Eidgenössische Technische Hochschule Zürich
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Agent-based Modelling of Social Systems

Project Report

Diffusion of Solar Communities & Influence of Extremists

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Contents

1 Abstract

The diffusion of solar photovoltaic (PV) systems has the potential to decarbonize a large portion of the energy consumption in cities. However, consumers' lack of awareness and uncertainty about solar PV hinder the diffusion the technology. Opinion dynamics around the technology are thus of pivotal importance for understanding how policy interventions could accelerate the uptake of the technology. Previous research points to the disproportionate influence of individuals with strong opinions – so-called "opinion extremists" – on other individuals within their social network. Such opinion extremists, therefore, provide a potential lever for policy interventions. In this article, we explore the role of opinion extremists in the emergence of cooperation for the diffusion of solar PV in cities. For this purpose, we develop an agent-based model that represents a fraction of the building owners in Alt-Wiedikon district in Zurich, Switzerland. We simulate four scenarios with different distributions of opinion extremists to analyze their impact on the uptake of individual and community solar PV. Our results confirm the insights from previous research and observe a dynamic not yet reported in the literature. While agents with strongly negative views reduce PV adoption in all scenarios, their impact is disproportionately larger on the adoption of individual solar than of solar communities. The opposite is true for agents with strong positive views. These results are exploratory and should be interpreted cautiously since we could not validate our model empirically due to the unavailability of historical data. Nevertheless, they suggest that targeted policy interventions to support a more positive view of the technology could prove effective, particularly for the diffusion of solar communities in cities.

Keywords: opinion dynamics, diffusion of innovations, solar photovoltaics, agent-based model

2 Introduction and Motivations

Global CO_2 emissions continued to rise in recent years driven by growth in energy demand [1]. As the world's population rapidly urbanizes, the share of global final energy that is consumed in cities – already about two-thirds – increases[2]. The de-carbonization of urban energy systems is, therefore, a priority for climate change mitigation policies.

Distributed solar energy offers a promising tool to address this challenge. Solar photo-voltaic (PV) systems transform the sunlight into electricity and can be installed on the rooftops of buildings. In the decade since 2009, the price of solar PV modules has fallen around 90%, making solar power cheaper than electricity from the grid in an increasing number of countries[3]. Despite this fact, the diffusion of rooftop solar remains very far from its potential. A recent high-resolution estimation calculates it is as much as one-fourth of EU electricity consumption[4]. The lack of awareness of potential adopters, concerns about the system performance and the lack of suitable rooftop space are among the most important barriers to faster diffusion of solar PV[5].

The appearance of energy communities provides a new path forward to accelerating solar PV adoption. Solar communities are associations of individual consumers that own a fraction of a solar installation. By installing larger systems and sharing their electricity generation, solar communities can tap into economies of scale and enhance the use of solar power on-site, making adoption more attractive economically[6]. By requiring the cooperation of individual consumers, the formation of solar communities could trigger social dynamics that facilitate the increase of awareness about the technology, improve the attitude towards it, and reduce the uncertainty around its performance. A recent European directive (EU 2019/944) and new Swiss regulation about self-consumption (EnergieSchweiz 2019) recognize these advantages and aim at encouraging energy communities. For these interventions to be effective, though, a better understanding of how individual consumers decide to become part of a solar community is required.

There is an extensive amount of literature on the adoption of solar photovoltaic, including numerous articles that employ agent-based models. Until very recently, however, most of the existing research was centered upon individual adoption. Rai and Robinson[7], as a prominent example, studied the integration of social, behavioral, economic and environmental factors through an agent-based model of energy technology adoption. The article highlights the critical role of social and behavioral factors, often neglected in favor of economic variables. However, it does not include the possibility of solar community adoption. More recently, Mittal, Krejci and Dorneich[8] and Schiera, Minuto, Bottaccioli, Borchiellini and Lanzini[9] developed models that introduced this possibility for the particular cases of utility-provided community solar and communities between apartment owners of a single building, respectively. One of the most relevant cases for solar communities, those formed between different buildings within a city district, has remained largely unexplored.

Another research area has focused on the role of opinion dynamics within the diffusion of solar PV. While both Rai and Robinson[7] and Schiera and colleagues[9] integrated social dynamics in their papers, the influence of opinion extremists on solar adoption, and, more specifically, on the diffusion of individual and community systems, was not analyzed. This is surprising given the research showing, on the one hand, the relevance of opinion leaders and their social networks in the context of solar PV adoption [10][11] and, on the other, the disproportionate impact of opinion extremists[12]. There is an important knowledge gap to bridge in combining these streams of academic literature.

This article extends prior knowledge by focusing on the role of opinion extremists in the diffusion of individual and community solar systems within a city district. We try to answer the question: *What is the role of opinion extremists in the diffusion of individual and community solar photovoltaics in cities?* For doing so, we developed an agent-based model that represents the decision-making of building owners based on economic and social factors. Each agent has unique attributes and is part of a small world network within which it interacts with other agents and develops opinion dynamics that determine the emergence of solar PV adoption. The results of our research highlight the impact of agents holding extreme positions towards the technology, and, in particular, stress the distinct influence of one-sided extremism and polarization on individual and community solar.

The remainder of this article contains a description of our methodology, followed by a review of our results and their discussion, and it finishes with conclusions and implications.

3 Methodology

We developed a new agent-based model to simulate the behavior of a population of building owners, which we then employed to run a series of experiments with different opinion distributions in the agents' population.

3.1 Model Overview

The purpose of our agent-based model (ABM) is to investigate the phenomenon of emerging cooperation in the context of solar communities. In particular, we evaluate the influence of individuals with extreme and certain opinion – so-called opinion extremists – on the number of solar communities.

The ABM represents the decision-making of building owners on whether to adopt rooftop solar individually or join a solar community based on economic and social factors. The decision-making process has two steps, inspired by the theory of planned behavior [13], where agents first determine if they develop the intention of adopting solar individually, of joining a community, or neither, and then implement the behavior (i.e., adopt individually or try to join a community).

The ABM runs between 2019 and mid-2033 in 150 monthly time steps. Each month, building owners make the decision whether to invest in rooftop solar or join a solar community (figure 1). To make this decision, they calculate the utility of investing in solar power based on (1) their opinion about solar PV, (2) the profitability of investing in solar PV, and (3) the persuasion of neighbors that want to be members of a solar community. If the utility is high enough, the agent adopts rooftop solar individually. If the utility is even higher, the agent adopts rooftop solar and joins a solar community.

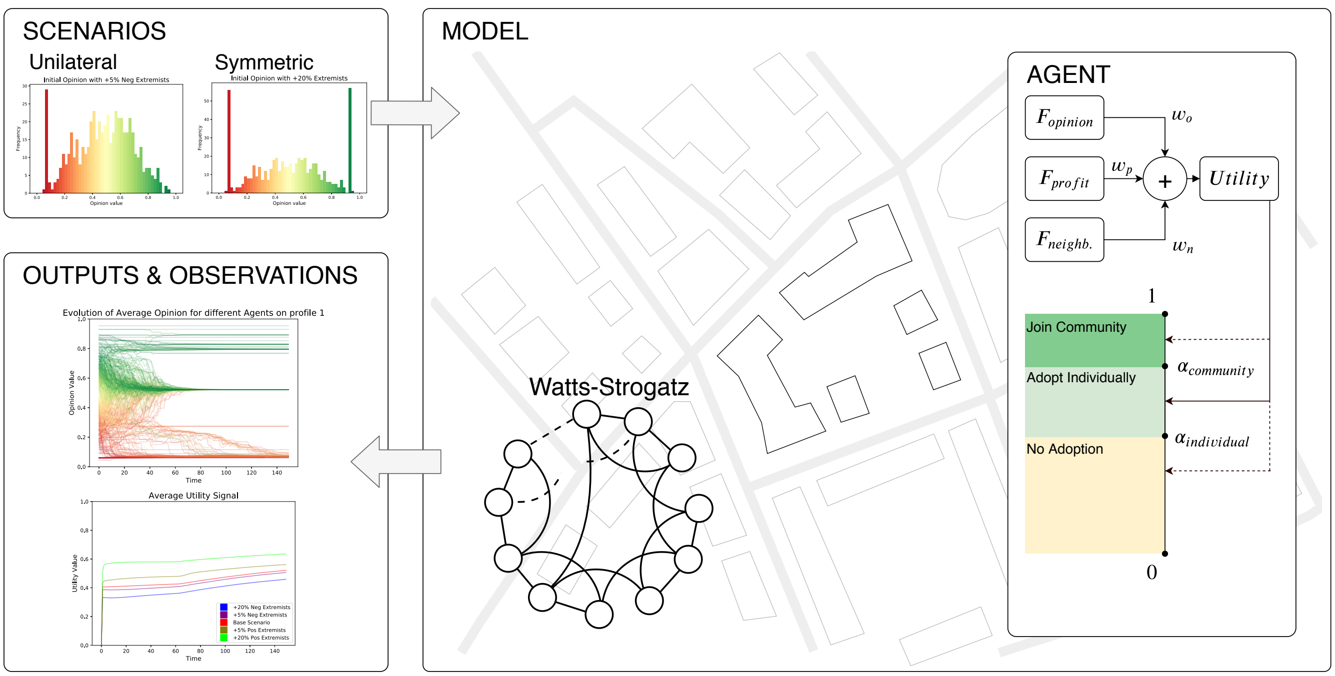

Figure 1: Schematic representation of the overall agent-based model

We explore our research question in the context of the Alt-Wiedikon district in Zurich, Switzerland. This case has practical implications given the recent Swiss regulation of energy communities (EnergieSchweiz 2019). Our results could help inform policy decisions about this legal framework.

Each agent represents the owner of one of the 545 buildings in our dataset. The dataset contains information about the geographical location of the agent (i.e. the centroid of the building area) and the block (i.e. set of buildings with at least one adjacent wall) to which the agent belongs. The dataset also has information about each buildings annual energy demand and potential solar generation, which were obtained through simulations using the City Energy Analyst (CEA) model in a previous article[14]. According to statistics from the City of Zurich, the large majority of the buildings in Alt-Wiedikon have a single owner, which justifies our focus on building owners[14].

3.2 Agent initialization

The attributes that characterize the agents are location coordinates, building identifier, block, electricity demand, solar potential, self-consumption level, opinion, and opinion uncertainty (see Table 1).

Geographical information about the Alt-Wiedikon district provides data about the location of the agent's building and the block it belongs. Simulations using the CEA model provide data about the building's annual electricity demand and potential solar generation based on its rooftop area. Both, geographical and energy data were collected from previous research[14]. The self-consumption level was estimated from hourly load and generation profiles derived from the simulations using the CEA model. For its computation, the size of the rooftop solar PV system was assumed to be set according to the annual electricity demand – if the generation potential was larger than annual electricity demand – or to the maximum available rooftop area, otherwise.

The opinion of agents about solar PV can range between 0 and 1, with 0 as the lower bound representing an extremely negative opinion, and 1 as the upper bound for an extremely positive opinion. Opinions are initialized using a Beta distribution, which is defined by the mean and variance. The opinion uncertainty is initialized from the opinion value in a deterministic fashion (see Table 1). We define negative extremists as agents with an opinion of 0.06, and positive extremists as agents with an opinion of 0.94, both with low opinion uncertainties of 0.03.

Each agent has a social network through which it interacts with other agents that influence each other's opinions. To initialize social networks, we implement a small-world network(SWN)[15]. A SWN using a Watts-Strogatz graph is defined by the number of agents in the model n, the connection to the k nearest neighbors, and the probability p of rewiring the connections (see Table 1). SWNs have been used extensively in the literature exploring the adoption of solar PV [7][9]. The model creates the SWM connecting each agent to its k closest neighbors. With a probability p, a local connection is rewired to a random agent further away. These values were chosen based on typical values in the literature, and to fit the empirical properties of certain SWNs. The SWN was designed to have a clustering co-efficient of 0.25 (academia social network [16]) and average shortest path length of 3.65 (film actor network [15]). This hybrid derivation attempts to characterize a real network between our agents - building owners.

Variable Name	Value (min, max, avg)	Source
Agent Attribute		
Building id	1-545	[14]
Building blocks	1-82	[14]
Electricity demand	(0.1; 1,052.1; 38.6) MWh/yr	[14]
Solar potential	(0; 475.3; 37.5) MWh/yr	[14]
Solar self-consumption	(0; 1; 0.51)	Assume
Opinion (x)	Beta(μ =0.5, σ^2 = 0.2)	Assume
Uncertainty (u)	$x(1-x)$	Assume
Positive Extremists		
Opinion (x)	0.94	Scenario
Uncertainty (u)	0.03	Scenario
Negative Extremists		
Opinion (x)	0.06	Scenario
Uncertainty (u)	0.03	Scenario
Watts Strogatz Graph parameters		
Number of agents (n)	545	[14]
Initial regular neighbors (k)	8	Derived
Probability of rewiring (p)	0.28	Derived

Table 1: Overview of agent-based model variables

3.3 Agents' decision making

Agents follow a two-step decision-making process inspired by the theory of planned behavior [13]. First, each agent determines their intention, whether to do nothing, to install individual PV or to join a solar community. Second, if the agent develops the intention to adopt solar, it checks if it is possible and acts in consequence. If the agent develops the intention of installing individual PV, it does so right away (i.e. no constraints). If the agent wants to join a solar community, it needs to find at least one other agent in its block who also has the intention to join a solar community. During the first step, each agent i calculates the perceived utility U_i of solar as the sum of the weighted and normalized opinion on solar $F_{opinion}$, perceived profitability F_{profit}, and influence of neighbors that have developed the intention to join a solar community $F_{neighbor}$ (see Equation 1).

$$U_i = w_o F_{opinion,i} + w_p F_{profit,i} + w_n F_{neighbor,i} \quad (1)$$

If the agent's utility U_i surpasses the threshold for individual rooftop solar adoption α_{ind}, the agent develops the intention to install a solar PV system on its rooftop. If the agent's utility U_i surpasses the threshold for community solar adoption α_{com}, the agent develops the intention to join a solar community (see Equation 2). The agent continues calculating the utility until the end of the simulation, so it can develop the intention to join a solar community even after adopting rooftop solar in an earlier time step. We assume that the threshold for community solar is higher than for rooftop solar (see Table 2).

$$\text{intention} = \begin{cases} \text{none} & U_i \leq \alpha_{ind} \\ \text{Individual Solar} & U_i > \alpha_{ind} \\ \text{Community Solar} & U_i > \alpha_{com} \end{cases} \quad (2)$$

Parameter	Description	Value	Source
w_o	Weight for opinion	0.8	Manually calibrated
w_p	Weight for profitability	0.2	Manually calibrated
w_n	Weight for neighbor factor	0.4	Manually calibrated
α_{ind}	Individual adoption threshold	0.5	Assumption
α_{com}	Community adoption threshold	0.75	Assumption

Table 2: Overview of values for agents' utility calculation parameters

In the second part of the decision-making process, agents that developed the intention to adopt rooftop solar individually directly adopt. Agents that developed the intention of joining community solar, however, install a solar PV system on their rooftops and then check if other agents in the same block also developed the intention to join a solar community or are already part of one. If that is the case, the agent creates or joins the community solar; if not, the agent just adopts solar rooftop individually.

In the following, we briefly outline how the agents calculate their opinion, profitability, and exposure to neighborhood solar.

3.3.1 Opinion

Every time step, each agent chooses randomly one other agent in its small-world network and interacts with it. Following the Relative Agreement model as it is used in [12], two agents influence each other's opinion over an interaction. The change of the opinion xi of agent i when interacting with agent j is proportional to their relative agreement. Relative agreement for agent i is defined as the difference between the overlap and non-overlap between both agents' opinion segments divided by the width of the opinion segment of agent i. The following equations depict the calculation of the overlap, the non-overlap, the agreement, the relative agreement, respectively the opinion and uncertainty of agent i after the interaction.

$$\begin{aligned} h_{ij} &= \min(x_i + u_i, x_j + u_j) - \max(x_i - u_i, x_j - u_j) \\ nh_i &= 2u_i - h_{ij} \\ a_i &= h_{ij} - nh_i \\ ra_i &= \frac{a_i}{2u_j} \\ x_i &\longleftarrow x_i + \mu\, \mathrm{ra}_i (x_j - x_i) \\ u_i &\longleftarrow u_i + \mu\, \mathrm{ra}_i (u_j - u_i) \end{aligned}$$

In the above equations, h_{ij} is the overlap of opinion and nh_i is the non-overlap region for agent i. a_i is defined as agreement and ra_i is the relative agreement. μ is an arbitrarily chosen gain. Also, $F_{opinion,i}$ is equal to the opinion x_i.

3.3.2 Profitability

Agents calculate the perceived profitability of solar investments based on a simple payback period estimation for a rooftop solar system on the top of their buildings. Surveys have shown a direct relation between the payback period of solar installations and the willingness to invest in them by consumers [17]. Our ABM builds upon a simplified representation of the observed empirical relation.

To calculate the payback period, agents divide the solar Investment cost I_{PV} by the annual cash flow CF_{PV}. The annual cash flow comprises avoided costs CF_{AC}, feed-in remuneration CF_{FIR}, and operation and maintenance costs CF_{OM}. We hereby assume, first, that agents size rooftop solar systems to meet their annual demand while considering constrictions due to rooftop size and shadowing. Second, we assume that solar electricity generation is directly proportional to system size. Finally, we assume that rooftop solar price is independent of its size. Equations below show the calculation of the payback period. Table 3 depicts the values of the input parameters for the profitability calculation.

To represent learning in the solar power industry, we include annual price reduction of rooftop solar by 4% based on recent historical data for Switzerland IEA-PVPS, 2019. Further, we assume an annual increase in electricity prices of 4.5%, based on recent data for Zurich (ElCom, 2019). The remuneration data has been retrieved from EWZ 2016.

$$
\begin{aligned}
F_{profit} &= 1 - \frac{PT_i}{PT_{max}} \\
\text{Where,} & \\
PT_i &= \frac{I_{PV}}{CF_{total}} \\
&= \frac{(\text{pv-price})\ .\ (\text{pv size})_i}{CF_{AC,i} + CF_{FIR,i} + CF_{OM,i}} \\
CF_{AC,i} &= (\text{el-price}).\,\text{sc}.\,\text{sy}.\,(\text{pv-size})_i \\
CF_{FIR,i} &= \text{fir}.\,(1 - \text{sc}).\,\text{sy}.\,(\text{pv-size})_i \\
CF_{OM,i} &= (\text{pv-price})\ .\ (\text{pv-size})_i\,.\,\text{om}
\end{aligned}
$$

Parameter	Description	Value	Source
PT_{max}	Maximum payback time	25 years	[17]
sc	Self-consumption	30%	Assumption
sy	Solar PV yield in Switzerland	980 kWh/kW$_p$	IEA-PVPS, 2019
om	Operation and maintenance costs	1.5%	[18]
fir	Remuneration - elec. fed to grid	0.08 CHF/kWh	EWZ, 2016
el-price	Price of electricity (initial value)	0.5 CHF/kWh	IEA-PVPS, 2019
pv-price	Price of PV system (initial value)	0.75 CHF/kW$_p$	IEA-PVPS, 2019

Table 3: Overview of input parameters for profitability calculation

3.3.3 Neighborhood Influence

The agents calculate their exposure to the persuasion of their neighborhood to join a solar community as the share of neighbors that are members of or want to join a solar community

$$F_{neighbor} = \frac{\text{neighbors}_{community}}{\text{neighbors}_{total}}$$

4 Implementation and Scenarios

We investigate the role of opinion extremists in the diffusion of individual and community solar photovoltaics in cities through three scenarios - baseline, one-side, and symmetrical extremism. A total of nine scenario variations were simulated by altering the fraction of opinion extremists in the population of agents (see Table 4).

The baseline scenario excludes extremists and serves as a reference to identify the impact of varying numbers of positive and negative extremists in the other scenarios. The one-side extremism scenario reflects on the question of how extreme opinions of a few agents can affect the adoption behavior of the entire population. We define four scenario variations by defining 5% and 20% of the population as positive or negative extremists. Finally, the symmetrical extremism scenario represents a polarization of the population for which we include four variations.

To highlight the evolution of the agents throughout the simulations of the model, we employ a color code that identifies the initial value of their opinion from low in red to high in green

Scenario Family	Scenarios			
Baseline	Base Case			
One-sided Extremism	20% negative	5% negative	5% positive	20% positive
Symmetric Extremism	5% extremism	10% extremism	20% extremism	40% extremism

Table 4: Overview of scenarios

(see Figure 2). Given the stochastic inputs of our model (e.g., in the initialization of the agents' opinions), we need to run a large number of simulations of the ABM and analyze our results statistically. Through trial and error, we determined that batches of 50 simulation runs would be representative samples of the behavior of our model.

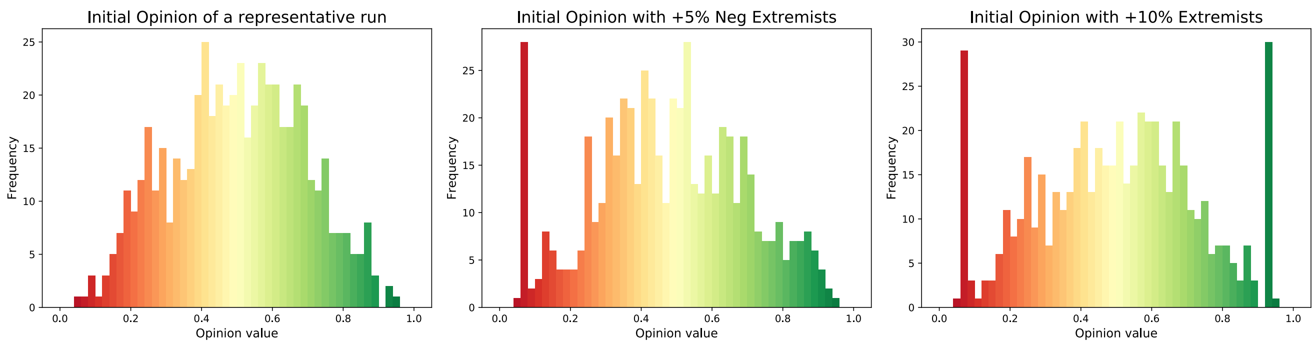

Figure 2: Initial opinion distributions among agents for a single run of the baseline scenario (left), one-side extremism scenario with 5% negative extremists (middle), and symmetrical extremism scenario with 10% extremists (right).

5 Simulation Results and Discussion

We explore the results of our simulations by first observing the evolution of the diffusion of solar PV in the baseline scenario, which contains a moderate distribution of opinions among agents, and, then, in the one-side and symmetrical extremism scenarios.

5.1 Results for baseline scenario

The baseline scenario shows an initial jump in the average number of agents adopting individual solar followed by an almost linear increase until the end of the simulation. However, only a few agents join solar communities with a gradual increase over time (see Figure 3).

The average evolution of the values for opinion, profit, and neighbor helps to explain these results (Figure 4). While the average opinion does not change over time, the gradual increase of the profitability of solar PV – as installation prices go down and electricity prices go up – corresponds with the linear growth of individual rooftop solar adoptions and triggers first intentions for community solar. Subsequently, as more agents develop the intention to join solar communities, the influence of these agents upon others in their building blocks (i.e. the neighbor influence) grows.

To improve our understanding of the evolution of opinion, profit, and neighborhood further and its impact on agents' utility, we also look at the values on an agent-level (see Figure 5). In the opinion evolution plot, we can observe that the opinion of most agents converges towards the average value of 0.5. There are also some instances when agents do not change their initial opinions

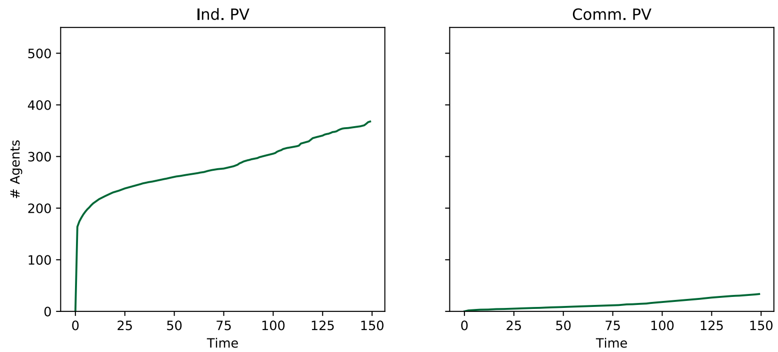

Figure 3: Evolution of the average number of agents with individual and community solar in the baseline scenario

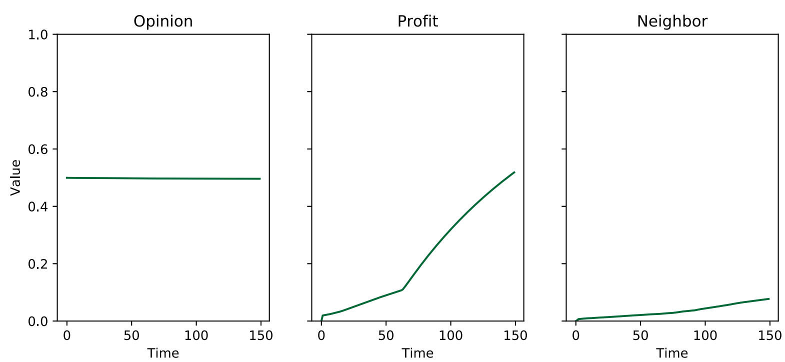

Figure 4: Evolution of the average values across all agents and simulation runs of the (left) opinions about solar PV, (center) the profitability for each agent of solar PV, and (right) the neighbor influence, in the baseline scenario

(see the horizontal lines), which can be explained by considering that agents with very extreme ideas (opinion extremists) or agents that are isolated from other like-minded agents, do not update their opinions. Either because their uncertainty intervals do not overlap with agents in their social network or because their opinions are so strong they barely change (see section 3.3.1). In the profit evolution plot, the varying degree of agents' self-consumption explains the heterogeneity of the profit value. For each kWh the agent self-consumes, the agent has electricity bill savings amounting to the electricity price, while feeding surplus electricity to the grid is remunerated on a lower level. The neighborhood value is very stochastic as it depends on the initial agent initialization. The value can be very high in a run in that, for example, many positive extremists are located in one building block.

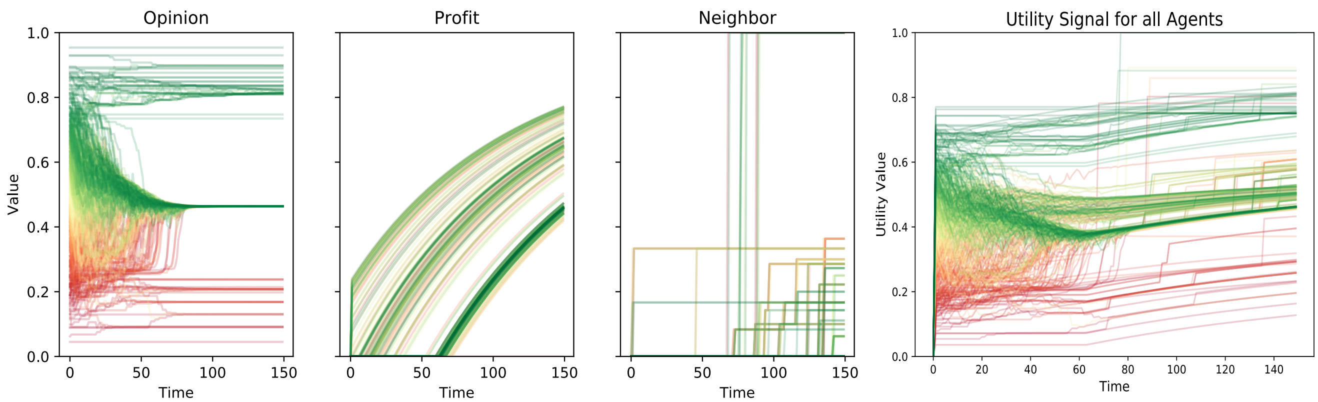

Figure 5: Evolution of opinion, profit, neighbor and utility for individual agents in a baseline scenario simulation

A spatial representation of the end of the simulation provides insights into how solar communities are formed (see Figure 6). For example, we observe a number of agents with the intention of joining a solar community (light green) that could not do it because they had no neighbors or they had not developed the idea to join a solar community.

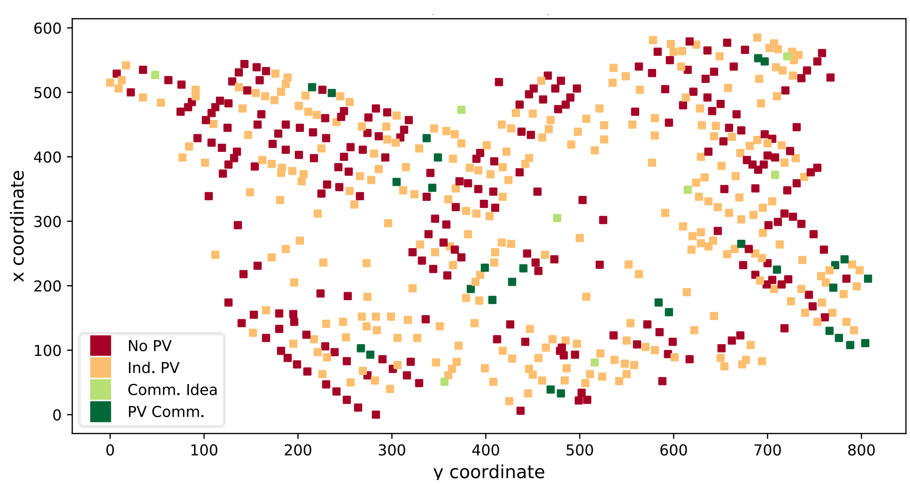

Figure 6: Spatial distribution of agents in Alt-Wiedikon district and their solar adoption status at the end of a representative simulation run for the baseline scenario

5.2 Results for Extremist Scenarios

This section presents the simulation results for the one-sided and symmetrical extremist scenarios.

5.2.1 Results for one-side extremism scenarios

Compared to the baseline scenario, increasing the number of positive extremists between 5% and 20% of the population increases the initial uptake of both individual and community solar. However, this difference compared to the baseline scenario becomes smaller over time (see Figure 7). For example, the 5% positive extremist scenario shows an average of around 100 agents more adopting individually at the outset of the simulation than the baseline scenario. However, at the end of the simulation, this difference reduces to around 10 agents. This is surprising as we expected extremists to have a strong and lasting influence on other agents.

Two reasons explain these results. First, the initial jump/depression in adoptions represents the change in the installations by extremists and their impact on the neighbor influence. Positive extremists start the simulation with higher utilities that lead them to install, while the opposite is true for negative extremists. In addition, the extremely high opinion of positive extremists lead them to develop the intention of joining solar communities. This, in turn, heavily impacts the utility of agents in the same block as positive extremists through the neighbor influence, triggering much more solar communities than in the baseline or negative one-side extremism scenarios (see Figure 7).

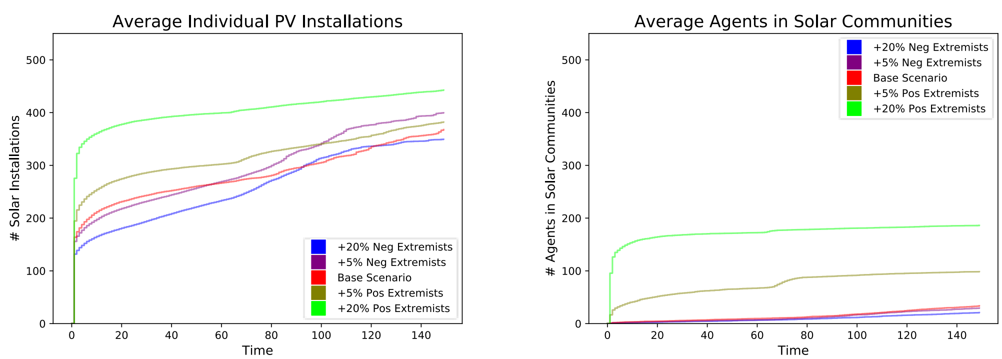

Figure 7: Evolution of the average number of agents with individual and community solar in one-side extremism scenarios

Second, the low uncertainty of extremists' opinions causes its fading influence over the simulation. This striking result emerges from the relative agreement algorithm. Agents have one opinion value and one uncertainty interval around that opinion. For two agents to influence each other's opinion, their uncertainty intervals need to overlap (see section 3.3.1). The very low uncertainty of our extremists (see Table 1) isolates them from agents other than those with very similar opinions. A good metaphor to understand these results is that fanatics pro- or anti-solar lack credibility among individuals with moderate opinions. As a consequence, moderates tend to move back to the center as fanatics become more isolated over time. This reflects clearly on the evolution of the average opinion (see Figure 8).

The evolution of average individual adoptions until half of the simulations is largely explained by the opinion dynamics, and, afterwards, the increasing profitability of solar PV takes over, boosting the utility of agents (see Figure 8).

Taking a closer look at the evolution of agents' opinions, we observe a confirmation of our explanations (see Figure 9). While extremists initially influence other agents in their social network

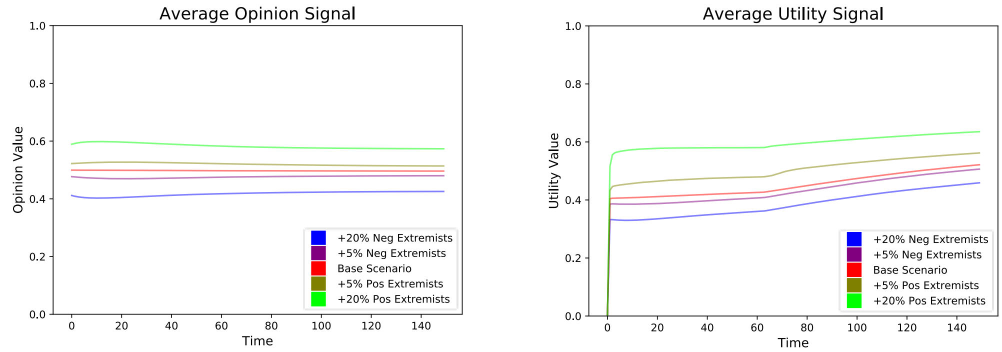

Figure 8: Evolution of the average values across all agents and simulation runs of the (left) opinions about solar PV, and (right) the agents' utilities, in the one-side extremism scenarios.

that already had a very similar opinion, the majority of agents gradually moves in the opposite direction. This is explained by the lack of overlap in opinions between moderate agents and fanatic extremists, and holds true for both positive and negative extremists. In turn, the opinion of the population converges towards an average value skewed in the opposite direction of where extremists are.

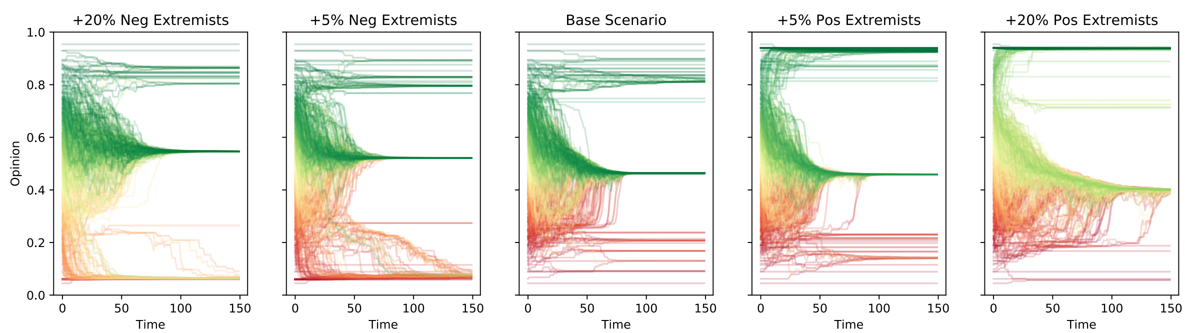

Figure 9: Evolution of opinion for individual agents through representative simulation runs of the one-side extremism scenarios

5.2.2 Results for symmetrical extremism scenarios

Symmetrical extremism or "polarization" of the population affects the number of agents adopting both individual and community solar. The impact of increasing polarization on individual solar is not linear and seems to reach its maximum with around 10% of positive and negative extremists. Surprisingly, this is different for solar communities, where the more polarized the population, the more agents join solar communities.

As polarization increases, and, thus, the number of positive extremists, we observe the same pattern of initial increase in adoptions for both individual and communities as in the one-side extremism scenarios with positive extremists. The effects of higher opinions and neighbor influence at the outset of the simulation explain why until the middle of the simulation adoption grows with polarization (see Figure 10). The slow uptake after that point is explained mainly by the improving profitability of solar PV, that increases the utility of agents identically in all scenario variations (see Figure 11).

Polarization differs most from one-side extremism during the late evolution of the model. The

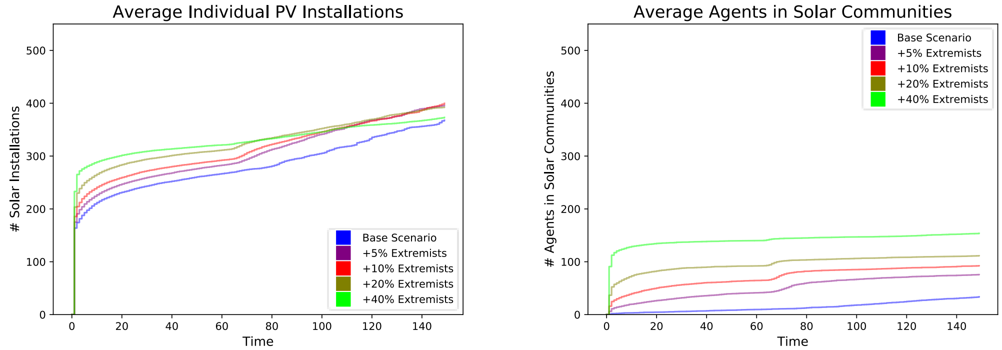

Figure 10: Evolution of the average number of agents with individual and community solar in symmetrical extremism scenarios.

isolation of fanatic extremists now occurs on both extremes of the opinion spectrum (see Figure 12). The larger the share of extremists (i.e. the more polarization), the faster agents with opinions close to the extremes are sucked into extremist opinions, and the emptier the opinion spectrum becomes around moderately positive and negative opinions (e.g., 0.3 and 0.7). This reduces the changes of turning moderate agents with negative views on solar to move to the center of the spectrum. This is visible by attending to how the color of agents in the lower half of the opinion spectrum changes from red (in the base scenario) to light orange (in the +40% extremists scenario, see Figure 11). Because the color indicates the initial opinion of the agents, Figure 12 demonstrates that as polarization intensifies fewer agents that began with rather negative opinions about solar converge towards a more positive view. As a result, individual adoptions in lower polarization scenarios eventually grows to surpass that of higher polarization scenarios.

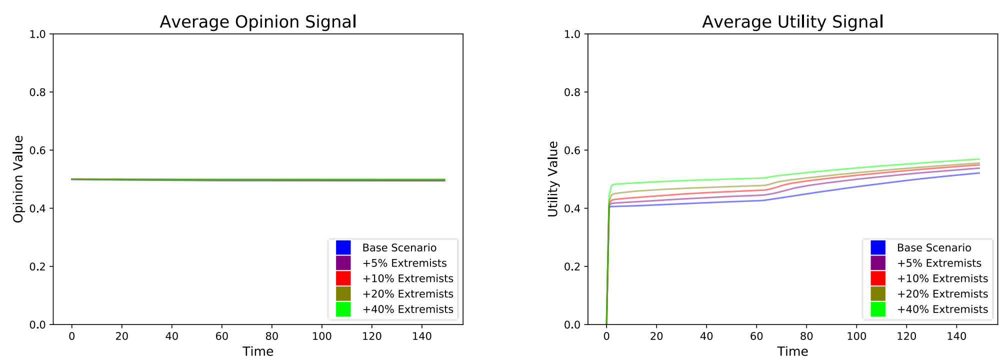

Figure 11: Evolution of the average values across all agents and simulation runs of the (left) opinions about solar PV, and (right) the agents' utilities, in the symmetrical extremism scenarios.

6 Discussion

In the following, we discuss (1) the influence of one-sided extremism, and (2) the impact of polarization, on the diffusion of technologies at two diffusion stages: emerging vs mass-market.

Scenarios with one-sided extremism demonstrate that extremists can have a sizeable impact on the evolution of solar adoption. However, their influence changes as the technology moves from the emerging to the mass-market phase of diffusion. This is explained by the "prevalence of the

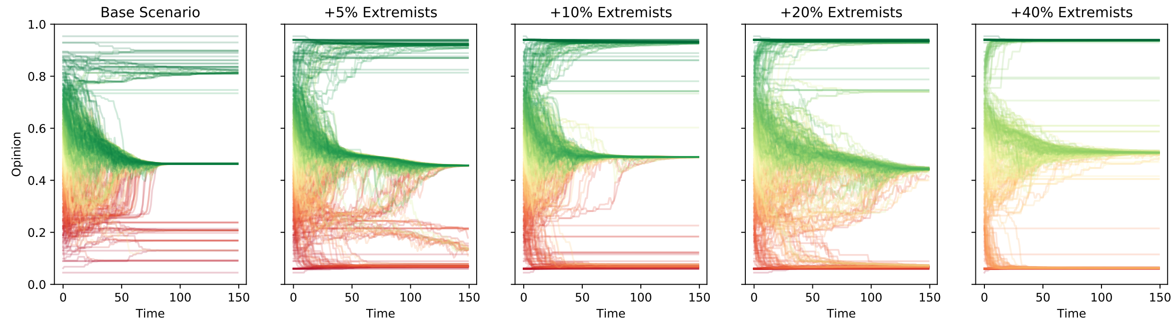

Figure 12: Evolution of opinion for individual agents through representative simulation runs of the symmetrical extremism scenarios.

moderates" as the rising isolation of fanatic extremists makes the opinion of the majority of agents converges towards centrist views after leaning towards the extremist positions. Compared to the baseline scenarios, we observe that one-sided extremism: (1) can boost/depress initial adoption of solar by altering the utility of agents, (2) raise/reduce the average opinion the population achieves over time, and, for positive extremists, (3) can reinforce neighbor influence enhancing solar community adoption. Overall, this means that positive extremists have stronger effect than negative extremists on adoption of solar, particularly of solar communities. A large number of positive extremists boosts the number of agents in solar communities much more than a large number of negative extremists reduces it. The pressure of agents willing to join solar communities counter-balances the presence of negative extremists within their blocks. Policymakers aiming to accelerate the diffusion of solar communities within cities would then want to increase as much as possible the number of positive extremists.

Scenarios with symmetrical extremism display distinctive results for the emerging and the mass-market phases of solar diffusion. As the polarization of the population intensifies, the larger presence of positive extremists boosts initial adoption, but this effect wears off in the mass-market phase. A hollowing of moderately positive and negative opinions as polarization grows produces lower long-term adoption of individual solar. This does not hold true for solar community, where the initial jump in adoption in polarized variations with a lot of positive extremists couples with the neighbor influence to overcome the effect of hallowing moderate opinions. This surprising result, polarization increases solar communities but not individual adoption, reinforces the observation that positive extremists exert a more relevant influence than negative ones in community solar but not on individual solar. Another reason for trying to leverage the ability of positive extremists to accelerate solar community diffusion.

7 Summary and Outlook

The diffusion of solar photovoltaic (PV) systems has the potential to decarbonize a large portion of the energy consumption in cities. However, consumers' lack of awareness and uncertainty about the technology hinder the diffusion of solar PV. Improving our understanding of the opinion dynamics among building owners and, in particular, the role of opinion extremists, presents opportunities for accelerating the uptake of solar energy through policy interventions. This article analyzed the role of opinion extremists through the simulation of seven scenarios in the context of individual and community solar PV adoption in the district of Alt-Wiedikon in Zurich, Switzerland, between 2019 and 2033 in 150 monthly time steps.

All our scenarios suggest a rapid growth of individual rooftop solar in the next years thanks to the combined effects of increased profitability and neighbor influence. This is in line with previous literature showing the relevance of economic and social factors[7]. Our principal contribution is the deeper analysis of the role of opinion dynamics and extreme views on the technology. The two takeaways are (1) positive extremists boost solar community more than negative extremists depress it, while the opposite is true for individual solar, and (2) polarization of opinions alter the pattern of solar adoption even if average opinions in the population remain unchanged. The implications of our results, although very exploratory at this stage, are twofold. First, the presence of negative or positive extremists have a large impact on the adoption of solar PV. In order to increase diffusion of the technology, promoting a positive and certain opinion about it could prove an effective policy, especially for solar communities. Even more so than trying to reduce negative extremism. Second, polarization can slow down the transition towards sustainable energy. It reduces total adoption of solar PV even despite boosting solar communities thanks to positive extremists. Measures to contain polarization of society around a technology – or at least to transform it into one-sided positive extremism – could result in an acceleration of its diffusion.

This research has major limitations that impose caution in the interpretation of its results and open the door to future work in the field. The agent-based model and its parameters could not be validated due to the unavailability of historical data. Exploring the opinion dynamics around individual and community solar through surveys would provide a stronger empirical basis upon which a more robust model could be developed. In addition, a thorough sensitivity analysis would allow a better understanding of the boundaries within which the model can provide meaningful insights. Future work could focus on aspects such as the evolution of the social networks of the agents, a detailed analysis of the economic elements of the decision-making, or a more nuanced view of the interactions between agents that give birth to the cooperation into solar communities. Finally, the implications for policymakers are necessarily limited by the absence of interactions between the agents and the regulatory and policy context. In order to inform decision-makers, future research could explore how interventions could alter the possibilities available to agents and their behavior.

8 Supplementary information, code and data availability

This article is accompanied by an appendix that contains additional information about the estimation of key model parameters such as decision-making weights. The entire code is available publicly on a GitHub repository, which also contains the data employed for this study.

9 Acknowledgements

The authors would like to thank Prakhar Mehta and Danielle Griego for generously making available a simplified and anonymized dataset for buildings in the Alt-Wiedikon district that they employed in another research project, see [14].

10 Individual Contributions

J. Fornt-Mas, S. Kovvali, A. Nuñez-Jimenez, M. Schwarz contributed equally to the conceptualization of the model. A. Nuñez-Jimenez collected the data and parameters from literature. J. Fornt-Mas, S. Kovvali led the development of the code with contributions by A. Nuñez-Jimenez, M. Schwarz. S. Kovvali created and managed the GitHub repository. J. Fornt-Mas led the visualization of results. A. Nuñez-Jimenez, M. Schwarz led the writing and formatting of the report.

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