Research Proposal

Decisions at the Grid's Edge: Monte Carlo Pathways to Optimized PV Expansion in Swiss Residences

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Abstract

Due to the global push for distributed photovoltaic (PV) systems, grid capacity will be a limiting factor for further expansion in the near future. Additional installations can cause a negative externality by hindering other production in the same grid circuit. This calls for a detailed modeling approach that captures the negative impact of a PV installation on neighbor's production capability. Using spatial data at the individual house level for over 1.15 million Swiss single-family houses, I propose a stochastic Monte Carlo method to model theoretical PV expansion pathways until 2050 from a social planer's and economic individual's perspective. I use an open data grid approximation to determine local exceedances caused by the modeled expansions more accurately. This is the cornerstone for further research on a dynamic feed-in permit that is designed to mitigate grid congestion without requiring intense regulator monitoring.

1 Introduction

The debate about the energy transition has been accelerated in Europe in recent years both due to more political attention to climate change and a surge in fossil fuel prices. From local communities to supranational unions, policymakers at all levels are increasing their efforts to reduce carbon emissions. Expanding renewable energy sources is thus an essential step towards further electrification of societal life. Photovoltaic (PV) electricity production will play a decisive role in this transition and is predicted to surpass hydro in 2024 and eventually coal in 2027 with 2350 GW or 22 percent of global cumulative power production capacity (IEA, 2022).

Because these new production units are to a large part installed on residential infrastructure connected to the local distribution system, overloading of grid components has been observed already. This requires costly grid updates or curtailment of production units which slows down the future deployment of renewables (REN21, 2023). Switzerland is no exception to this development, both promoting PV within renewable energy legislation targeting a 45 TWh production in 2050 and anticipating future grid investments of CHF 75 to 85 billion as a result.

In light of these costly ambitions, several studies investigate how to expand PV capacity efficiently in consideration of the negative effects to a finite grid capacity. A solid understanding of this matter will help to avoid PV-related grid congestions and pave the road for it to become a primary electricity production technology. So far, academic and regulatory literature addresses the problem by either estimating a suitable PV allocation across the country from a social planner's perspective or by modeling grid outcomes for predetermined expansion scenarios. Both approaches contain little detailed information that could be used to design a mitigating policy mechanism e.g. how much a single PV installation adds to grid congestion in a circuit.

This research proposal contributes to the literature by proposing a new method to quantify PV-induced gird impacts more accurately. Based on extensive spatial data, I assign each house an individual probability of installing a PV panel which is used to model a theoretical expansion pathway in a Monte Carlo fashion. Based on a realistic low-voltage grid approximation, these modeled results will identify how individual, uncoordinated decision-making for PV accentuates negative effects on local networks. The next objective is to design an economic permit mechanism that mitigates grid congestion and supports a more efficient PV implementation, all while requiring little regulatory action.

This section introduces the topic and motivation of the proposal. Section 2 explains the current

Swiss PV subsidies, addresses shortcomings in the estimation methods for future grid investments and formulates the research contribution. The specific spatial data and methodology that is applied are presented in Section 3 and 4, while Section 5 outlines further research applications of the proposal.

2 Literature Review

2.1 The Need for PV

The global importance of PV that introduced this proposal is also mirrored at a smaller national level in Switzerland. Under the current energy law (Publikationsplattform Bundesrecht, 2016), the Swiss federal government is keen on expanding renewable energy capacity up to 11.4 TWh (excluding hydropower) by 2035. The upcoming legislature ("Mantelerlass", Verband Schweizerischer Elektrizitätsunternehmen [VSE], 2023) currently under debate in the Swiss parliament, sets even more ambitious targets for renewables production of 35 TWh by 2035 and 45 TWh by 2050. This push for electrification can also be seen in the scientific literature for energy system modeling. Recent future scenario models from academic scholars (Marcucci, Guidati, and Giardini, 2021, Gjorgiev et al., 2022, Paul Scherrer Institut [PSI], 2013, summarized by Marcucci and Schaffner, 2023), the federal administration (Bundesamt für Energie [BFE], 2020) and an industry leaders (VSE, 2022) predict an average PV capacity build-up to a 28 TWh production in 2050 to achieve the net zero target for carbon emissions in the same year. Fortunately, this capacity can be built on existing infrastructure without causing additional land use competition. Taking into account all well-orientated roof and facade surfaces, the Swiss Association of Independent Energy Producers estimated that an additional 67 TWh could be produced annually (Verband Unabhängiger Energieerzeuger [VESE], 2021).

It is not surprising that PV is considered the primary technology to achieve the set targets for future electricity production. Despite wind power having a large potential (MeteotestAG, 2022) and is being perceived as a valid renewable energy source, strong local opposition has repeatedly prevented the construction of projects after having negative second thoughts about the local implementation (Cousse et al., 2020). Given this resentment for wind power and the almost entirely positive perception of residential PV on the other hand (Sütterlin and Siegrist, 2017), it is not surprising that PV is most considered for the Swiss electricity transition.

2.2 About Endorsement Policies

Considering the large PV potential on existing Swiss rooftops (VESE, 2021), promoting individual installations is a promising strategy. In this section, I give an overview of the structure of typical subsidy schemes and their possible shortfalls due to unintended side effects. Public endorsement policies usually take the form of an installation subsidy, a guaranteed feed-in tariff, tax credits or a self-consumption rate to change the economic evaluation in favor of a positive investment decision (Matisoff and Johnson, 2017, De Groote and Verboven, 2019, Feger et al., 2022).

When analyzing subsidy schemes academically, authors tend to examine what type of mechanism is most efficient, meaning which achieves the highest adaptation rate with the smallest possible spending. A prominent example by De Groote and Verboven, 2019, finds that customers undervalue future feed-in tariff returns and therefore suggest upfront installation subsidies to avoid wasteful spending. Langer and Lemoine, 2022 even argue to increase the upfront investment subsidies over time, to achieve higher PV adaptation but not to overcompensate early adopters. In its subsidy program, Switzerland followed De Groote and Verboven, 2019, switching from a production-remuneration (KEV[1], BFE, 2009) to a before-installation subsidy in 2014 (EIV[2], BFE, 2018a). Figure 1 shows the introduction of both policies with the total number and relative change of installations over the last 30 years. Considering the visual effect of both the KEV and EIV implementation, it is uncertain if the policies were inefficient, as many others have been (Matisoff and Johnson, 2017).

Since classic subsidy schemes focus only on a singular objective, they can lead to other unfavorable outcomes besides inefficiencies, despite being designed with good intentions. While electricity grid constraints are elaborated in more detail in the coming section, I can already foreshadow that the increase in PV production starts to exceed the current grid capacity and will lead to costly grid updates (BFE, 2022; Ismael et al., 2019; Heilscher et al., 2017). The strain imposed on the grid through more PV installations features characteristics of a negative externality and depends on production capacity, timing and self-consumption. From an economist's perspective, this effect can be reframed as an ambient pollution problem where a house's new PV

[1] "Kostendeckende Einspeisevergütung (KEV)": a guaranteed, cost-covering feed-in tariff for residential PV producers, financed through a consumption surcharge of Rp 0.45 / kWh (BFE, 2008)

[2] "Einmalvergütung (EIV)" for small installations ($<$ 100kW): a compensation covering up to 30 percent (of a reference installation of comparable size) or up to 60 percent of the investment costs if the owner is committed to making no self-consumption.

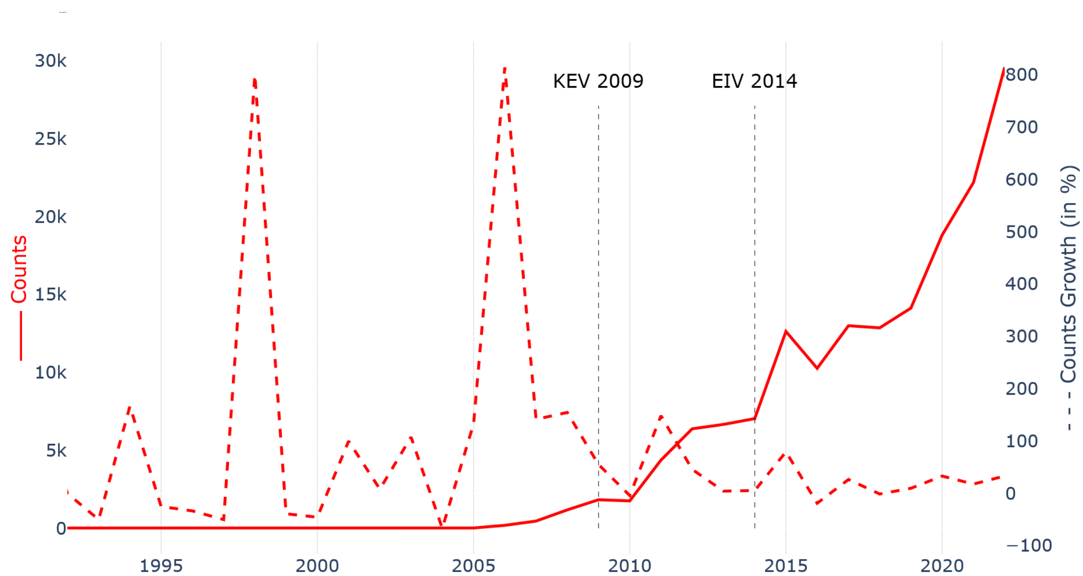


Figure 1: *Total number (and growth rate) for newly connected, small PV installations (< 100 kW) in Switzerland, 1992 to 2022 (BFE, 2023a).*

installation might "pollute" the grid, in this case prohibiting a neighbor's unit from producing at full capacity without grid update or curtailment action. Montgomery, 1972 and Tietenberg, 1995 provide seminal literature on non-uniform, ambient pollution mainly examining concentrated air pollution related to the Clean Air Act[3], discussing ambient permit systems in general, zonal permit systems and permit trading rules as possible solutions.

By making a few adjustments, this framework can fit the case of a negative PV externality. As every house is physically connected to the grid, it is possible to measure to what maximal extent an installation affects the neighboring houses' production. This solves both the location and dispersion uncertainty addressed by Tietenberg, 1995 and the question about optimal zone sizes (Krysiak and Schweitzer, 2010), as each low-voltage grid circuit serves as a natural permit zone with the grid operator as a well-informed regulator. Other than an overarching pollution target, each zone attempts to minimize cost by not exceeding its grid capacity. This rules out the need for inter-zone permit trading because households do not operate multiple installations in different grid circuits. The notion of a pollution permit is however still relevant because a PV's orientation

[3]A federal law regulating stationary and mobile air pollution to establish National Ambient Air Quality Standards in the US (United States Environmental Protection Agency [EPA], 1970).

and capacity determine the grid occupation relevant for neighbors, comparable to different air pollution intensities depending on the surrounding plants' stack height in Tietenberg, 1995 or Atkinson, 1983. Similar to a green technology investment (e.g. stack scrubbers), a PV owner can minimize pollution by optimizing his self-consumption and only feeding a certain volume into the grid during a fixed time window given a purchased permit. This still allows trading between feeders in a given zone, depending on their excess production that cannot be shifted or absorbed through self-consumption. This relieves the regulator from setting an optimal compensation price that avoids excess feed-in. Instead, he can issue permits for a maximal capacity feed-in over e.g. hours for each day, where a producing installation owner compensates all connected grid neighbors for hindering their production during a certain hour. Time-varying permit prices for each zone then set the clear incentive not to simply maximize production but to provide a feed-in that fits the local grid's capacity and is more useful to the operator.

The notion of a dynamic steering mechanism is not new for Switzerland. Feger et al., 2022 proposed not a permit design but a heterogeneous subsidy that accounts for individual buildings' sun exposure, incentivizing only a particular fraction of households for a PV installation with the most productive roof partitions. All though their main objective is not less grid congestion but adequate grid financing under strong PV expansion, it still shows how the idea of adjustable policy instruments is already promoted in the literature.

2.3 A Restriction in Grid Capacity

Historically, distribution grids at the low-voltage level were constructed to deliver electricity from centralized production sites to end consumers. The introduction of small, decentralized PV installations now alters this purpose in a new direction, causing a considerable impact on the grid infrastructure. A key attribute of PV panels is their highly correlated production in a single network, leading to large, uncertain feed-ins during the day, that exceed the grid capacity(e.g. over and under voltages, overloading of transformers and feeders (BFE, 2022; Ismael et al., 2019; Heilscher et al., 2017)).

For a local grid, the hosting capacity (HC) is the maximal amount of PV capacity that a network can integrate while still functioning satisfactorily (Rossi et al., 2015; Heilscher et al., 2017). At the limit, an additional production unit would exceed the HC and require a curtailing action to reduce the production within a time window or a grid update to facilitate larger inflows in the future. The HC therefore shows the expansion potential for further production units in a single network (Smith et al., 2011) and is essential to achieve the full economic benefit of renewable power generation and avoid unnecessary grid investments (Adefarati and Bansal, 2016).

Mitigating HC congestion is feasible if the number of new PV installations is small enough. But in light of the expansion requirements for Switzerland stated in Section 2.1 the question is not if the distribution grid is reaching a limit, but rather where and when. This is also acknowledged by the Swiss Federal Office for Energy which followed up their scenario predictions for a zero carbon emission society by 2050 in the National Energy Perspective (BFE, 2020) with another report (BFE, 2022) that solely addresses the resulting consequences for the electricity grid. This second model estimates that the medium voltage section will be most affected by the increase and that the lowest voltage levels only require approx. 10 percent more cable length and approx. 30 percent more transformers at a total cost of ca. CHF 3 billion every five years until 2050 (see NE7 in Figure 2). To estimate the grid update requirements in BFE, 2022 the authors use a Model Grid Analysis ("Modellnetzanalyse"), a method that highly simplifies grid topology

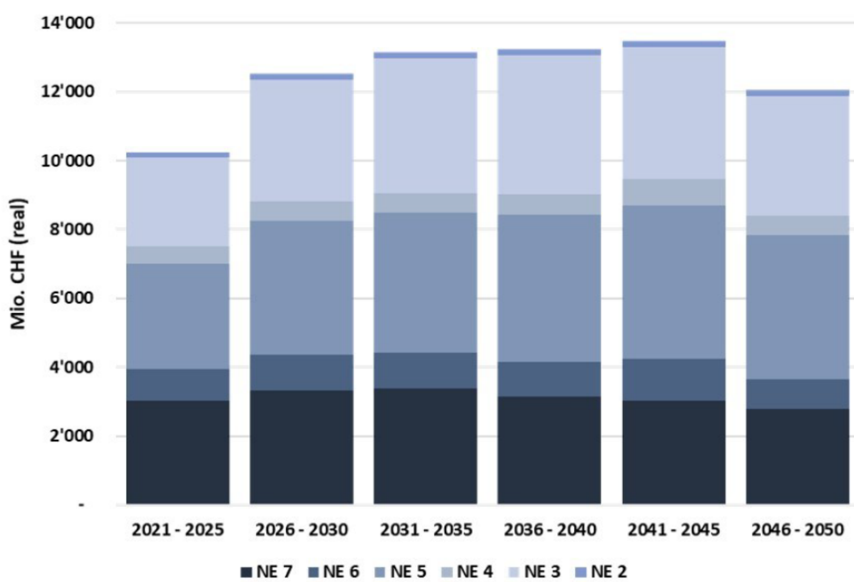


Figure 2: *Development of total investment need for the ZERO Basis scenario by grid level (NE2 = highest voltage, NE7 = lowest voltage) in real prices for 2020 (BFE, 2022, p.44. Fig. 2.8)*

features to ease computations. It assumes that feeders, connectors and transformers at the lowest grid level are homogeneously spaced across an area as illustrated in Figure 3. To still allow for spatial heterogeneity between regions (e.g. urban vs rural parts), the Swiss area is partitioned into roughly 2200 sub-regions[4], which are transformed into these homogeneous structures to then later receive the scenario determined PV capacity.

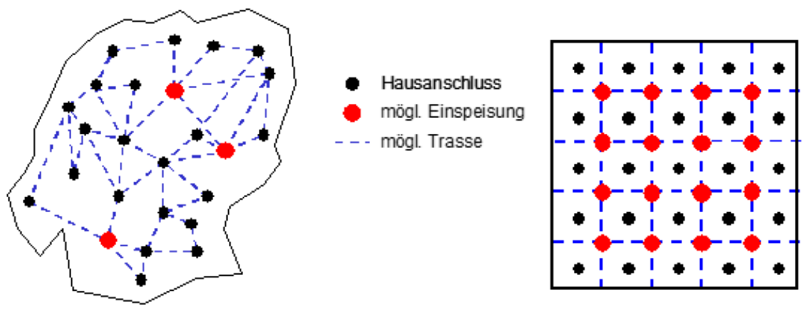


Figure 3: *Comparison between real and assumed distribution task for the gird provider in the Model Grid Analysis BFE, 2022, p.44, Fig.2.8).*

While this approach is unsuitable for planning an optimal grid topology, the authors argue it is sufficiently accurate (10-15 percent deviation from the real number of transformers and cable length) to approximate the required investments for the transition. However, assuming a uniform distribution of location and grid capacity for all connectors as in Figure 3 is problematic, even for 2200 differentiated areas. Houses with high production potential and profitable feed-ins will most likely be clustered in semi-rural to rural areas, given a large roof surface and a low demand because of the small number of residents. Müller and Trutnevyte, 2020 give partial evidence to this, showing how PV panels are not homogeneously distributed but spatially clustered and highly correlated with socio-economic and building-specific factors. These clustered areas will at the same time feature a small grid capacity with no historic reinforcement because they only required ordinary residential load up to now. Aggregating data even for small areas might therefore omit these two factors and lead to an underestimation of grid capacity requirements. In a similar example, Smith et al., 2011 show how cloud coverage leads to more strain on the grid, which is only visible in a non-aggregated setup that accounts for individual houses.

[4]It is not explicitly mentioned in BFE, 2022, but the authors probably chose administration areas of all 2136 Swiss municipalities for a more detailed estimation.

The way BFE, 2022 estimates the roof potential for new PV per municipality is another reason for concern. For each region, the roof partitions are aggregated by suitability. The pre-existing PV capacity is then distributed to the most suitable surfaces. This simplification is unnecessary and most likely underestimates the PV expansion potential and the grid impact for every region.

Heilscher et al., 2017 also use roof potential and random installation distribution across houses to find a combination that requires minimal grid investment. However, they exclude roofs with existing panels and do not redistribute existing capacities to more productive surfaces.

Given the mentioned concerns, the Model Network Analysis appears oversimplified and does not predict a realistic PV expansion for the future. There are more accurate methods, such as Müller and Trutnevyte, 2020 that choose a spatial regression approach to predict PV increase at a district level for Switzerland. Another example is Gupta et al., 2021 who estimate the hosting capacity for PV installations at the medium voltage level with a linearized optimal power flow and extend it through storage technology to maximize power production with minimal grid investment. While the two papers apply more sophisticated and realistic methods for PV expansion, both still use data that is aggregated into small areas, omitting individual household decision-making, low-voltage grid constraints, installation capacity and location.

This short review shows how there is no work examining PV expansion at the individual house roof level at a national scale in Switzerland. Data availability and ease of access are one of the main reasons why the presented authors (BFE, 2022; Müller and Trutnevyte, 2020; Gupta et al., 2021) do not consider data at such a granular level. The Swiss electricity market is not yet completely liberalized and serves end customers through more than 570 monopolistic operators, making it impossible to obtain high resolution data from a single source. Fortunately, there is a solution to this problem. Kays et al., 2017 use OpenStreetMap (OSM) data to create a realistic approximation of all German electricity grid levels. As low-voltage cables follow roads, they connect all houses to the closest connector and then map all radial road circuits to the nearest medium-voltage transformer, which features its own OSM tag. They continue aggregating upwards until the highest voltage level is reached and interconnected by the overhead connectors (plotted in OSM). This allows for a realistic approximation of different grid levels without the collaboration dependency on grid operators. A similar algorithm has been created by Banze, 2020 which is also able to approximate Swiss grid structures.

2.4 Research Contribution

I have shown in Section 2.2 how the current Swiss PV subsidy design focuses on capacity expansion through before-installations remuneration without further regard for unintended consequences. Section 2.3 demonstrates how further decentralized PV expansion poses severe upgrade requirements to low-voltage grids and how HC can be a constraining factor for future expansion. If Switzerland wants to reach the production targets listed in Section 2.1, then it is evident that the grid will encounter a large number of constraints in the near future, and possibly even larger than estimated in the low-voltage levels. My proposed research contributes to the literature by outlining how this problem can be quantified more accurately and how it could be mitigated from an economic perspective.

In the first step, I combine a low-voltage grid approximation with a more realistic theoretical PV expansion model to consider all aspects of uncoordinated household decision-making in estimating upcoming grid congestions. To the best of my knowledge, there is no publication for Switzerland that addresses the imprecisions described in Section 2.3 and promotes the use of a real-world data-based grid replicate as an alternative approach. The second step examines at what theoretical installation rate the predicted low-voltage congestion problems become severe. I further analyze if the model capacity exceedance is spatially clustered as expected and if it is correlated with other socio-economic factors. In a third step, I introduce a steering mechanism like the permit system presented in Section 2.2 that accounts for the estimated congestions, alters individual household incentives and avoids premature grid updates.

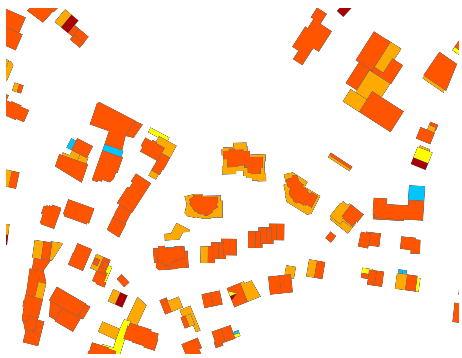
In the remaining sections of my proposal, I focus on the first and second objective by introducing a stochastic expansion model that relies on granular real-world data. Three model pathways consider different aspects of the installation decision and examine where the grid exceedance occurs most frequently in the Swiss low-voltage grid.

3 Data

The following section describes all input data used for the pathway modeling that contains a higher spatial resolution than area aggregates. Data at the municipality or district level can be later included but is not further elaborated here. As mentioned previously, data gathering for electricity demand and grid topology at the local distributor level is especially complex for

(a) *Low-voltage grid approximation from DaVe incl. connectors and lines (kV)*

(b) *Ann. resid. and comm. heating and cooling demand (MWh per ha)*



(c) *Ann. PV roof potential (kWh), in 5 categories from low (blue) to top (red)*

(d) *Location and annual production (kWh) for resid. PV installations < 30 kVA*

Figure 4: *Illustration of the most relevant data sources showing key features for an identical area in Davos Switzerland (N 46.086°, E 9.841°).*

Switzerland and a main obstacle for regulators and scholars to conduct more detailed analyses. I use the algorithm developed by Banze, 2020 (DaVe) that utilizes OSM data to derive a grid approximation across all grid levels. DaVe creates a grid structure by connecting all house objects to the nearest street, which simulates the connector underground as illustrated in Figure 4a. Line and transformer capacities are estimated using an average demand capacity per area and land use[5]. DaVe continues to partition the local grid structure upwards such that each area is served by a low to medium-voltage transformer. This upward aggregation to the higher transformer level is repeated until the entire grid is continuously approximated from low to highest-voltage

[5]The author assumes a capacity of 2 MW/km^2 for residential, 10 MW/km^2 for industrial and 3 MW/km^2 for commercial land use.

transmission. For my purpose, I only use the low-voltage distribution grid approximation[6], which the author of Banze, 2020 provided based on the latest OSM data in October 2023.

To determine the approximated electricity consumption for every Swiss household I follow the approach of Gupta et al., 2021 and BFE, 2022. Both use the publicly available raster for annual residential and commercial heating and cooling demand[7] (BFE, 2018b) in MWh per hectare, shown in Figure 4b. I then weigh the total weekly electricity demand (BFE, 2023d) by the heating and cooling raster and map it to the individual overlapping buildings. These two data sources allow me to approximate the total weekly consumption for each Swiss house given the latest electricity consumption report.

When analyzing PV potential, many authors usually resort to data providers that indicate the total sun radiation for a given region. However as the new PV installations require already-built structures, I use a data set measuring the surface potential of building facades (BFE, 2023b) and roof partitions (BFE, 2023c) which are used by both Heilscher et al., 2017 and BFE, 2022 and is updated annually since 2016. As shown in Figure 4c, both sources contain detailed information (e.g. surface tilt, azimuth and surface area) which is much better for predicting future production potential than only average solar radiation in the area.

Similar to PV potential, many publications use imprecise data to determine the current installed PV production units. Pronovo AG, accredited by the Swiss Federal Office for Energy to implement and manage the previously presented subsidy schemes KEV and EIV, publishes a data set (BFE, 2023a) containing all Swiss electricity producing facilities including residential PV. The data ranges from 1989 to 2023, is monthly updated and contains the first date of operation and production capacity for each installation unit.

The decision to invest in a residential PV installation is a large investment determining future electricity consumption. I include data on economic levers such as household PV feed-in tariffs that affect production reimbursement and investment profitability. In the Swiss electricity market, residents face a local monopolistic provider that fixes the price. The Association for Independent Energy Producers issues a public listing of all tariff schemes for all district grid operators (VESE, 2023). As the counterpart to feed-in is consumption, I also include the public electricity price data

[6]Because creating the approximation for all of Switzerland was computationally demanding, the author provided a first subsample for the municipality Davos-GR.Latter approximations will follow in the actual research phase

[7]The data set omits industry hotspots (in a separate data set), covering heat demand for residential and commercial buildings which can be served with low temperatures between 12° to 90° Celsius.

for all providers (Eidgenössischen Elektrizitätskommission [ElCom], 2023). The costs for a new installation are based on the publicly available Swiss PV-investment calculator (energieschweiz, 2023), featuring detailed house-specific calculations.

As an investment in PV panels is a costly decision, it not only has to be economically viable but requires an adequate capital stock. A house with a high production potential might still be unlikely to invest in an installation due to the lack of savings. To allow for income effects in PV installations, I will receive access to a spatial raster that depicts the average Swiss household income per hectare. This data is not publicly available and will be offered by Wüest & Partner, a leading Swiss quantitative real estate agency.

The Swiss Federal Registry for Buildings and Dwellings from the Federal Statistics Office (Bundesamt für Statistik [BFS], 2017a) contains every building for the entire infrastructure in Switzerland (built and under construction) and their installed heating technology (BFS, 2017b). This allows me to exclude all buildings that are not applicable for residential-sized PV installations (e.g. industrial buildings, offices, schools, churches, etc.) and also differentiate between single and multi-family homes. This is important as multi-family homes are more likely to house tenants who do not decide about a PV installation compared to single-party homes, which are more likely to house the actual owner. Both data sets were published in 2017, but the API (BFS, 2023) features more recent 48 hours old data.

4 Methodology

4.1 Modeling Approach

As shown in Section 2.4, the first step in my proposed research is to provide a more accurate modeling approach for a theoretical PV expansion pathway. Half of it is accomplished by using a real-world grid replicate (Banze, 2020), and the other half by simulating an accurate PV expansion across Swiss houses which is described here. My goal is not to use simple scenarios or only general optimizations from a social planner's perspective but to consider individual house-by-house decision-making.

There is not one but a variety of methods to estimate the effect of increased PV on HC, but when modeling large samples of small installations Mulenga et al., 2020 propose stochastic methods[8] because they allow for a high number of uncertainties compared to other deterministic or time series models. Heilscher et al., 2017 follow this suggestion and use Monte Carlo to distribute PV and examine its HC effects, but from a social planner's perspective. Argüello et al., 2018 use a truly house-specific probability function that assigns the likelihood of a PV installation dependent on the break-even duration of the investment to predict a realistic expansion path. I combine these two approaches by distributing future installations through a probability function as Argüello et al., 2018 in a Monte Carlo fashion similar to Heilscher et al., 2017. I then examine if the new installations cause grid constraints and if they vary significantly due to path dependencies.

Figure 5 gives a step-by-step illustration of all stages that occur in one prediction iteration. I introduce the following notation to increase the readability within the scheme. A residential, single family owned house $i = 1, ..., N$ decides every year $y = 2024, ..., Y$ to build a PV installation ($PV_{iy} = 1$) or to wait for the next period ($PV_{iy} = 0$). $PVtopo$ represents the roof topology for all households and indicates if a roof has an installation ($PVtopo_{iy}(PV = 1)$) in year y with all technical specifications[9]or not. In this case, $PVtopo(PV = 0)$ describes the house's production potential given its roof features. The marginal construction capacity cc_y defines how much PV capacity has already been built in year y with TCC_y defining the annual construction limit.

The algorithm starts by creating the initial topology, assigning the relevant characteristics ($PVtopo_{i,2024}(PV = 0/1)$ to all N houses in 2024. If TCC_y is not exceeded, each house is assigned a probability $p(PV_{i,2024})$ for an expansion this year, depending on the pathway assumptions. The algorithm then picks a house i^* from the distribution and checks if the roof meets the side constraint sc_i (HC). If so ($PVtopo_{i^*,2024}(PV = 0) < sc_{i^*}$), the installation is built and the capacities and constraints are updated ($cc_{2024} + cc_{i^*}; sc + sc_{i^*}$). Otherwise, the house is dropped for this run and a new house is drawn from the distribution. It is important to highlight that the side constraint is not used in all pathways. If no side constraint is applicable, the selected house directly builds an installation. Once construction capacity is met ($cc_{2024} = TCC_{2024}$), a new year begins ($y + 1$) and $cc_{y=2025}$ is reset to 0. This continues until $y = 2050$, at which time the algorithm exits and a full iteration is complete.

This computation is now repeated multiple times to allow for randomness in the expansion over

[8]The authors refer to a large number of methods e.g. Monte Carlo, point estimation, multi-linear simulation, Gram-Charlier expansion, Cronish Fisher expansion or Latin Hypercube Sampling for faster run time.

[9]Technical information contains: Date of initial usage and power capacity for initial production and after possible upgrade

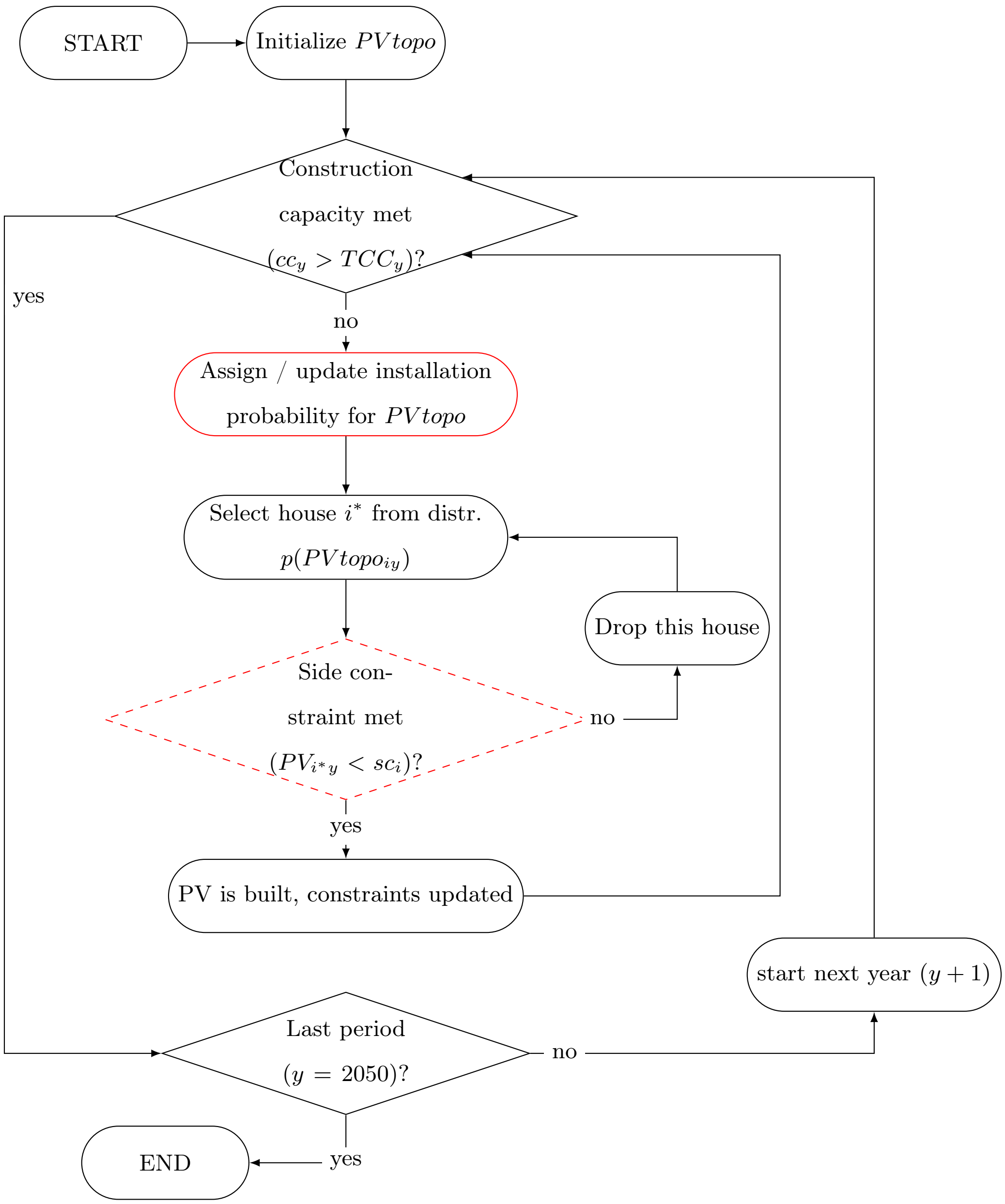


Figure 5: *Algorithm illustrating a Monte Carlo iteration. Diamonds: marking decisions. Red: Differences between pathways. Dashed line: Not included in every pathway.*

the large sample, as suggested by Mulenga et al., 2020 and practiced by Heilscher et al., 2017. The repetition in modeling allows me to examine the possible path dependencies in pathways that have a side constraint. How many iterations are needed depends on the observed outcomes and has not been observed yet. The outcome of interest would be grid congestion after a small number of years. If this occurs frequently enough to observe a clear difference between the expansion pathways, then a low number of runs is sufficient. However, if the congestion moments are rare, then I need to adjust the assigning probability functions such that congestions are overrepresented in a controlled manner to model enough congestion observations with adequate runtime. For now, I assume that enough variability is represented in the three pathways and suggest to run the algorithm in the low hundreds of iterations, each containing a prediction for the PV topology in Switzerland in 2050.

The iterations are then matched to the OSM approximated low-voltage grid to detect negative grid impacts. In a simple statistical analysis, I examine how many grid congestions occur on average, capturing where and by how much the current grid lines and transformers are exceeded.

First, I consider a simple comparison, revealing if there is a significant difference in grid congestion between the different pathways across the entire observation period. I then examine at what rate of PV installation these congestions become most severe. Second, I filter expansion paths by congestion levels, slowly adding less optimal iterations to see if there is stability in the houses that received an installation. A large variation would indicate path dependencies, where a house's choice has a large impact on neighbors in the circuit. I also examine correlations across socio-economic and spatial factors to see whether adverse effects of PV installations only affect a certain subset of houses (e.g. old neighborhoods with old lines, rich neighborhoods with sufficient capital stock etc.). Third, I reproduce the congestion mapping described just before but on a year-to-year basis to examine if installation-induced congestions are time-dependent. This will show if the rate of grid congestion spreads only spatially or slowly rises in all grid zones over time.

4.2 Three Expansion Pathways

The goal for each pathway discussed in this section is to include different viewpoints from decision-makers in the theoretical expansion. The main difference between the paths, the probability distribution for installations and the side constraint, are both marked red in Figure 5.

The first path "Economic Individual" aims to capture a model world in which all the decisions are made by uncoordinated individual house owners based purely on their own economic merit with no constraining HC. I try to mimic the approach of Argüello et al., 2018, where each house computes a payback period for the investment based on electricity consumption, price and feed-in tariff. The installation probability is set at 100 percent if it takes five years or less to regain the full payback, then quadratically declines to 0 percent for a payback period of 25 years or longer, as shown in Figure 6. To allow for capital stock effects, the probability is set to 0 if the installation costs are larger than 15 percent of the yearly household income[10]. As individual owners do not consider the grid's hosting capacity, no side constraint is applied.

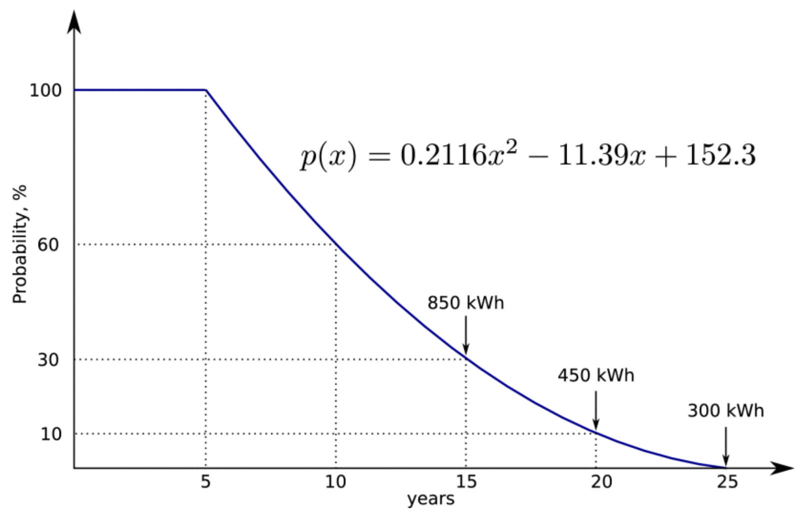


Figure 6: *Probability of installation for residential customers as a function the payback period of the investment (Argüello et al., 2018, Fig.6)*

The second path "Technically Optimal" represents a counterfactual to the "Economic Individual" with a central planer that assigns installations to houses to maximize total electricity production and inflict minimal grid congestion. I will again use a quadratic probability function similar to Argüello et al., 2018, such that the house with optimal exposure and the largest roof partition receives the highest installation probability. To minimize the adverse effects on the grid, this path enforces a side constraint so that an additional installation's excess feed-in remains within the HC. The side constraint is only relaxed if the next installation would exceed the HC on any roof in the sample. Then PV is again installed on the most suitable roofs until the annual construction capacity is met because in this case, a capacity violation is no longer avoidable.

The third path, "Random Allocation" represents a middle ground between the first and second paths. As the name suggests the probability of installation for all houses is uniform regardless of suitability and with no applicable side constraint. This path by itself carries little additional

[10]This cutoff threshold is chosen based on back-of-the-envelope calculations and will later be adjusted

information value but it serves as a comparison to examine if the other paths are indeed different from a pure random allocation.

4.3 Assumptions

Despite the use or real-world data, the theoretical model just described relies heavily on several strong assumptions. The construction capacity TCC_y is assumed to be a constant, set to the average of installed capacity (BFE, 2023a) in the last two years (2022 and 2023). Next, PV is only installed through an active decision and not as part of an age-related building renovation. Further, I only consider the existing building stock (from 2023 onward) and ignore future buildings as I do not have any indication about their roof exposure. The sample of houses only contains single-family homes, because these houses are much more likely to be owned by their inhabitant where it's just one party facing the price signals and receiving the full cost and benefits from a PV installation. An intersection of current PV installations and building classes in Table 1 shows that 63 percent of existing, small-scale PV (ca. 11 kW) is indeed built on single-party-owned houses, making this a reasonable sample to focus on. This leaves the algorithm a sample of ca. 1.15 million single-party houses[11] to distribute PV installations to. The share of 4.4 percent of non-identified buildings in Table 1 will strongly decrease once the intersection is redone with the most updated data from the building registry API (BFS, 2023). I assume a household does not install PV on the entire roof surface but only on the most favorable partition, equivalent to the cost calculation method by energieschweiz, 2023. After an installation, the house does not expand or reinforce panels at any later stage and covers its entire electricity demand with self-consumption. This particular strong assumption will later be relaxed to model a more realistic feeding pattern to the grid.

4.4 Limitations & Shortcomings

In the proposed research, several limitations need to be acknowledged. While I try to identify individual house characteristics as well as possible, several imprecisions remain e.g. weekly electricity demand, grid mistakes in DaVe or the missing level of actual self-consumption to name just a few. Also, the assumption that variables such as building stock, construction capacity,

[11] This is ca. 35.8 percent of the entire Swiss building infrastructure (total of 3.2 million buildings registered in BFS, 2017a).

PV Distribution for Swiss Houses

Building type	PV counts	%-Share	Avg. Capacity
Single houses	116292	62.7%	11.5
Double-Row houses	21371	11.5%	18.4
Multi-party houses	21270	11.5%	23.6
Shared housing (e.g. elderly)	357	0.2%	61.2
Non-residential buildings	18074	9.7%	96.6
Building not identified	8211	4.4%	40.6
Total	185575	100.0%	23.4

Table 1: *Summary all Swiss PV installations by building types, (intersection of BFE, 2023a and BFS, 2017a, capacity in kW)*

electricity prices and feed-in tariffs or total demand remain static over time until 2050 is a drastic oversimplification.

Despite many simplifying assumptions, computational runtime for assigning PV installations will still remain a problem. As the algorithm covers almost the whole sample 27 times (every year until 2050) to determine probabilities and assign PV installations, it is likely that efficient data aggregation operations are crucial to diminish runtime to a solvable amount. To defuse this problem for the time being, I will first work on a subsample for ten municipalities [12], which are also the main subject of research in a prominent Swiss scientific project (Swiss Energy Research for the Energy Transition [SWEET], 2023) and represent three archetypal regions (cities, midlands and the alps).

To fully model the suggested permit system proposed in Section 2.2, I need to change the time subscript now set at y from years to hours. This will cause large new data requirements (e.g. sun radiation per installation, hourly self-consumption etc.) and yet another increase in runtime. This is why I currently propose a year-based model, to later get a better understanding of the computational requirements for a more sophisticated methodology.

[12] The municipalities selected in the SWEET project: Davos, Chur, Sirnach, Buttisholz, Aarau, Luzern, Liestal, Turgi).

5 Outlook

I want to conclude this proposal by giving a short notion on the steering mechanism that incentivizes individual decision-making to minimize grid exceedance, given that I managed to setup my model for hourly observations. Section 2.2 closed by showing how each grid circuit is a natural zone that can regulate grid congestions through time and capacity-dependent feed-in permits. The permit price would be determined by the amount of feed-in (exponentially increasing in price) and the timing (higher prices for peak hours with over-production). Assuming that I had this information, I would use all socio-economic and spatial data sources to assign each house a load archetype ("senior", "traditional family household" or "flexible working household") that features a specific demand curve during the day. After this categorization for single-party-owned Swiss houses is complete, I will introduce an intra-zone permit scheme, where the price depends on the amount of kWh that cannot be fed to the grid because of HC constraints. This group of inhibited producers is then compensated through the purchased permits. Installation owners who can still shift self-consumption will feed in at a less congested hour and avoid purchasing a permit. The permit scheme sets thus a large incentive to build a more suitable PV installation for the grid requirements because a house's roof orientation now also determines the production hours during the day next to the overall productivity.

At a later stage, I will try to establish a collaboration with a large distribution gird operator that covers a heterogeneous enough area in Switzerland. This will satisfy the new data requirements for grid capacity, household consumption and feed-in which was previously only approximated. This step will then change this research from a theoretical prediction to a real empirical application and propose a clear suggestion on how to best address the negative grid impacts from PV installations that are already becoming visible today.

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