PV technology in Swiss municipalities. However, the effects we find of higher electricity prices on the expansion of PV systems are mixed. The models indicate that the impact of electricity prices on PV adoption varies by housing type. Households living in single-family homes show greater sensitivity to electricity prices compared to households living in apartments.

The remaining sections of this paper are structured as follows: The first part provides an in-depth analysis of the existing literature, offering a comprehensive background on the topic. Section 3 explores the factors influencing the profitability of a photovoltaic system. Subsequently, our econometric model is introduced in section 4, followed by a detailed presentation of the data in section 5 and the presentation of our results in section 6. Finally, this research concludes with avenues for future research and the most relevant policy recommendations.

2 Literature Review

Research on the expansion of solar photovoltaic (PV) systems in Switzerland has highlighted the significant role of economic incentives and policy frameworks. Studies like Panos and Margelou (2019) have shown that factors such as economic profitability, income, environmental benefits, awareness, and social influence all contribute to investment decisions in PV systems. These studies employed an agent-based model (ABM) to simulate the adoption of rooftop PV systems in Swiss single- and two-family houses, demonstrating that financial incentives and peer effects significantly drive the adoption process over time.

The Swiss feed-in tariff scheme, which guarantees a fixed price for electricity generated by PV systems and fed back into the grid, has been instrumental in promoting PV deployment. However, research by Weibel (2011) suggests that the current Swiss feed-in tariff system may hinder PV growth due to its limitations. According to Weibel, potential improvements, such as increasing the PV share of the fund and adjusting tariffs according to price developments, could enhance the effectiveness of the feed-in tariff system and promote sustainable growth in the renewable energy sector. A cross-case study by Karneyeva and Wüstenhagen (2017) further supports this claim, showing that while feed-in tariffs have historically been effective, recent tariff reductions have led to decreased investment due to increased political and revenue risks. Using a qualitative comparative analysis (QCA) framework and a difference-in-differences (DID) approach, they examined the impact of feed-in tariffs on PV deployment and found that while feed-in tariffs have been effective in driving PV growth, their effectiveness diminishes as tariffs decrease and risks increase. Recent research by Bloch et al. (2019) explored optimizing residential PV systems with battery storage under different advanced electricity tariff structures. Using a mixed-integer linear programming approach, the study found that block rate tariffs were most effective for economic viability and minimizing grid usage, while capacity-based tariffs relied on PV curtailment. This highlights the importance of advanced tariff structures for improving the financial and operational efficiency of residential PV systems.

While economic incentives are important, research has also shown that other factors like social norms, peer effects, and environmental concerns play a significant role in household participation in urban PV projects in Switzerland (Koch & Christ, 2018). Through semi-structured interviews with participants and non-participants in an urban PV project, they found that environmental motivations, a sense of ownership, and local considerations were important drivers for participation, while financial constraints and reservations about PV technology were barriers. Curtius et al. (2018) further explored the role of social influence by examining the impact of descriptive and injunctive norms on intentions to install PV systems among Swiss homeowners. They found that observing neighbors with PV systems and perceiving social pressure to adopt PV significantly increased homeowners' intentions to install PV, suggesting that policymakers should consider strategies that create regional hotspots (snowball approach) rather than applying uniform nationwide incentives (shotgun approach) to leverage social contagion and accelerate PV adoption.

Additionally, using cluster analysis and structural equation modeling (SEM), Kammermann and Dermont (2018) found that the beliefs and attitudes of political elites and the general public, particularly regarding climate change skepticism, significantly influence the acceptance and implementation of clean energy policies, including PV systems. They highlight that political ideology and party affiliation play a crucial role in shaping public opinion and support for renewable energy policies.

There is significant heterogeneity in PV deployment across Swiss municipalities, with complex interactions between federal, cantonal, and municipal regulations potentially creating barriers to adoption in some areas (Schmidt et al., 2023). Using a techno-economic model to simulate the profitability of solar PV battery systems for various household types across municipalities, the authors found that the profitability of PV systems varies significantly due to policy fragmentation. They suggest reducing fragmentation by harmonizing and removing unnecessary regulatory barriers to accelerate rooftop solar PV deployment. Thormeyer et al. (2020) used hotspot analysis and stepwise regression to show that the spatial distribution of PV projects in Switzerland is uneven, with some areas having significantly more projects (hotspots) than others (cold spots). This distribution was influenced by several factors, most notably the urban-rural divide, with rural areas, particularly those with significant agricultural and forestry activities, tending to have more PV projects than urban areas. Other factors, such as the structure of the municipal economy, socio-demographic characteristics, regional spillover effects (where the presence of PV projects in one area influences adoption in neighboring areas), and local policies also played a role. To address these complexities, they recommend using spatially explicit models to increase PV deployment in Swiss municipalities. These models would consider spatial variations in electricity prices, feed-in tariffs, and other factors to develop more effective policy recommendations.

Building on existing research, this study expands the analysis to cover a seven-year period, allowing for a deeper understanding of the long-term dynamics of PV deployment. Unlike previous studies that focused on shorter timeframes, this longitudinal approach offers valuable insights into trends and patterns that may be overlooked in shorter-term analyses.

3 Profitability of a Photovoltaic System

The amortization period and, consequently, the profitability of photovoltaic installations for households are influenced by a number of factors. These include the cost of installing PV systems, electricity prices, feed-in tariffs, subsidies, and tax breaks for installing PV systems, all of which vary by municipality and canton. The impact of these elements will be discussed in detail below.

3.1 Electricity Prices

The installation of photovoltaic systems represents an economic opportunity for households, as they allow for the direct production of energy rather than the purchase of it from a supplier. The price of electricity charged by the supplier is determined mainly by the energy produced by the supplier and the energy purchased from other producers on the market. The prices Swiss suppliers pay on the European market are influenced by a number of factors, including climatic variations, the level of production and consumption of electricity, network transmission constraints, and the geopolitical context affecting the price of gas. As a result, the cost of procuring electricity from external generators can fluctuate considerably (Romande Energie, 2023, 2024).

In addition to the cost of energy, the price of electricity also depends on the grid usage tariff, the charges to the municipality and to the canton, and the grid surcharge (Admin.ch, 2023c). Consequently, the electricity prices that households pay depend on their location, as well as their energy supplier. The prices applied by the suppliers can change from year to year. The Swiss electricity market is subject to regulations in such a way that prices cannot vary during the year. Announcements regarding changes in electricity prices are typically made in August for the following year, and the reasons for such changes must be justified (ElCom, 2024a).

It is notable that Switzerland is a country with a high number of electricity suppliers. These are predominantly owned by cantons or municipalities, with more than 600 suppliers in total (VSE, 2024). However, it is important to recognize that 70% of these suppliers do not actually produce the electricity that they sell (swissinfo.ch, 2022). Instead, they must purchase it from other sources, which raises questions about their ability to anticipate shocks and market trends (Romande Energie, 2023). This is reflected in the significant variation in electricity prices across the country. Each supplier is responsible for supplying energy to a specific area. Swiss households are typically not free to choose their supplier (if their consumption is less than 100,000 kWh/year) (ElCom, 2024a).

In conclusion, the installation of a photovoltaic system enables households to become more independent of the electricity prices they would otherwise have to pay as consumers. This paper will analyze the impact of electricity prices on the expansion of photovoltaic systems across municipalities.

3.2 Feed-In Tariffs

According to the Swiss Energy Law, local electricity suppliers must purchase and remunerate electricity generated by photovoltaic (PV) systems. This payment, called the feed-in tariff, is what households with PV systems receive for extra energy they supply to the grid. Each electricity supplier in Switzerland can set its own payment rates within the law's guidelines, leading to a substantial variation in tariffs (VESE, 2024b).

Until 2018, these feed-in tariffs were subsidized by the government via the so-called *Feed-in remuneration at cost (KEV)*, managed by the federal agency for the federal support program for renewable energies *Pronovo AG*. Introduced in 2009, *KEV* was implemented to promote electricity generation from renewable energies (SFOE, 2021). The main goal was to offset the difference between the production costs of electricity from renewable sources and the market price. During that time, using locally generated electricity, such as a PV system, was not seen as financially feasible due to low electricity market prices. The *KEV* aimed to enhance the attractiveness of investing in photovoltaic technology, thus encouraging an increase in overall electricity production from renewable sources (SFOE, 2022).

Today, *KEV* subsidies are no longer available for new installations. The subsidized feed-in tariff *KEV* has been permanently substituted with a cost-focused feed-in tariff system and a one-time payment that will be further discussed in detail in the chapter about subsidies. Hence, the feed-in tariff went from a subsidized feed-in tariff to market-based feed-in tariff. This market-based feed-in tariff is entirely dependent on electricity suppliers. Consequently, there is significant fluctuation in the feed-in tariff both within a year and across municipalities, as prices are determined by the amount of energy sold. To illustrate, PV installations will generate more energy than households use for their own consumption during periods like summer, leading to more surplus energy being sold to electricity providers. However, for homeowners, the previous *KEV* was a more financially attractive option than the current investment grants, as it provided full-cost funding (Schmidt et al., 2023). As of today, around 12,000 PV installations benefit from the feed-in tariff system (Pronovo, 2024b).

Nevertheless the current status of the feed-in tariff is subject to further developments. Specifically, on June 9, 2024, the Swiss population voted on *the Federal Act on a Secure Electricity Supply from Renewable Energy Sources* (Admin.ch, 2024). This newly accepted federal law extends development efforts until 2035, primarily aiming to increase electricity generation from renewable sources and to reinforce Switzerland's supply independence (Admin.ch, 2024). A significant feature of this new law is its goal to standardize the feed-in tariff (SFOE, 2024b). Currently, each electricity supplier has the freedom to set prices independently, resulting in significant price variations (VESE, 2024b). However, with the implementation of this new law, the feed-in tariff system will change. Indeed, measures are introduced to harmonize minimum compensation for small photovoltaic installations (SFOE, 2024b). According to this new Energy Law, for PV installations below 150 kW, the Federal Council has established minimum feed-in tariff rates (SFOE, 2024a). For instance, the minimum rates for PV installations under 30 kW is 4.6 ct./kWh, which is below the feed-in tariff on average over the past few years. Between 30kW and 150 kW, the minimum feed-in tariff is 0 ct./kWh if the installations are for personal use and 6.7 ct./kWh otherwise. In essence, the implementation of this new law leads to a regulated feed-in tariff. This study will investigate how feed-in tariffs affect the development of PV installations in different municipalities.

3.3 Subsidies

In Switzerland, photovoltaic systems of all sizes are subsidized at the federal level with so-called *non-recurrent remuneration (EIV)*, managed by the *Pronovo AG*. The *EIV* covers a maximum of 30% of the relevant investment costs of the installed PV system at the start of operation. This one-time payment remunerates a basic contribution and a performance contribution per installed kW. In 2023, CHF 600 million were available for the subsidization of photovoltaics (SFOE, 2022). The level of the subsidy depends on the size of the PV system (Swissolar, 2024):

- *Non-recurrent remuneration for small PV installations (KLEIV):* PV systems are considered small if they have a capacity of 2 kWp to 100 kWp (Pronovo, 2024a). This one-time payment can only be claimed after the PV system is installed and operational. Larger PV systems can also apply for the KLEIV, although the installed capacity above 99.9 kW is not subsidized (Swissolar, 2024).

- *Non-recurrent remuneration for large PV installations (GREIV):* PV systems are considered large if they have a capacity above 100 kWp. Unlike small PV systems, large PV systems do not have to be installed before a subsidy is granted.

- *High non-recurrent remuneration for PV installations without self-consumption (HEIV):* As of 2023, high non-recurrent remuneration is granted to PV installations without self-consumption and with a capacity of 2kWp up to 150 kWp (Pronovo, 2024a). For these systems, up to 60% of the relevant investment costs are covered by the HEIV (Pronovo, 2024a). If the system has a capacity above 150 kWp, the subsidy is awarded by means of auctions (Swissolar, 2024).

At the federal level, additional subsidies are available for systems with a tilt angle of more than 75°, which are typically installed on building facades and therefore produce more energy even in winter when roof-mounted PV systems are covered with snow. For the same reason, PV systems located 1500 meters above sea level receive additional subsidies. Building-integrated PV systems also receive higher subsidies due to their higher installation costs (Pronovo, 2024a).

In addition to the federal non-recurrent remuneration, some cantons and municipalities offer subsidies to promote photovoltaic energy. However, only 9 out of 26 cantons grant additional investment subsidies for PV systems (Schmidt et al., 2023).

Due to the significant changes in subsidies over time and the lack of comprehensive data capturing these changes across federal, cantonal and municipal levels, subsidy data cannot be used for our analysis. While the website *energiefranken.ch* provides an overview of current subsidies for PV systems at all levels, reconstructing the evolution of these subsidies is challenging. Calculating the actual subsidies paid to households at all three levels of government is beyond the scope of this paper. Therefore, subsidy data are not included in our analysis.

3.4 Installation Costs

The prices of photovoltaic systems have exhibited two opposing trends over the past decade. On the one hand, there has been a nearly 50% reduction in panel prices caused by technological advancements and shifts in production to Asia. On the other hand, installation costs have increased due to recent procurement challenges and rising demand (infomaison, 2023). However, there is a lack of data on installation costs of PV systems in Switzerland, on cantonal and municipal levels. Consequently, while installation costs represent a significant factor in the decision-making process for households considering the installation of a photovoltaic system, this factor cannot be analyzed in an academic context using a data-driven approach.

3.5 Taxation

Another factor influencing the profitability of PV systems is taxation. The tax deduction for photovoltaic installations significantly impacts investment costs for property owners, enhancing the accessibility and financial appeal of these systems. As of 2023, deductions for PV investment costs are allowable not only for federal taxes but also across all cantons (Lüthi & Russi, 2023). However, the deductibility of expenses related to photovoltaic installations varies based on the specific regulations of each canton and municipality. Due to the challenging availability of taxation data, we will not incorporate it into our analysis.

In conclusion, this study aims to assess the impact of electricity prices and feed-in tariffs on photovoltaic (PV) output in Swiss municipalities. Despite the significance of subsidies, installation costs, and taxation, these variables are either not available for longer time periods or require considerable effort to obtain, rendering them inaccessible within the scope of this paper.

4 Econometric Model

This paper investigates the effect of electricity prices and feed-in tariffs on the installed PV capacity in Swiss municipalities using panel data from 2017 to 2023. Our basic econometric specification is a fixed effects model, which can be expressed as follows:

$$\begin{aligned}\text{Output per Resident}_{it} = \alpha &+ \beta_1 \text{Tariff}_{it} + \beta_2 \text{Electricity Price}_{it} \\ &+ \sum_{c=1}^{C-1} \sum_{y=1}^{T-1} \gamma_{cy} (\text{Canton}_c \times \text{Year}_y) + u_i + \epsilon_{it}\end{aligned} \tag{1}$$

where:

- $\text{Output per Resident}_{it}$ is the dependent variable, representing the cumulative sum of the total output of all installed PV systems per municipality i at time t, measured in watt peak (Wp) per resident.
- Tariff_{it} is the feed-in tariff for municipality i at time t.
- $\text{Electricity Price}_{it}$ is the electricity price for municipality i at time t.
- $\sum_{c=1}^{C-1} \sum_{y=1}^{T-1} \gamma_{cy} (\text{Canton}_c \times \text{Year}_y)$ are canton-by-year fixed effects, capturing unobserved heterogeneity across cantons and years.
- u_i represents municipality fixed effects, accounting for time-invariant unobserved characteristics of municipalities.
- ϵ_{it} is the idiosyncratic error term.

The outcome variable, PV output per resident, standardizes the total PV capacity by the population size of each municipality, providing a comparable measure of PV adoption across municipalities. Our primary explanatory variables are the feed-in tariff and electricity prices. The feed-in tariff (Tariff_{it}) represents the financial incentive provided to households for the surplus energy they contribute to the grid. The electricity price ($\text{Electricity Price}_{it}$) represents the cost of energy for households. Both variables vary across municipalities due to different energy suppliers. By including canton-by-year fixed effects ($\sum_{c=1}^{C-1} \sum_{y=1}^{T-1} \gamma_{cy}$), we account for regional and temporal shocks that could simultaneously affect multiple municipalities within the same canton.

The selected specification is designed to capture the economic incentives that influence household decisions to install photovoltaic (PV) systems. It is hypothesized that higher electricity prices and feed-in tariffs will increase the attractiveness of PV installations, thereby increasing the total PV output in a municipality. This model is consistent with economic theory, which suggests that financial incentives and cost savings play significant roles in household investment decisions regarding renewable energy technologies. However, previous empirical studies have used different specifications to examine the adoption of renewable energy technologies, usually with more control variables and a shorter period (Schmidt et al., 2023; Thormeyer et al., 2020). Unfortunately, including additional control variables would have exceeded the scope of this paper.

It seems plausible to suggest that unobserved characteristics of municipalities, such as the political environment or geographic factors, may exert an influence on both the price of electricity and the feed-in tariffs in a given municipality. Consequently, we hypothesize that the random effects assumption—which assumes no correlation between the individual-specific effects u_i and the explanatory variables—is likely to be violated. Therefore, we opt for the fixed effects model over the random effects model, to control for time-invariant unobserved heterogeneity across municipalities (u_i). This helps mitigate bias arising from omitted variables that are constant over time but vary across municipalities. Since the fixed effects model focuses on the effect of time-variant variables within a municipality, it essentially removes the effect of all time-invariant characteristics (observed or unobserved) by differencing out the individual-specific intercepts. To ensure the robustness of our results, we will conduct several additional tests:

1. **Alternative Specifications:** We will estimate alternative models, such as pooled OLS, to compare and validate our findings.

2. **The Hausman test:** To assess whether a random effects model is inconsistent and a FE model should be used, we will run a Hausman test.

3. **Lagged Variables:** Since we assume that households response to electricity prices and feed-in tariffs may be delayed, we estimate our model with lagged explanatory variables.

In summary, our econometric model leverages fixed effects and canton-by-year fixed effects to identify the impact of feed-in tariffs and electricity prices on PV adoption in Swiss municipalities. By addressing potential endogeneity concerns and controlling for unobserved heterogeneity, this specification aims to provide credible and robust estimates of the effects of these economic incentives on PV energy adoption.

5 Data

This paper uses administrative panel data for municipalities in Switzerland from 2017 to 2023. We compiled a balanced panel data set on the output of photovoltaic installations, feed-in tariffs and electricity prices for 1'771 municipalities over a period of seven years.

5.1 Data on the Output of Photovoltaic Systems

The data on the output of photovoltaic systems in municipalities is provided by *VESE*, the association of independent energy producers in Switzerland. The *VESE* data is based on the

photovoltaic systems recorded by *Pronovo* that are in operation and have been subsidized either by the *feed-in remuneration at cost (KEV)*, the *non-recurrent remuneration (EIV)* or the *financing of additional costs (MKF)*, the predecessor of the *KEV* (VESE, 2024a).
The dataset includes the address, installed capacity, and the date of in-service operation for each photovoltaic system. The oldest system in the dataset was installed in 1988, while the newest was installed in 2024. As of December 2023, the installed photovoltaic (PV) systems in Switzerland had a capacity of approximately 5,000 megawatts peak (MWp), representing an increase of approximately 3,000 MWp since 2017 (compare Figure 1).

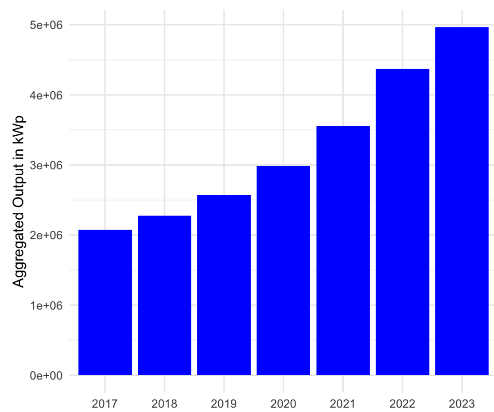

Figure 1: Aggregated Output of PV Installations in Switzerland (in kWp)

In addition to VESE, Swissolar and the Swiss Federal Office of Energy also publish the output of total PV systems sold in Switzerland. Based on the cumulative market data from Swissolar, the total output of PV systems in Switzerland is higher than the value published by VESE. Since no one knows exactly how many PV systems are currently in operation in Switzerland, it can be assumed that VESE's value represents a lower limit and the Swissolar market data an upper limit (VESE, 2024a).
We compute the cumulative sum of the total output of all installed PV systems per municipality from 2017 to 2023, providing insights into the installed capacities for each year. The output of photovoltaic systems is measured in watt peak (Wp). Initially, the dataset encompassed information on 2134 municipalities, as of February 28, 2024. This dataset was

subsequently matched with data on the 2131 existing municipalities as of January 1, 2024. There is a notable disparity in the output of photovoltaic (PV) systems across municipalities, as illustrated in Figures 2 and 3 (graphs for all years from 2017 to 2023 are available in the Appendix B). From 2017 to 2023, the average photovoltaic (PV) output increased from 897 kilowatts peak (kWp) to 2,237 kWp. The data indicate that urban municipalities tend to exhibit higher PV output levels. The municipality of Zurich recorded the highest absolute output in 2017 and 2023, with approximately 20,480 kWp and 52,110 kWp, respectively. Throughout the entire time period, there were municipalities that did not have any PV installations.

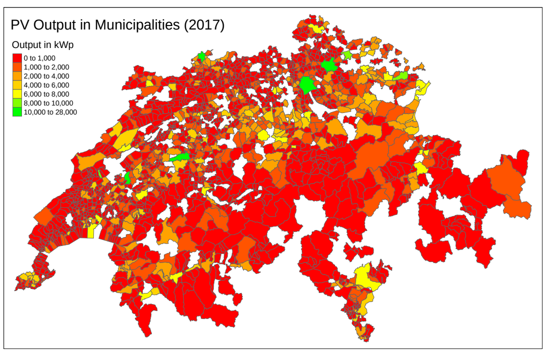

Figure 2: PV Output in 2017

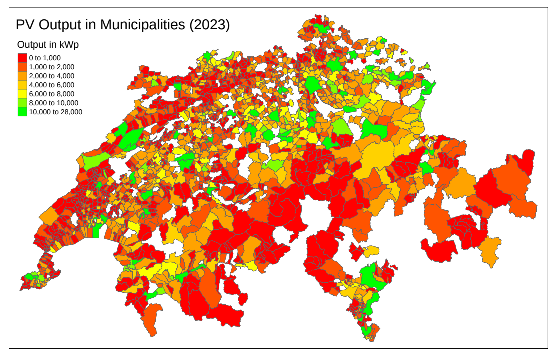

Figure 3: PV Output in 2023

To facilitate a more accurate comparison of the expansion of photovoltaic installations across municipalities, we compute the PV output per resident. The municipal resident data for the period between 2017 and 2023 were sourced from the Federal Statistical Office. To compute the annual PV output per resident, we divide each year's PV output by the municipality's population for each year. As illustrated in Figures 4 and 5, there is a notable rise in the PV output per resident over the course of our analysis period (graphs for all years from 2017 to 2023 are available in the Appendix B). The mean photovoltaic output per resident increased from 0.36 kWp in 2017 to 0.78 kWp in 2023. Nevertheless, considerable heterogeneity in PV output per resident is observed across municipalities, with values ranging from 0 to 17.4 kWp per resident in 2023.

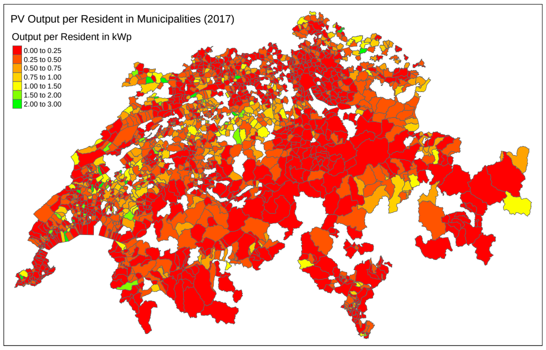

Figure 4: PV Output/Resident in 2017

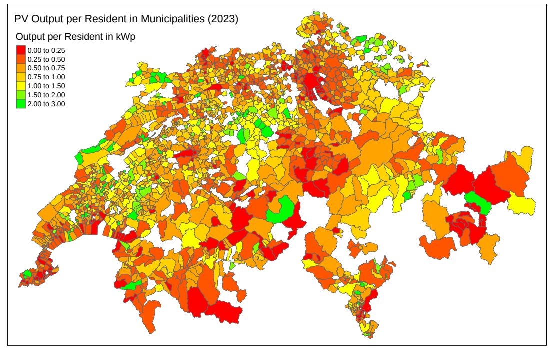

Figure 5: PV Output/Resident in 2023

To quantify the degree of photovoltaic expansion in comparison to the actual potential of PV energy production in Switzerland, we compute the actual annual PV output as a percentage of the potential for each municipality. This paper utilises data on the photovoltaic energy potential of Swiss municipalities provided by the Federal Department of Environment, Transport, Energy and Communications. Following the methodology of VESE, we employ the variable including roofs and facades (Scenario 3). In 2017, the aggregated PV output represented 2.2% of Switzerland's potential, while in 2023 it increased to 5.5%. The moderate increase in the PV output as a percentage of the potential is illustrated in Figures 6 and 7 (graphs for all years from 2017 to 2023 are available in the Appendix B). The mean percentage of potential PV output reached increased from 2.2% in 2017 to 5.3% in 2023. The variation in the percentage of potential output achieved in 2023 ranged from 0 to 47.9%.

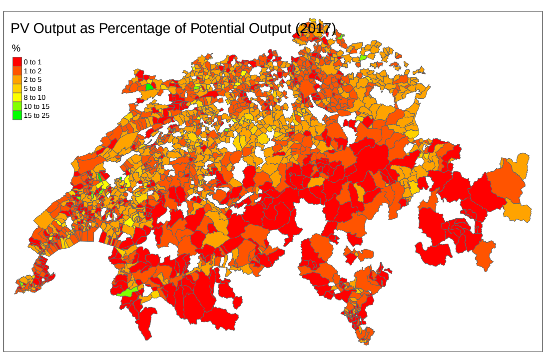

Figure 6: PV Output as Percentage of Potential Output in 2017

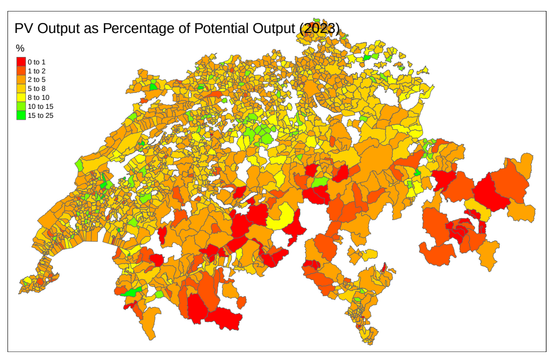

Figure 7: PV Output as Percentage of Potential Output in 2023

5.2 Data on the Feed-In Tariffs

The data on the feed-in tariffs of photovoltaic systems in municipalities are provided by *VESE*, the association of independent energy producers in Switzerland. *VESE* compiles the feed-in tariffs based on the information provided by the energy suppliers since 2015. At that time, *VESE* was able to record the feed-in tariffs of 70 out of approximately 650 energy suppliers, which together supply 77% of the Swiss residential population with electricity. For 2017, *VESE* was able to collect data on 422 suppliers, which together power 95% of the population. Since 2019, *VESE* collects the feed-in tariffs of all major electricity providers, which together supply 98% of the population.

VESE's original dataset contains tariffs from 663 electricity providers spanning the years 2015 to 2024, comprising a total of 50 distinct tariffs. For our analysis we aggregate the energy tariff and the tariff for the guarantee of origin (HNK). The purpose of guarantees of origin (HNK) is to create transparency for end consumers by indicating where their electricity comes from. Whilst electricity providers are obliged to purchase the surplus energy from PV installations, they do not have to remunerate the guarantee of origin (HNK). For this reason, we use the aggregate of the energy tariff and the guarantee of origin tariff as a measure for the total feed-in tariff for our analysis.

In cases where energy providers offer varied energy tariffs based on factors such as energy supply from PV systems or seasonal fluctuations, *VESE* computes the effective annual average tariff for a PV system. We use energy and guarantee of origin tariffs for the first power class, as it represents the predominant tariff structure for household PV systems. Feed-in tariffs are measured in centimes per kilowatt-hour (centimes/kWh).

This paper matches the original dataset provided by *VESE* on the feed-in tariffs of each electricity provider with the municipalities as of January 1, 2024. For municipalities with multiple electricity providers, we adhere to the methodology established by *VESE* and only retain the largest and most significant electricity provider per municipality. Furthermore, municipalities where feed-in tariffs are reported to be zero due to the unavailability of data are excluded from the analysis. Following the aforementioned matching process, the resulting dataset comprises 2064 municipalities.

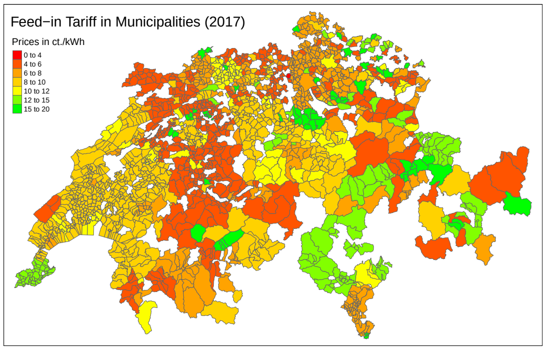

Figure 8: Feed-In Tariffs in 2017

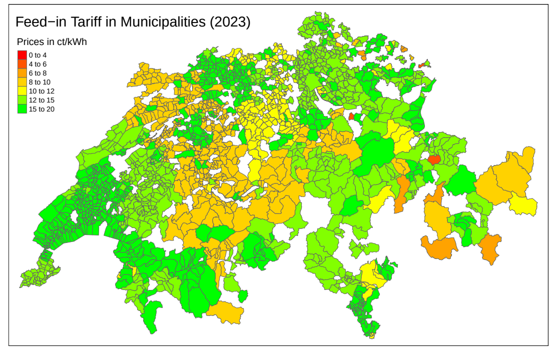

Figure 9: Feed-In Tariffs in 2023

As illustrated in Figures 8 and 9, there is a notable degree of heterogeneity in the level of feed-in tariffs across municipalities (graphs for all years from 2017 to 2023 are available in the Appendix B). In general, there has been an increase in feed-in tariffs over the course of the time period under analysis. In 2017, the average remuneration paid by Swiss electricity providers for electricity fed into the grid was 8 centimes per kWh. By 2023, the mean remuneration paid by electricity providers had increased to 14.2 centimes per kWh. Nevertheless, there is considerable variation in feed-in tariffs, with rates ranging from 5 to 37.5 centimes per kWh in 2023.

5.3 Data on Electricity Prices

This paper utilizes electricity prices sourced from the *Swiss Federal Electricity Commission ElCom* (ElCom, 2024b). We use the total electricity costs which are comprised of the grid usage tariff, the energy price, the charges to the municipality, and the grid surcharge. Electricity prices are measured in centimes per kilowatt-hour (centimes/kWh).

The original dataset contains the electricity prices for consumption profiles for typical households as well as commercial and industrial enterprises. To analyze the effect of electricity prices on the decision of households to install PV systems, we will only consider the electricity prices paid by households. *ElCom* provides eight different consumption profiles for households, based on the energy consumed and the installations present. Since the typical household in Switzerland consumes 5,000 kWh annually, we chose category 4, which has an energy consumption of 4,500 kWh per year, as it closely approximates the average (ElCom, 2021).

Nevertheless, we will subsequently perform robustness checks with other household categories. Following the integration of the electricity data with our dataset on PV power and feed-in tariffs, we obtained a final sample of 1'771 municipalities with no missing variables for the specified time period.

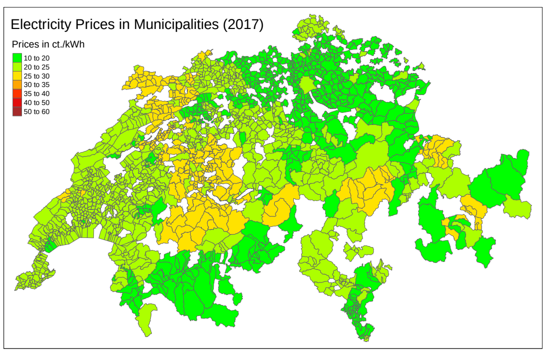

Figure 10: Electricity Prices in 2017

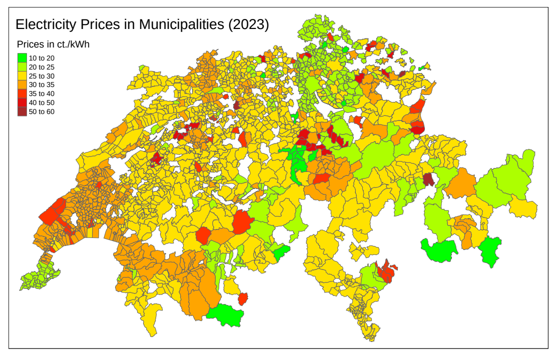

Figure 11: Electricity Prices in 2023

As illustrated in Figures 10 and 11, the cost of electricity for households has risen considerably in 2023 in comparison to 2017 (graphs for all years from 2017 to 2023 are available in the Appendix B). The average price paid by households for electricity in 2017 was 20.4 centimes per kWh, which increased to 27.7 centimes per kWh in 2023. Furthermore, the degree of variation across municipalities increased considerably over the course of our analysis. In 2017, the average price paid by households in our dataset was between 11.5 and 26.6 centimes per kWh. By 2023, this had increased to a range of between 14.3 and 58.8 centimes per kWh.

6 Results

This chapter presents the results of our analysis on the impact of feed-in tariffs and electricity prices on photovoltaic (PV) adoption in Swiss municipalities, using a fixed effects model with canton-by-year dummies, and discusses the robustness checks performed.

Table 1: Fixed Effects Model

	Dependent variable:
	Output per Resident (kWp)
Tariff	0.002^{***}
	(0.001)
Electricity Price H4	-0.002^{**}
	(0.001)
Canton-Year Dummies	yes
Observations	12,397
R^2	0.579
Adjusted R^2	0.501
F Statistic	91.069^{***} (df = 158; 10468)
Note:	*p<0.1; **p<0.05; ***p<0.01

Table 1 presents the results of our fixed effects model, which controls for feed-in tariffs, electricity prices, and canton-by-year fixed effects. Our findings indicate a positive and statistically significant effect of feed-in tariffs on PV output per resident, supporting our hypothesis that higher remuneration for electricity production incentivizes households to install PV systems. Conversely, the model reveals a negative and statistically significant effect of electricity prices on PV output per resident, which contradicts our initial hypothesis that higher electricity prices would encourage households to increase their own energy production. Our results remain robust when re-estimated using a pooled OLS regression, as shown in Appendix A. Despite the Hausman test suggesting a random effects model, we opted for a fixed effects model due to the violation of the random effects assumption (see Appendix A).

Table 2: Fixed Effects Model with Different Electricity Price

	Dependent variable:
	Output per Resident (kWp)
Tariff	0.004
	(0.004)
Electricity Price H3	0.017***
	(0.006)
Canton-Year Dummies	yes
Observations	12,397
R^2	0.687
Adjusted R^2	0.629
F Statistic	145.484*** (df = 158; 10468)
Note:	*p<0.1; **p<0.05; ***p<0.01

Although our findings are statistically significant, it is important to exercise caution when interpreting them. The average PV output per resident increased from 0.36 kWp in 2017 to 0.78 kWp in 2023, an annual average increase of 0.07 kWp. Thus, while the effects of feed-in tariffs and electricity prices that we find are moderate, they are not negligible. Interestingly, the negative impact of electricity prices aligns with previous research findings (Thormeyer et al., 2020). However, as Table 2 shows, the results depend on the different electricity prices used. If the electricity price H3 for households consuming 4,500 kWh per year in a *4-room apartment* is used, the model suggests a positive and statistically significant effect of electricity prices on PV output per resident. However, using this model specification renders the positive effect of feed-in tariffs statistically insignificant. These results contrast the finding of our previous model using the electricity prices H4 for households consuming 4,500 kWh per year in a *5-room apartment*.

Using additional electricity price specifications, such as H5 and H6, which represent prices for households living in single-family homes with increased energy consumption, also indicate a positive effect of electricity prices on PV output per resident, as shown in Table 3.

This indicates that the impact of electricity prices on PV adoption varies by housing type. Table 3 shows that households living in single-family houses appear to be more responsive to electricity prices than households living in apartments, as demonstrated in Table 1 and 2. The effect of feed-in tariffs on PV output per resident remains in both models positive but statistically insignificant.

Table 3: Comparison of Fixed Effects Models with Different Electricity Prices

	Dependent variable:	
	Output per Resident (kWp)	
	(1)	(2)
Tariff	0.004	0.004
	(0.004)	(0.004)
Electricity Price H5	0.017***	
	(0.006)	
Electricity Price H6		0.016***
		(0.006)
Canton-Year Dummies	yes	yes
Observations	12,397	12,397
R^2	0.687	0.687
Adjusted R^2	0.629	0.629
F Statistic (df = 158; 10468)	145.481***	145.473***
Note:	*p<0.1; **p<0.05; ***p<0.01	

Table 4 illustrates the model specification incorporating lagged control variables and canton-by-year fixed effects. This model accounts for potential delayed responses to feed-in tariffs and electricity prices, acknowledging the time required for households to decide to install a PV system and complete the installation. By using lagged variables, we assume that feed-in tariffs and electricity prices influence the following year's PV output rather than the current year's. The results are comparable to those of the initial model specification and are robust when using the lagged H3 electricity price. The model indicates a slight positive impact of feed-in tariffs on PV output and a negative, statistically significant effect of electricity prices on PV output. However, we consider the model specifications without lagged variables to be a more accurate representation of reality, as the assumption that feed-in tariffs and electricity prices *only* affect the following year's PV output seems overly restrictive.

Table 4: Fixed Effects Model with Lagged Controls

	Dependent variable:
	Output per Resident (kWp)
Lagged Tariff	0.001^{*}
	(0.001)
Lagged Electricity Price H4	-0.010^{***}
	(0.002)
Canton-Year Dummies	yes
Observations	10,626
R^2	0.558
Adjusted R^2	0.462
F Statistic	83.539^{***} (df = 132; 8723)
Note:	*p<0.1; **p<0.05; ***p<0.01

In addition, it is reasonable to assume that the negative effect of electricity prices will dissipate over time. Given the significant increase in electricity prices since 2023, it is plausible that the long-term effects of these higher prices may differ from the short-term negative impacts we observed, potentially turning positive.

7 Conclusion

This study investigated the influence of electricity prices and feed-in tariffs on the adoption of photovoltaic (PV) systems in municipalities across Switzerland. Our work contributes to existing literature by analyzing the impact of electricity prices and feed-in tariffs on the expansion of PV systems over a seven-year period. The use of a fixed effects model with panel data on 1,771 municipalities from 2017 to 2023 revealed that higher feed-in tariffs have a positive effect on the adoption of PV systems in Swiss municipalities. Nevertheless, the impact of elevated electricity prices on the expansion of PV systems is mixed. Our fixed effects models demonstrate that the influence of electricity prices on PV adoption exhibits considerable variation contingent on housing type. The results indicate that households in single-family homes exhibit a greater sensitivity to electricity prices than those in apartments. This discrepancy can be attributed to the fact that homeowners are more directly influenced by electricity prices and feed-in tariffs, as they have the authority to make investment decisions and install PV systems. Conversely, tenants are dependent on their landlords to make such decisions. It is possible that landlords may be less motivated by these economic incentives, as they do not directly benefit from the cost savings or revenue generated by PV systems.

It should be noted that the scope of this analysis is limited by several factors. The robustness of our model is constrained by the fact that we were only able to analyze 1,771 out of the 2,131 municipalities in question. Thus, future research should address these data limitations. Including additional control variables, such as tax incentives, subsidies, house prices, political environment, and homeownership rates, could further enhance the granularity and depth of the analysis. Moreover, our model may face endogeneity issues, as PV output could influence electricity prices. Identifying an appropriate instrumental variable to address this potential endogeneity could be a valuable direction for future research. Additionally, due to the recent nature of the increase in electricity prices, it is currently impossible to assess its long-term effect on PV output. It would be therefore interesting to continue research on this subject over the coming years to determine whether the negative impact we found in some of our estimations turns positive in the future.

The findings of this study provide a basis for several policy recommendations. First, as previously stated, there is little evidence that households living in apartments react to changes in electricity prices. This lack of reaction may be attributed, at least in part, to the fact that the issue is not particularly salient. Consequently, the optimal solution for encouraging PV installations on apartment buildings would be to implement a multifaceted approach, including an increase in subsidies and tax incentives. These elements impact homeowners rather than tenants, which may encourage landlords to invest more in PV installation. Moreover, the harmonization and simplification of policies governing the installation of PV systems on apartment buildings may facilitate their expansion.

Second, this study does not find strong evidence that households significantly respond to feed-in tariffs. Similar to electricity prices, it is reasonable to assume that feed-in tariffs are not particularly salient to households when considering the installation of a PV system. Instead, households may place greater importance on subsidies and tax incentives. Nevertheless, households may soon benefit from minimum feed-in tariffs. Given the Swiss population's acceptance of the Federal Act on a Secure Electricity Supply from Renewable Energy Sources, the minimum feed-in tariffs suggested by the Federal Council are likely to be implemented. However, there has been a debate as to whether the minimum feed-in tariffs are set at an insufficient level. The theoretical justification for minimum feed-in tariffs is that they enhance investment security for households by protecting them from the volatility of market electricity prices. Consequently, it is expected that the adoption of PV systems will increase as a result. Nevertheless, this study does not find evidence to support the proposition that minimum feed-in tariffs should be significantly higher, as households do not increase PV output to an extent that would justify such increases.

Ultimately, the decision to prioritize household PV systems or large-scale PV installations is inherently political. The expansion of the grid network will be a prerequisite for the substantial increase in PV electricity production from households. Nevertheless, small household PV systems are typically more readily accepted by the public than large-scale mountain PV installations, as evidenced by recent votes in affected municipalities. Given the imperative to increase its PV output, Switzerland must decide which approach to take.

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Appendix A: Tables

Table 5: Pooled OLS Regression Results

	Dependent variable:
	Output per Resident (kWp)
Tariff	0.005^{**}
	(0.003)
Electricity Price	-0.008^{***}
	(0.003)
Constant	0.577^{***}
	(0.086)
Canton-Year Dummies	yes
Observations	12,397
R^2	0.107
Adjusted R^2	0.094
Note:	*p<0.1; **p<0.05; ***p<0.01

Table 6: Fixed Effects vs Random Effects Models

	Dependent variable:	
	Output per Resident (kWp)	
	Fixed Effects	Random Effects
	(1)	(2)
Tariff	0.011***	0.011***
	(0.0004)	(0.0004)
Price of Electricity H4	0.020***	0.020***
	(0.001)	(0.001)
Constant		−0.019
		(0.019)
Canton-Year Dummies	no	no
Observations	12,397	12,397
R^2	0.233	0.207
Adjusted R^2	0.105	0.207
F Statistic	1,611.036*** (df = 2; 10624)	3,233.228***
Note:		*p<0.1; **p<0.05; ***p<0.01

Appendix B: Figures

PV Output in Municipalities

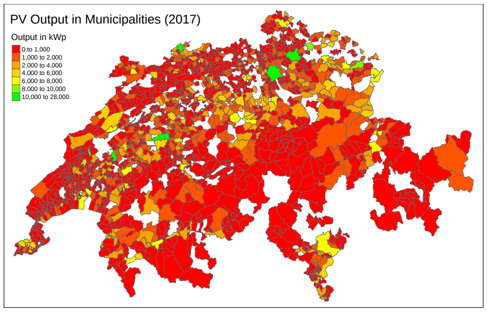

Figure 12: PV Output in 2017

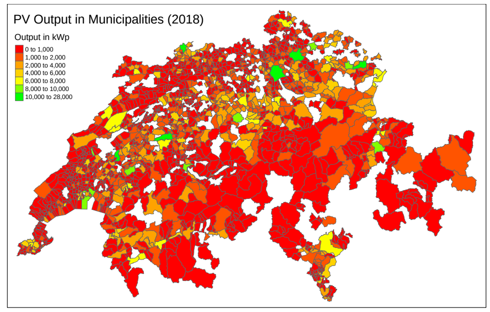

Figure 13: PV Output in 2018

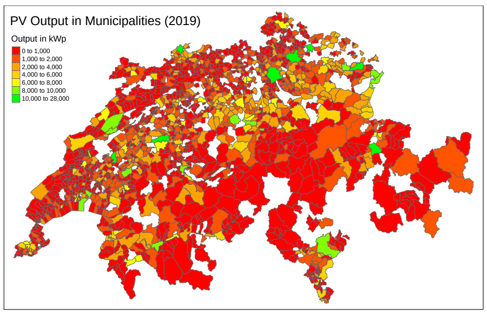

Figure 14: PV Output in 2019

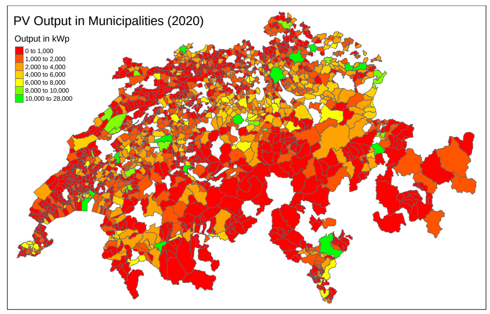

Figure 15: PV Output in 2020

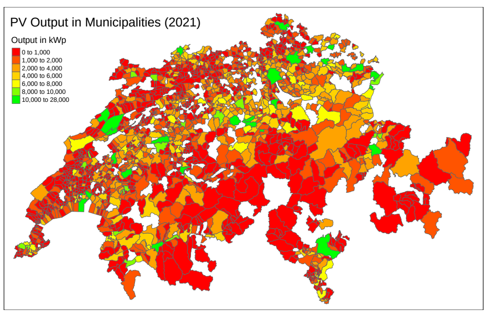

Figure 16: PV Output in 2021

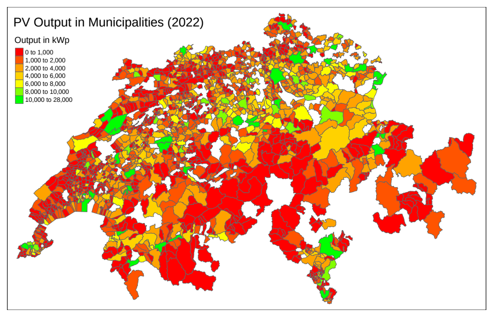

Figure 17: PV Output in 2022

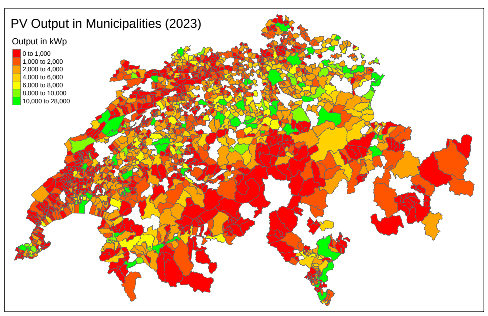

Figure 18: PV Output in 2023

PV Output as Percentage of Potential Output

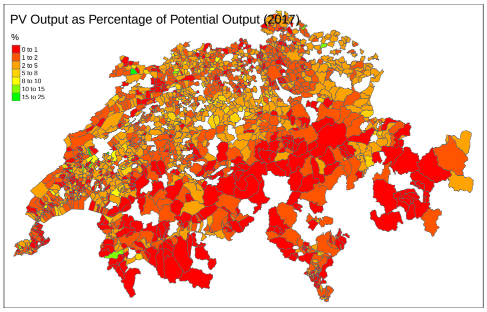

Figure 19: Percentage of PV Output in 2017

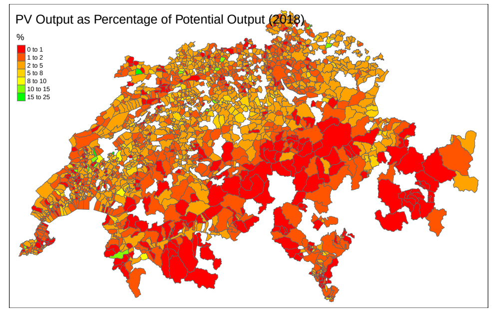

Figure 20: Percentage of PV Output in 2018

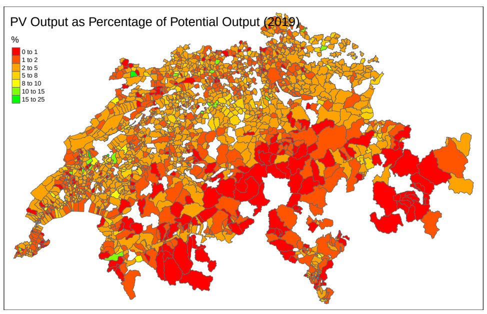

Figure 21: Percentage of PV Output in 2019

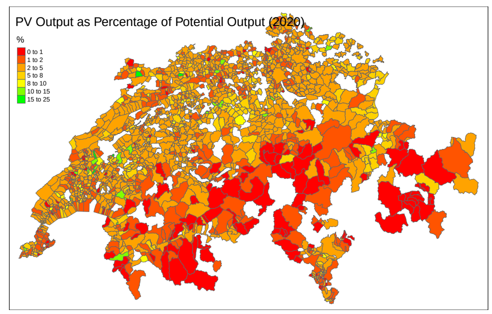

Figure 22: Percentage of PV Output in 2020

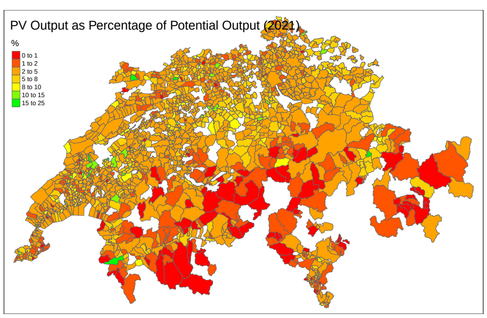

Figure 23: Percentage of PV Output in 2021

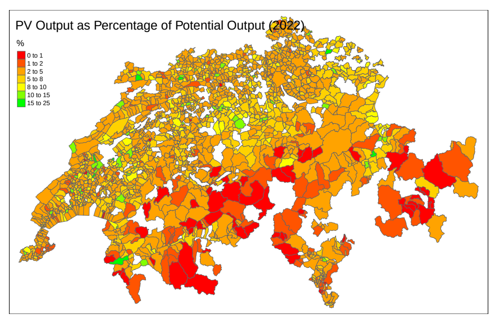

Figure 24: Percentage of PV Output in 2022

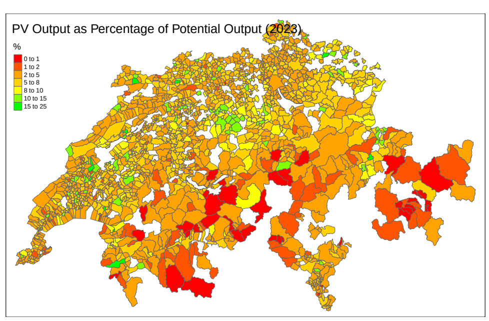

Figure 25: Percentage of PV Output in 2023

PV Output per Resident

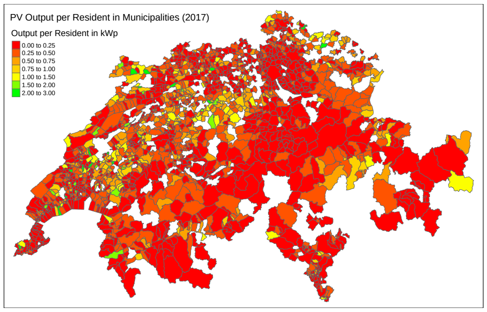

Figure 26: PV Output per Resident in 2017

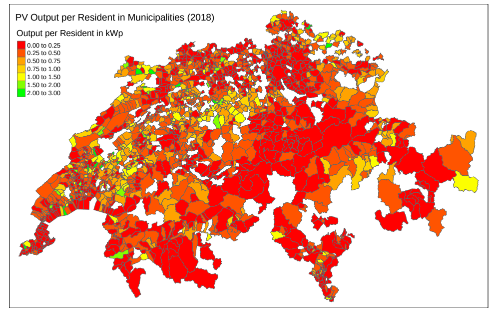

Figure 27: PV Output per Resident in 2018

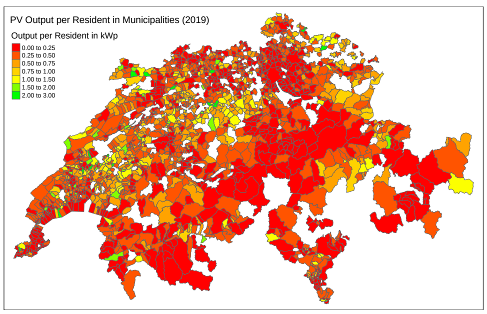

Figure 28: PV Output per Resident in 2019

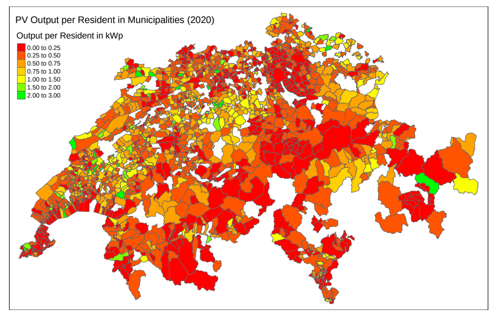

Figure 29: PV Output per Resident in 2020

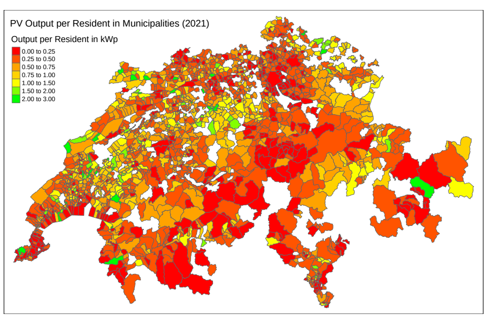

Figure 30: PV Output per Resident in 2021

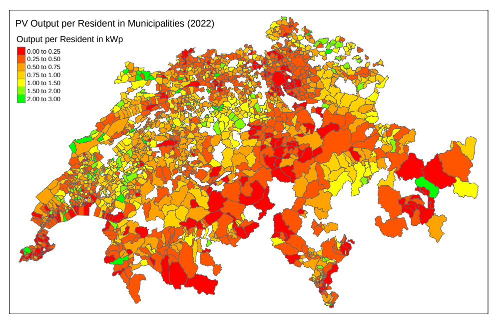

Figure 31: PV Output per Resident in 2022

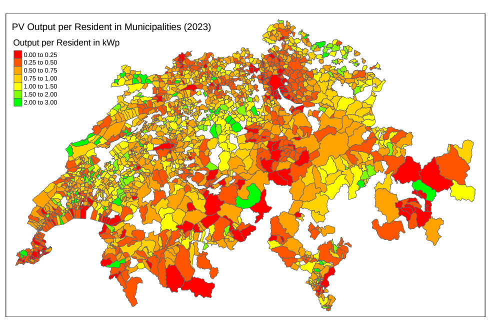

Figure 32: PV Output per Resident in 2023

Electricity Prices

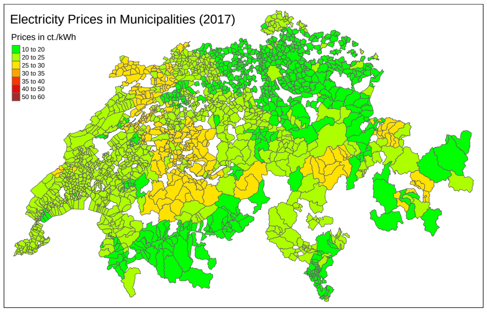

Figure 33: Electricity Prices in 2017

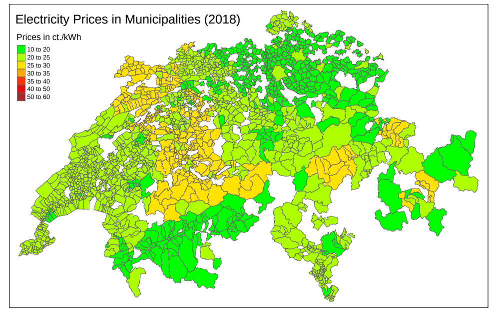

Figure 34: Electricity Prices in 2018

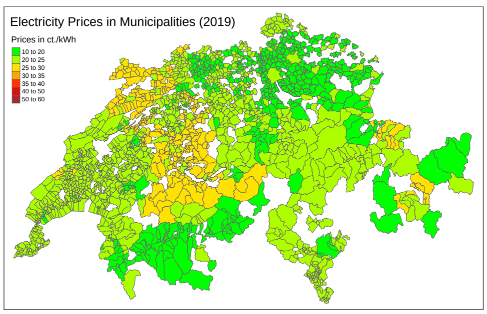

Figure 35: Electricity Prices in 2019

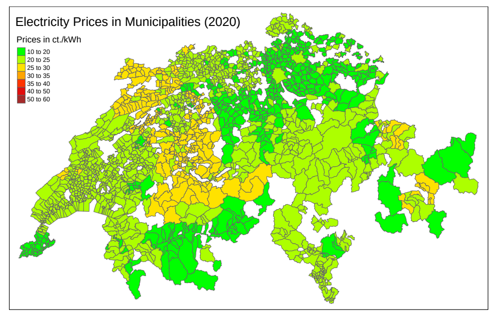

Figure 36: Electricity Prices in 2020

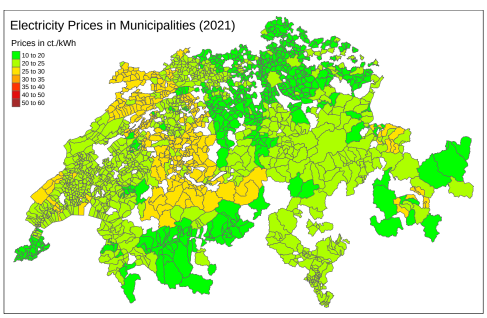

Figure 37: Electricity Prices in 2021

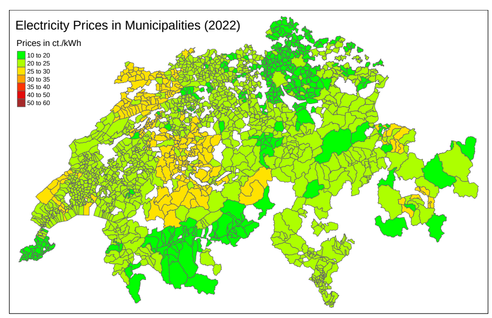

Figure 38: Electricity Prices in 2022

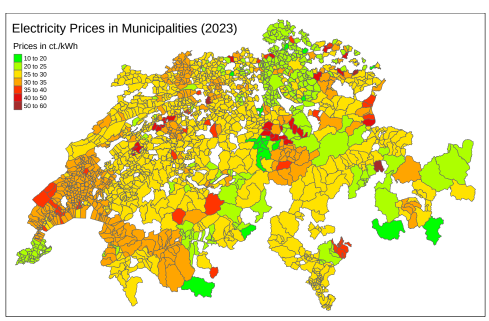

Figure 39: Electricity Prices in 2023

Feed-In Tariffs

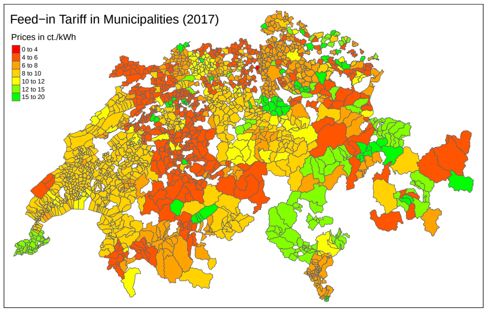

Figure 40: Feed-In Tariffs in 2017

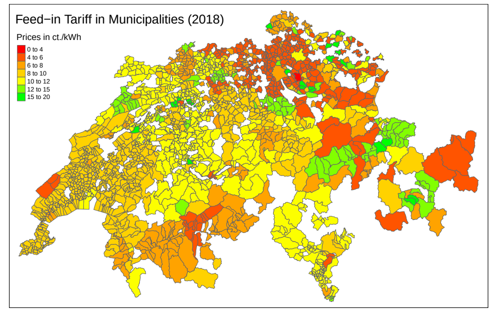

Figure 41: Feed-In Tariffs in 2018

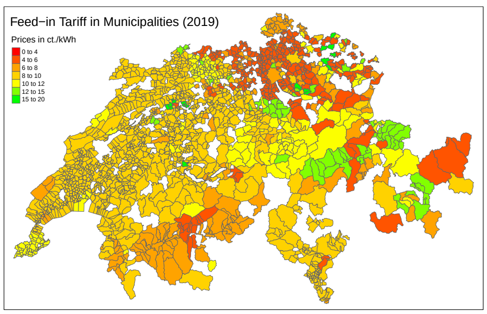

Figure 42: Feed-In Tariffs in 2019

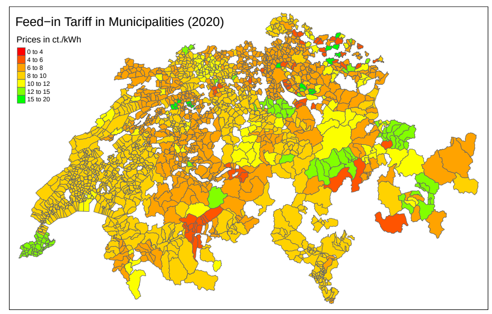

Figure 43: Feed-In Tariffs in 2020

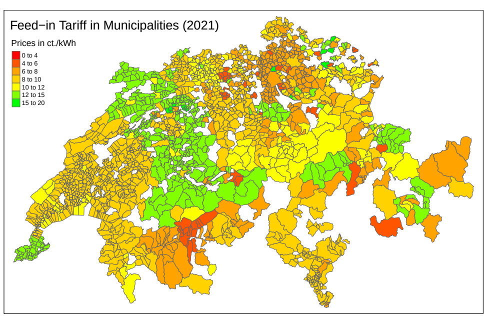

Figure 44: Feed-In Tariffs in 2021

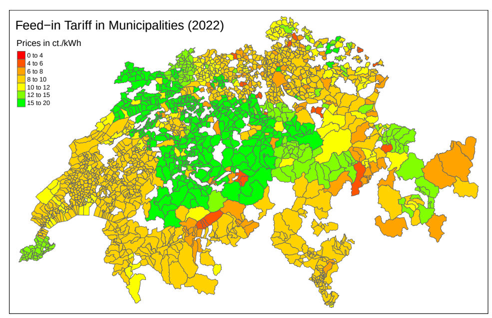

Figure 45: Feed-In Tariffs in 2022

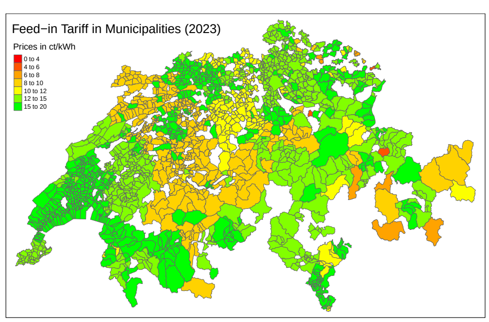

Figure 46: Feed-In Tariffs in 2023