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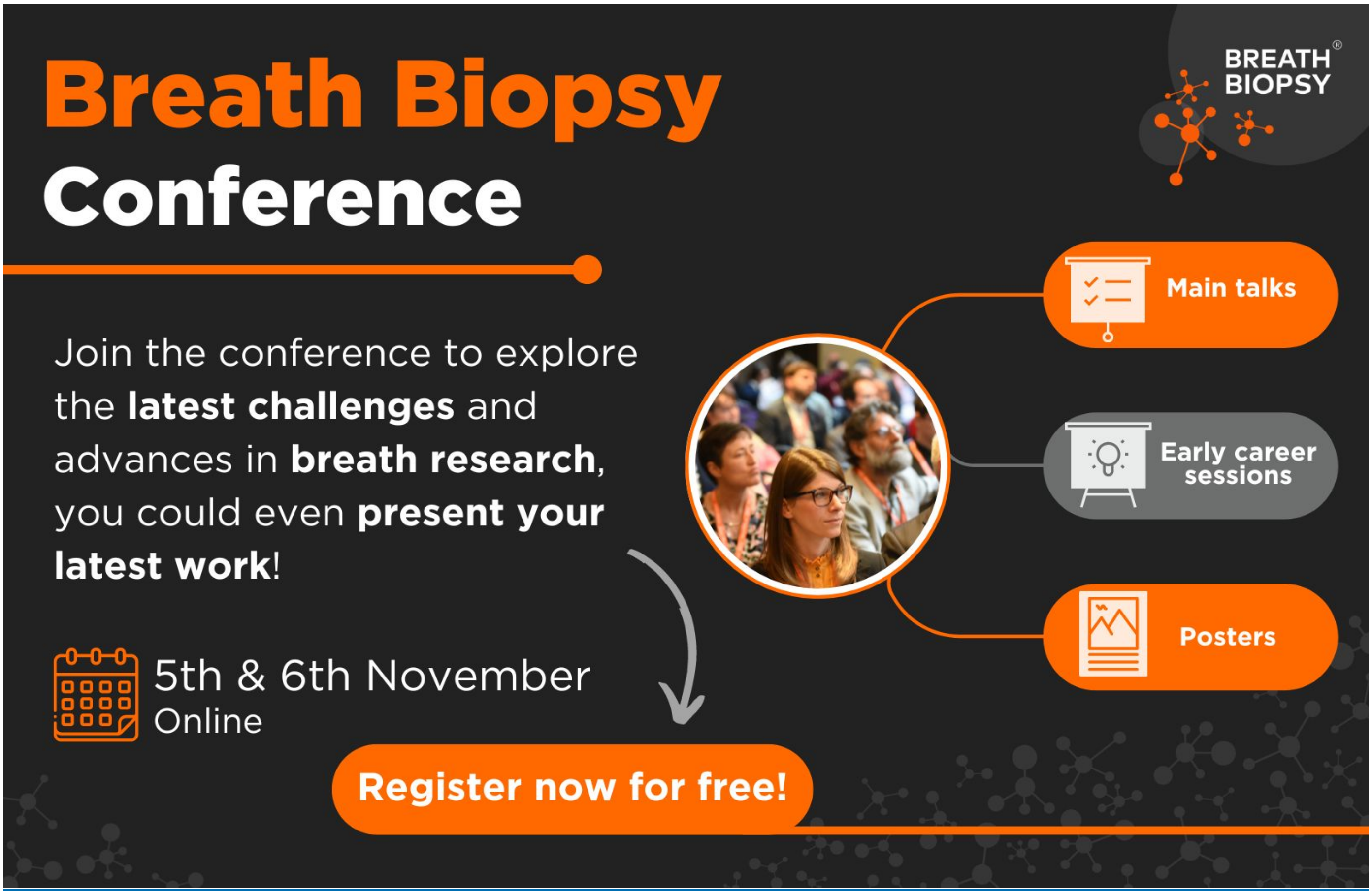

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LETTER

Distributional justice, effectiveness, and costs of current and alternative solar PV incentive schemes in Switzerland

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Abstract

Like many other countries, Switzerland offers various incentives to promote residential solar PV, but not all households have equal access to them. Using a microsimulation approach based on merged data from the Swiss Household Budget Survey and Household Energy Demand Survey, we evaluate the current Swiss incentive scheme in terms of how equally the internal rates of return of PV installations, the amounts of obtainable incentives, and the saving months to accumulate the investment are distributed across households. The current, regionally heterogeneous scheme is then compared with alternative, nationally uniform designs based on the required public spending, effectiveness in promoting profitable and affordable PV, and distributional equality. The current scheme leads to a large disparity in the economic profitability of installations and incentive amounts obtainable across various socio-demographics. Larger, the highest-income, and rural households can obtain more incentives and install more profitable PV systems. Lower-income households must save the longest to install PV. Incentive schemes with a nationally uniform investment grant or a feed-in tariff threshold could offer a good alternative to the current scheme in terms of justice, public spending, and effectiveness. The insights on heterogeneous versus uniform PV incentives and the developed methodology could be transferred elsewhere.

1. Introduction

Solar photovoltaics (PV) is expected to play a key role in decarbonizing the global energy system (Haegel *et al* 2019, Jaxa-Rozen and Trutnevyte 2021, IPCC 2023). In Switzerland, solar PV is also envisioned to become the main technology of the energy transition (Heinisch *et al* 2023, Trutnevyte *et al* 2024) and so far PV uptake has been fast when compared to other technologies (Zielonka *et al* 2023). In 2023, there were 4.6 GW of PV in Switzerland (SFOE 2023), requiring two- to six-fold increase by 2035 and eight- to ten-fold by 2050 (SFOE 2022, Trutnevyte *et al* 2024). Switzerland and many other countries therefore implemented multiple policies to speed up PV deployment, such as subsidies, tax rebates, and feed-in tariffs (FiTs) (Wen *et al* 2021, Schmidt *et al* 2023). The additional specificity of Switzerland is that incentives are regionally heterogeneous due to federalism as, in addition to the federal-level ones, there are incentives that vary at the municipal and cantonal (state) levels too. In other countries, this approach could be seen as advantageous as it allows willing regions to promote PV beyond the country-level goal and because it can increase the chances of finding optimal policy environments. However, heterogeneity of incentives can be also an obstacle to PV deployment (Schmidt *et al* 2023), for example, as it raises complexity for investors. To further understand the implications of regionally heterogeneous versus uniform incentive designs, this study evaluates the effectiveness of current and more uniform financial PV incentives in promoting new capacity, along with potential cost and distributional justice implications (Lamb *et al* 2020, Kime *et al* 2023, Zimm *et al* 2024). This study also presents a novel methodology to prospectively evaluate which societal groups can benefit the most and the least from policy incentives to inform policy design.

Distributional justice, which is concerned with the allocation of policy benefits and burdens across societal groups and space (McCauley and Heffron 2018, Bennett *et al* 2019, Sasse and Trutnevyte 2019), is particularly relevant for evaluating financial incentives. Low perceived policy justice can become a driver for public rejection and a barrier to policy implementation (Bergquist *et al* 2020, Jenkins *et al* 2021). However, the majority of policy evaluation studies on distributional justice so far focused on carbon pricing and energy taxes (Dorband *et al* 2019, Büchs *et al* 2021, Ohlendorf *et al* 2021). Among the few that focused on incentives to promote renewable technologies, a US study found that counties with higher household income had disproportionately benefited more from PV incentives via rebates, grants, federal investment tax credits, and FiTs (Vaishnav *et al* 2017). In Lithuania, higher-income households were found to represent a disproportionately large share of potential recipients of investment subsidies for various residential technologies, given that investments are not affordable to many lower-income households even with subsidies (Lekavičius *et al* 2020). In Germany and Australia, the cross-subsidization of FiTs, when FiTs are financed by all electricity consumers but only benefit PV owners, was found to have an overall regressive effect as lower-income households were charged a higher relative net financial burden (Nelson *et al* 2011, Winter and Schlesewsky 2019). Previous studies also revealed disparities in PV adoption across multiple regional and socioeconomic factors of the population, such as ethnicity, income, or rurality (Lukanov and Krieger 2019, Thormeyer *et al* 2020, Dokshin *et al* 2024), possibly indicating disparities in accessing financial incentives. While most of the previous studies repeatedly pointed to the importance of household income for benefiting from PV support, other socio-economic factors and household location were rarely investigated (Torné and Trutnevyte 2024).

In this study, we evaluate the distributional justice across households of the current, fragmented landscape of PV incentives in Switzerland, and compare the current scheme with nationally uniform designs. We aim to answer the following research questions: How are the financial benefits of the current incentive scheme (measured by the promoted installations' internal rate of return (IRR), the amount of incentives obtainable, and the saving months needed to accumulate the investment) distributed across Swiss household types, defined using household structure, income, canton, and settlement type? How do the current fragmented and alternative nationally uniform schemes compare in terms of distributional justice, required public spending, and economically profitable and affordable PV capacity promoted?

2. Methodology

As shown in figure 1, this study uses a representative sample of Swiss households (section 2.1), acquired by merging data from the Swiss Household Budget Survey (HBS) (FSO 2023a) and the Swiss Household Energy Demand Survey (SHEDS) (Weber *et al* 2017). Using a microsimulation approach (section 2.3) and considering current and alternative incentive schemes (section 2.2), we quantify individual PV business cases for all households that are dwelling owners and do not yet have PV. This information is then used to evaluate the distributional implications of the current PV incentive scheme and to compare the current and alternative schemes in terms of distributional justice, public spending, and effectiveness (section 2.4).

2.1. Representative household sample

The representative sample of Swiss households (Torné and Trutnevyte 2024) was acquired by merging data from two surveys: the HBS (FSO 2023a) and the SHEDS (Weber *et al* 2017). The HBS contains sociodemographic and economic characteristics of 9955 households from 2015 to 2017, and the SHEDS contains information on dwelling characteristics and energy-related equipment of 10 825 households from 2018 to 2021 from every canton except Ticino. These databases were merged through non-parametric statistical matching by Torné and Trutnevyte (2024) to build a synthetic population database of 46 844 households, representative of 77.1% of the diversity of Swiss households in the HBS, excluding the canton of Ticino. For every household in the synthetic sample, there is information on basic descriptives (settlement type, canton of residence, monthly gross income, household structure, dwelling tenure), dwelling characteristics (whether the dwelling is a flat or a house, date of construction, size, and whether the dwelling already has a heat pump and PV), disposable income, housing costs, and electricity expenditure and consumption per year. The electricity cost in each household's municipality is taken from Elcom (2023). Missing values of electricity consumption were imputed through linear regression (see appendix A1). Descriptive statistics for the main relevant variables are available in tables A2 and A3 of appendix A2.

2.2. Current and alternative incentive schemes

We evaluate current and 28 alternative PV incentive schemes in Switzerland (table 1). Currently, PV policy is fragmentated due to federalism (Schmidt *et al* 2023), as in addition to the federal investment grant (Pronovo 2023), some cantons and municipalities also incentivize the installation of PV panels with a one-time subsidy (EKZ 2022). The initial investment net of subsidies can also be deducted from the taxable income of the owners in most cantons (Swiss

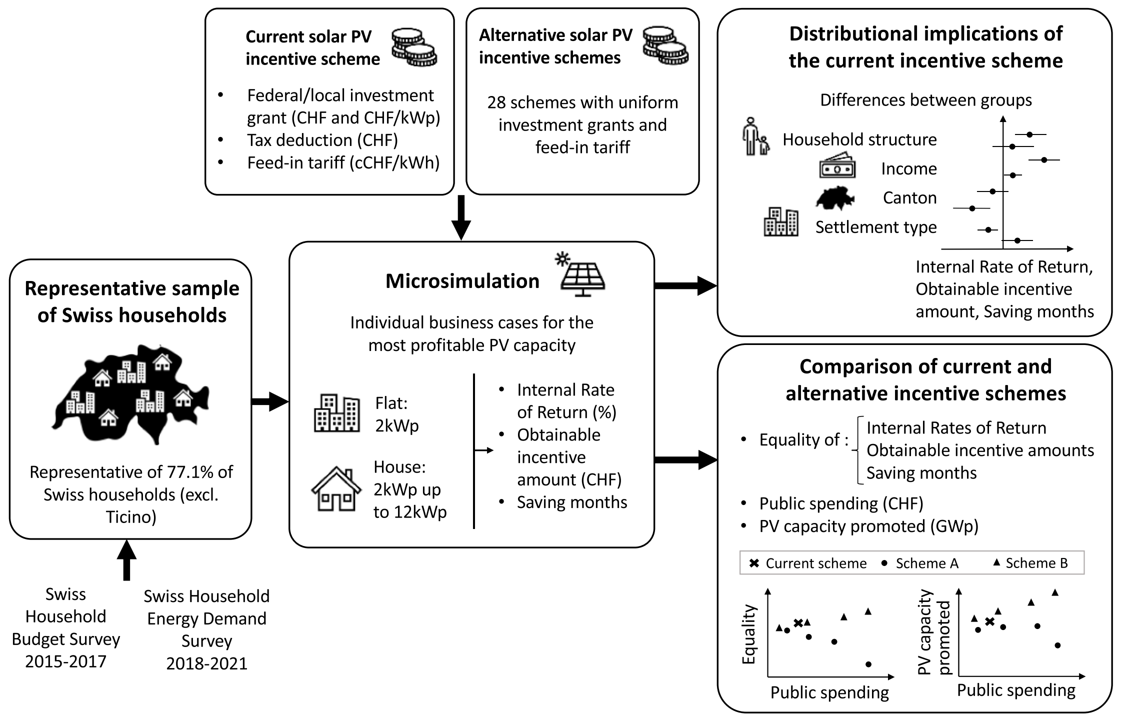

Figure 1. Workflow of the study.

Table 1. Current and alternative incentive schemes in this analysis.

Current scheme (2022)	Alternative schemes		
	Scheme A	Scheme B	Scheme C
Federal investment grant: 200 CHF (for 2–5 kWp installations) + 400 CHF kWp^{-1} (Pronovo 2023)			
Local investment grant (depends on municipality and canton) (EKZ 2022)	Uniform investment grant—fixed: 12 options: grants of 100, 200, 300, 400, 500, 750, 1000, 2000, 3000, 4000, 5000, 6000 CHF	Uniform investment grant—capacity-based: 12 options: grants of 10, 20, 30, 40, 50, 75, 100, 150, 200, 250, 300, 350 CHF kWp^{-1}	Local investment grant (depends on municipality and canton) (EKZ 2022)
Tax deduction (depends on monthly gross income, household structure, and municipality) (Federal Tax Administration 2022)			
Non-uniform feed-in tariff (utility-specific) (Vese 2022)			Non-uniform feed-in tariff (utility-specific) completed up to a threshold: 4 options: threshold of 6, 8, 10, 12 cCHF kWh^{-1}

Solar 2020, Suisse énergie 2023), while most electricity utilities offer FiTs (Vese 2022). This fragmentation can be seen as an advantage as it allows willing cantons or municipalities to incentivize PV more than the federal average, but it can also be an obstacle to PV deployment (Schmidt *et al* 2023). Hence, we consider three types of alternative designs for nationally harmonized incentives (table 1). Alternative schemes A and B include uniform investment grants, fixed and capacity-based respectively, that substitute local investment grants and complement the current federal grant. Alternative scenario C contains a more uniform FiT, as FiTs were shown to be highly effective at fostering PV capacity in neighboring countries as Germany (Hoppmann *et al* 2014). As utilities are mostly owned by public authorities (Schmidt *et al* 2023), they are assumed to elevate and finance current FiTs up to a certain threshold. Within schemes A, B, and C, the level of the incentive is varied to obtain a total of 28 options for alternative PV incentive schemes, covering a range of total promoted PV capacity as a result of modeling business cases. This range includes the current scheme as well as more ambitious ones. Tax deductions remain unchanged across all schemes.

2.3. Microsimulation of PV business cases

The effect of incentive schemes on PV business cases is simulated at the household level for the sample from section 2.1. Business cases consider municipality-specific irradiation (Pfenninger and Staffel 2013, Heinisch *et al* 2023), load profiles of five representative households (Pflugradt 2016), and the annual electricity consumption of each household from the sample. Three parameters are quantified as shown in appendix A3:

- IRR in percentage points: it is a measure of the profitability of the PV installation and is equal to the interest rate at which the net present value of the installation cost and its revenues, including incentives, would be zero:

$$\sum_{n=0}^{N} \frac{c_n}{(1+IRR)^n} = 0 \qquad (1)$$

  where N is the project's lifetime in years (SFOE 2021), and c_n the cashflow in CHF (Swiss francs) for every year n. Further details on the calculation and input values for the cashflows c_n are available in appendix A3.
- Amount of obtainable incentives in CHF, over the entire lifetime of the PV installation: it is a measure of the support that the household has access to. It is the sum of all grants, tax deductions, and revenue from the FiT (see equation (2)),

$$S_{\text{sum}} = S_{\text{PRU}} + S_{\text{local}} + S_{\text{tax}} + \sum_{1}^{N} f_{\text{revenue,n}} \times \frac{1}{(1+r)^{n-1}} \qquad (2)$$

  where S_{PRU} is the federal investment grant (Pronovo 2023), S_{local} is the local investment grant (EKZ 2022), and S_{tax} is the tax deduction of the solar PV investment (Swiss Solar 2020, Suisse énergie 2023), all in CHF. $f_{\text{revenue,n}}$ is the revenue from the feed-in-tariff in CHF (Vese 2022) for every year n, and r the discount rate (Schmidt *et al* 2023) (see appendix A3).
- Saving months needed to accumulate the initial investment: it is a measure of the financial effort that the household must make to install PV. It is calculated by dividing the initial investment by the households' saving capacity per month (see equation (3)),

$$T = \frac{INV}{DI - LMI} \qquad (3)$$

  where INV is the initial investment in CHF, DI is the household's disposable income in CHF month^{-1}, and LMI is the monthly income required to make ends meet in CHF month^{-1} (calculated as described in appendix A3). Saving months T are capped at the 99th percentile of the obtained distribution (160 months) to limit the impact on results of extremely high values.

For households living in flats, the PV installed capacity is assumed to be 2 kWp (Pongelli *et al* 2023, FSO 2022), the typical size of the system that can be assigned to each apartment. For households living in single-family houses, we consider capacities ranging from 2 kWp to 12 kWp with 2 kWp increments (Pongelli *et al* 2023), retaining the capacity that gives the highest IRR for further analysis (Schmidt *et al* 2023). Battery systems are not considered as they tend to lower the IRR of the installations (Schmidt *et al* 2023). Business cases are only made for dwelling owners who do not already have PV: out of the 46 844 households in the whole sample, 12 422 fall into this category.

2.4. Quantification of distributional implications and comparison of alternative incentive schemes

First, the distributional implications of the current PV incentive scheme across various household groups are evaluated by displaying the statistical distribution of the IRRs, obtainable incentive amounts, and saving months, and by using ordinary least square linear regression to compare differences between the means of household groups defined by a specific household descriptive and controlled by the rest of household descriptives. Both methods account for the cross-section statistical weights of each household in the database. Distributional impacts are evaluated across four household characteristics: settlement type, canton of residence, household structure, and equivalized income quintile. Second, we use three policy evaluation criteria for the comparison of the current and alternative incentive schemes:

- Equality in the distribution of benefits: it is measured using the Gini coefficient (Gini 1912) of the distribution of the IRRs, the amounts of incentives obtainable, and the saving months. We choose the Gini coefficient as it accounts for the distances among all points of a distribution. The Gini coefficient was conceived to measure income inequality but has been adapted across fields (Jacobson *et al* 2005, Sasse and Trutnevyte 2020, Sitthiyot and Holasut 2020).
- Public spending: it is measured as a net sum of money paid by public entities during the lifetime of the PV installation by the federal, cantonal, and municipal levels, including investment grants, tax

deductions, and complements to the current FiTs, minus the tax on FiT revenues.

- Effectiveness: it is measured as the total economically profitable and affordable PV capacity that is promoted by each incentive scheme, i.e. the total capacity with a higher IRR than the real discount rate of 3% (on top of inflation) (Schmidt *et al* 2023) and that requires less than 36 months of saving time (Scarpa and Willis (2010).

3. Results

3.1. Distributional implications of the current incentive scheme

With the current fragmented incentive scheme, 29% of Swiss dwelling owners who do not already have PV could install an economically profitable PV system with an IRR higher than the assumed real discount rate of 3% (figure 2). The largest variations in the IRRs can be observed across household structures and cantons. There is a much lower share of profitable installations for one-person households and single parents (3% to 16% of the business cases) than for couples and 'other' household structures (23% to 54%); the latter are multi-person households without family ties, but represent a very low share of owners without PV (2.5%). On average, men under 65 living alone can install the least economically profitable installations, while households with the 'other' structure the most profitable, with a difference of 5% in the average IRR between the two household groups (see figure 3). Across cantons, the share of profitable installations ranges from 5% in Zurich to 57% in Lucerne, with a difference of 3% in the average IRR between households in Zurich (benefiting the least) and households in Lucerne and Bern (benefiting the most). Small variations in the IRRs can also be observed across settlement types and income groups, with differences of around 1% in the average IRR between the groups that benefit the most and the least. IRRs are lower on average in urban areas than in periurban or rural ones. 41% of rural households could install a profitable PV system, against 30% and 25% of periurban and urban households respectively. The IRR of installations tends to be slightly higher for higher income household groups, one of the contributing factors being that they can deduct the investment from taxable income against a higher marginal tax rate. The share of profitable installations ranges from 22% for the lowest-income group (first quintile) to 31% for the highest-income group (fifth quintile).

With the PV system of the most profitable size, larger and younger households can obtain more incentives than people living alone, who in the majority do not have access to them (figure 2). Across cantons, households from the canton of Lucerne can obtain the highest amount of incentives. There is no such noticeable difference across settlement types and income groups, although rural households can obtain higher amounts of incentives than urban and periurban households and the lowest-income group can obtain fewer incentives (figure 3). On average, the same household groups that can obtain the highest amounts of incentives also have the most profitable PV systems (figure 3), because of the strong correlation between the two parameters. However, the regression results show that average differences in obtainable incentive amounts across household groups are slightly less significant. When considering all households (not only dwelling owners that do not yet have PV), the differences between household groups become more apparent (see figure A1 and table A4 in the appendix A4). Higher-income households, households from rural and periurban areas, older couples without children, couples with children, and other household structures on average can obtain the most incentives, while lower-income households, households in urban areas, people under 65 living alone, and households from the canton of Zurich can obtain the least incentives.

In terms of saving months, there is a considerable difference across household structures and income groups. Men over 65 years old who live alone have particularly high financial barriers, as 25% of them would need to save more than 46 months (figure 2). In all other household structures, 75% of the households need less than 14 months. There is a drastic increase in the saving months needed for the lowest-income group: 25% of households in this group need more than 25 months while in other income groups, 75% of the households need less than 5 months. On average, the household groups that need to save the shortest ('other' household structure, couples with children, the highest-income, rural and periurban households, households in the canton of Lucerne) are the same as the ones that receive the highest amount of incentives (figure 3). The ones that need the most saving months on average are one-person men over 65, the poorest households, urban households, and those living in the canton of Vaud. Yet, there are many non-significant results for differences in average saving months, especially across household structures, considering the error bars (figure 3).

3.2. Comparison of current and alternative incentive schemes

Some general trade-offs appear when comparing the current and alternative schemes (figure 4). On the one hand, the distributional equality of IRRs and obtainable incentives tends to increase with higher incentive levels and net public spending, except for equality in IRRs which decreases with larger capacity-based investment grants. On the other hand, higher investment grants—not FiT thresholds—that require more public spending result in a more unequal distribution of affordability (i.e. saving months), especially

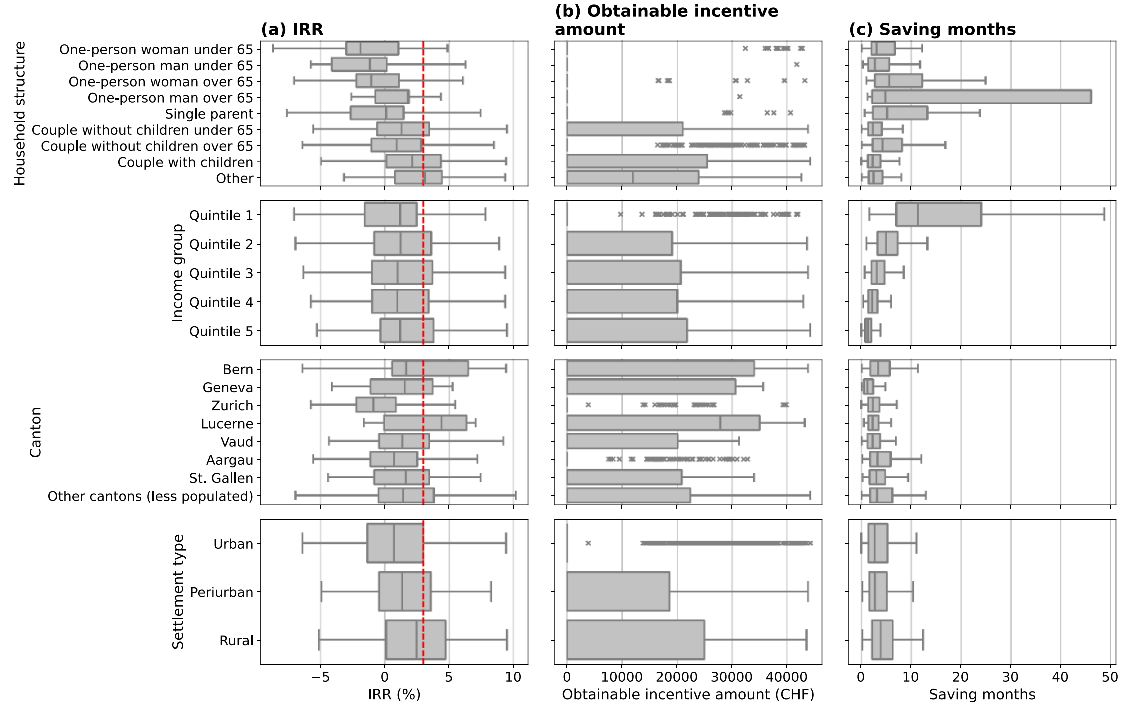

Figure 2. Distribution of (a) IRRs in %, (b) obtainable incentive amounts in CHF, and (c) saving months across household groups. The boxplots show the median IRR, obtainable incentives amount, and saving months as a line. The box indicates the first and third quartile, and the whiskers, the range of data without outliers. In (a) we include the threshold of profitability at IRR 3% as the dotted red line. In (b) we include outliers to better visualize the ensemble of results. We consider that households that cannot pass the 3% IRR threshold with incentives do not apply to them and therefore do not get any incentive amount. For income groups, households are divided into five quintiles of equivalized disposable income. The 1st quintile represents the least affluent households and the 5th, the most affluent ones.

for fixed investment grants. This is because low investment grants result in more saving months and in more households with saving months capped at 160 months. Since the Gini coefficient measures the disparities in saving months among households, this results in higher equality for lower incentive amounts or, in other words, in higher inequality for higher incentive amounts.

Overall, increased incentive levels and increased public spending promote more total profitable and affordable PV capacity (figure 4). Incentive schemes with capacity-based investment grants and those with a FiT threshold are more effective in promoting profitable and affordable PV capacity per unit of public spending (particularly a 100 CHF kW^{-1} grant and a minimum FiT of 12 cCHF kWh^{-1}) than incentive schemes with a fixed grant. For schemes with small fixed grants, total profitable and affordable capacity promoted increases with the grant up to a tipping point of 3000 CHF, from which it substantially decreases. This is because the individual capacities that are most profitable for households decrease with high fixed investment grants. While with the current scheme 2 kWp is the most profitable PV system size for 39% of business cases, with an additional fixed investment grant of 4000 CHF it is for 72% of cases, and with one of 6000 CHF for 100%. The windfall profits, i.e. subsidies paid out to households who do not need them to invest profitably in PV, are almost non-existent as, without support, the total profitable and affordable capacity is only estimated at a negligible level of 8.5 MW or 0.3% of the total profitable and affordable capacity resulting from the current incentive scheme.

While keeping nearly the same public spending level as the current incentive scheme, a fixed uniform investment grant of 500 CHF instead of local grants offers better equality in terms of profitability of installations (IRR), slightly better equality in obtainable incentives, and very similar equality in terms of saving months (figure 4). The trade-off is promoting slightly less profitable and affordable capacity. Among schemes that promote more capacity than the current one, those with minimum FiT thresholds are appealing because, together with capacity-based investment grants, they are the most effective in promoting capacity per unit of public spending. They offer more equality in the distribution of installation IRRs and obtainable incentives than the current scheme and schemes with capacity-based grants. They also offer more equality in the distribution of saving months than schemes with capacity-based grants. Uniform capacity-based investment grants are also cost-effective in promoting capacity and most likely easier to implement. Yet, they increase inequalities in the profitability of installations with respect to the current scheme and lead to higher inequalities in total obtainable incentive amounts than the rest of

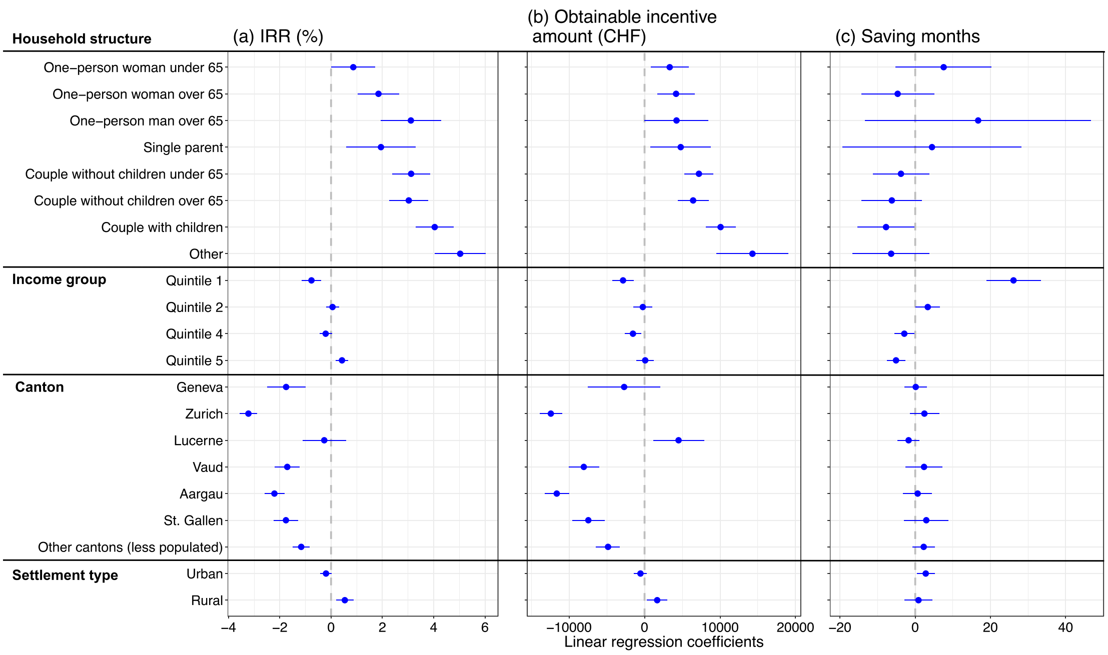

Figure 3. Ordinary least square regression between (a) IRR in %, (b) obtainable incentive amount in CHF, and (c) saving months, and household characteristics. We consider that households that cannot pass the 3% IRR threshold with incentives do not apply for and therefore do not get any incentive amount. Regression coefficients show differences between the means of household groups defined by a specific household descriptive, controlled by the rest of household descriptives, and as compared to reference categories. The following reference categories are used: 'one-person man under 65' for household structure, 'quintile 2' for income groups, 'Bern' for canton, and 'periurban' for settlement type. The error bar of each coefficient represents its 95% confidence interval. If it crosses zero on the *x*-axis, the coefficient is not significant ($p < 0.05$), which means that there is no statistically significant difference with the reference category. If the error bars of different coefficients overlap, differences in the coefficients of these household groups are not statistically significant. For income groups, households are divided into five quintiles of equivalized disposable income. The 1st quintile represents households that are the least affluent and the 5th, the most affluent.

the schemes. The latter is due to the big difference in installation sizes between houses and flats and the fact that with this scheme the subsidy is proportional to this size. Last, fixed grants of 3000 CHF or less require more public spending than other schemes for the same capacity promoted and lead to higher inequality of PV affordability than other schemes, but they would most likely be easier to implement than FiT thresholds and, unlike capacity-based grants, increase both the equality of PV profitability and of obtainable incentive amounts.

4. Discussion

Previous literature assessing how benefits from solar PV incentives are distributed mainly focused on income groups, and higher-income households were found to benefit more (Vaishnav *et al* 2017, Lekavičius *et al* 2020). We show the same trend in Switzerland if we consider all households including those that cannot install PV (figure A1 in the appendix A4). When considering only dwelling owners who do not yet have PV, results slightly change. There is only a small increase in obtainable incentive amount and PV profitability with higher income as compared to the contribution of other factors. Unlike other studies, we also find that larger households, households in the canton of Lucerne, and rural households can benefit more from current PV incentives, while single-person households and households in urban and periurban areas can benefit less. As single-person households including women and older people who can benefit less from incentives are also found to have higher income-based poverty rates (Hümbelin *et al* 2021), incentives can exacerbate existing inequalities. However, among the poorer (income-based) there are also the rural households, a large share of which live in individual houses, that can install bigger PV systems and obtain a slightly higher amount of incentives than urban and periurban households. This, together with other potential contributing factors, leads to more profitable PV systems and a potential countering effect for inequality. Since the PV capacity that can be installed in flats with respect to houses is limited, and since smaller PV systems can enjoy fewer incentives and tend to be less profitable, the type of housing has a noticeable impact on the distribution of incentive benefits. One-person households tend to live more often in flats than houses, especially women and younger people, which in part explains why they have lower access to the incentive benefits.

In Switzerland, more uniform investment grants on top of the current federal grant as suggested by Schmidt *et al* (2023) or setting a minimum threshold of FiT could more equally distribute the benefits of PV across households in terms of total obtainable

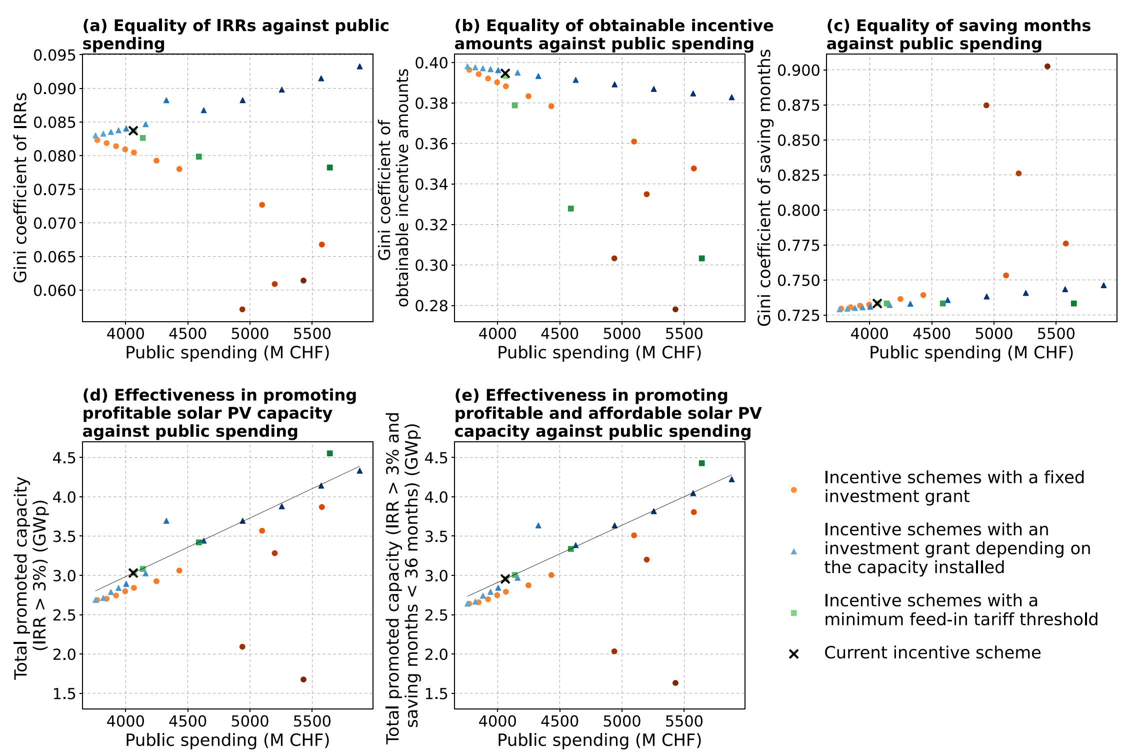

Figure 4. The tradeoff between public spending on PV incentives and the Gini coefficient of the distribution of (a) IRRs, (b) obtainable incentive amounts, and (c) saving months, and between public spending and profitable and affordable PV capacity promoted, using indicators of (d) total PV capacity with IRR higher than 3% only, and (e) total capacity with IRR higher than 3% and requiring less than 36 saving months. In (d) and (e), the black line has a slope equal to the cost-effectiveness in GWp $MCHF^{-1}$ of the current scheme. Schemes above it have higher (thus better) cost-effectiveness than the current scheme, and the ones below, have lower cost-effectiveness. For each color gradient, the darker the color, the higher the level of the new incentive given. A Gini coefficient of 0 corresponds to perfect equality and 1 to perfect inequality. Results displayed in terms of public spending and total PV capacity are obtained from a sample with 77.1% the size and diversity of the whole Swiss household sample as per captured by the HBS (FSO 2023a), thus do not represent total values for the whole Switzerland.

incentive amount and the profitability of PV installations. Higher and more uniform FiTs—like the ones that led to a massive deployment of PV in Germany and Italy (Hoppmann *et al* 2014, Kërçi *et al* 2022)—would at the same time maintain equality among households in terms of PV affordability. As with additional uniform capacity-based investment grants, FiT thresholds could also promote the deployment of PV in Switzerland more cost-effectively than the current scheme. Despite its benefits, minimum FiT thresholds would not lower the upfront costs of PV, unlike additional uniform investment grants. Due to the mixed ownership of utilities (although many are publicly owned for the most part (Schmidt *et al* 2023)) who set the FiTs, minimum thresholds also might be more difficult to implement than other harmonization measures. Another element to consider is that, if implemented, provisions forbidding utilities to lower their FiT would have to be included as those with a higher FiT than the threshold set by the federal government could want to adopt this lower level of compensation. Overall, while the current heterogeneous incentives approach might have some advantages, more uniform incentive schemes can offer a good alternative in terms of cost-effectiveness and distributional equality of the incentive benefits. However, if the alternative to heterogeneous incentives is no incentives at all because no common policy can be agreed upon, the former appears to be a better option to promote PV since more incentives accelerate PV deployment as they translate into more total profitable and affordable capacity for households.

Our study also has implications for policymaking in other countries. In some contexts, regionally heterogeneous incentive schemes might have some advantages over national uniform schemes, like increased political feasibility, the leeway for regions to increase ambition, and the greater chances to find optimal policy designs. In the case that no common policy can be agreed upon at a national level, heterogeneous schemes can also become the only option to promote PV. However, using the case of Switzerland, we show that regionally heterogeneous incentive schemes are not necessarily better than nationally uniform ones in terms of cost-effectiveness and distributional equality. This finding, added to the fact that nationally uniform schemes can be simpler to implement from a practical standpoint and send a clearer signal to PV investors (Schmidt *et al* 2023), calls at least for the evaluation on a case-by-case basis which approach is more suitable. Our quantitative method is a tool for such evaluation, for comparing specific incentive designs, and for identifying which societal groups benefit from incentives.

Although we considered a variety of potential PV incentives, we did not cover neither incentives that vary in time nor future evolution in PV and electricity prices. Households can receive different amounts of incentives depending on when they apply and when PV prices are expected to decline, so future research could account for these changes. It could also account for the evolution of household and dwelling characteristics in time, thus moving from a static to a dynamic microsimulation approach. Our results are also conditional to the quality of the underlying survey data, which had some missing values for electricity consumption and did not contain data from households in the canton of Ticino. The merged survey data is, however, quite representative with considerable information on dwelling characteristics and household socio-demographics, allowing us to disaggregate the distribution of financial benefits to many more dimensions than income. Regarding the business cases, we evaluated the investment in PV systems in isolation, but in reality PV could become profitable to more households when combined with heat pumps or electric vehicles. Future work should focus on these combined investments and associated incentives. Distributional justice could have been evaluated through other principles than equality too, like sufficiency, utility, and priority (Torné and Trutnevyte 2024). Finally, we obtained interesting takeaways for policymaking when comparing current and alternative PV schemes, but other schemes could also be investigated. Future research could even evaluate incentives for promoting community-based PV projects or the effect of green leases to help with the deployment of PV in tenant-occupied buildings. From a methodological perspective, future research could also move from the simulation to the optimization of policy design. Public acceptance of alternative schemes (Sobri *et al* 2021, Stadelmann *et al* 2023) as well as the relationship between the distribution of financial benefits and the actual uptake of PV (Müller and Trutnevyte 2020, Thormeyer *et al* 2020) should be investigated too to understand the broader role of distributional effects.

5. Conclusion

The analysis of distributional impacts across household groups from energy policies other than carbon or energy taxes is still a nascent research field. Using a microsimulation approach in Switzerland, we show large disparities in benefits from PV incentives across household structures and cantons. Among dwelling owners who do not yet have PV, those who can benefit the most from the current incentives are larger, the highest-income, and rural households. While the current, regionally heterogeneous PV incentive schemes in Switzerland may seem appealing for other countries to allow leeway for willing subnational regions to increase ambition, we find that there are more typical, nationally uniform schemes that are more favorable in terms of cost-effectiveness and distributional equality among households. If public entities were willing to spend more on PV incentives, minimum FiT thresholds could promote PV with very similar or higher cost-effectiveness while maintaining equality in terms of PV affordability and increasing equality in PV profitability and the amount of incentives given to households. Incentive schemes that would be easier to implement, such as uniform fixed or capacity-based investment grants instead of local grants, would come with the trade-off of less cost-effectiveness and less equality, respectively. In addition to these policy insights on nationally heterogeneous versus uniform PV incentives, our methodological approach for quantifying distributional impacts of energy policies on household groups beyond income could be also transferred to other countries, as far as similar household-level datasets exist.

Data availability statement

The data cannot be made publicly available upon publication because they are owned by a third party and the terms of use prevent public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

A1. Imputation of electricity consumption values
The SHEDS (Weber *et al* 2017) has data on the electricity expenditure (in CHF) and the electricity consumption (in kWh) of households per year. However, these values were not reported for 30% of the households for electricity expenditure and for 56% of households for electricity consumption. The

survey values for the electricity consumption were disregarded since too many of them were missing or did not make sense. For this reason, the electricity consumption per household that was used to calculate the cashflow was computed from the electricity expenditure values of the survey, divided by the electricity cost. For every household, the cost of electricity in cCHF kWh^{-1} was obtained from the Elcom (2023) database for a household profile type H4 (4500 kWh year^{-1}) which represents a dwelling of five rooms with an electric stove and dryer (without electric water heater). Since 30% of values of electricity consumption at this point were still missing, these were imputed through an ordinary least square linear regression. The household variables used as determinants were the number of household members, the dwelling tenure, whether the dwelling is a flat or a house, its size, and presence of a heat pump. The details of the linear regression are the following (table A1):

Table A1. Ordinary least square regression results for electricity consumption imputation.

	Electricity consumption in kWh year^{-1}
(Intercept)	1400.623 ***
	(146.055)
Number of household members	248.006***
	(34.35)
Tenant (ref= Owner)	−519.457***
	(106.668)
House (ref= Flat)	2007.352***
	(116.849)
Accommodation size (in sqm)	10.809***
	(0.71)
Having a heat pump (ref = No)	678.826***
	(95.858)
Adjusted R^2	0.267
F-statistic	436.9

All continuous predictors are mean-centered and scaled by 1 standard deviation. *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

A2. Descriptive statistics of the household sample

Table A2. Descriptive statistics for the main relevant variables of the whole synthetic household sample, cross-tabulated with household descriptives. The sample was obtained by merging the HBS (FSO 2023a) with the SHEDS (Weber *et al* 2017) and is representative of 77.1% of the original HBS sample excluding households from the canton of Ticino.

		% of households within descriptive	Disposable income minus minimum income to make ends meet, i.e. saving capacity (CHF month^{-1})		Electricity consumption (kWh year^{-1})		Living in Flat or House		Having solar PV	
			Mean	Std. dev	Mean	Std. dev	Flat	House	No	Yes
Household structure	One-person woman under 65	12.5	2201.2	2619.8	2018.7	1626.1	94.2%	5.8%	94.7%	5.3%
	One-person man under 65	13.1	2539.9	2296.7	2480.2	3171.4	93.2%	6.8%	92.0%	8.0%
	One-person woman over 65	8.2	1077.0	2008.0	3022.0	4300.1	87.5%	12.5%	93.7%	6.3%
	One-person man over 65	1.3	2108.5	1701.4	2802.8	2231.3	79.5%	20.5%	93.1%	6.9%
	Single parent	3.1	2020.1	2259.0	3064.1	2529.2	87.9%	12.1%	93.1%	6.9%
	Couple without children under 65	21.8	5831.4	5324.2	3479.4	3119.8	69.4%	30.6%	91.0%	9.0%
	Couple without children over 65	11.5	3379.2	3338.9	4885.4	4210.0	53.9%	46.1%	89.7%	10.3%
	Couple with children	25.8	6041.1	5731.4	4902.0	3591.0	55.5%	44.5%	86.4%	13.6%
	Other	2.6	6392.6	5480.7	3979.9	3082.5	72.3%	27.7%	91.5%	8.5%
Equivalized disposable income group	Quintile 1 (lowest income)	20.0	537.8	1297.1	3267.4	3745.2	81.7%	18.3%	93.7%	6.3%
	Quintile 2	20.0	2398.2	1533.1	3534.3	3138.9	72.2%	27.8%	90.8%	9.2%
	Quintile 3	20.0	3569.2	2117.3	3602.0	3168.4	71.8%	28.2%	91.0%	9.0%
	Quintile 4	20.0	5065.1	2766.7	3864.0	3700.1	71.2%	28.8%	89.7%	10.3%
	Quintile 5 (highest income)	20.0	9309.9	7184.7	3978.7	3703.9	65.7%	34.3%	87.7%	12.3%

(Continued.)

Table A2. (Continued.)

		% of households within descriptive	Disposable income minus minimum income to make ends meet, i.e. saving capacity (CHF month^{-1})		Electricity consumption (kWh year^{-1})		Living in Flat or House		Having solar PV	
			Mean	Std. dev	Mean	Std. dev	Flat	House	No	Yes
Canton	Bern	13.0	3708.9	3955.2	3607.9	3193.2	74.0%	26.0%	89.7%	10.3%
	Geneva	5.0	3926.9	6052.3	2341.6	2608.4	96.1%	3.9%	95.0%	5.0%
	Zurich	20.6	4829.7	6026.7	3259.1	2905.7	80.9%	19.1%	92.1%	7.9%
	Lucerne	4.1	4581.0	3924.1	2811.1	2330.0	77.6%	22.4%	91.7%	8.3%
	Vaud	9.7	3842.2	4892.1	3266.8	3190.4	82.4%	17.6%	88.2%	11.8%
	Aargau	7.0	4861.6	4216.7	4825.1	4476.2	55.1%	44.9%	87.0%	13.0%
	St. Gallen	5.0	3830.4	3628.1	3723.7	4787.4	70.0%	30.0%	89.9%	10.1%
	Other cantons (less populated)	35.6	3959.9	4085.1	4033.6	3694.5	64.3%	35.7%	90.7%	9.3%
Settlement type	Urban	68.7	3983.6	4978.3	3176.3	3173.0	82.5%	17.5%	92.2%	7.8%
	Periurban	19.3	4944.7	4055.0	4602.5	3762.7	51.1%	48.9%	86.5%	13.5%
	Rural	12.0	4032.7	4083.4	4820.2	4267.6	50.1%	49.9%	88.0%	12.0%
Dwelling tenure	Owner	36.9	5836.7	6042.7	5354.3	4279.7	35.3%	64.7%	84.7%	15.3%
	Tenant	63.1	3204.4	3391.4	2652.7	2477.6	94.3%	5.7%	94.0%	6.0%
Total		**100.0**	**4175.3**	**4726.6**	**3649.2**	**3511.3**	**72.5%**	**27.5%**	**90.6%**	**9.4%**

Table A3. Descriptive statistics for the main relevant variables of the synthetic household sample including only owner-occupants without solar PV already installed, cross-tabulated with household descriptives.

		% of households within descriptive	Disposable income minus minimum income to make ends meet, i.e. saving capacity (CHF month^{-1})		Electricity consumption (kWh year^{-1})		Living in Flat or House	
			Mean	Std. dev	Mean	Std. dev	Flat	House
Household structure	One-person woman under 65	3.9	3629.6	5961.6	3183.3	2328.4	73.7%	26.3%
	One-person man under 65	4.4	3817.6	3171.6	4716.1	6954.8	68.1%	31.9%
	One-person woman over 65	7.3	1730.3	3260.0	4157.4	4338.0	56.7%	43.3%
	One-person man over 65	1.2	2101.9	1822.6	4982.6	2980.1	46.4%	53.6%
	Single parent	1.1	3152.8	2849.4	4225.9	2122.0	42.8%	57.2%
	Couple without children under 65	23.7	6656.2	6465.1	5066.6	4241.4	35.4%	64.6%
	Couple without children over 65	22.2	3862.7	3782.2	5682.3	4718.9	38.2%	61.8%
	Couple with children	33.8	7533.5	7111.1	6245.8	3786.5	27.7%	72.3%
	Other	2.5	7704.7	8002.3	6252.3	4146.9	31.3%	68.7%
Equivalized disposable income group	Quintile 1 (lowest income)	14.0	1149.2	1532.3	5823.1	5330.9	37.0%	63.0%
	Quintile 2	18.8	3052.4	1649.5	5185.6	3678.7	33.9%	66.1%
	Quintile 3	21.9	4330.2	2824.5	5176.8	3853.8	38.9%	61.1%
	Quintile 4	21.5	6119.4	2478.2	5611.9	4342.6	40.9%	59.1%
	Quintile 5 (highest income)	23.8	11 181.5	9748.1	5611.3	4620.1	38.4%	61.6%
Canton	Bern	13.9	4787.9	5104.4	4706.4	3536.8	41.5%	58.5%
	Geneva	1.1	11 764.8	17 450.4	4517.2	5142.4	57.3%	42.7%
	Zurich	15.5	6632.4	9558.7	5467.6	4197.0	48.2%	51.8%
	Lucerne	3.6	7568.5	5141.9	4578.5	3067.8	43.5%	56.5%
	Vaud	5.8	7124.0	7081.9	4461.9	3581.9	40.1%	59.9%
	Aargau	10.6	5705.0	4452.8	6585.6	5192.7	31.1%	68.9%
	St. Gallen	4.7	5498.0	3733.8	5120.5	2848.5	32.8%	67.2%
	Other cantons (less populated)	44.7	5117.4	4625.1	5697.9	4617.7	34.4%	65.6%
Settlement type	Urban	53.7	5766.0	7470.3	4818.0	4107.1	49.0%	51.0%
	Periurban	29.6	5806.4	4356.8	6037.7	4058.3	29.8%	70.2%
	Rural	16.7	5080.9	4048.4	6533.8	5204.7	17.2%	82.8%
Total		**100.0**	**5663.6**	**6195.2**	**5465.9**	**4355.4**	**38.0%**	**62.0%**

A3. Calculation of the individual PV business cases

Internal rate of return

The IRR is calculated with equation (A1), and it is the interest rate at which the net present value of the solar PV installation is zero:

$$\sum_{n=0}^{N} \frac{c_n}{(1+IRR)^n} = 0 \quad \text{(A1)}$$

where N is the project's lifetime, set to 30 years (SFOE 2021), and c_n the cashflow in CHF (Swiss francs) for every year n (see equations (A2) and (A3)).

The initial investment INV and the cashflow c_n in CHF are calculated with equations (A2) and (A3):

$$c_0 = -INV = -(CAPEX \times CAPA - S_{PRU} - S_{local} - S_{tax}) \quad \text{(A2)}$$

$$c_n = E_{\text{old}} - E_{\text{new,n}} - OPEX \times p_n + f_{\text{revenue,n}}(1 - tax_{\text{hh}}); \forall n > 0 \quad \text{(A3)}$$

where $CAPEX$ is the capital cost of the system in CHF kWp^{-1} (calculated as per equation (A5)). $CAPA$ represents the PV capacity of the installation in kWp. S_{PRU} represents the federal investment grant (Pronovo 2023), S_{local} corresponds to the cantonal and municipal investment grants (EKZ 2022) and S_{tax} represents the investment tax deduction (Swiss Solar 2020), all in CHF. S_{tax} is calculated by multiplying the revenue tax rate corresponding to each household tax_{hh} (Federal Tax Administration 2022) by the investment net of subsidies INV. E_{old} and $E_{\text{new,n}}$ represent the old and the new household's expenditure for buying electricity from the grid in CHF year^{-1}, before and after investing in solar PV. $OPEX$ refers to the PV system maintenance and operation costs in CHF kWh^{-1} and p_n is the PV production in each year in kWh year^{-1}. The OPEX cost of PV installations is 3.5 cCHF kWh^{-1} according to the Swiss Federal Office of Energy (SFOE 2017, 2021). Due to degradation, the PV system is assumed to have a production p_n of 0.5% less each year (SFOE 2021). $f_{\text{revenue,n}}$ is the gross revenue in CHF year^{-1} gained from the electricity fed to the grid, which is taxed at tax_{hh}, and calculated as in equation (A4):

$$f_{\text{revenue,n}} = FIT_{\text{supplier}} \times (p_n - sc_n) \quad \text{(A4)}$$

where FIT_{supplier} is the feed-in-tariff in cCHF kWh^{-1} (Vese 2022); p_n is the PV production in kWh year^{-1}; sc_n is the self-consumption of PV electricity by the household in kWh year^{-1}.

The CAPEX, or the PV installation's capital cost in CHF kWp^{-1}, depends on the PV capacity installed $CAPA$ (in kWp). Due to economies of scale, the larger the capacity installed, the lower the capital cost per kWp will be. The CAPEX is calculated with equation (A5) according to Bloch *et al* (2022):

$$CAPEX = \frac{5523}{CAPA^{0.4862}} + 156.2 \times e^{-0.2321\,CAPA} + 578.4. \quad \text{(A5)}$$

The new household's expenditure for buying grid electricity after installing PV $E_{\text{new,n}}$ in CHF year is calculated with equation (A6):

$$E_{new,n} = E_{old} - sc_n \times e_{cost} \quad \text{(A6)}$$

where E_{old} is the old household's expenditure for buying grid electricity in CHF and corresponds to the calculated or imputed values of electricity consumption times the electricity cost e_{cost} in cCHF kWh^{-1} (Elcom 2023). sc_n is the yearly value of the self-consumption of PV electricity in kWh year^{-1} and represents the overlap of the hourly profiles of the household electricity consumption (Pflugradt 2016) and solar PV electricity generation. Both profiles are in hourly values, for one year.

The electricity consumption profile for every household is obtained by combining the total annual electricity consumption values from the household sample with a typical yearly load profile corresponding to each of the households' structure. As done in the SWEET EDGE White paper (Schmidt *et al* 2023), the profiles were generated through the LoadProfileGenerator application (Pflugradt 2016) for five different household structures:

- couple, 30–64 years old, with work (CHR02)
- family both at work, 2 children (CHR27)
- single woman, 1 child, with work (CHR22)
- single with work (CHR07)
- multigenerational home: working couple, 2 children, 2 seniors (CHR15).

The hourly PV production profile was obtained by multiplying the PV capacity in kWp with Swiss municipality-specific PV capacity factors from 2013 given in kWh kWp^{-1} (Pfenninger and Staffel 2013).

Amount of incentives obtainable

The obtainable incentive amount S_{sum} in CHF is calculated with equation (A7) for the lifetime of the system:

$$S_{sum} = S_{PRU} + S_{local} + S_{tax} + \sum_{1}^{N} f_{revenue,n} \times \frac{1}{(1+r)^{n-1}} \quad \text{(A7)}$$

where S_{PRU} is the federal investment grant (Pronovo 2023), S_{local} is the local investment grant (EKZ 2022), and S_{tax} is the tax deduction of the solar PV investment (Swiss Solar 2020), all in CHF. $f_{revenue,n}$ is the revenue from the feed-in-tariff in CHF (Vese 2022) for every year n calculated as equation (A4). This revenue is calculated for the entire lifetime of the PV system N, set to 30 years (SFOE 2021), considering a 0.5% degradation rate of the system (SFOE 2021), and a 3% discount rate r (Schmidt *et al* 2023).

Saving months

The saving months T are calculated with equation (A8):

$$T = \frac{INV}{DI - LMI} \tag{A8}$$

where INV is the initial investment, DI the disposable income per month, and LMI the monthly income required to make ends meet, all in CHF.

The disposable income DI is available for each household in the database. It accounts for the monthly gross income minus the compulsory expenditures: social security contributions, taxes, basic health insurance premiums, alimony paid, and other maintenance payments paid to other households. The monthly income required to make ends meet LMI is set as the sum of the expenses for subsistence according to the Swiss Conference of Welfare Organizations (CSIAS 2020), the rent or mortgage of each household from the household database, and other basic expenses like insurance (FSO 2023b).

A4. Distribution of solar PV incentives across all households

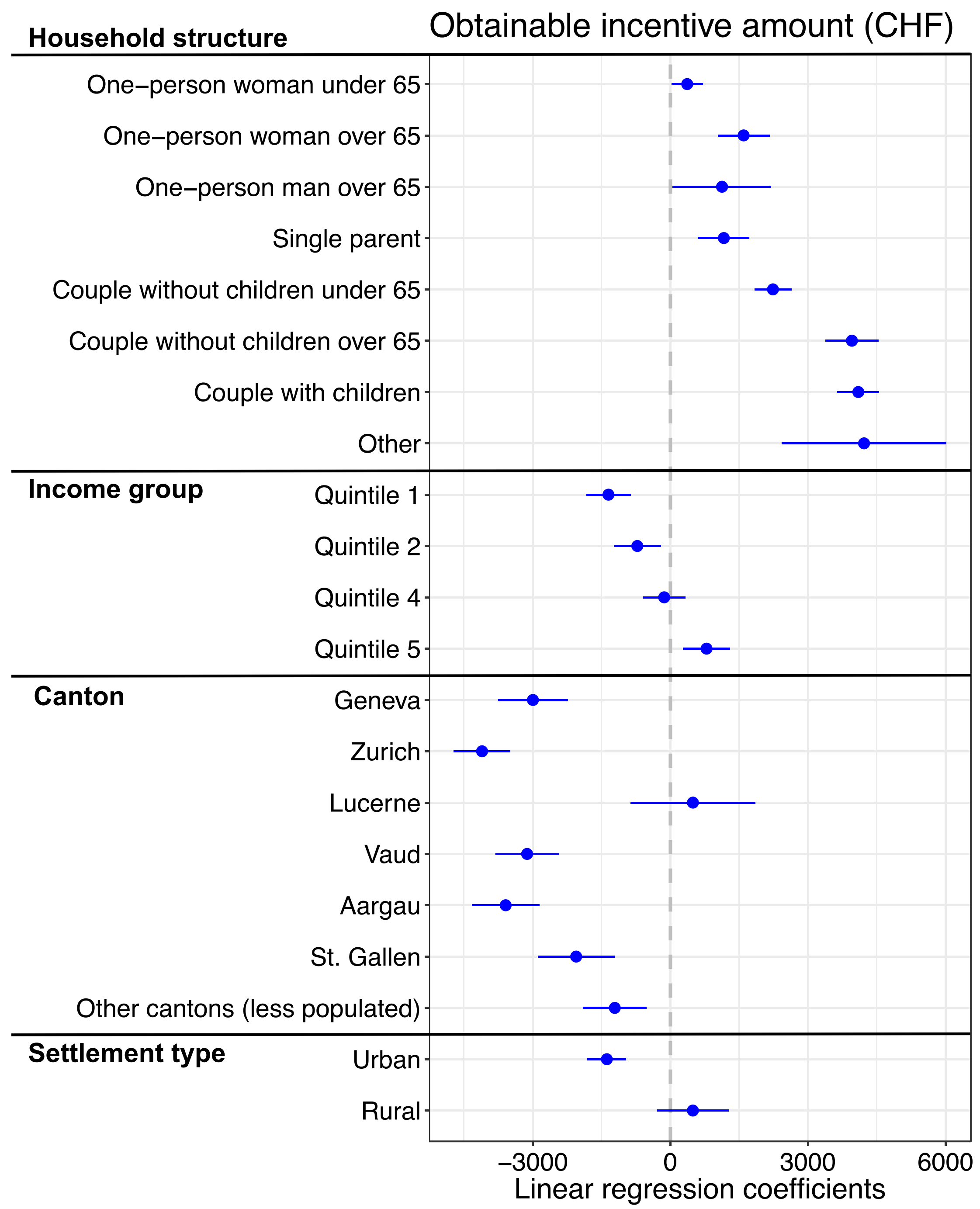

Figure A1. For all Swiss households—including the ones who cannot install solar PV—ordinary least square linear regression between household descriptives and the amount of incentives obtainable under the current scheme. We consider that households that cannot pass the 3% IRR threshold with incentives do not apply for and therefore do not get any incentive amount. Regression coefficients show differences between the means of household groups defined by a specific household descriptive, controlled by the rest of household descriptives, and as compared to reference categories. Reference categories are 'one-person man under 65' for household structure, 'quintile 2' for income groups, 'Bern' for canton and 'periurban' for settlement type. The error bar of each coefficient represents its 95% confidence interval. If it crosses zero on the x-axis, the coefficient is not significant ($p < 0.05$), which means that there is no statistically significant difference with the reference category. If the error bars of different coefficients overlap, differences in the coefficients of these household groups are not statistically significant. For income groups, households are divided into five quintiles. The 1st quintile represents households that are the least affluent and the 5th, the most affluent.

Table A4. Results of the ordinary least square regression between household descriptives and the amount of incentives obtainable under the current scheme for the sample including all Swiss households. Reference categories are 'one-person man under 65' for household structure, 'quintile 2' for income groups, 'Bern' for canton and 'periurban' for settlement type. Regression model details are available in the table footnote[a].

	Est.	S.E.	*t* val.	*p*	VIF
(Intercept)	3444.92	410.72	8.39	0.00	
One-person woman under 65	366.76	170.32	2.15	0.03	4.97
One-person woman over 65	1597.54	283.69	5.63	0.00	4.97
One-person man over 65	1125.46	536.40	2.10	0.04	4.97
Single parent	1165.19	278.27	4.19	0.00	4.97
Couple without children under 65	2236.77	200.68	11.15	0.00	4.97
Couple without children over 65	3958.03	289.40	13.68	0.00	4.97
Couple with children	4096.89	228.55	17.93	0.00	4.97
Other	4222.76	895.54	4.72	0.00	4.97
Quintile 1 (lowest income)	−1350.21	241.37	−5.59	0.00	2.93
Quintile 2	−720.82	257.14	−2.80	0.01	2.93
Quintile 4	−134.28	230.91	−0.58	0.56	2.93
Quintile 5 (highest income)	789.21	255.76	3.09	0.00	2.93
Geneva	−2996.27	379.35	−7.90	0.00	3.05
Zurich	−4105.82	307.69	−13.34	0.00	3.05
Lucerne	491.81	680.08	0.72	0.47	3.05
Vaud	−3123.55	346.81	−9.01	0.00	3.05
Aargau	−3591.01	367.20	−9.78	0.00	3.05
St. Gallen	−2053.31	417.31	−4.92	0.00	3.05
Other cantons (less populated)	−1211.73	346.92	−3.49	0.00	3.05
Urban	−1384.98	212.01	−6.53	0.00	1.45
Rural	491.09	388.19	1.27	0.21	1.45

[a] *Dependent variable:* Subsidy_amount. *Model type:* survey-weighted linear regression:
svyglm(formula = Subsidy_amount ∼ Household_structure + Eq_DI_quintile+ Kanton + Settlement_type, design = data_svy). *Standard errors:* Robust.

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