The Impact of self-consumption regulation on individual and community solar PV adoption in Switzerland: an agent-based model

Prakhar Mehta1,2, Danielle Griego1, Alejandro Nunez-Jimenez2, Arno Schlüeter1

1 Chair of Architecture and Building Systems, Department of Architecture, ETH Zürich, Stefano-Franscini-Platz 1, 8093 Zürich, Switzerland
2 Group for Sustainability and Technology, Department of Management, Technology and Economics, ETH Zürich, Weinbergstrasse 56/58, 8092 Zürich, Switzerland

pmehla@student.ethz.ch, griego@arch.ethz.ch, anunez-jimenez@ethz.ch, schlueter@arch.ethz.ch

Abstract. The new Energy Act in Switzerland came into force in January 2018 with very encouraging provisions for community solar PV systems – clearer financial and legal structures under the ZEV (Zusammenschluss zum Eigenverbrauch). However, there is no ex-ante scientific research as to how this new policy will fare, especially with changing electricity prices and falling solar PV costs. Agent-based modelling is a useful technique to simulate the adoption of new technologies and is used for community solar PV adoption in this work. The agent-based model developed in this research uses energy data generated from a district model of nearly 2000 building blocks in the city of Zürich using the City Energy Analyst (CEA). This approach is used to analyse the dynamic levels of adoption of individual and community solar PV systems when modelling factors such as geographical location of agents, environmental attitudes and peer effects, electricity and solar PV prices as well as legal regulations. A scenario without any such regulation is also modelled for comparison. The current work indicates that adoption levels are exceeded with the large building blocks considered, and the ZEV regulations do incentivize community PV system adoption for greater adoption levels at better system economics.

1. Introduction

With the planned decommissioning of nuclear plants in Switzerland and its replacement with renewable energy sources, Switzerland’s electricity mix is set to undergo a major transformation in the coming years. The Energy Strategy 2050 [1] has set a target of 11.4 TWh of electricity to be produced by renewables (excluding hydropower) by 2035, a 450% increase from the 2.5 TWh produced in 2017. Solar photovoltaic (PV) systems will likely be the driving force behind this increase, up to 6 TWh by 2035 [1] thanks to falling prices and ease of operation.

However, the diffusion of PV systems has been rather slow. In 2017, solar energy in Switzerland accounted for 2.1% of electricity production, below the average 3.5% in the EU-28 and far smaller than the 6.2% of neighbouring Germany [2]. In order to accelerate diffusion, the Energy Act 2018 introduced newer, clearer provisions to further encourage the adoption of individual and community solar PV systems [3]. Community solar systems are owned by and supply electricity to several individuals, who share the costs of installation and operation. These systems tend to be cheaper per unit power than individually owned installations, thanks to exploiting economies of scale. More importantly, by
combining complementary load profiles, community solar systems can achieve higher self-consumption ratios (SCRs) than individual systems. In the Swiss context of very low feed-in tariffs, greater self-consumption is crucial for the feasibility of solar PV installations. Realizing these advantages, the Energy Act included ‘Zusammenschluss zum Eigenverbrauch’ (ZEV) i.e. ‘Self-consumption Communities’ regulations that incentivize community-scale PV systems to share electricity generated with building tenants and neighbouring buildings. Although this is very promising to increase the penetration of solar PV in urban contexts, the impact of these policies in coming years remains unknown.

1.1. Research Objectives
The primary objective of this research is to analyse and explore individual and community solar PV adoption under the Energy Act [3], which elements of the regulation will have a greater impact on the adoption levels, and provide insights into the potential dynamics to be expected. This work can inform policymakers about potential benefits and shortcomings of the new regulation, for example, regarding the barriers to form communities for the installation of solar PV systems, individual and community PV adoption levels and whether these levels are in line with the renewable energy targets set for 2035 [1].

1.2. Literature Review
1.2.1. Current regulations
Under the ‘Zusammenschluss zum Eigenverbrauch’ regulations, building owners can install solar panels on their roofs and sell the electricity to their tenants at prices not greater than the retail price of electricity [3]. The investment payback for the owner comes from increased self-consumption and corresponding reduced electricity purchase from the grid. Federal subsidies depend on the installation size but in general cover up to 30% of installation costs, while the low feed-in tariff levels by the local utility indirectly promote increased self-consumption. To form communities, the properties must be adjacent to each other, where mergers cannot extend over public land (e.g. roads) and private property, and all properties must be connected behind the same point on the grid [3]. These lead to strict restrictions for who can legally form such communities.

1.2.2. Modelling the diffusion of innovations
There are different approaches to modelling the decision-making of individuals that drives the diffusion of innovations. Wilson and Dowlatabadi [4] summarized them into four diverse perspectives: conventional and behavioral economics, social psychology, sociology and attitude-based decision-making within which the Theory of Planned Behavior (TPB) [5] stands out. It states that behavior is preceded by an intention, which comprises an individual’s attitude towards the behavior, subjective norms (e.g., social pressure) and perceived behavioral control (i.e. his/her ability to perform the behavior in question). We adopt the TPB to inform our modelling, which has been shown well-suited to study the diffusion of solar photovoltaics [6], [7].

Peer effects (opinions of a person’s network) are important in the adoption of solar PV [8]–[10], and active peer effects through close family and friends have been shown to be more important than passive peer effects such as physically seeing an installed PV system in the neighbourhood [11].

Individuals can have very different opinions and networks, for which Agent-based modelling (ABM) can be used as a bottom up technique to examine how agents’ micro-level behavior influences the population’s macro-level emergent phenomena. Approaches like System Dynamics (SD) and Bass models have also been used for diffusion of innovations but typically do not account for micro-level influences like peer-to-peer interactions [6] and the heterogeneity of individuals [12], and ABM has gained traction recently especially for the adoption of solar PV. For example, Rai et. al. [7] used a theoretical and empirically driven ABM based on the TPB to model PV adoption by individual homes in the USA. Similarly, Sachs et. al. [13] created an ABM with multiple decision-making steps for representing behaviors leading to investments in the decarbonisation of the energy sector in the UK. Though ABM has difficulties with model calibration and can require huge computational power, it suits our case particularly well due to the importance of modelling peer effects and a heterogeneous population. Existing research only looks at the diffusion of individual solar PV systems, whereas this work adds an additional option in the decision-making process for the adoption of community solar PV systems.
2. Data and Methodology

2.1. The Case Study: Alt-Wiedikon district, Zürich

Zürich’s Alt Wiedikon district makes for a good case study to test the adoption of solar PV because of greater than average solar potential and wide variety of building types which can take advantage of complementary load profiles to form community shared PV systems. The model of nearly 2000 building blocks (multiple individual buildings aggregated into one block) included over 13 broader building typologies (Figure 1), which were categorized into three – residential, commercial and public (Figure 1). The City Energy Analyst [14] energy model is used to generate hourly electricity demand, solar PV sizes and hourly PV production data of the district. This data is used as inputs for the ABM, along with electricity prices, subsidies and feed-in tariffs [3] and solar PV prices [15]. Electricity prices and feed-in tariffs are assumed to be constant throughout the simulation period, while PV prices keep falling according to [16] and subsidies are stopped in 2030, in accordance with current regulations [3].

Before running the ABM, the district is divided into smaller ‘plots’ where agents can form and share a community PV system according to the criteria outlined in the ZEV regulations [3]. Agents with yearly electricity demands greater than 100 MWh are removed from the analysis, since their option to buy electricity on the significantly cheaper wholesale markets makes economic indicators very different. This leaves the district with 716 blocks. Figure 1 shows a summary of the pre-processed data with initial candidates by building type for who can form a community for shared PV, and their PV capacities considering the maximum available roof area for each building.

![Figure 1: Building typologies in Alt-Wiedikon, Zürich](image)

### Table 1: Categories of building types and available PV capacities

| Building Types | All Buildings | All Buildings less than 100 MWh Demand | Can Form Community |
|----------------|--------------|----------------------------------------|--------------------|
|                | No. of Buildings | PV Cap (kWp) | No. of Buildings | PV Cap (kWp) | No. of Buildings | PV Cap (kWp) |
| Residential    | 1053          | 122246       | 526              | 19191         | 423               | 14521           |
| Commercial     | 291           | 48463        | 143              | 7427          | 109               | 5349            |
| Public         | 93            | 11839        | 47               | 1865          | 34                | 1179            |
| **Total**      | **1457**      | **182548**   | **716**          | **28483**     | **566**           | **21049**       |

2.2. Methodology of the Agent-based model.

The purpose of our agent-based model is to simulate the diffusion of solar photovoltaics in an urban environment. In particular, we aim at representing the decision-making of building owners when considering the adoption of an individual or a community solar PV system.

2.2.1. Model entities, scope, and process overview. There are two types of entities in the model: the observer, tasked with time-keeping and the update of global variables, and the agents. The population of agents represents potential adopters of PV who own one building block in the city’s district differentiated by the type of use of their property: residential, commercial, and public, (see Figure 1). The population of agents is 716 and is determined by assigning one owner to each building block in the district of Alt-Wiedikon. Each agent is characterized by a set of attributes, such as its environmental awareness and its network of contacts, that determines its behavior (see section 2.2.2).

The model simulates the future evolution of solar PV diffusion between 2018 and 2035, with yearly time steps. The inputs of the model are the rules for adoption of individual and community solar PV systems contained in the ZEV regulation, while the model’s outputs are the dynamics of the diffusion of solar PV systems. Each time step (i.e. year), the model begins by updating the global variables such as solar PV prices. Agents are then asked whether they want to install a solar PV system, which they determine following a two-step approach. First, agents must develop the intention to install, and, only if they do, evaluate whether to adopt either an individual or a community system. Our ABM allows the
representation of randomness through variables assigned as probability distributions, which requires the use of multiple simulation runs to interpret the results. We employ 100 simulation runs for our scenarios.

2.2.2. Agent decision-making mechanism. Figure 2 shows a schematic representation of how we adapt the Theory of Planned Behavior into a two-step decision-making process by the agents:

2.2.2.1 Stage 1: Intention: In the first stage, agents determine if they develop the intention to adopt solar PV. Whether an agent develops the intention to adopt solar PV is contingent on three variables:

a. **Attitude toward the behavior, range** $[0,1]$: We represent the agent’s attitude by modelling its general environmental awareness and assign one value from a Gaussian distribution derived from survey data [17]. Additionally, 3.5% of agents are considered early adopters and assigned a higher environmental awareness based on empirical data from Minergie labels.

b. **Subjective Norms, range** $[0,1]$: Our model includes this element as active peer effects between agents, modelled through a small-world network built for each agent, and measured as the fraction of those contacts with installed solar PV [6], [18].

c. **Perceived behavioral control (PBC), range** $[0,1]$: We represent this variable with the perceived economic benefit of the behavior measured for each agent as the profitability index, defined as the ratio of all future cash flows to the initial investment and scaled between 0 and 1.

The agent develops the intention to adopt if the weighted sum of (i) attitude, (ii) subjective norms and (iii) perceived behavioral control surpasses an intention threshold of 0.5. Additionally, our model captures the persuasive influence of neighbours willing to form a community PV system together, represented by the ratio of neighbours (i.e. agents in the same ‘plot’) with developed intention to all neighbours of the agent. (Eq. 1).

$$
\text{Intention} = (w_1 \ast \text{attitude} + w_2 \ast \text{subj. norms} + w_3 \ast \text{pbc}) + w_4 \ast \text{neighbour persuasion}
$$

(1)

2.2.2.2 Stage 2: Behavior: Once the agent has developed an initial idea to adopt, it has the option to choose between an individual PV system or a community PV system with neighbouring agents who have also developed the intention to adopt. The agent decides based on which alternative has the highest net-present value; a maximum negative NPV up to 5% of investment cost was allowed during model calibration. If the community system has a higher NPV, then the community adopts and the agent which initiated the adoption is nominated as an ‘Energy Champion’ for that community. We consider the local utility EWZ’s ‘Solarsplit’ product [19] which levies costs of smart meter installation for shared systems as a proxy for costs of cooperation in our NPV calculations.
2.3. Model validation and initialization.
Available Swiss historical PV adoption data was not segregated for urban regions until 2015 and the latest data was of 2016. To find appropriate weights for Eq. 1, the model was calibrated (while disallowing community formation) to fit to historical, aggregate country level adoption data. This data was scaled for the district considered and projected into the future for 5 years until 2022 as we assumed adoption levels will follow a similar rate of increase in the near future. We examined the model behavior in a thorough sensitivity analysis to achieve the least root mean square error (best model fit) of simulation results vs projected trend. The ABM was initialized with 3 PV systems in 2018.

2.4. Scenarios.
We explore two policy scenarios (1) current ZEV regulation (ZEV), and (2) no ZEV regulations (no-ZEV) – same subsidy and feed-in tariff levels but removing community formation.

3. Results
The current ZEV regulations mean only 566 of 716 buildings in our model can form communities with other buildings. A total of 732 unique possible community combinations exist with demands less than 100 MWh/year. 547 of these consist of buildings of the same typology, whereas 185 are mixed-typology communities. Figure 3(a) shows the results of the ZEV scenario. The total installed PV capacity follows the trend until 2023 and then increases sharply, at a rate of 1000 kW/year, as PV prices fall and peer effects increase. Contrary to expectations, it is the individual and not community PV systems which drive the adoption trend. This is due to the aggregation of buildings into building blocks, leading to large PV sizes. Individual systems (adoption by one individual block) hence have good NPVs so that economies of scale do not really matter. In reality, a majority of these individual adoptions represent blocks of more than one building and would be community PV systems. Adoptions flatline after 2030 as investment subsidies run out. This immediately drives down the PBC variable which fails to recover enough by the end of the simulation period, hence remaining agents do not cross the intention stage of the ABM. The simulation ends on average with 8000 kWp installed capacity, 19% being multi-building block community systems, and exceeds Swiss targets of 4000 kWp (scaled for this district) by two times.

The no-ZEV scenario helps understand the difference if the ZEV regulations to form communities wouldn’t exist, while keeping subsidies and prices constant. No communities can be formed, and Figure 3(b) shows the total (i.e., individual) adoption level. Similar to the ZEV scenario, no adoptions occur after 2030. The simulation ends on average with 6500 kWp installed capacity, about 1500 kWp less than the ZEV scenario but still exceeds targets 1.6 times. This 1500 kWp gap between the two scenarios is the level of community PV system adoptions under the ZEV scenario. An analysis of results shows that in a typical ABM run, while the investment costs per kW across scenarios are the same, the combined NPV of all adopters in the ZEV scenario is -22 CHF/kW, 38.8% higher than -36 CHF/kW in the no-ZEV scenario due to economies of scale. Based on this analysis, the ZEV regulations thus help with increased adoption levels at better NPVs, leading to significant cost savings.
4. Conclusion
In this work, we have used an agent-based model to simulate the adoption of individual and community solar PV systems in Zürich’s Alt-Wiedikon district under the two scenarios – with and without ZEV regulations. In both scenarios, adoption targets are exceeded, the shapes of the adoption curves are very similar, and the lack of subsidies post 2030 halves the rapid growth levels abruptly. This is a preliminary indicator that PV prices may not fall enough and either greater feed-in tariffs, a reduced magnitude but extended duration of subsidies, or both may be required to keep up the adoption rates. The ZEV regulations lead to 23% higher total adoption levels through community formation at 38.8% higher NPVs than if no such regulations were in place to help form communities. These results used building blocks of individual buildings, indicating adoption targets can be exceeded if neighbouring buildings cooperate and install larger, economic PV systems. Higher resolution energy data would improve the results of this work by avoiding aggregation of buildings into building blocks. A limitation of this work is that it neglects blocks with demands greater than 100 MWh/year, which are likely have larger roof areas for bigger, cheaper PV systems and can drive community adoption. It would also be interesting to see whether relaxed ZEV regulations can help form communities with better complementary load profiles and better system economics.

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