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Business structure of electricity distribution system operator and effect on solar photovoltaic uptake: An empirical case study for Switzerland

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ABSTRACT

Distribution System Operators are responsible for overseeing the connection of distributed energy sources, such as solar photovoltaic, to the low voltage electricity grid. While solar PV could contribute significantly to the decarbonization of the electricity supply, the technology's proliferation is not necessarily aligned with the business objectives of the Distribution System Operators. We conduct a statistical analysis to test whether solar photovoltaic in Switzerland is affected by the business model of the local Distribution System Operator. Our results indicate that the technology uptake patterns differ according to the business model despite a non-discriminatory connection policy. We conclude that Swiss policymakers provide additional support for solar photovoltaic in areas served by limited companies, due to their energy-generating potential, as well as those served by local municipalities, to achieve more consistent adoption rates. The findings of our work support future organizational studies of individual Distribution System Operators and comparisons to other jurisdictions with multiple Distribution System Operators of varying business models.

1. Introduction

Reducing the carbon emitted by the world's energy systems is required to meet the imperatives of global climate change (Rogelj et al., 2018; IRENA, 2021a). One low-carbon electricity generation technology that is expected to contribute is solar photovoltaic ("PV"). Solar PV has relatively low environmental impact compared to other electricity generation technologies (Amponsah et al., 2014) and is cost-competitive or cost-advantageous to fossil fuels in terms of lifetime levelized cost of electricity(IEA, 2020; IRENA, 2021a; IEA PVPS, 2021). The Intergovernmental Panel on Climate Change ("IPCC") suggests that over 50 EJ/per year of solar-powered electricity production would be required to achieve a "stringent" mitigation scenario various scenarios (Bruckner et al., 2014), although forecasts for actual future uptake vary significantly (Jäger-Waldau, 2021; Jaxa-Rozen and Trutnevyte, 2021; Victoria et al., 2021; BloombergNEF, 2021). Recent scholarship (Jaxa-Rozen and Trutnevyte, 2021; Victoria et al., 2021) suggests that a significant portion of the variation stems from modelling assumptions, such as integration costs and sectoral electrification patterns, as well as who is producing the forecast and whether IPCC scenarios are being used and other modelling assumptions. Notably, the same literature highlights that there are many forecasts that find the IPCC target to be achievable. In practice, there is also widespread support for the technology, as evidenced by the over 130 countries which have financial policies supporting solar PV deployment (IEA, 2020; IRENA, 2021a).

Solar PV is particularly well-poised to address urban electrification and increase local renewable energy supply because it can be easily installed on rooftops and building facades. Globally, up to 9000 GW of solar PV could installed on rooftops alone (IEA, 2019). The development of multi-energy systems, energy districts, and "self-consumption societies", which is expected facilitate access to these rooftops (e.g., on apartment buildings), as well as provide more efficient usage of self-generated electricity and facilitate market access for excess production as communities work together to meet local energy needs (Mancarella, 2014; Jäger-Waldau et al., 2020; Heendeniya et al., 2020). By 2050, residential adoption is expected to contribute 40% of overall solar PV capacity by 2050 (IRENA, 2019b). However, development of decentralized forms of energy generation, such as small-scale solar PV, is complex. The energy landscape evolves from the decisions of many actors (Malerba, 2002; Adil and Ko, 2016), such as consumers, businesses, regulatory bodies, vendors, and installers. In such a complex system, it is therefore necessary to understand how actors engage and influence others.

In addition to the individual solar PV "adopter", another important

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actor is the technical authority responsible for connecting the solar PV unit to the existing low-voltage electricity network. These actors are referred to as Distribution System Operators ("DSOs"), or sometimes as a Distribution Network Operators). Despite their technical mandates, integrating distributed energy technologies poses several technical and organizational challenges for DSOs.

This study is an initial analysis of whether DSO business type has affected solar PV uptake by using Switzerland as a case study. Specifically, we ask:

- Is the DSO type related to specific community attributes?
- How do solar utilization rates between different DSO types compare?
- Are some DSO types generally more active in solar PV installation than others?
- Do communities achieve higher rates of solar PV adoption based on the type of DSO present?

Swiss federal data (Swiss Federal Electricity Commission (2019); Swiss Federal Department of Justice and Police and Swiss Federal Office of Justice n.d.) for the year 2019 exists for over 600 DSOs in Switzerland operating in four different business structures: cooperatives ("co-ops"), municipal operations, limited companies, and public sector institutions. The number and diversity of DSOs facilitate a data-based comparison between the business types, providing a basis that can be used to support further studies in other jurisdictions.

This work makes three main contributions. First, to the best of the authors' knowledge, it marks a first national-level data-based analysis of DSO business structure on distributed renewables uptake. This therefore addresses an existing research gap (Kennedy et al., 2017). Second, we observe a difference in solar PV uptake according to DSO type, thereby identifying a new and understudied influence on distributed solar PV uptake. Third, we provide direct policy recommendations based on our findings for the Swiss case.

The remainder of this paper is structured as follows. Section 2 provides further background on DSOs and the Swiss case. Section 3 introduces the methods used for the study. Section 4 presents the results and discusses important findings, while Section 5 presents the policy implications and draws conclusions.

2. Background

2.1. Distribution system operators and the proliferation of distributed generation

DSOs are important actors for future many future energy technology developments, including consumer-sited solar PV generation (Bain & Company, Inc., 2020, IRENA, 2019a; Kennedy et al., 2017; Kristov, 2019; Prettico et al., 2021). By definition, DSOs are responsible for the technical operation of the distribution (or low voltage) electricity grid, which is where most solar PV is expected to be connected (IRENA, 2019a). Depending on the number of customers served and degree of market liberalization, they may also be legally or functionally separate from the electricity retail branch (European Parliament, 2009; Association of Swiss Electricity Companies, 2014). In addition, they are also central actors: they interact with the Transmission (high voltage) System Operator, their local communities, and other DSOs. DSOs are present in all electric power systems in some shape or form, thus making them a valuable constant that can be examined from system to system.

DSOs, like their transmission-level counterparts, hold a natural monopoly over a portion of the electricity infrastructure, making them key actors in decarbonizing lower voltage electricity systems. Because they are responsible for the technical maintenance and operation of the electricity distribution grid, DSOs are always involved with residential solar PV installation.

While decarbonization is an important societal goal, it does not necessarily align with the business case of DSOs or for energy utilities more generally. Technically, management of the electricity network may become more complicated with the installation of solar PV because it incorporates more components or require retrofits of existing infrastructure (Passey et al., 2011; Parag and Sovacool, 2016).

Decentralized generation may also threaten utilities' existing business models (PwC, 2013; Kristov, 2019). The first challenge is a direct threat to revenue: consumers who begin to generate electricity necessarily displace energy that would have otherwise been delivered.

The second challenge is that the presence of distributed generation can increase energy losses within a system (Passey et al., 2011; Ochoa and Harrison, 2011), thereby decreasing the efficiency of energy supplied. This may lead to regulatory issues in jurisdictions with either performance-based and cost-of-service regulation (Lowry and Kaufmann, 2002), due to loss of allocative efficiency and potential increase of consumer costs. More generally, it is thought that utilities are both less able to cope with distributed energy sources than with larger renewables project (Passey et al., 2011; Richter, 2012). Kennedy et al. (2017) suggests that there are several business models that could help local utilities be both sustainable and profitable; however, challenges in practice remain significant and the authors call for further research into the role of the business model and policy development.

It is necessary to tightly regulate electricity distribution to protect the consumer from the (natural) monopolies in the distribution grid; however, the character of the utilities themselves may nonetheless affect solar PV uptake. Namely, utilities may differ according to how they are able to respond to the three aforementioned challenges posed by PV: how to technically integrate the systems, how to maintain the revenue stream, and how to administrate the program. Utilities which struggle with these factors may offer "passive resistance via long delays and high costs for interconnection" or, where feed-in tariffs are offered, "may set the feed-in-tariff too low for [distributed generation] to be attractive" (Passey et al., 2011). Sioshansi (2015) suggests that government intervention may be required to ensure that "traditional power utilities are provided the incentives to play a supportive rather than an inhibiting role in this transition."

Utilities may also offer different degrees of passive resistance in how they promote solar PV uptake. Direct marketing, industry partnerships, and household assessment services are all examples of active promotion mechanisms that utilities could use to overcome end-consumers' information barrier; however, how willing they are to do so is still subject to their own business interests. This point is relevant given that numerous prior studies have shown the importance of information sharing by trusted sources to be a critical factor in small-scale solar PV uptake (Bollinger and Gillingham, 2012; Noll et al., 2014; Palm, 2017; Rai et al., 2016; Palm and Lantz, 2020).

Utility ownership may be analyzed following the general organizational and management literature, where it has previously been argued that firm differences are essential for understanding economic performance, e.g. as by Nelson (1991). Theories of the firm – property rights theory, transaction cost theory, agency theory, and resource-based theory being the most important (Peng et al., 2016) – suggest that the structure, goals, financing of a firm will affect its performance.

Several authors have applied these theories to the sustainability outcomes of utilities. For example, Traxler and Greiling (2019) studied the sustainable public value reporting of electricity utilities and relied on agency theory, strategic stakeholder theory, and legitimacy theory to support their analysis. Homsy (2020) found that American municipally-owned water and electricity utilities had greater sustainability outcomes than their private counterparts, largely due to increased coordination among municipal departments. In another American study, Stephens et al. (2017) found that publicly-owned utilities tended to have more positive perceptions of customer-sited electricity generation.

In sum, DSOs play an increasingly important role in the energy transition; however, a research gap remains in understanding the importance of the role played so far and their remaining potential

(Kennedy et al., 2017).

2.2. Swiss context

The Swiss Federal Electricity Commission lists over active 600 DSOs active in Switzerland for end-of-year 2019 (Swiss Federal Electricity Commission, 2019), making it an outlier in comparison to other countries in terms of absolute number as well as (the extremely small) number of customers served by DSO (Küfeoğlu et al., 2018). Four different DSO types are present in Switzerland: respectively, there are 329 municipal utilities, 111 co-ops, 135 limited companies, and 46 public sector institutions (Swiss Federal Department of Justice and Police and Swiss Federal Office of Justice n.d.). Municipal, co-op, and public-sector institutions DSOs are more closely aligned with the notion of public utilities than those which are limited companies. Notably, Swiss DSOs are not functionally unbundled from electricity retail (Raemy, 2015). This means that customers are beholden to purchasing electricity from the local DSO and cannot choose an alternative supplier.

Swiss DSOs must provide non-discriminatory connection to the grid (Swiss Federal Assembly, 2016). Exceptions are permitted when the new generation would exceed 3 MW, have a final production (after self-consumption) exceeding 5,000 MWh, or joined the Feed-In Tariff program after 2012. Neither of the first two conditions would pose a barrier for most residential or commercial consumers. Nonetheless, DSOs are permitted to establish the conditions for grid connection, including items such as a connection fee and maximum power injection (Swiss Federal Electricity Commission, 2015).

Switzerland is currently in the process of restructuring its energy system. A major prompt for the restructuring is the phase-out of Swiss nuclear power plants (IEA, 2018), which currently represent about one third of Swiss national electricity production (Swiss Federal Office of Energy, 2021). The remaining portion of Swiss electricity supply seasonally depends upon international imports (winter) and production from hydroelectric facilities (summer); while increasing the capacity of both of these sources is possible, it has been deemed preferable to increase national production capacity for both economic and political reasons (Swiss Federal Office of Energy, 2020a).

Solar PV production is expected to significantly contribute to filling the production gap left by the closure of nuclear stations. Solar PV has strong annual generation potential in the country: upper estimates from the Swiss Federal Office of Energy place the maximum generation potential at 67 TWh (Swiss Federal Office of Energy, 2019); this is significant, given that Switzerland's annual electricity consumption is consistently on the order of 60 TWh (Swiss Federal Office of Energy, 2021). Notably, solar PV could also contribute between 27% and 65% of winter electricity demand (Bucher and Schwarz, 2020), thus supporting weaker winter hydroelectricity production and reducing dependency upon international imports. The Swiss government currently expects solar PV production to meet 20% of current electricity demand by 2050 (Swiss Federal Office of Energy, 2020c).

Additionally, public reception for solar panels is relatively high. The capacity installations have increased approximately 20-fold between 2010 and 2019 (Swiss Federal Office of Energy, 2020d), and ranking Switzerland 7th for 2019 gross installation and 11th in terms of total capacity in 2020 in Europe (IEA PVPS, 2020; IRENA, 2021b). Of those who had not yet installed solar PV, many residents have intentions to do so in the short to midterm future (Curtius et al., 2018).

Various policy mechanisms have been enacted to help reach the goals of the Energy Strategy 2050, of which national subsidization schemes have been the most prominent. A federal feed-in-tariff scheme was introduced in 2008 and, despite the comparatively high rate of subsidization, was met with criticism due to the program oversubscription and subsequent long wait times to receive the subsidy (Weibel, 2011). The feed-in tariff scheme was phased out starting in 2014 in favor of a one-time subsidization scheme to help reduce the backlogs (Pronovo AG n.d.).

3. Methods and data

3.1. Methods

We apply several exploratory data-based methods to determine whether DSO type has affected solar PV uptake in Switzerland.

First, we determine whether the presence of a DSO type is related to specific community attributes (Section 4.1). We visually inspect the DSO type according to location and then check whether the DSO type is correlated to the particular characteristics of community using a linear discriminant analysis (Balakrishnama and Ganapathiraju, 1998). This process controls for the possibility that DSO type confounds an underlying relationship between community influence (i.e., specific factors within the community, such as income) and solar PV uptake.

Next, we consider the utilization of solar potential as well as overall engagement or activity in solar PV by DSO (Section 4.2 and 4.3). We investigate the utilization rates of difference DSOs by considering nationally available solar potential and utilization rates over time. Utilization of solar potential is the most informative metric to consider, as it directly relates to overall energy produced by solar PV. Installed capacity and number of installations are considered relevant performance variables as they respectively serve as proxies for the nominal impact on renewable energy production and for overall activity in renewable energy (Thormeyer et al., 2020; Müller and Trutnevyte, 2020). We measure utilization according to national capacity as well as by individual DSOs over time. DSO installation activity is investigated using chi-square test of independence and mosaic displays (Friendly, 1994).

In Section 4.4, we investigate whether the higher levels of solar PV adoption are related to the type of DSO present. To do so, we generate empirical Cumulative Distribution Functions of community performance according to the DSO type present in the community. We then perform two-sample Kolmogorov-Smirnov testing to check whether the observed distributions are significantly different from one another. Beyond checking for differences distribution, we verify whether any DSO type outperforms the other by testing for first- and second-degree stochastic dominance between DSO types. To avoid drawing conclusions based solely on outlier performance, we only consider the median 80% of the municipalities for the dominance testing.

Throughout this work, we consider several different performance measures in evaluating the relative performance of the DSOs, as summarized by Table 1. Considering different metrics facilitates the consideration of slightly different aspects of solar PV adoption and helps distinguish strong performers on absolute and relative bases. We also consider two metrics for the utilization of solar potential: first, as measured by total available area and second, as estimated total area coverage. The reason for considering both metrics is that electricity generation from rooftop solar PV is a function the irradiance at a given location and constrained by the total available rooftop area; as such, both the available sunshine and rooftop areas could be limiting factors on potential to install solar PV.

Table 1
Summary of performance metrics considered.

Measure	Proxy	Unit
Installed capacity	Overall activity	kWp
Installed capacity per capita		kWp/person
Number of installations		Number of solar panels/person
Number of installations per capita		Number of solar panels/person
Utilization of solar potential	Useful energy generation	Energy generated/Predicted energy generating potential
Utilization of available area		Area covered by solar panels/ Available rooftop area for solar panels

Notably, the methods used herein do not include a regression analysis, which is typical for studying influential factors in solar PV adoption, as done in: Graziano and Gillingham (2015); Reeves et al. (2017); and Müller and Trutnevyte (2020). To properly apply regression methods, complete information about the cost of adoption and existing electricity tariff at the time of installation would be required. Acquiring this data is a challenging task given the geographic and temporal scope considered, as well as the over 600 DSOs present for the selected case study. The methods used here therefore present an alternative approach to studying the driving factors for solar PV adoption.

3.2. Data

We rely on numerous sources to create two datasets for analysis, as shown by Fig. 1. We retrieve and merge data about individual solar PV installations from the Swiss Federal Office of Energy (Swiss Federal Office of Energy, 2020b) and Pronovo (Pronovo AG, 2020). Pronovo is a public company established to administer federal solar PV funding programs and whose data was accessed under the Freedom of Information Act (Swiss Federal Assembly, 2014). For cases where there were fewer than four individual installations within a given postal code, installations were aggregated to protect privacy; this aggregation represents less than 2% of the raw installed power capacity of the installations within the Pronovo dataset, and is therefore a minor assumption. Both data sets include the installation size, location by postal code, federal support mechanism, and construction dates.

We then proceed to affiliate each solar PV installation and DSO to a municipality. First, we use data provided by the Swiss Federal Offices of Topography provides geographic data (Swiss Federal Office of Topography, 2020) to locate each solar PV installation within a municipality. This step is required to correct human errors within the original datasets (e.g., disambiguation between municipalities with the same name; the municipality has been merged since the installation was recorded in the data set; spelling errors). DSOs coverage areas are listed on website of the Swiss Federal Electricity Commission, 2019), while their official names and business types of each verified using the Swiss Central Business Name Index (Swiss Federal Department of Justice and Police and Swiss Federal Office of Justice n.d.). We use the most recent data available; the analysis therefore considers the 2,202 Swiss communes established as of January 1, 2020, and the DSO service areas as of end of year 2019. We consider the communes and DSO coverage areas as constant throughout the study period (2008–2019) to facilitate a fair comparison. Given that relatively few municipal mergers were observed over this period (Swiss Federal Office of Statistics, 2021) and the generally slow rate of change in electricity distribution, we expect these assumptions to have little effect on the overall results of this study. To minimize the uncertainty of our results, we discarded installations that could not be confidently attributed to a DSO service area or to a specific municipality; this occurred in cases where a postal code referred to more than one municipality or where no information about DSO was available. The total data set includes 69,743 installations and 1.71 GW of installed capacity, and accounts for approximately 69% of the nationally-installed total at end of year 2019. Appendix A. Extended results provides further details about the data set.

Data about solar PV utilization is also collected at the level of the municipality. Walch et al. (2020) provides estimates of the total rooftop area available for solar PV in Switzerland. These results are reconfigured to provide estimates for the level of the municipality using open GIS software (QGIS.org, 2020) and geographic boundaries provided by the Swiss Federal Office of Statistics (2020). The total installed area calculations rely on current industry-standard solar panel sizes (SunPower n.d.; EnergySage n.d.; Wholesale Solar, 2019). We estimate the capacity factor (percent utilization of available solar irradiation) for each municipality using results from Walch et al. (2020) and the industry-standard solar panel characteristics previously introduced. Our estimates are in-line with a national capacity factor estimated from other sources (Swiss Federal Office of Energy, Swiss Federal Department of Transportation, Energy, and Communication, and Swissolar, 2015; Swiss Federal Office of Energy, and Swiss Federal Department of Transportation, Energy, and Communication, 2020). Finally, we source socioeconomic characteristics of the municipality from the Swiss Federal Office of Statistics (2019b).

4. Results and discussion

Results were generated using R (R Core Team, n.d.) and openly available packages (Ripley and Venables, 2002; Neuwirth, 2014; Wickham et al., 2018; Meyer et al., 2020; Sarkar et al., 2020; Wickham, 2020) were used to facilitate the analysis. Conclusions drawn from the utilization indicators (utilization of rooftop area and generation

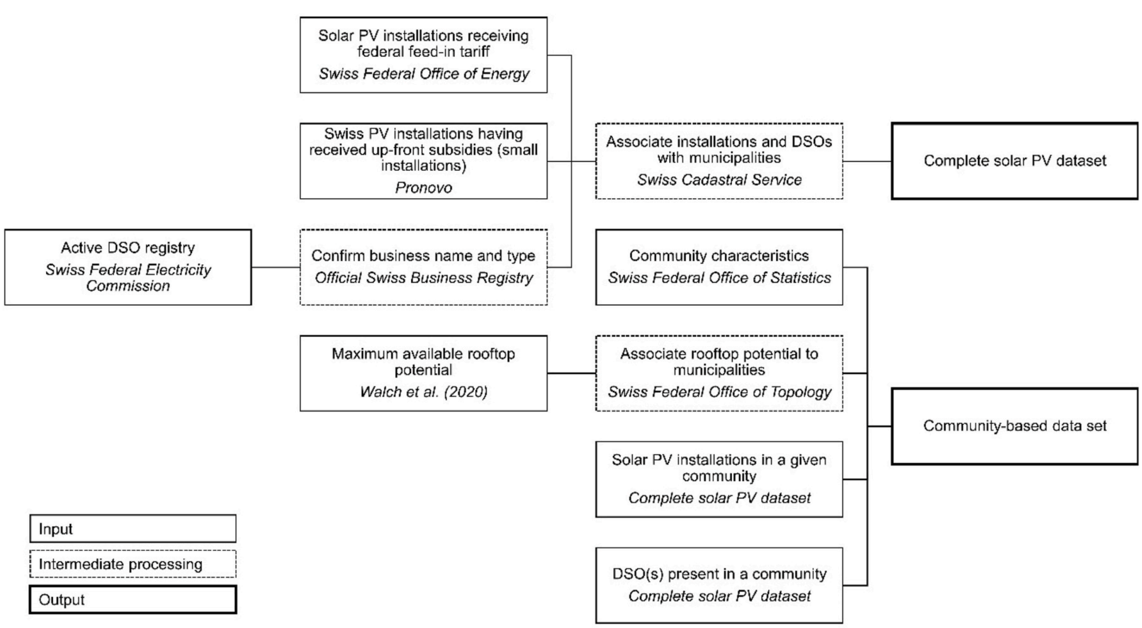

Fig. 1. Data processing flowchart.

potential) are consistent; as such, only the results shown for utilization of available rooftop area are shown in the main body for the sake of brevity. Appendix A. Extended results presents the complete results.

4.1. DSOs and communities served

Fig. 2 presents the active DSO by business type and municipality in Switzerland for end-of-year 2019. Generally, the presence of DSO type is distributed across the country. There is a greater prevalence of limited companies in the southwest, while there is a concentration of municipally-operated DSOs in the northeast. The concentrations of municipalities served by co-ops and public-sector institutions respectively appear in the cantons of Geneva, Obwalden, Nidwalden, Glarus, & Zurich and in Baselland; however, co-ops and public sector institutions are not exclusive to these cantons. The largest municipalities (the cities of e.g., Zurich, Geneva, Basel, Lausanne, Bern, St. Gallen, and Luzern) all only have one type of DSO present. We conclude that the presence of DSO type in a given location can neither be wholly attributed to a specific canton or geographic region.

The type of DSO present in a given community can also not be predicted solely based on community characteristics. The summary statistics presented in Table 2 show that the communities served by the various DSO types vary widely. This variation, particularly between municipal and limited-company DSOs, leads to the practical conclusion that the type of DSO present in a given community cannot be predicted based solely characteristics of the community itself (Appendix A. Extended results). Consequently, the results discussed below may be understood as related the DSO type, or other factors masked by the DSO type, rather than as resulting from socioeconomic factors within the community itself.

Although the communities served by the various DSO types are rather heterogeneous, a broad conclusion is that limited-company & public-sector institutions DSOs and co-ops & municipal DSOs are generally more similar in terms of customers to supply and physical service areas, as illustrated by Figs. 3 and 4. The comparatively smaller service areas of the co-op and municipal DSOs can be explained by the fact that they are, understandably, more geographically limited than the limited companies or public sector institutions. It also underlines the fact that a pro-solar limited-company or public-sector institution DSO would, on average, have greater impact on overall solar deployment than the average municipal or co-op DSO. Policies explicitly targeting DSOs that are limited companies and public sector institutions may therefore represent more efficient options for increasing solar PV uptake compared to policies focused on as municipal operations or co-ops.

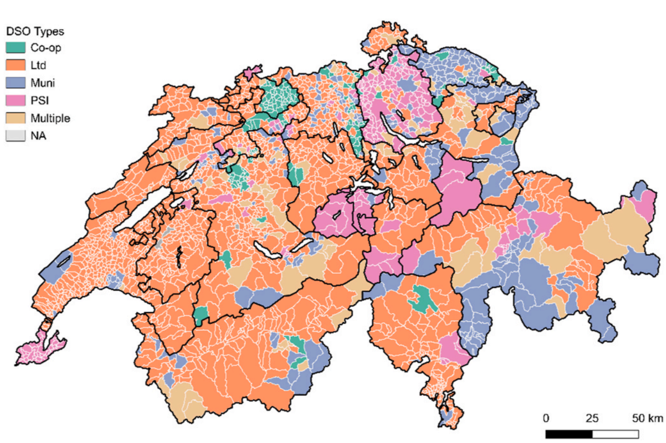

Fig. 2. Presence of DSOs across Switzerland by municipality in 2019. “NA” indicates that no data was available for these municipalities. Co-op: cooperative. Ltd: limited company. Muni: municipal operation. PSI: public sector institution.

4.2. Utilization of solar potential

Fig. 5 illustrates the nationally available rooftop area and utilization by DSO type and illustrates that there is generally low utilization of solar energy potential across all DSO types. Areas served by limited companies have the strongest relative performance, with over 6% of their available rooftop area covered by solar PV. By comparison, areas served by municipal, public-sector institution, and co-op DSOs have covered approximately 5.6%, 5.3%, and 4.4% of their available potential, respectively. The similarity between overall utilization rates is positive in that there are no gross differences between solar PV adoption patterns across areas served by different DSO types. It is nonetheless remarkable that the order of solar utilization rates in DSO service areas correspond exactly to the gross available rooftop area: Limited-company DSOs serve the greatest total area and also have the greatest utilization rate, while municipal DSOs have the second greatest total area and utilization rate, and so on. This observation could result from larger service areas bringing greater opportunity for willing solar PV adopters and suitable site selection; it could also be a function of the DSO type itself. For a definitive answer, the relationship should be monitored as solar PV penetration levels increase and the “low-hanging” opportunities are filled.

We emphasize again that the greatest potential for rooftop solar generation potential is in service areas controlled by limited companies. This is potentially a large challenge as private enterprises are under the least direct control of public interest, i.e. the successful implementation of Energy Strategy 2050, despite the current relative success of areas managed by limited companies. While it has been argued that competition is necessary for innovation (Nelson, 1991; Malerba, 2002), the forces of which would be more active on private DSOs than their government-owned counterparts, empirical findings present mixed results (Tang, 2006; Acharya and Xu, 2017). Supporting private enterprises to develop competitive, pro-solar business strategies is therefore a non-trivial but potentially valuable policy action.

Fig. 6 shows that the utilization of solar potential improves with time across all DSO types. The gradual improvement over time is expected given the general trend towards increased solar PV uptake. The rate of uptake differs significantly amongst individual DSOs, particularly between municipal and co-op DSOs. This is expected given the different underlying available solar potential and characteristics of communities served. By nature, municipal and co-op DSOs are more geographically constrained to a given service area than other DSO types and their varied performance can be more directly attributed to the variance of communities and DSOs themselves (e.g., in terms of local population, individuals working within a given DSO). By contrast, it appears that the utilization of solar potential is most similar amongst the public-sector institution DSOs; in other words, the performance of any given public sector institution is likely to be more representative of the group’s performance than for other DSO types. This observation may suggest that public-sector institution DSOs are most subject to within-group *status quo* bias or that structural barriers inhibit public sector institution-served areas from being leaders in solar PV.

Notably, no limited-company or public-sector institution DSO has managed to attain a “breakthrough” result (30% utilization or higher) obtained by some municipal and co-op DSOs after almost a decade of national financial solar PV. The absence of such a performance indicates an absence of a solar PV champion within either of those DSO types. Indeed, this could be a function of structural barriers for public sector institutions and difficulty finding a profitable business case for limited companies.

Utilization rates have stagnated for some DSO service area across all DSO types. This can be seen by the concentration of flat lines near the bottom of each quadrant in Fig. 6. This observation is concerning as it reveals that after 10 years of public subsidies, barriers to adoption remain in specific service areas. Laggard DSOs and areas should be identified and analyzed for why such little solar PV has been installed.

Table 2
Community characteristics by DSO type. Mean value listed beside standard deviation (in parentheses).

Socioeconomic factors		DSO Type							
		Cooperative N = 111		Limited company N = 135		Municipal operations N = 329		Public sector institution N = 46	
Residents	Thousand people	2.48	*(3.40)*	2.94	*(5.21)*	4.81	*(11.1)*	9.27	*(31.5)*
Population density	People/km^2	303	*(296)*	357	*(635)*	474	*(730)*	858	*(1400)*
Senior citizens	% residents	19.0	*(3.68)*	19.2	*(4.83)*	19.2	*(4.22)*	18.5	*(3.52)*
Income	Thousands CHF	71.0	*(11.3)*	72.4	*(35.4)*	69.7	*(23.2)*	88.3	*(45.6)*
Private household rate	Private households/person	0.423	*(0.0258)*	0.425	*(0.0379)*	0.433	*(0.0350)*	0.417	*(0.0396)*
Household size	People/household	2.34	*(0.144)*	2.34	*(0.200)*	2.30	*(0.184)*	2.38	*(0.233)*
Total area	km^2	13.3	*(22.6)*	18.2	*(32.7)*	26.9	*(43.3)*	21.0	*(49.7)*
Built-up area	% of total area	12.5	*(8.12)*	13.4	*(13.4)*	15.5	*(15.6)*	22.8	*(19.8)*
Agricultural area	% of total area	51.1	*(14.6)*	46.6	*(20)*	42.6	*(18.5)*	42.4	*(17.1)*

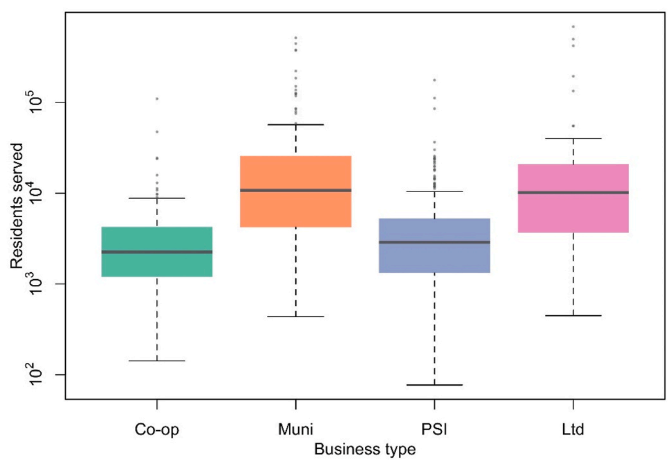

Fig. 3. Residents served by DSO by type. Co-op: cooperative. Ltd: limited company. Muni: municipal operations. PSI: public sector institution.

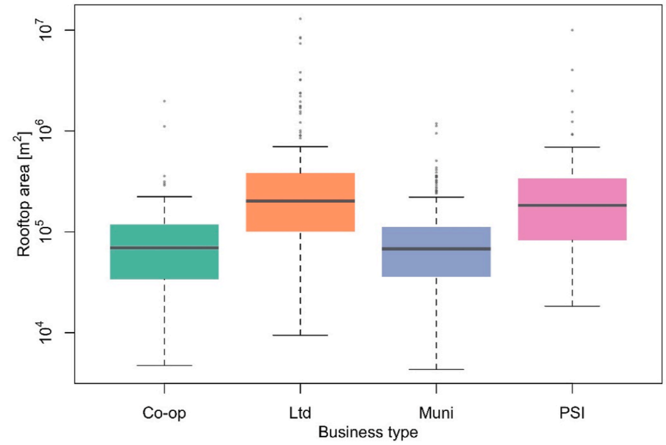

Fig. 4. Rooftop area within the service zone of each DSO by type. Co-op: cooperative. Ltd: limited company. Muni: municipal operations. PSI: public sector institution.

4.3. *DSO installation activity*

The number of installed solar PV panels is a proxy for how actively DSOs are engaged with solar PV irrespective of installation size. The mosaic plots in Figs. 7 and 8 show limited-company and municipal DSOs to be overrepresented in the top quartiles for solar PV engagement on both absolute and per capita bases. Public sector institutions are also overrepresented in the top quartile for total installations; however, unlike limited companies, they are underrepresented in terms of per capita installations. Public sector institutions' greater number of overall

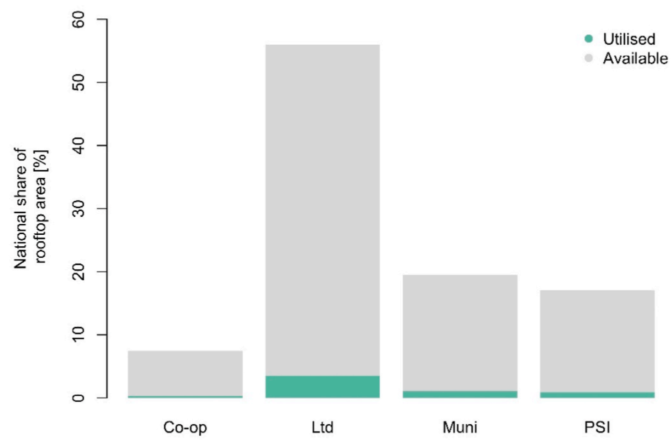

Fig. 5. Nationally available rooftop area and utilization by DSO type. Co-op: cooperative. Ltd: limited company. Muni: municipal operations. PSI: public sector institution.

installations appears to be due to an overall larger presence as opposed owing to any particularly high activity.

These results are consistent when performing sensitivity testing towards group sizing (i.e., considering top/bottom 50%, quartiles, deciles, etc.).

4.4. *Performance distribution by community*

Fig. 9 presents the distribution of all performance measures according to fraction of communities served and by DSO type as heatmaps. The figure demonstrates illustrates how solar PV uptake varies in communities served by DSO type, without controlling for community characteristics.

The distributions for all performance metrics and business types follow the same general pattern: the distribution is skewed towards the lower end of the performance scales. However, there is some differentiation in the upper tails; this implies that bulk performance seems to be similar across DSO types, but the identification of the leader depends strongly on the metric considered. For example, plots E and F of Fig. 9, show that there is no clear association between DSO type and leader in terms of utilization of solar potential, while some DSO types are clearly associated with the strongest performances exhibited according to the other metrics such as in plots A, B, C and D. In agreement with the findings of Section 4.4, communities served by limited-companies and municipal operations DSOs are among the strongest in terms of installed power per capita and number of installations per capita (as indicated by the shading on the right side of the heatmaps in Fig. 9). The distribution of communities served by public sector institutions tend to either be comparatively less successful than other communities, or fall into the top-most category. The discrepancy between absolute and per capita performance (plots A and C compared to plots B and D, Fig. 9) suggests

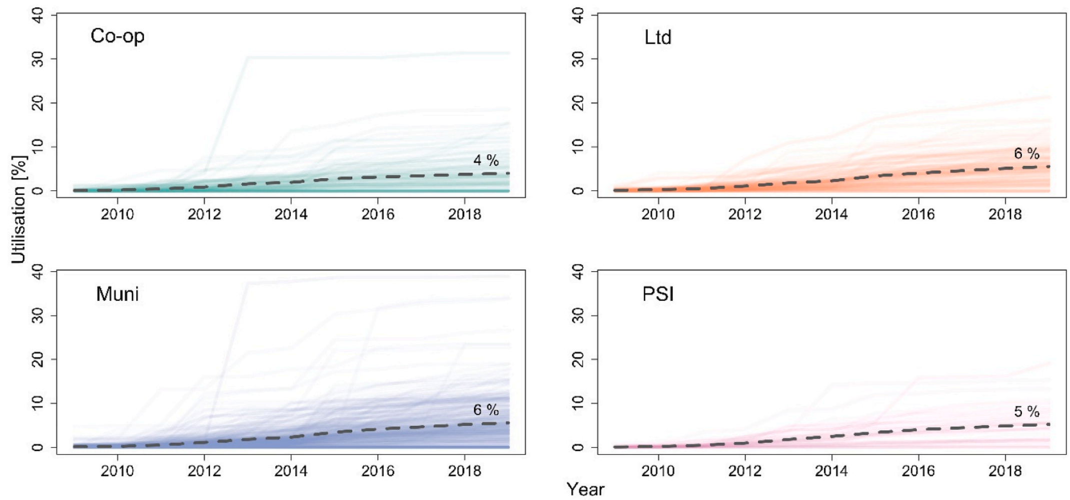

Fig. 6. Density plot of percent utilization of available area over time by DSO and municipality. Darker colors indicate overlapping of trend lines. Within-DSO average utilization is indicated by dashed lines and 2019 average is indicated for reference. Co-op: cooperative. Ltd: limited company. Muni: municipal operations. PSI: public sector institution.

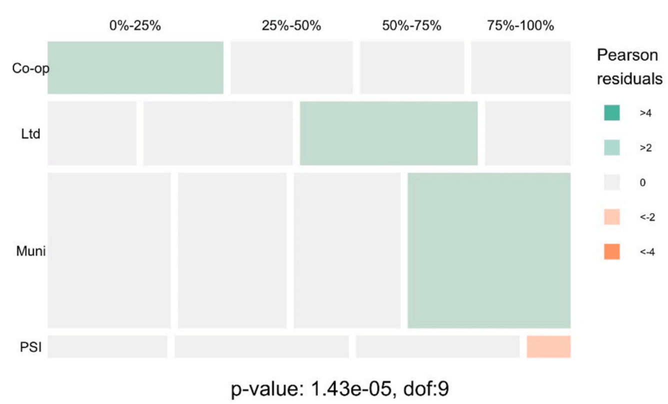

Fig. 7. Independence of DSO type and number of installations per capita. The shading of the cells indicates the strength of the finding. Co-op: cooperative. Ltd: limited company. Muni: municipal operations. PSI: public sector institution.

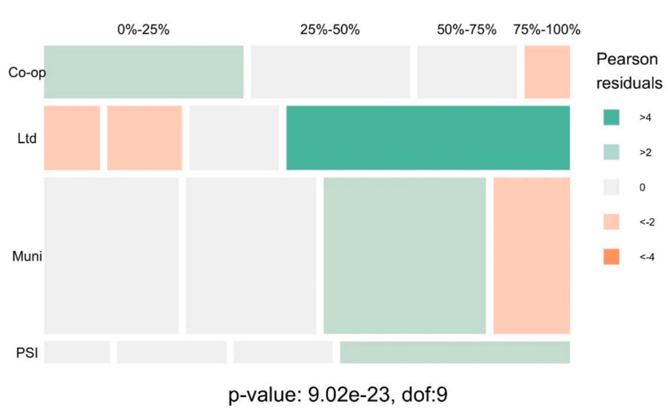

Fig. 8. Independence of DSO type and number of installations. The shading of the cells indicates the strength of the finding. Co-op: cooperative. Ltd: limited company. Muni: municipal operations. PSI: public sector institution.

that communities served by public sector institutions benefit more from greater opportunity in terms of potential adopters and adoption sites. This finding is also supported by the skewed utilization distributions shown in plots E and F of Fig. 9.

Of all performance measures considered in Fig. 9, the number of installations per thousand residents (plot D) appears to be the most evenly distributed between DSO types, particularly amongst communities served by co-ops and limited companies. The dispersion of the co-ops result is somewhat surprising, given that communities served by co-op DSOs tend to be less diverse compared to communities served by other groups, as presented by Table 2, and their more geographically concentrated presence, as shown in Fig. 1. This finding is perhaps a function of the variety of governance schemes and attitudes within the co-ops themselves.

The quantitative comparison of the distributions is consistent with the differences observable in Fig. 9. To this aim, Table 3 presents the results of Kolmogorov-Smirnov testing for significant differences between different DSO pairs and metrics for the median 80% of communities, i.e., excluding outlier communities.

Significant differences between distributions are detectable for most cases. This finding concretely supports the idea that the process generating the different community-level outcomes differs between DSO types. In other words, the processes governing solar PV uptake differ following whatever DSO type is present.

Table 4 presents direct performance comparisons, using first and second-degree stochastic dominance testing on the median 80% of communities. In conjunction with Table 3, Table 4 confirms that beyond simple difference, the distributions of a given DSO type are clearly out- or underperforming the others. Remarkably:

- Communities with public sector institutions underperform all others in terms of lowest installed solar PV power capacity & number of installations per capita and significantly underperforms communities with limited-company and co-op DSOs in terms of utilization;
- Communities with municipal DSOs outperform all others in terms of installed solar PV capacity and weakly outperform those with limited-companies and co-op DSOs in terms of number of installations;
- Communities with limited-company DSOs outperform all others in terms of installed solar PV per capita and number of installations per capita.

The underperformance of communities with public sector institutions is the most striking and consistent finding across all results presented in Table 3, Table 4, and Fig. 9. These observations signal a combined lack of activity and a lack of overall installations. Although

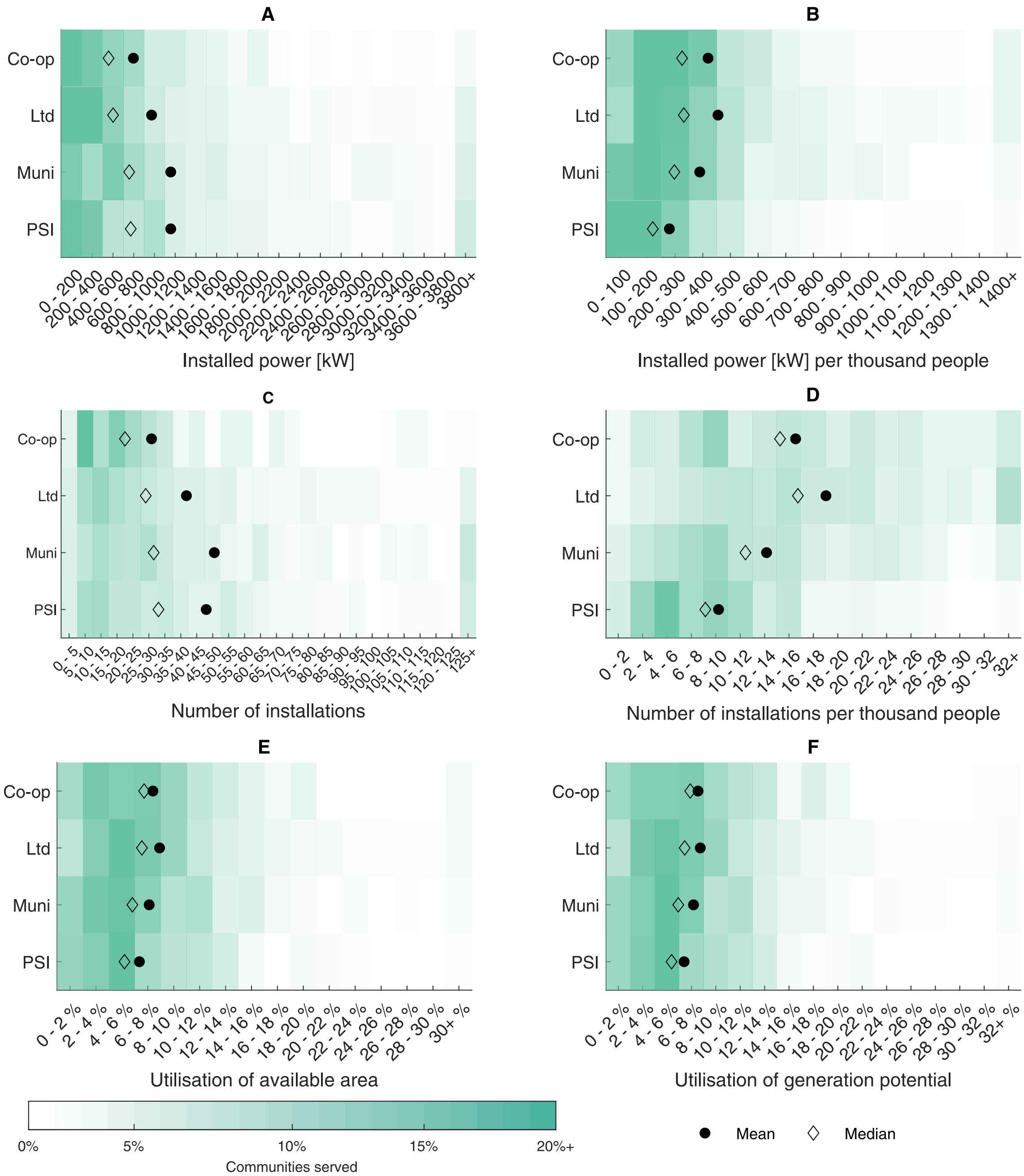

Fig. 9. Performance distribution by DSO type measured by the fraction of the communities served. Co-op: cooperative. Ltd: limited company. Muni: municipal operations. PSI: public sector institution.

the potential solar generation in areas managed by public sector institutions is only the 3rd greatest of all DSO types, as shown in Fig. 6, the relatively higher incomes served suggest that addressing the barriers facing public sector institutions could be particularly fruitful: disposable income tends to be a positive predictor of PV adoption (Graziano and Gillingham, 2015).

The relatively strong performance of communities with municipal DSOs corresponds with the suggestion from Homsy (2020) that the interdepartmental coordination of municipal operations benefit sustainability outcomes. However, the strong performance observed for absolute installed power and number of installations does not translate to equally dominant performance in population-normalized terms; this mismatch indicates that municipal operations might face a scaling challenge.

By contrast, communities with limited-company DSOs do not face the same challenge, as their successful performance in terms of population-normalized metrics indicates. Typically, introducing renewable energy generation into larger, urban areas is considered difficult, due to competition for solar access (Moraitis et al., 2018; Adil and Ko, 2016). Identifying strategies or actors who have figured out how to manage these challenges most effectively will be key to sharing and replicating their successes. In this regard, the observation that limited companies are relatively strong performers will be important for deriving future policy actions.

5. Conclusion and policy implications

5.1. Conclusion and policy implications

Distribution System Operators (DSOs) are responsible for the

Table 3
Results of Kolmogorov-Smirnov testing. Significance levels are reported for α = 0.05 (*), α = 0.01 (**), and α = 0.001 (***).

DSO Type		Performance metric					
		A	B	C	D	E	F
		Installed power	Installed power per capita	Number of installations	Number of installations per capita	Utilization of available area	Utilization of generation potential
Cooperative	Limited company			***	*		
Cooperative	Municipal operation	***		***	*		
Cooperative	Public Sector Institution	**	***	***	***	*	**
Limited company	Municipal operation	***	**	*	***		
Limited company	Public Sector Institution	**	***		***	***	***
Municipal operation	Public Sector Institution		***		***		

Table 4
Stochastic dominance of business type by performance metric. Pairwise first order stochastic dominance shown in bolded text; second order stochastic dominance shown as italicized text. Median 80% of values considered.

Performance metric	Business 1	Business 2	Performance metric	Business 1	Business 2
A Installed power	Cooperative	**Limited company**	B Installed power per capita	Cooperative	*Limited company*
	Cooperative	**Municipal**		*Cooperative*	Municipal
	Cooperative	**Public Sector Institution**		**Cooperative**	Public Sector Institution
	Limited company	**Municipal**		**Limited company**	Municipal
	Limited company	**Public Sector Institution**		**Limited company**	Public Sector Institution
	Municipal	Public Sector Institution		**Municipal**	Public Sector Institution
C Number of installations	Cooperative	**Limited company**	D Number of installations per capita	Cooperative	**Limited company**
	Cooperative	**Municipal**		**Cooperative**	Municipal
	Cooperative	**Public Sector Institution**		**Cooperative**	Public Sector Institution
	Limited company	**Municipal**		**Limited company**	Municipal
	Limited company	**Public Sector Institution**		**Limited company**	Public Sector Institution
	Municipal	Public Sector Institution		**Municipal**	Public Sector Institution
E Utilization of available area	Cooperative	*Limited company*	F Utilization of generation potential	Cooperative	Limited company
	Cooperative	Municipal		Cooperative	Municipal
	Cooperative	Public Sector Institution		**Cooperative**	Public Sector Institution
	Limited company	Municipal		*Limited company*	Municipal
	Limited company	Public Sector Institution		**Limited company**	Public Sector Institution
	Municipal	Public Sector Institution		*Municipal*	Public Sector Institution

physical connection of solar PV to the low-voltage electricity system networks and are therefore essential actors in increasing distributed on solar PV uptake. Even in cases where the DSO is obligated to connect solar PV plants, the business value of solar PV may lead to an absence of direct support of the technology.

We ask whether differences in solar PV uptake are observable according to DSO type in an empirical study of Switzerland. The four DSO types – limited companies, cooperatives, municipal operations, and public sector institutions – show similar aggregate levels of total solar utilization, but differ in other regards. For instance, the higher gross installed capacity of public sector institution DSOs tends to correlated to the larger area served by public sector institutions rather than particularly intense levels of activity. By contrast, limited-company DSOs show high levels of installed total capacity and number of installations in terms of both absolute and per capita bases, demonstrating deeper and more successful engagement than public sector institutions despite their similarities in terms of residents and area covered. DSOs that are structured as municipal operations and as cooperatives both tend to have smaller service areas than those structured as limited companies and public sector institutions, likely as a function of the more geographically-constrained business types themselves. The relatively large number of municipal DSOs in the country make the group an important contributor to actual installed solar PV capacity; however, weaker performance in terms of per capita performance suggests some challenges in larger municipalities. Co-op DSOs serve fewer and smaller service areas and is reflected in terms of overall installed capacity. The solar PV activity varies widely for co-op DSOs and has both standout performers as well as laggards, which suggests a wide variety in the organizations themselves given the relative similarity of the communities served by co-op DSOs compared to those served by other DSO types.

Several specific policy recommendations can be drawn for the Swiss case study. Most importantly, Swiss policymakers should:

- Support the uptake of consumer-sited solar PV areas managed by limited-company DSOs;
- Seek to increase the consistency of solar PV uptake in areas managed municipally-operated DSOs;
- Seek to understand and address the roadblocks for solar PV installations in areas served by public sector institutions.

Private DSOs provide distribution service to areas with the greatest share of rooftop area and rooftop solar potential in Switzerland; growth in these areas is therefore of utmost importance to future solar PV uptake. Policymakers could support the acceleration of solar PV installation in areas privately managed in several ways. First, they could help facilitate access to public buildings on which to install solar PV. Public buildings – such as schools, hospitals, and administration centers – are obvious candidate locations. Where public facilities are insufficient, government policymakers could also facilitate such programs between the DSO and local private entities having suitable solar PV installation space, such as by introducing lower property taxes for landlords who make their rooftops available for solar PV generation. The DSOs in Zurich and Geneva, both public sector institutions, have implemented schemes whereby renters can have solar PV installed in their name in an aggregated facility (Elektrizitätswerk der Stadt Zürich n.d.; Services industriels de Genève, 2020). Given that renters occupy 56% of all residential units in Switzerland (Swiss Federal Office of Statistics, 2019a), introducing similar programs in areas served by limited companies could unload a significant portion of adopters.

Policymakers could also support DSOs by offering guidance and training on the technical aspects of the integration of solar PV into existing distribution systems. The knowledge sharing could increase the likelihood of DSOs being able to develop profitable business plans that integrate more solar PV. It is likely that many of the smaller DSOs could also benefit from such training, given the resource challenges facing smaller organizations (Seyfang et al., 2013). In addition, offering training and technical assistance would likely increase the consistency of municipal DSOs by helping align the DSO operations with greater municipality sustainability objectives, as suggested by Homsy (2020), and achieving economies of scale. Providing help to the municipal DSOs is key given the great number of different, active municipal DSOs and their combined service area.

Relative to the areas served by other DSO structures, solar PV uptake is stagnating in regions managed by public sector institutions. This is potentially due to (1) the passive resistance fostered attributable to the business structure of public sector institutions, or (2) the characteristics of the areas served by public sector institutions, which, on average, are larger and wealthier compared to other business types (Table 2). Wealth has been found to be important predictors of PV adoption, albeit inconsistent in whether they are positive or negative predictors (Alipour et al., 2020). Nonetheless, given the under-utilized capacity in areas served by public sector institutions – that is, nearly 20% of available rooftop solar potential in Switzerland – investigating the hurdles to installation of solar PV in areas managed by public sector institutions is worthwhile.

It is worth asking if the challenge facing public sector institutions may be the business structure itself. Public sector institutions are government institutions but without the benefit of coordination to other government branches; at the same time, they function as private institutions that must subscribe to the more stringent regulation and oversight of government agencies. Globally, many public sector institutions developed as a transition form of business as electricity markets liberalized (Peng et al., 2016); given the apparent struggle facing public sector institutions and comparatively stronger outcomes of communities served by municipal DSOs, it may be worth asking whether this business structure is compatible with evolving energy goals. The challenge facing public sector institutions may also be due to characteristics of the underlying communities not investigated here, i.e., the built environment or political preference. Determining which of these factors is present, if at all, it outside the scope of this study but is noted for future work. One method of doing so would be by interviewing representatives from different DSOs in an exploratory qualitative study.

5.2. Contributions and future work

Three main contributions arise from this work. First, to the best of the authors' knowledge, it marks a first national-level data-based analysis of DSO business structure on distributed renewables uptake. In particular, while there have been many recent studies on solar PV uptake in Switzerland (Assouline et al., 2018; Curtius et al., 2018; Koch and Christ, 2018; Sasse et al., 2019; Müller and Trutnevyte, 2020; Thormeyer et al., 2020; Walch et al., 2020), as far as we are aware, none have investigated the role of the DSO. Second, we provide evidence that DSO structure can impact the uptake of distributed solar PV. Although Switzerland's non-discriminatory grid connection policy applies to all DSOs, we find that solar PV installation varies by DSO structure in a statistically significant manner. This finding is directly relevant to Swiss policymakers, for whom we suggest concrete policy recommendations. Moreover, the findings may also be relevant to policymakers in other countries who have multiple DSOs and DSO types, such as in Austria, Argentina, Poland, Spain, Italy, and the United States, among others (Küfeoğlu et al., 2018; Prettico et al., 2021).

Several avenues exist for future work. First, the results for the Switzerland-specific case study could be complemented by organizational studies of the DSOs themselves. Particularly valuable would be to study the attitude of larger, limited-company DSOs to attempt to identify the factors that led to strong absolute and per capita growth of solar PV uptake. In addition, we suggest further work exploring whether there are causal factors that are masked by DSO type, such as built environment. Understanding these relationships will become more important as easy-to-install locations become saturated and barriers facing each DSO type become a greater hindrance to future development. Finally, the relationship of solar PV uptake to the characteristics of individual, commercial, & industrial energy consumers, and the relationship of solar PV vendors and installers requires further study.

DSOs are influential actors in the energy system and developing policies that target these actors could therefore represent an efficient public policy development strategy. Understanding the influence of DSO structure on solar PV deployment will not only further the uptake of solar PV itself, but also the other distributed energy technologies that DSOs will likely be responsible for integrating.

CRediT authorship contribution statement

Katherine Emma Lonergan: Data curation, Software, Formal analysis, Validation, Writing – original draft, Visualization, Conceptualization, Methodology, Project administration. **Giovanni Sansavini:** Supervision, Resources, Writing – review & editing, Conceptualization, Methodology, Project administration.

Declaration of competing 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.

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APPENDIX

A.1 Data considered

Table A1
Installations considered and estimated share of national solar capacity.

Year	Total installed capacity [GW]	Estimated share of national solar capacity [%]
2009	0.044	57.7
2010	0.078	63.8
2011	0.172	78.2
2012	0.360	83.1
2013	0.594	78.9
2014	0.745	69.5
2015	1.050	75.5
2016	1.255	75.6
2017	1.411	74.2
2018	1.578	72.8
2019	1.708	68.6

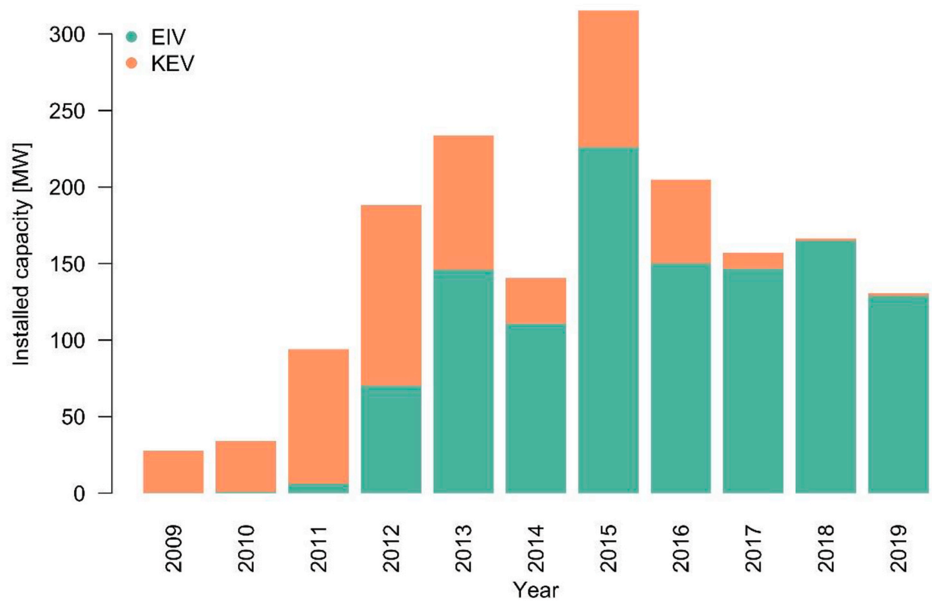

Fig. A1. Installations considered by support scheme and year of installation. KEV designates installations supported by a Feed-in Tariff, while EIV designates installations supported by an up-front subsidy.

A.2 Linear Discriminant Analysis (LDA) of communities and DSO type

A leave-one-out cross-validation of the LDA is not an accurate prediction method of what kind of DSO will be present in a given community when considering the socioeconomic factors listed in Table A 2. Socioeconomic factors considered for LDA. The results of the LDA, presented in Table A 3. Confusion matrix of cross-validated Linear Discriminant Analysis, show unsatisfactory results for the data set: although a misclassification rate of 35.5% is not unreasonable, the confusion matrix reveals that this rate was only achieved because of undue bias towards estimating the DSOs as limited companies.

In an attempt to improve the prediction, we remove the communities served by limited companies from consideration, as suggested by the initial result. While more this change leads to some co-op and municipal DSO being accurately predicted, the overall error rate remains high at 52.5%. We therefore conclude that the listed socioeconomic factors are insufficient for predicting the presence of a given DSO type.

Table A 2
Socioeconomic factors considered for LDA

Socioeconomic factor	Unit
Residents	Thousand people
Population density	People/km^2
Senior citizens	% residents
Income	Thousands CHF
Private household rate	Private households/person
Household size	People/household
Total area	km^2
Built-up area	% of total area
Agricultural area	% of total area

Table A 3
Confusion matrix of cross-validated Linear Discriminant Analysis

Actual DSO type					
		Cooperative	Limited company	Municipal operations	Public Sector Institution
Estimated	Cooperative	0	1	0	0
	Limited company	191	1471	332	234
	Municipal operations	0	0	0	0
	Public Sector Institution	0	23	13	30

Table A 4
Confusion matrix of cross-validated Linear Discriminant Analysis for a reduced data set

Actual DSO type				
		Cooperativepublic	Municipal operations	Public Sector Institution
Estimated	Cooperative	29	36	15
	Municipal operations	154	271	171
	Public Sector Institution	8	38	78

A.3 Nationally available rooftop solar potential and utilization

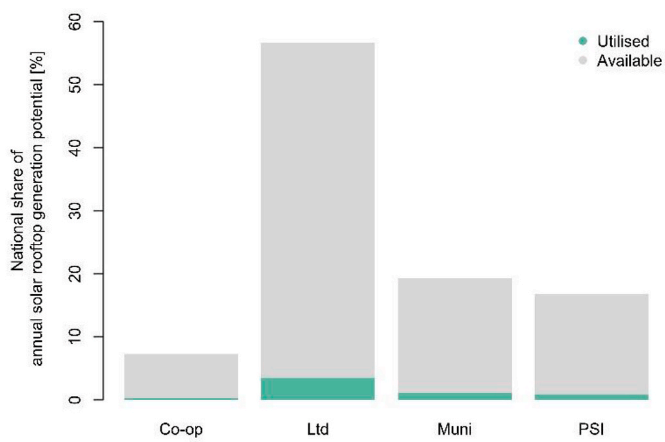

Fig. A 2. Nationally available rooftop solar potential and utilization. Co-op: cooperative. Ltd: limited company. Muni: municipal operations. PSI: public sector institution.

A.4 Independence of DSO type and installed power capacity

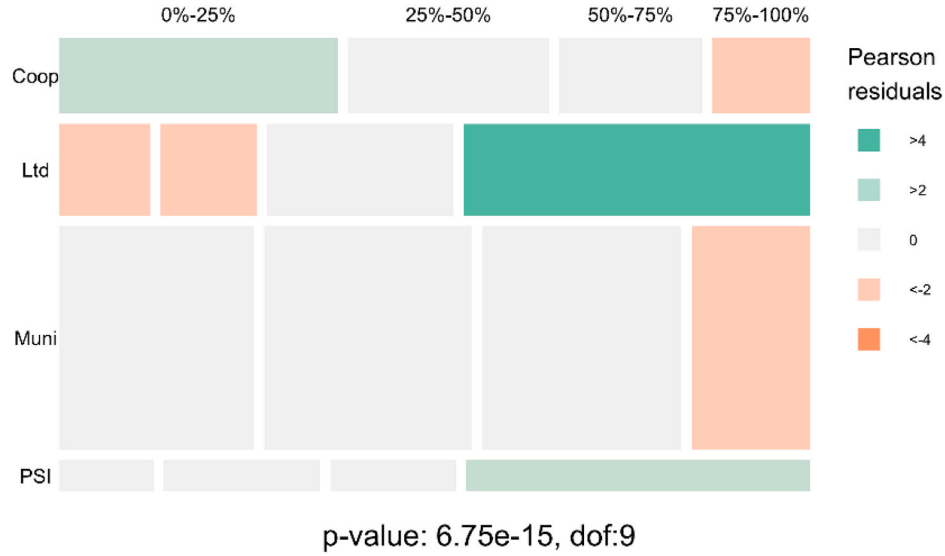

Fig. A 3. Independence of DSO type and installed power capacity. Co-op: cooperative. Ltd: limited company. Muni: municipal operations. PSI: public sector institution.

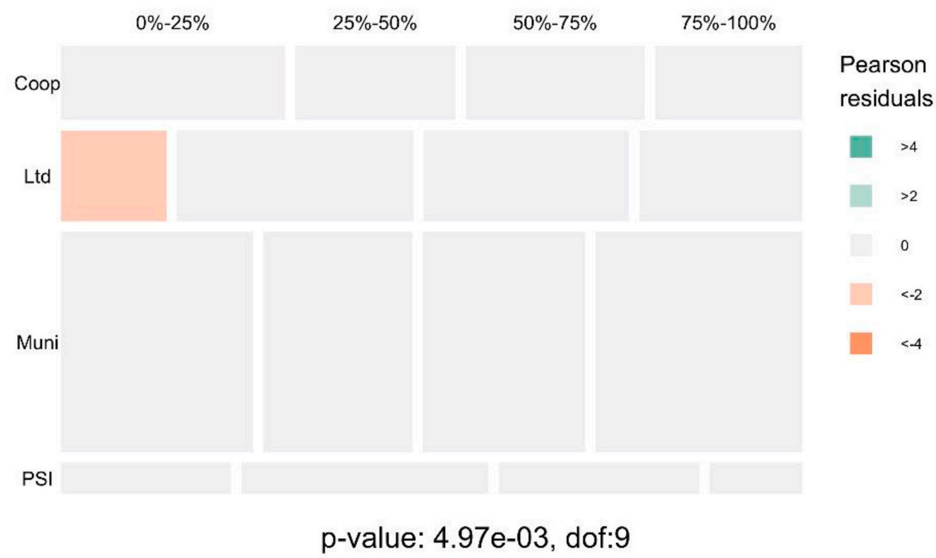

Fig. A 4. Independence of DSO type and installed power capacity per capita. Co-op: cooperative. Ltd: limited company. Muni: municipal operations. PSI: public sector institution.

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