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The Impact of Self-consumption Regulation on Individual and Community Solar PV Adoption in Switzerland: an Agent-Based Model

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Zurich, June 17, 2019

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"I love deadlines. I like the whooshing sound they make as they fly by."

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Abstract

Historically, Swiss solar PV adoption has been slow but Switzerland's Energy Strategy 2050 requires electricity production from renewables to increase 4.5 times by 2035 compared to 2017. The new Energy Act in Switzerland came into force in January 2018 with investment subsidies for practically all PV system sizes and very encouraging provisions for community solar PV systems clearer financial and legal structures under the 'Zusammenschluss zum Eigenverbrauch' (ZEV) or 'Self-consumption Community' Regulations. This thesis looks at how individual and community PV adoption in Zurich will evolve until 2035 under the new regulations, especially with falling solar PV system prices. Using the Theory of Planned Behaviour, a decision-making methodology for individual and community solar PV adoption by building owners in Zurich's Alt-Wiedikon district is developed and simulated with an Agent-based Model. The agent-based model uses hourly energy data generated from a model of nearly 2000 building blocks in Alt-Wiedikon using the City Energy Analyst (CEA), together with factors such as geographical location of agents, environmental attitudes and peer effects, electricity and solar PV prices as well as legal regulations. The results indicate that PV adoption targets for 2035 are exceeded even though adoptions cease in 2030 due to lack of subsidies. However, cheap wholesale electricity prices can deter PV adoption by large consumers. The ensuing policy implications of these developments are discussed to conclude this thesis.

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List of Acronyms

ZEV	Zussammenschluss zum Eigenverbrauch (Self-Consumption Community) - used interchangeably with Community PV Systems
PV	(Solar) Photovoltaic
SD	System Dynamics
ABM	Agent-based Modelling
DoI	Diffusion of Innovations
TPB	Theory of Planned Behavior
PBC	Perceived Behavioural Control
TWh	Tera Watt-hour
kWp/MWp	kiloWatt Peak/MegaWatt Peak (commonly used for PV system capacity)
DC	Direct Current
AC	Alternating Current
SCO	Solar Community Organisation
GIS	Geographical Information System
OSM	OpenStreetMap
SFOE	Swiss Federal Office of Energy
SWN	Small-world Network
SCR	Self-consumption Ratio
RMSE	Root Mean Square Error

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Introduction

1.1 Motivation

Switzerland has very clear goals for the future of its energy system, as laid out in the Energy Strategy 2050 [8] which was voted on and accepted in 2011. One of the main goals of the strategy is the planned decommissioning of nuclear plants in Switzerland and its replacement with renewable energy sources. This means that Switzerlands electricity mix is set to undergo a major transformation in the coming years. The Energy Strategy 2050 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 [1]. Solar photovoltaic (PV) systems will likely be the driving force behind this increase, up to 6.5 TWh by 2035 [9] thanks to falling prices and ease of operation. In terms of installed capacity in Switzerland, PV systems must grow from 1.6 GWp in 2017 to 7 GWp by 2035.

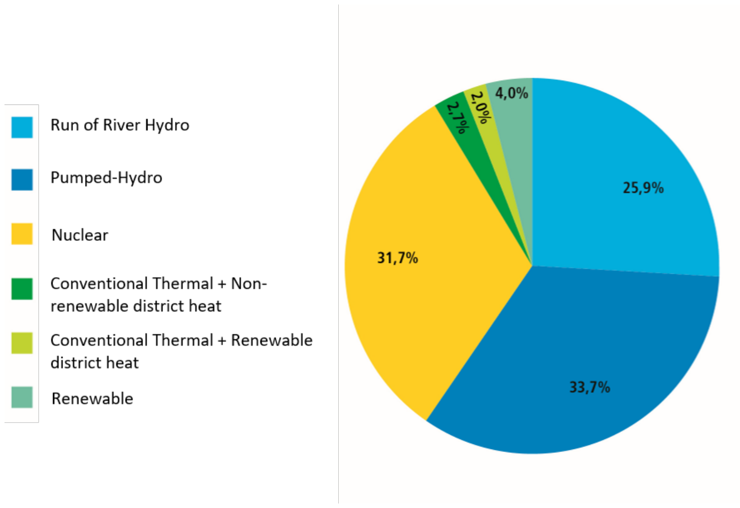


Figure 1.1: Swiss Electricity Mix 2017 [1]

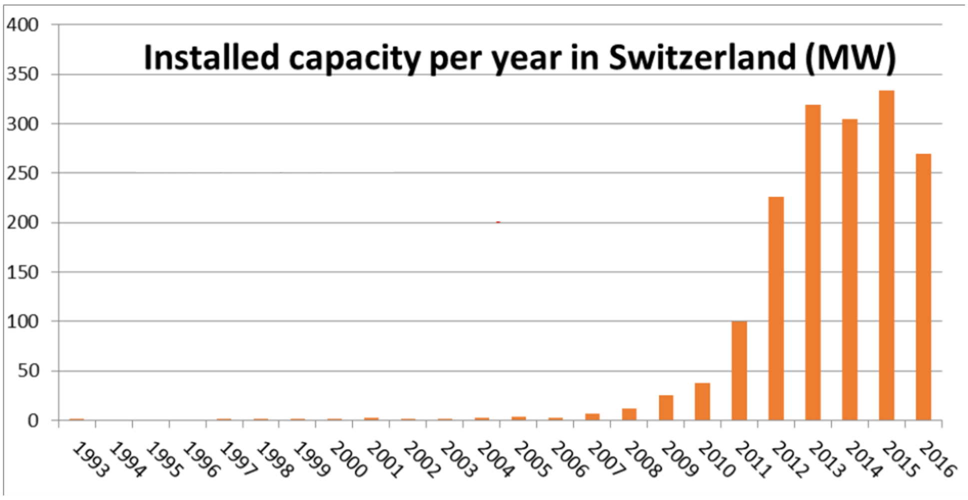


Figure 1.2: Historical PV Adoption in Switzerland [2]

However, the historical diffusion of PV systems in Switzerland has been rather slow and only started to grow post 2011 1.2. In 2017, solar energy in Switzerland accounted for only 2.1% of electricity production, below the average 3.5% in the EU-28 and far smaller than the 6.2% of neighbouring Germany [1]. In order to accelerate diffusion, the Energy Act 2018 [10] introduced newer, clearer provisions to further encourage the adoption of individual and community solar PV systems [10]. Investment subsidies are made available to practically all PV system sizes (2 kWp - 50 MWp; past regulations had an upper limit of 30 kWp) and community PV systems are allowed. Community solar PV systems are usually owned by and supply electricity to several individuals, who share the costs of the 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 remuneration levels, 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 PV systems to share electricity generated with building tenants and neighbouring buildings. Although this is very promising to increase the penetration of solar energy in urban contexts, the impact of this policy in coming years remains unknown.

1.2 Literature Review

1.2.1 Decision-making and the Diffusion of Technologies

While the new ZEV regulations do make the formation and operation of ZEVs clearer and seemingly more profitable, research needs to look at how exactly these will diffuse in Switzerland. There are different approaches to modelling the decision-making of individuals that drives the diffusion of innovative new technologies. Wilson and Dowlatabadi [11] summarized the decision-making models into four diverse perspectives: Utility-based decision models and behavioral economics, social and environmental psychology, sociology and attitude-based decision-making. Within the attitude-based decision making models, Rogers' Diffusion of Innovations (DoI) model [12] is quite dominant and widely referred to. According to Rogers, diffusion may be defined as "the process in which an innovation is communicated through certain channels over time among the members of a social system." An innovation is defined as an idea, practice or technology perceived as new [11]. Four core elements determine the diffusion of innovations: the characteristics of the innovation, the structure of the social system where the adoption and diffusion takes place, the communication channels within the social system, and the time-frame of the innovation-decision process [12]. In addition, Rogers described five factors that influence the adoption of an innovation:

- Relative advantage: how much better is the innovation compared to what people currently use,
- Compatibility: how compatible is the new innovation with existing problems and needs,
- Complexity: how easy/difficult is the new innovation for people to use,
- Trialability: how possible it is to test the new innovation before committing to adopt; and
- Observability: how visible is the new innovation to potential adopters.

Rogers also brought up the concept of adopter categories - innovators, early adopters, early majority, late majority, and laggards - and how the majority of the population tends to be in early and late majority of adoption. Innovators are an exciting category, as these are the people who want to be the first ones to try a new technology, even though it may not be proven or feasible.

Furthermore, the DoI emphasizes attitudes and outcomes, similar to the the Theory of Planned Behavior (TPB) from psychology. Developed by Icek Ajzen as an extension to the Theory of Reasoned Action [3], it states that behavior is preceded by an intention, which comprises of three components (refer Figure 1.3):

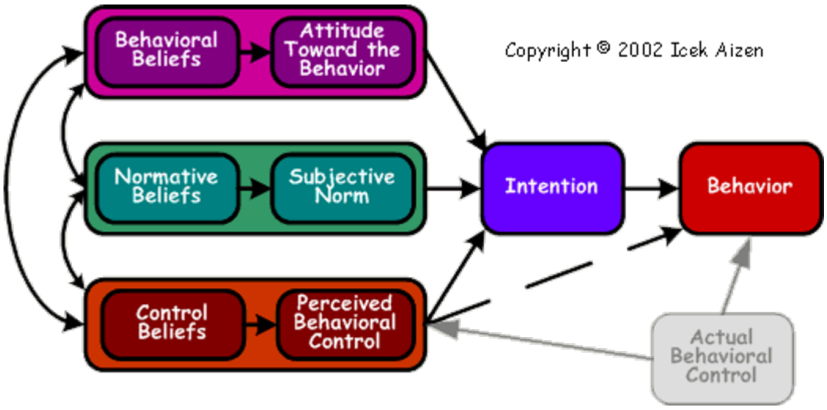


Figure 1.3: The Theory of Planned Behaviour [3]

- Attitude toward the Behavior: This measures the degree to which the individual has a positive or negative opinion about the behaviour in question. For example, if an individual believes that pollution from petrol cars is bad for the environment and electric cars are greener, then he/she has a positive attitude towards buying an electric car.

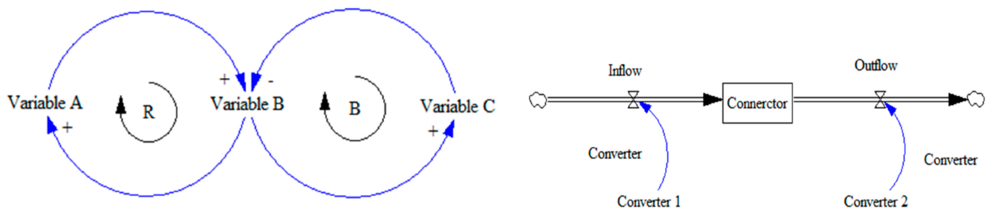
- Subjective Norms: This is the individual's perceived social pressure with regards to performing the behavior in question. For example, an individual is more likely to buy an electric car if he/she thinks that close friends and family also consider electric cars to be better than petrol cars.

- Perceived behavioral control (PBC): This refers to the individual's belief/confidence in his/her ability to perform the behaviour in question. It is often linked to the skills possessed by the individual or the amount of money needed. For example, even if an individual has a positive attitude towards electric cars, he/she may not buy one because it is too expensive.

The TPB has been shown to be well-suited to study the diffusion of solar photovoltaics and has been used in a number of studies [13, 14]. However, human beings are not always rational, and a variety of factors affect decision making. Predicting the future decision-making of individuals is tricky, but there are a few tested methodologies such as System Dynamics, Bass and Agent-based models, as discussed below.

1.2.2 Modelling the Diffusion of Technologies

In this section, the different techniques to model the diffusion of technologies are discussed.



(a) Causal Loop Diagram (b) Stock-Flow Diagram

Figure 1.4: Diagramming tools used in System Dynamics [4]

Traditional Methods vs. Agent-based Modelling

Traditional Approaches like System Dynamics (SD) models and Bass models have been used to model the diffusion of innovations. SD is a top-down information feedback method and is convenient to construct and validate [4]. It generally involves the use of diagramming tools like Causal Loop Diagrams (CLDs) and/or Stock-Flow Diagrams (SFDs) as in Figure 1.4 to explain the structure of a complex system. CLDs are helpful in mapping the structure of a complex system and which variables dynamically influence the system, and are a more qualitative way of understanding the system. On the other hand, SFDs help in the quantitative analysis of the system through use of integral or differential equations. Figure 1.5 explains the various steps involved in the SD modelling process.

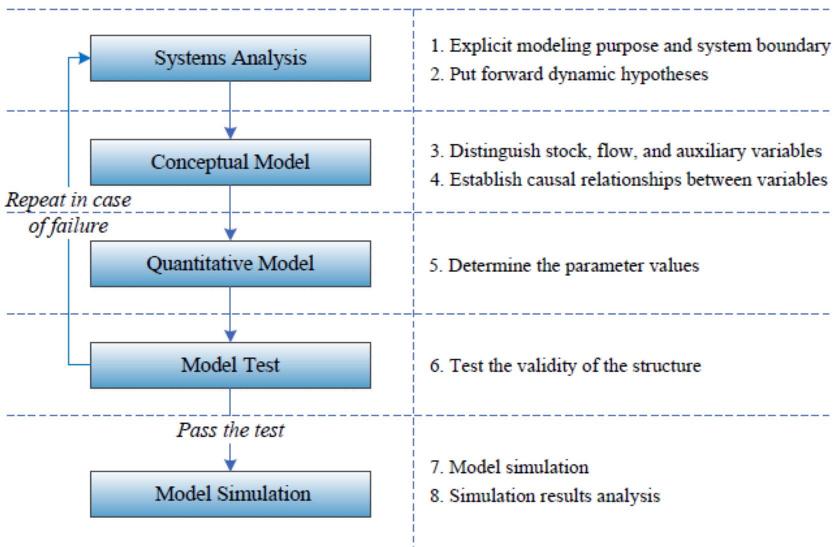


Figure 1.5: A flowchart of System Dynamics Modelling [4]

SD Models, along with early aggregate models such as Bass Diffusion Models [15] in their use of differential and integral equations are good for deriving aggregate, macro-level information but typically do not account for micro-level influences like peer-to-peer interactions [13] or the heterogeneity of individuals [16]. In reality, individuals can have very different opinions and networks, for which Agent-based modelling (ABM) can be used. An ABM is "a system modelled as a collection of autonomous decision-making entities called agents" [16], and is a bottom up technique to examine how agents' micro-level behaviour influences the population's macro-level emergent phenomena. This is especially useful when the population is heterogeneous and when "the interactions between agents are complex, nonlinear, discontinuous or discrete," [16].

While comparing SD and ABM, Bonabeau [16] notes that SD models tend to represent global average decision making and smooth-out fluctuations while ABM allows for fluctuations due to "individual decision making by agents as opposed an average global flow." These are important as under certain conditions, such fluctuations can be amplified and may lead to counter-intuitive system (macro-level) behaviour. Although ABMs provide many advantages over SD and Bass Diffusion models, they do have difficulties, especially with model calibration and validation as also noted by Rai et. al [14] where they highlight the importance of empirical ABM with thorough validation. ABMs can also require huge computational power, which can be a limitation in terms of time and resources. Eventually, this work uses ABM because of the importance of the interactions between and heterogeneity of people making decisions in reality, and the ability to represent geographically explicit data like the relative locations of agents.

Examples of Agent-based Modelling for solar PV adoption

ABM has gained traction recently, especially for the adoption of solar PV. For example, in [13], Robinson et. al. simulate a spatially-resolved residential PV diffusion using a Geographic Information System (GIS). An interesting takeaway from their work is the use of the Relative Agreement (RA) algorithm [17] to operationalize the subjective norms component of the TPB. That is, agents influence each others' opinions when they interact with each other, based on their own opinions and uncertainties around the opinions. Robinson and Rai [18] also use the relative agreement algorithm, with a behavioural model in terms of attitude and control motivated by the TPB and employ payback period as the financial decision criterion. Rai et. al. [14] use a theoretical and empirically driven ABM based on the TPB to model PV adoption by individual residential homes in the USA. In their ABM, agents must cross thresholds for both economic (based on payback period and individual control beliefs and attitudinal activation (based on agent attitudes influenced by the RA algorithm). This is a very comprehensive research which used high resolution data from multiple data streams and surveys, and has been a point of comparison for this thesis, regarding the quality of data and methods used.

Sachs et. al. [19] created an ABM with multiple decision-making steps for representing behaviors leading to investments in the decarbonisation of the energy sector in the UK. Instead of the TPB, they employ the bounded rationality theory which assumes that individuals make decisions based on their own rules and heuristics, in order to have a satisfactory rather than an optimal solution [20]. The agents in their ABM can have different investment strategies for the different technologies (short-term planning, long-term planning, energy-saving, emission-reduction and comfort level) and can decide based on a single- or multi-objective decision strategy. Furthermore, agents have a 'search rule', representing different information gathering strategies and are segregated based on the SINUS-Milieu Typology [21]. This research shows how an ABM can be used to include a multitude of decision making possibilities while accounting for social milieus of the population. Palmer et al. [22] also use the SINUS-Milieu Typology for their agents socio-economic backgrounds in Italy. To model the individual residential PV adoption decision process, they use a multi-attribute utility function with four factors converted into linear partial utility functions influencing the agents decision making process: economic utility based on the expected payback period of the PV system, communication utility based on the number of links to other adopters, environmental utility depending on the amount of CO2 emissions saved, and an income utility depending on the households income.

In sum, a variety of approaches to model individual solar PV adoption using ABMs have been tried with previous research, but none for community solar PV adoption. Bounded rationality and utility functions are not able to capture irrationality of decision-making effectively, which is well accounted for by the TPB and used in this work. The smaller scope of this work compared to Palmer et al. [22] (discussed later in section 2.1) makes the use of SINUS-Milieu too detailed to model the socio-economic differences between agents and is hence disregarded.

Peer Effects

A primary advantage of using ABM, as discussed earlier and evident from its use in literature to model the diffusion of innovations, is its ability to include interactions between different agents which can influence macro-level emergent phenomena. This interaction between agents is generally described as peer effects in literature, and is segregated in to two types active (direct communication with a peer) and passive (observation or other ways to become aware of something) peer effects [23].

A variety of studies have looked into peer effects. Palm et al. [24] performed a mixed-methods (quantitative and qualitative) study in Sweden where they conducted a survey with 92 Swedish PV adopters (65 responses) and followed up with 16 of them via telephonic interviews. They found that peer effects reduced barriers related to some attributes specific for PV technology with respect to Rogers' Diffusion of Innovations theory[12]. Contacts with PV adopters helped overcome the low trialability and low observability of PV partly by reducing its (perceived) complexity. Their results indicated that peer effects were a significant aspect throughout the decision-making process and the main function of peers was to provide a confirmation that solar PV technology worked as intended. It was also shown that the active peer effects took place through existing social networks and not through unacquainted neighbours; and that passive peer effects such as simply seeing an installed PV system were less important than the active peer effects from contacts with installed PV. This contrasts with other literature where it has often been assumed that passive peer effects are important and seeing installed PV systems leads to contact between neighbours [23, 25, 26, 27, 28, 29].

Wolske et. al. [30] explain residential solar PV adoption by an integrated framework combining variables from TPB, DoI and Value-Belief-Norm theory. An important finding with regards to peer effects is that consumers will tend to speak to PV system providers only if they already have trustworthy information about costs and performance of PV systems, which they seek from experiences of personal acquaintances in their social networks. This again highlights the importance of active peer effects from people in the decision-maker's social network.

As a researcher, active peer effects in the context of solar PV adoption in a region can best be estimated through post-adoption surveys. To estimate pre-adoption dynamics in the social networks of agents in a region, some aspects of network theory can be applied. Rai et al. [13] create connections between agents through use of a small world network, also known as a Watts-Strogatz network [5], constructed from empirical geographical data in Austin, Texas in the USA. A small world network is a network between the extremes of a completely random and a completely regular network [5]. Here is how it was developed: it started from a regular network created by placing n vertices in a ring and connecting only the k nearest neighbours to each other. Watts and Strogatz then chose a vertex and an edge connecting a node to its nearest neighbour and with a probability p, reconnected this edge to another random vertex chosen uniformly at random over the entire ring with duplicate edges forbidden. Doing this for all vertices in a specific order until each edge in the original lattice has been considered once, an increasing probability p of reconnecting links leads to graphs as shown in Figure 1.6.

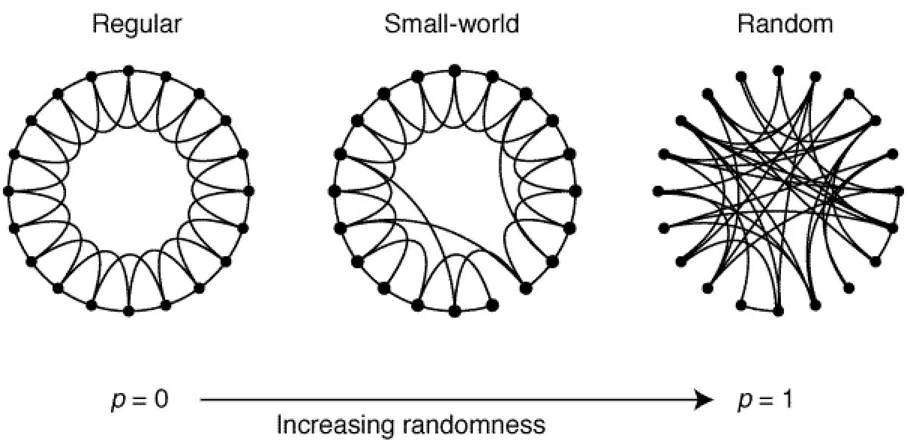


Figure 1.6: Random Rewiring Procedure: Regular to Small-world to Random network [5]

Intermediate values of p lead to a highly clustered network like a regular graph, but with small characteristic path length like a random graph. In a social network, this means that while people have their own clustered networks (connections to their close friends and relatives) in which people know each other (two close friends of a person are also likely to be friends with one another), a few of such connections are to people outside the clustered network. This greatly reduces the number of connections between any two random people in the entire, as is also commonly referred to by the term 'six degrees of separation' [5, 31]. In summary, small world networks can be used to suitably depict the social connections people may have and is used in this work.

Often with regards to the diffusion of new technologies, there is the mention of an 'Energy Champion' or an 'Opinion Leader', which is essentially an entity (person, organization, etc.) that champions the cause for the adoption of solar PV (or any innovation). Rogers [12] defines opinion leadership as "the degree to which an individual is able informally to influence other individuals' attitudes or overt behavior in a desired way with relative frequency. Opinion leaders are individuals who lead in influencing others' opinions." This means that for potential adopters in the process of decision-making on adoption, "one way to cope with the inherent uncertainty about an innovation's consequences is to try out the new idea on a partial basis....A demonstration can be quite effective in speeding up the diffusion process, especially if the demonstrator is an opinion leader." D. Noll et al. [32], in a study about Solar Community Organizations (SCOs; they are "formal or informal organizations and citizen groups that help to reduce the barriers to the adoption of residential solar photovoltaics...") in the US find that SCOs are successful as they "inform and influence consumer decision-making because of the trust networks they hold" and act as a link between consumers and government programs and solar companies. The status of SCO members "as trusted opinion leaders with a history of commitment to the local community" also plays an important role in the success of the SCOs. The role of such opinion leaders in the adoption of solar PV, especially community-scale systems, is hence important.

1.3 Problem Statement

State-of-the-Art Summary

Switzerland has a mountain to climb with respect to solar PV adoption in order to compensate for the phasing out of nuclear power plants. Solar PV is expected to make up for most of the replacement, and reach approximately 6.5 TWh of electricity produced, corresponding to about 7 GWp of installed PV capacity by 2035, up from 1.6 GWp in 2017. In contrast to past regulations, the newly introduced regulations in Switzerland provide subsidies to practically all PV system sizes, incentivize self-consumption and hence favour Community Solar PV (by virtue of better self-consumption ratios), but the effectiveness of such regulations remains unknown and un-researched. In urban contexts, community solar adoption could increase at a faster rate than individual solar. While this argument is valid if looked at from a purely technical or economic perspective, the diffusion of new technologies is also subject to irrational decision-making. Social and psychological factors need to be taken into account to predict future adoption levels of new technologies.

Existing research has looked at the diffusion and adoption of individual solar PV systems in great detail under many different environments and policies by employing a multitude of methodologies. However, no literature looking at the adoption of community solar PV systems was found. Taking inspiration from existing literature, the Theory of Planned Behaviour is chosen to implement the adoption of community scale solar PV systems, with importance to active peer effects using small-world networks and including the 'Energy Champion' concept for adoption of community PV systems. An Agent-based model is employed to model the decision-making as it can account for a heterogeneous population and interactions among the population.

The Statement

How will the dynamics of future solar PV adoption evolve in urban Switzerland, given the new regulations which incentivize individual solar PV adoption more than before, and allow the formation of self-consumption communities? Will community PV adoption outpace individual PV adoption? What potential policy implications and problems can be foreseen?

1.4 Objectives of Research

The primary objective of this thesis is to analyze and explore individual and community solar PV adoption under the Energy Act [10], 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.

- Objective 1: Use the ZEV regulations to illustrate potential choices of community formation in Zurich.
- Objective 2: Develop an adoption methodology for individual and community solar PV adoption using the Theory of Planned Behaviour and an Agent-based model.
- Objective 3: Explore the dynamics of individual and community solar PV adoption under the new regulations for the period 2018-2035 in the district of Alt-Wiedikon, Zurich.

1.5 Thesis Outline

This remainder of this thesis is structured as follows. Chapter 2 includes an explanation of the district chosen as a case study, data used from the City Energy Analyst energy model, an overview of current regulations and how they are used to define communities in the district and other input data such as electricity prices and PV system costs and subsidies. Then, the decision-making methodology and the Agent-based model and it's calibration are explained, the scenarios are described, and the assumptions in this thesis are clearly outlined. Chapter 3 describes the results obtained, segregated according to the various scenarios considered in the thesis. Chapter 4 discusses policy implications based on results obtained, and highlights the limitations and scope for future work of this thesis. Finally, Chapter 5 wraps up the thesis with key takeaways and personal reflections.

Data and Methodology

2.1 Choice of District: Alt-Wiedikon, Zurich

Zurich's Alt-Wiedikon district makes for a good case study to test the adoption of solar PV because of a greater than average solar potential and a wide variety of building types which can take advantage of complementary load profiles to form community PV systems. The choice of this district is also opportune, as it uses an energy model of the district developed on the City Energy Analyst (CEA) during Sabine Python's semester project at the Chair of Information Architecture [33] for energy data input to the ABM. Figure 2.1 shows the district with 6856 buildings of 13 different typologies [33].

Figure 2.1: 13 Building typologies in the district of Alt-Wiedikon

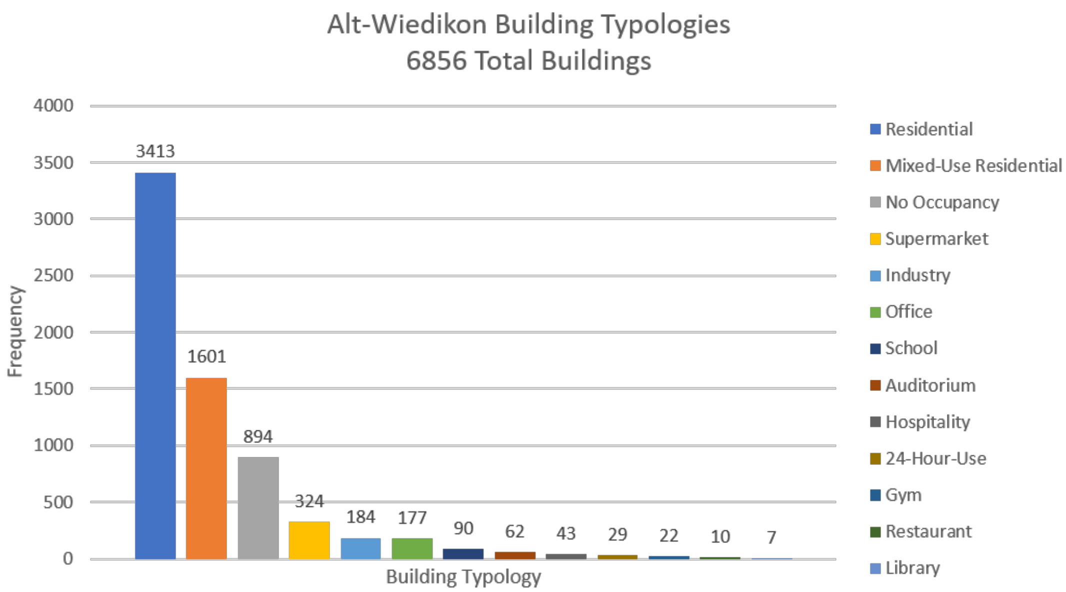
2.1.1 The City Energy Analyst Model

The City Energy Analyst (CEA) is “a computational framework for the analysis and optimization of energy systems in neighborhoods and city districts” which “allows analyzing the energy, carbon and financial benefits of multiple urban design scenarios in conjunction to optimal schemes of distributed generation,” [34]. The CEA platform makes it possible to create energy models of entire districts with many options to include and customize energy infrastructures and urban design options. The Alt-Wiedikon model prepared by Sabine Python [33] used data from the Statistics Office of Zurich and consisted of 6856 buildings with 39 typologies. These buildings were then aggregated into 1950 building blocks (multiple individual buildings considered as one block) and narrowed down to consist of 13 broad building typologies (refer Appendix : 6.1). The aggregation was done if the buildings shared a wall, Figure 2.2 shows the process. While aggregating, buildings of different typologies were assigned a typology based on the largest floor area while the occupancies were still modelled with the CEA as percentages of floor areas of the buildings involved. These grouping of buildings into building blocks was very beneficial for the speed of the CEA simulations; however, it is a limitation in this thesis as it reduces the information resolution of the buildings as shown in Figure 2.3 and increases the size of the buildings many-fold, which has an impact on solar PV adoption as will be discussed later in chapter 4. Henceforth in this report, the building blocks are simply referred to as buildings. The ‘Gym’ typology buildings in Figure 2.3b are erroneous and later removed from the final building stock.

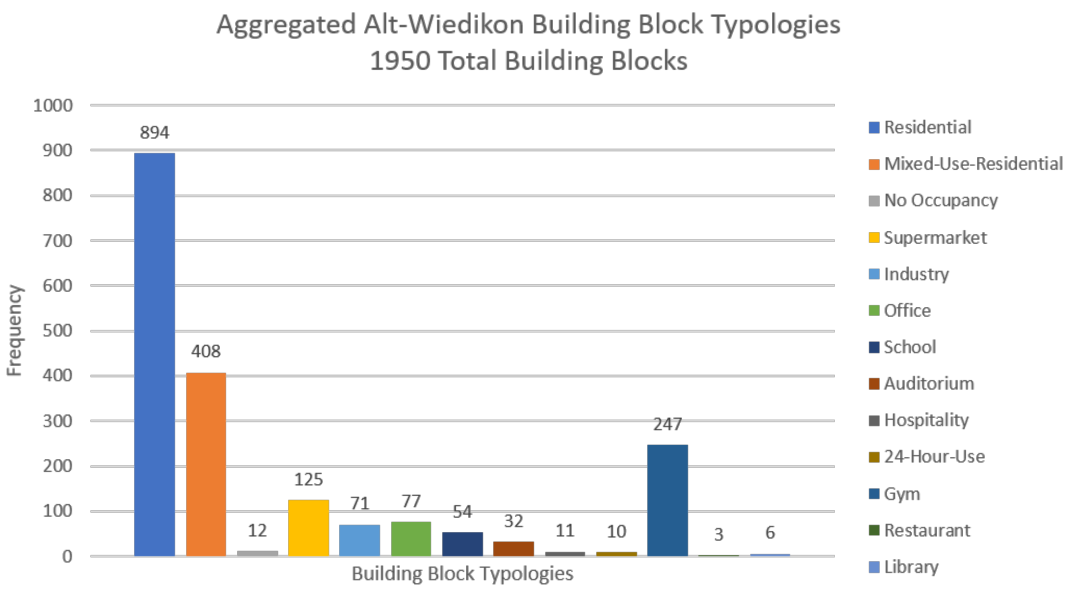
(a) Distinct buildings in Alt-Wiedikon, from OSM

(b) Aggregated Zones (Building Blocks) in Alt-Wiedikon

Figure 2.2: Aggregation of Buildings in Alt-Wiedikon for reduced CEA computation time



(a) Original Alt-Wiedikon Building Data



(b) Aggregated Building Blocks in Alt-Wiedikon, by Typology

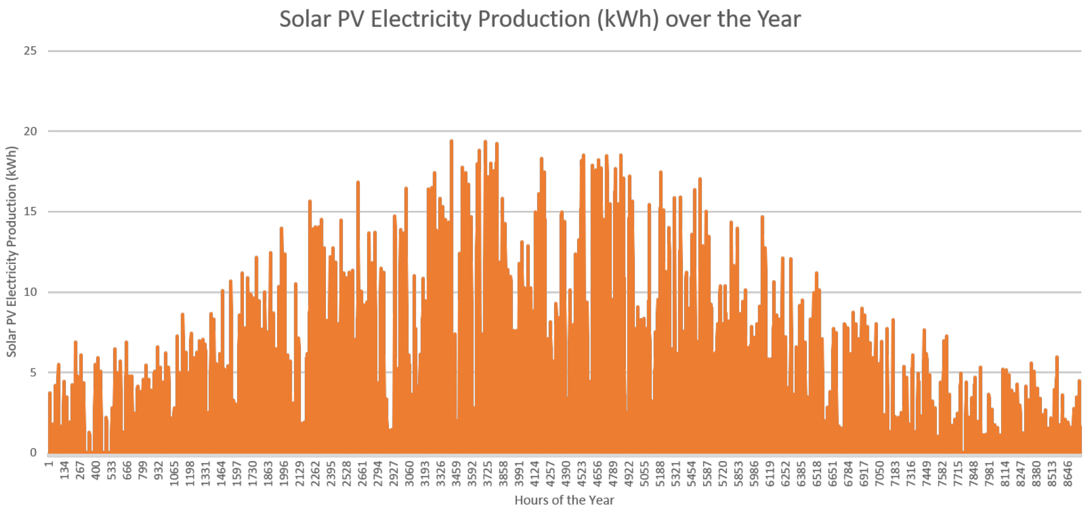
Figure 2.3: Aggregation of Building Data of Alt-Wiedikon

Data from the CEA

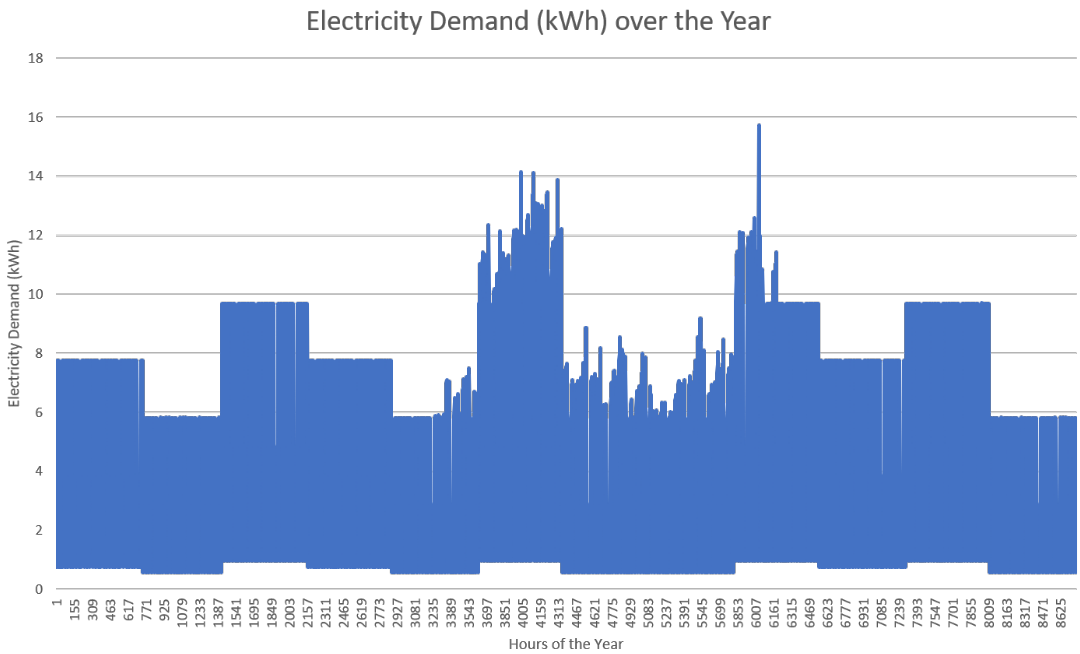
For this master thesis, 2 CEA tools are used to generate inputs for the ABM model. First, the Renewable Energy Assessment tool which gives the capacities of and hourly electricity produced from solar PV panels installed on roofs of the buildings (which are modelled as flat roofs). Figure 2.4a shows the yearly PV output for a typical building. The tool installs PV panels on surfaces of the roof receiving more than a threshold of solar radiation (defined as 800 kWh/m2/year for Zurich, as the Swiss Federal Office of Energy's (SFOE) Sonnendach tool [35] has 800 kWh/m2/year as the lower bound for an average solar radiation on a roof in Zurich). Please refer Appendix 6.4 for a comparison between CEA simulated PV production and SFOE data. After identifying appropriate surfaces, PV is installed on the roof based on optimal tilt angles, row spacing and surface azimuth. CEA does not simulate all panels but groups them by their respective tilt angles and orientations and then simulates the reduced number of panels that represent each group and multiplies the performances according to the number of panels in each group [36]. This could lead to a potential overestimation of the electricity produced from the panels as some of the un-simulated panels may be under a shadow. Important to note is that the PV electricity generated from this tool is in DC, hence an efficiency of 97% is assumed to convert it into AC. Figure 2.4a shows the annual PV production profile of a typical building in Alt-Wiedikon.

Second is the electricity demand data from the Dynamic Demand Forecast tool. The inputs to this tool are weather, geometry, architecture, occupancy, HVAC, internal loads and indoor comfort levels for the building blocks simulated. It outputs hourly energy consumption profiles for heating, cooling and electricity demands. The important data for this thesis are naturally the electricity demands, since PV panels do not provide heating or cooling directly. Figure 2.4b shows the annual electricity consumption of a typical building in Alt-Wiedikon. Demand in the summer months is not as smooth as in the rest of the year, due to increased need for cooling.

In summary, the City Energy Analyst energy model developed by Sabine Python [33] is used to generate hourly electricity demand, solar PV sizes (assumed to occupy the entire roof area, as output by the CEA) and hourly PV production data of the district. The 1950 buildings also include a few extra buildings outside the simulated buildings to account for reflective etc. effects on the outermost buildings. Excluding the extra buildings and removing erroneous buildings (the Renewable Energy Assessment tool returned zero PV electricity production over the year for 'Gym' typologies), the final building stock used in this work consists of 1437 buildings. The 13 building typologies are further narrowed down to 3 according to Table 2.1 to make the distinctions between typologies easier for the ABM. Figure 2.5 gives a graphical representation of the final building stock used in this work.



(a) Yearly PV Electricity Production



(b) Yearly Electricity Demand

Figure 2.4: A typical residential building in Alt-Wiedikon

Table 2.1: Reduction of 13 Building Block Typologies to 3

Building Typology	**Number of Buildings**	**Reduced Building Typology for the ABM**	**Reduced Number of Building Blocks**
Residential	894	Residential	1053
Mixed-Use Residential	408		
Gym	247	Commercial	291
Office	77		
Industry	71		
Hospitality	11		
Restaurant	3		
Auditorium	32		
Supermarket	125		
No Occupancy	12		
24-Hour Use	10	Public	93
Library	6		
School	54		

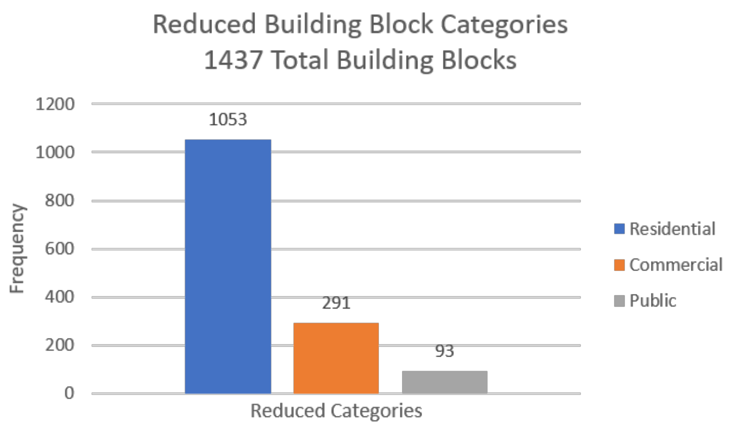


Figure 2.5: Final Building Block Typologies

2.2 Application of the Regulatory Framework to form Communities in Alt-Wiedikon

2.2.1 Current Regulations

The case for self-consumption communities is made stronger only recently by new regulations. The previous Energy Act of 1998 [37] contained provisions for a one-time subsidy of up to 30% of the investment costs available for PV systems smaller than 30 kWp [37] and only a feed-in tariff for systems greater than 30 kWp in size. While self-consumption was mentioned, it was only under Article 16 of the new Energy Act (EnG) [10] that self-consumption became explicitly regulated [38]. The New Energy Act (EnG 730.0) was approved by the Parliament in September 2016, voted into power by the population on 21 May 2017 and came into force on January 1 2018. It also made solar PV adoption easier by making a one-time remuneration of approximately 30% of the investment cost available to all PV systems ranging from 2 kW to 50 MW until 2030, as opposed to the earlier limit of 30 kW peak system size.

The regulations also contain specifics for self-consumption communities, or Zusammenschluss zum Eigenverbrauch, hereafter referred to as simply the ZEV regulations. Under these, anyone can form a self-consumption community or a ZEV with other electricity customers. A ZEV represents a single end user and has only a single grid connection, and can be formed as long as the following criteria are met [38]:

- The ZEV may be formed across several adjoining plots of land (including private or public roads), provided that the public or private landowners participate in the ZEV and that the network of the grid operator is not used. In addition, all participants must be final consumers at at least one of the participating properties at the place of production.
- A ZEV is only permissible if the production output of the plant or plants is at least 10 percent of the connection capacity of the merger.
- The internal organization (electricity production, distribution, measurement etc.) is a matter for the ZEV; the provisions of energy legislation, measurement legislation and the law of obligations apply. The electric utility only has to perform its power supply obligations concerning the ZEV as a whole.
- In the case of a ZEV with a power consumption of more than 100 MWh per year, access to the free electricity market is open. This threshold is usually met by about 30 apartments.

These regulations imply that there can be no ZEV formation across roads or other public properties. They also mean that all properties must be connected to the same electrical grid point so that they do not use the distribution grid and can be considered as one entity by the grid operator (EWZ in Zurich). These criteria are accounted for while forming the possible communities in section 2.2.2. Essentially, anyone can form a ZEV as long as the above conditions are met. This means that individuals living in single-family homes can collaborate with their neighbours to install a PV system together. Or tenants in a building could also form a ZEV and install solar panels on the roof, provided legal issues regarding roof space utilization are met. However, since a majority (89%) of apartments in the city of Zurich are rented [39], it is easy for tenants to join a ZEV formed by the building owner, which allows tenants to be free of the worries of earning a payback on the system in case they move. Under the ZEV regulations, the owner can install a rooftop PV system and provide self-generated electricity to his tenants, who can choose to join the ZEV or remain independent customers of the electric utility (EWZ). For this service, the owner may charge the tenants a price no greater than the EWZ retail electricity price [10, 38]. This price may include the investment and capital costs, running costs for operation and maintenance, administrative effort for measurement and billing and the costs for grid connection. Since EWZ maintains the electricity supply for the city of Zurich, they have introduced a special product called as Solarsplit for a ZEV, the details of which are explained in section 2.3. The investment payback for the owner comes from increased self-consumption and corresponding reduced electricity purchase from the grid.

The main ideology of the ZEV regulations is that a PV system in a ZEV can be run much more profitably due to the significantly higher self-consumption rate compared to individually owned systems. Furthermore, the larger ZEV is also open to the free market, which can likely increase interest in ZEV formation significantly.

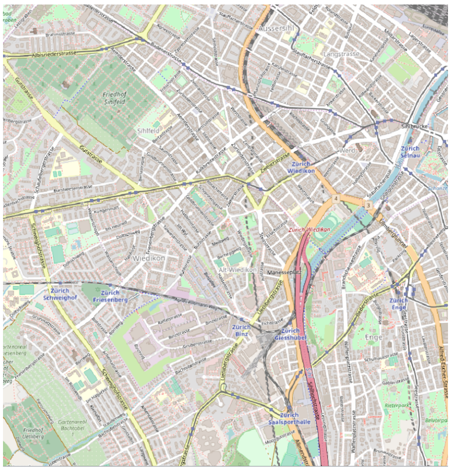
2.2.2 Formation of 'Plots' which allow Community PV

In principle, any building should be able to come together with any other building and create a community system. However, a self-consumption community (or, a ZEV) does not make sense if the buildings which are far away from one another that they cannot be connected behind the same grid connection point, dissolving the whole idea of a self-consumption community if the distribution grid must be used to balance the over- or under-production of electricity. The ZEV regulations help set the physical boundaries within which ZEVs can be formed.

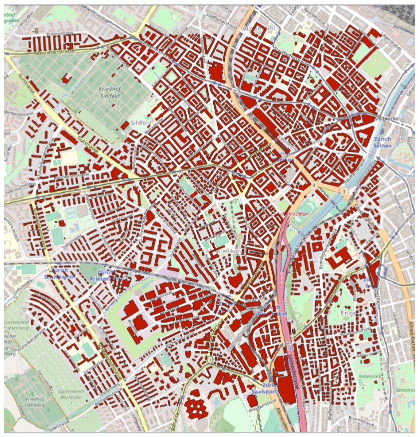
Keeping these regulations in mind, the process of making 'Plots' in the district of Alt-Wiedikon is now described. That is, how boundaries are created in between buildings to allow/prevent them to form a ZEV with other buildings. Mainly, it is the information about transport infrastructure (roads - vehicular and pedestrian, tramlines and railway lines) and other public property such as parks which serves to separate buildings from one another.

The QGIS model of Alt-Wiedikon from Sabine Python's work [33] is overlaid with open-source geographical data from OpenStreetMap (OSM) [40] of Zurich to have all necessary information together in one place. There were 22 types of transport infrastructure from OSM which are mentioned in the appendix. Of these 22 types, there were a few like 'footways', 'cycleways' etc. which were irrelevant to the ZEV regulations. A few other item types were simply a repetition of other types, probably due to overlapping definitions/purpose. These irrelevant transport infrastructures were filtered out via a

Python plugin to the QGIS software, and the appendix 6.2 includes all the information from OSM and what was kept/deleted. The intersections of the remaining infrastructure lead to the formation of the 'Plots'. The process is described in Figure 2.6.



(a) OpenStreetMap, Alt-Wiedikon



(b) QGIS Model overlaid with OSM data

(c) Relevant transport infrastructure for the ZEV regulations

(d) Plots, a few highlighted for visualisation

Figure 2.6: Formation of Plots in Alt-Wiedikon

Automating the filtering process did lead to a few unintended deletions from the data, which were then re-included based on visual inspection with Google Maps and OSM data. Another issue in creating these plots was that since the QGIS model of Alt-Wiedikon included building zones (section 2.1.1), the segregation based on transport infrastructure lead to a few buildings being in two different plots. These had to be manually corrected to only be in one plot, as it was decided for simplicity of possible community formations that one building can only be in one plot.

Finally, a total of 406 plots were formed, as in Figure 2.6d. That is, 406 isolated plots of land within which the buildings can potentially share electricity with a few other buildings (but not with not all others, as explained later) by forming a ZEV. Once the plots were formed, it was evident that a few plots were quite large with as many as 31 buildings in it and many were so small that only 1 building was part of it. Figure 2.7 shows the number of plots formed with 1, 2 or more buildings in them.

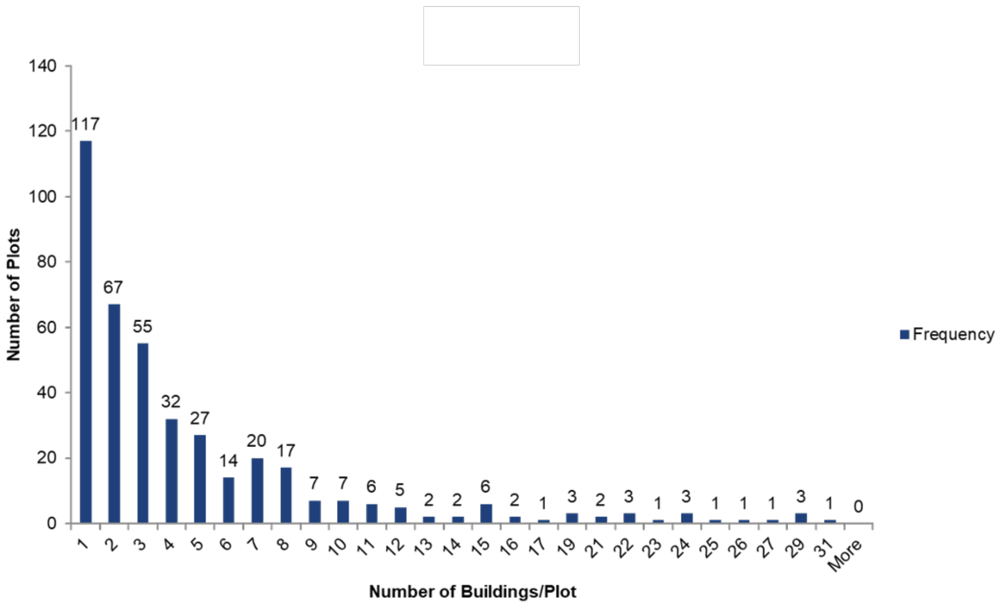


Figure 2.7: Number of Plots having x buildings/plot

The plots created give information on the number of buildings within the plot that can potentially form ZEVs, but these plots can be pretty large and the buildings within them may not be able to form a ZEV with just any other random building. This is due to the ZEV regulations which states that buildings must be adjacent to each other. Hence, a further refining of these plot was required to find which building can potentially form a ZEV with which other buildings in the plot. The adjacency rule was cumbersome to implement with the set-up of the Alt-Wiedikon QGIS model, hence a distance parameter was set to list all buildings within the same plot at a distance less than this distance parameter. The distance parameter was set as a function of the roof size of the building in question - 125 meters for large buildings with roof sizes greater than 2000 m^2, and 50 meters for small buildings with roof sizes less than 2000 m^2. These distances are with reference to the centroids of the buildings, and were obtained through a trial-and-error approach based on visual inspection of the model and its geography. Figure 2.8 explains this. In the plot shown (within the black box, which is the boundary of that plot), there are 10 buildings. Building A is the building in question. Since it has a roof area smaller than 2000 m^2, the distance parameter considered for it is 50 meters. All buildings in a radius of 50 meters within the same plot are deemed eligible to form a ZEV with this building. Of course, this method means that in some cases non-adjacent buildings may

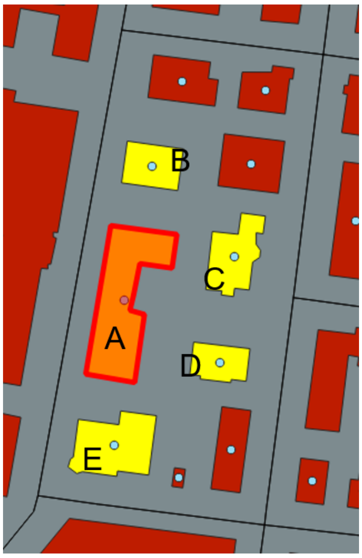


Figure 2.8: Possible ZEV members

Table 2.2: Buildings and their possible ZEV members

A	**B**	**C**	**D**	**E**
B	A	A	A	A
C	...	D	C	...
D	...	...	...	...
E	...	...	...	...

be part of ZEV, but it is still a robust way to create lists of buildings for each building to form a ZEV with. Table 2.2 shows how these lists look like for this case.

Now that the possible ZEV members have been identified, there can be various combinations of these buildings which can come together to form a ZEV. For instance, the building A from Table 2.2 can have 15 unique ZEVs: A-B-C-D-E, A-B-C-D,...,A-B,...,A-E. Such combinations are formed for all buildings, a PV system size equal to the sum of the roof sizes of the individual buildings is chosen and their net-present values are calculated, as explained later in section 2.4. As evident, the number of possible ZEVs grows exponentially with the number of eligible buildings a particular building has.

2.3 Data used in the ABM

This section gives an overview of the different types of data necessary to run the ABM, which will be explained in section 2.4

2.3.1 Subsidies and Feed-in Tariffs

The current regulations in place have fixed one-time remunerations (also known as investment subsidies) of up to 30% depending on the size of the PV system and are available until 2030 [10]. These are summarized in Table 2.3. Feed-in tariffs are dependent on the local electricity utility, and in the case of Zurich are as set by EWZ, shown in Table 2.4. These feed-in tariffs are applicable to all consumers with any PV system size.

Table 2.3: One-time Remuneration (Subsidy) for PV Systems

PV System Size	**Basic Fee (CHF)**	**Service Contribution (CHF/kW)**
<30 kW	1600	460
30 - 100 kW	1600	340
>= 100 kW	1400	300

2.3.2 Electricity Prices and the EWZ Solarsplit Product

Electricity prices in Zurich are quite cheap and are set by EWZ. Table 2.4 shows the prices for 2019, which are assumed to remain fixed for the ABM simulations into the future as well. Wholesale prices are taken as averages from Epexspot [6], refer appendix 6.3 for graphs. To assist their customers in forming a ZEV in line with the new regulations, EWZ have introduced a new product called the 'Solarsplit' [41]. This is aimed at building owners installing a PV system and selling the generated electricity to tenants who have agreed to buy electricity from the owner instead of EWZ. The Solarsplit lays out costs of installing smart meters and a service fee for EWZ, as shown in Figure 2.9. Smart meters help the owner charge tenants individually, and the installation costs are taken as a proxy for costs of cooperation to form the ZEV, as will be explained in section 2.4. Also, the owner is required to pay EWZ a flat rate of 4 Rp./kWh of self-consumed electricity, which serves as a fee for still being connected to the grid as before but consuming a much smaller amount of electricity. Any excess electricity generated is sold back to EWZ at a time-of-use feed-in tariff as shown in Table 2.4.

Table 2.4: Time-of-use Electricity Prices and Feed-in Tariffs

	Peak Hours (Mon - Sat 06-22 h) (Rp./kWh)	Off-peak Hours (Remaining) (Rp./kWh)
EWZ Basis Retail Electricity Price	24.3	14.4
Wholesale Electricity Price (Average 2017 and 2018, Epexspot)	6.0	5.0
EWZ set Feed-in Tariff	8.5	4.45

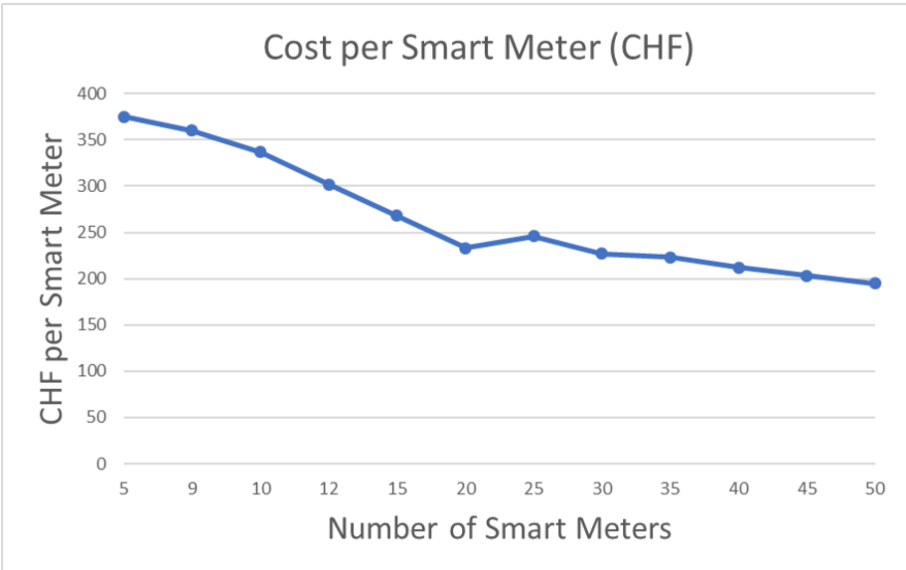


Figure 2.9: Smart Meter Costs from EWZ's Solarsplit Product

2.3.3 Solar PV System Costs, O&M Costs and Cost Projections

Solar PV system costs in Switzerland are well documented by Energieschweiz and are shown in Table 2.5. These costs are inclusive of material, planning, material, installation, as well as registration and commissioning of the PV system, but do not include possible later replacement of components (for example inverters), tax deductions or subsidies [7]. Operation and maintenance costs of PV systems in Switzerland are taken as 6 Rp./kWh from BfE documentation [42] and include the cost of maintenance, repair and replacement of inverters, solar modules, fuses, overvoltage protection, and further service costs like cleaning, billing, smart meter inspection and administrative costs and insurance.

Table 2.5: PV System Costs in Switzerland [7]

PV System Size (kW)	**Total Costs (CHF)**	**Total Cost per kW (CHF/kW)**
2	9710	4855
3	12370	4123.33
4	14850	3712.50
5	17190	3438
10	27230	2723
15	35520	2368
20	42820	2141
30	61680	2056
50	78420	1568.40
75	104490	1393.20
100	129550	1295.50
125	154150	1233.20
150	178490	1189.93
>150	Size*1100	1100

Solar PV system costs have been decreasing over the years, and the IEA Technology Roadmap 2014 [43] projects prices of the modules to halve by 2035, refer Appendix 6.3. This rate is applied to the Swiss PV system prices taken from EnergieSchweiz, assuming the same rate of decrease as the modules for the entire system.

2.4 Methodology of the Agent-based Model

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

2.4.1 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 the technology who own one building block in the Alt-Wiedikon district differentiated by the type of use of their property: residential, commercial, and public building owners (Figure 2.5). The population of agents is 1437 and it 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 2.4.2).

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 models outputs are the dynamics of the diffusion of solar PV systems. In 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. The ABM allows the representation of randomness through variables assigned as probability distributions, which requires the use of multiple simulation runs to interpret the results. 100 simulation runs for each scenario are run.

2.4.2 Agent Decision-making Mechanism

The decision-making process in this work follows the Theory of Planned Behaviour to simulate the decision-making by agents. Figure 2.10 shows a schematic representation of how the theory is adapted into a two-step decision-making process:

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 four attributes/variables:

   (a) **Attitude toward the behavior, range [0,1]:** The agent's attitude is represented by modelling its general environmental awareness. This is done by assigning one value from a Gaussian distribution derived from a study by Tiefenbeck et al. [44]. The study, although not related to the adoption of PV, does provide useful insight into the environmental attitudes of people in

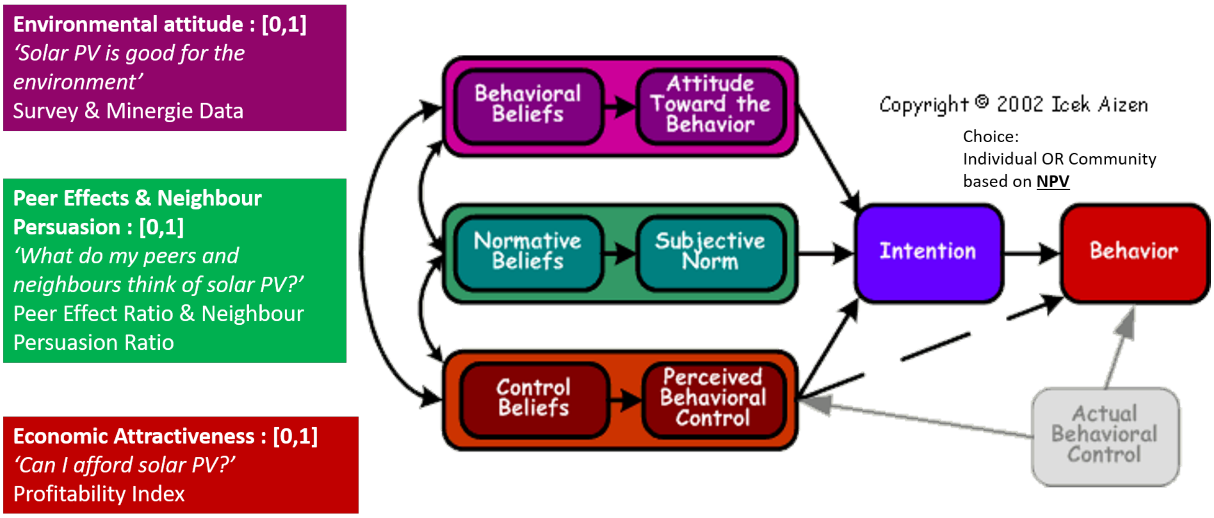


Figure 2.10: The Theory of Planned Behaviour, as used in this work, adapted from [3]

Switzerland through a survey. The environmental attitude mean score and standard deviation values are on a scale of 5, and are transformed to a scale of 1, to finally have a mean of 0.689 and a standard deviation of 0.18. Additionally, 3.5% of agents are considered early adopters [12] and assigned a higher environmental awareness based on empirical data from Minergie [45] labels. Minergie is a Swiss building standard for new and modern buildings. These buildings "are also characterized by very low energy consumption and the highest possible share of renewable energies," [45]. Information about the exact locations of Minergie buildings was obtained from the Minergie office and incorporated into the agent initialization.

$$attitude = gauss(0.698, 0.18) \tag{2.1}$$

(b) **Subjective Norms (Peer Effects), range [0,1]:** The model includes this element as active peer effects between agents, modelled through a small-world network (SWN) [13, 5], built for each agent, and measured as the fraction of those contacts with installed solar PV. For instance, if 5 out of 10 peers of an agents have already installed PV (in previous years), the peer effect for this agent would be 0.5.

$$Peer\ Effect = \frac{No.\ of\ connections\ with\ solar\ PV\ installed}{Total\ No.\ of\ connections} \tag{2.2}$$

To prepare the SWN, it was assumed that all agents in the model would be in the same network i.e. all of their close connections live in Alt-Wiedikon. This can also be understood as the network of building owners of Alt-Wiedikon who rely on peers within this network only to make decisions about their buildings. The SWN was prepared by fixing one agent's (i.e., a building; let's identify it as building A for the sake of discussion) location in the QGIS Alt-Wiedikon model and mapping the distances to all other agents. Then, the agents were arranged in a circle (recall Figure 1.6 in section 1.2) with building A as the reference and the nearest buildings (which are its nearest neighbours) placed next to it, and the farthest building diametrically opposite to building A. Through a simple Python code, the network was prepared with agents having an average of 10 connections in the network and a probability of 0.5 of breaking their connection with a nearest neighbour and forming one with any random agent in the network. While this way of creating a SWN is very accurate for the agent chosen as reference, it isn't quite accurate for all other agents as their nearest neighbour connections are based not on the distances with respect to themselves, but on the distances with respect to the chosen reference agent. However, since the agents are quite densely populated in the district, approximately half of the nearest neighbours of an agent are indeed placed next to it on the initial circle started out with.

(c) **Perceived Behavioral Control (PBC), range [0,1]:** This variable is represented 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. A net present value calculation helps to easily calculate the profitability index, and is also used later for the agent's decision between an individual and a community PV system.

$$Net\ Present\ Value = -Initial\ Investment + \sum_{1}^{n} \frac{Cash\ Flow}{(1+r)^t} \tag{2.3}$$

where r is the discount rate, assumed to be 5% in this thesis and t is the number of time periods ranging from 1 to n, with n being the duration considered for the evaluation of the NPV of the investment. In this thesis, n is assumed to be 25 years, which is a healthy lifespan for a PV system.

Equation 2.4

$$Profitability\ Index = 1 + \frac{NPV}{Investment} \tag{2.4}$$

The profitability index, by definition, is always greater than 1 for an investment with a positive NPV and lesser than 1 for a negative NPV. This means that the profitability indices calculated for the agents must be scaled to 1 in order to have consistency with the ranges of the other variables being input to the TPB. To also be able to distinguish between the 3 different agent types (residential, commercial and public), the re-scaling is done by dividing each agent's profitability index by the maximum profitability index of the agent in the population having the same typology. This method provided a sense of comparison to other agents, and also helps introduce a difference in the PBC between agent types. Equations 2.5, 2.6 and 2.7 show how this was achieved.

$$pbc_{i(res)} = \frac{Profitability\ Index_i}{Max.\ Profitability\ Index_{res}} \tag{2.5}$$

$$pbc_{i(comm)} = \frac{Profitability\ Index_i}{Max.\ Profitability\ Index_{comm}} \tag{2.6}$$

$$pbc_{i(pub)} = \frac{Profitability\ Index_i}{Max.\ Profitability\ Index_{pub}} \tag{2.7}$$

Since the ABM runs for 18 years between 2018 and 2035, there are changes in price levels of PV systems as described in section 2.3. The above profitability indices of the agents are hence calculated for every year in the simulation period outside of the ABM for reasons of computation time.

(d) **Neighbour Persuasion, range [0,1]:** This is an additional, unconventional term incorporated into the TPB to account specifically for community solar adoption and hence weighted separately from the above three variables. This variable serves to represent the persuasion coming from building owners in the same plot who are also considering adopting solar (in general, not particularly individual or community solar) in the same year and acts as a passive peer effect. This is measured for each agents as the fraction of buildings in their plot with a positive intention to adopt (as given by equation 2.9 if *intention* crosses the threshold). Equation 2.8 shows how this is calculated:

$$Neighbour\ Persuasion_i = \frac{No.\ of\ agents\ in\ plot\ with\ positive\ intention}{Total\ no.\ of\ agents\ in\ plot} \tag{2.8}$$

As evident, the neighbour persuasion is dependent on which agents are called first by the ABM. For example, in a plot of 5 agents, the first one to be called will have 0 neighbour persuasion as the other agents have not formed their intention yet. Assuming that this agent crosses the intention threshold, when the next agent from this plot will be called by the program, it will have a neighbour persuasion of 1/5. This variable also helps add more randomness to the model, since the order in which the agents are called is different every year of the simulation.

Equation 2.9 shows how the *intention* is calculated. If the value of *intention* crosses a threshold of 0.5 (explained in section 2.6), the agent moves on to Stage 2: Behaviour as explained in point 2.

$$\begin{aligned} Intention_i = w_{att} * attitude_i + w_{peer} * (Peer\ Effect)_i + w_{pbc} * pbc_i \\ + w_{persuasion} * (Neighbour\ Persuasion)_i \end{aligned} \tag{2.9}$$

2. **Stage 2 : Behaviour**
   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. 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. The local utility EWZ's 'Solarsplit' product 2.3.2 which levies costs of smart meter installation for shared systems are considered as a proxy for costs of cooperation in the NPV (and hence profitability index) calculations for a community PV system.

   Figure 2.11 shows a flowchart of the decision making process.

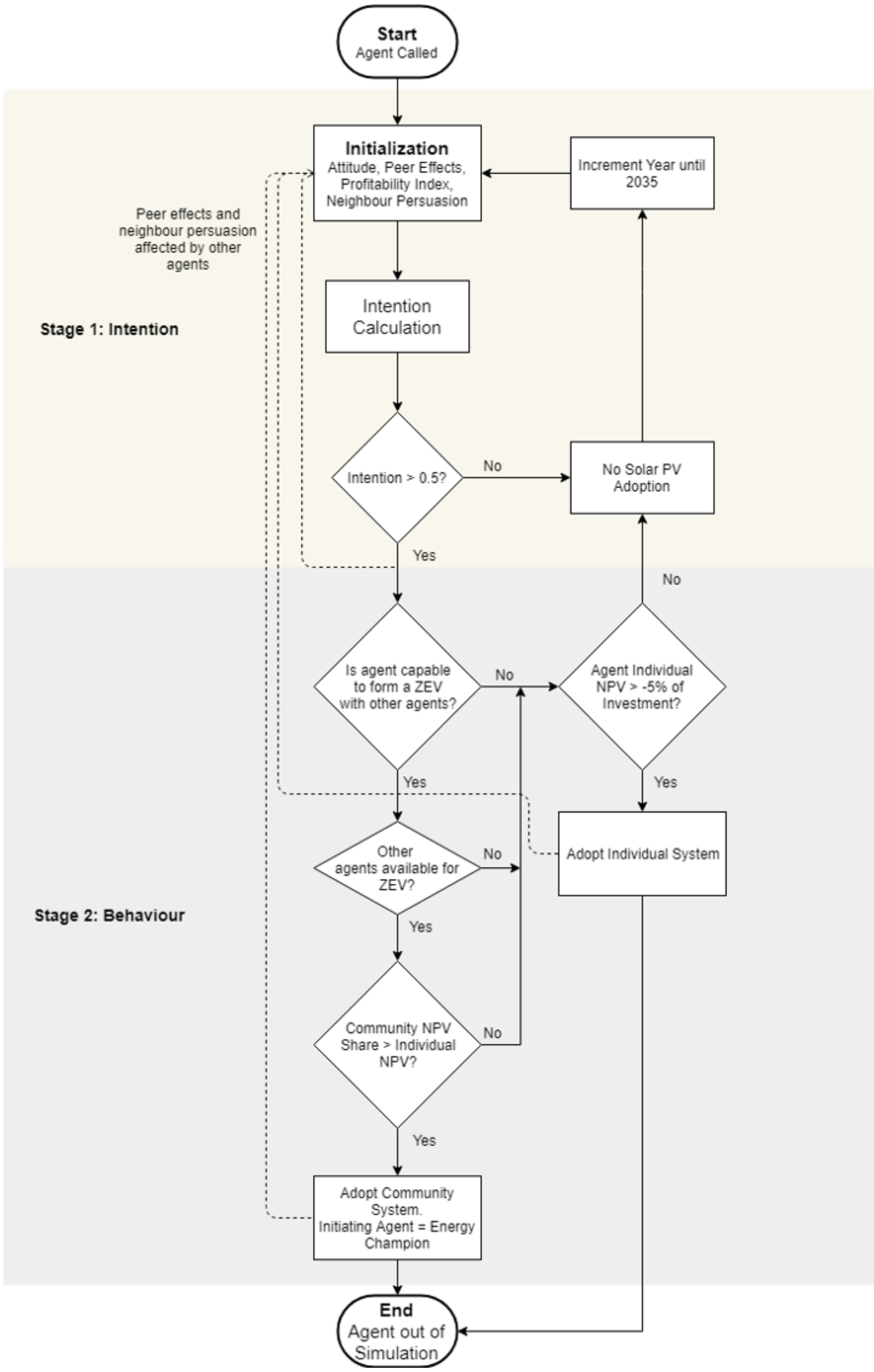


Figure 2.11: Flowchart detailing the decision-making process. Dotted lines indicate feedback from other agents.

2.5 Scenarios

A distinguishing criteria among the buildings in the district is the size of their demand. Since the ZEV regulations allow ZEVs with annual demands greater than 100 MWh to buy electricity on the wholesale market, the economics of PV systems completely change as the electricity prices are almost 4 times lower on the wholesale market for the peak hours, refer section 2.3. Because of the aggregation of buildings into blocks in the CEA energy model used to generate input data for the ABM, the annual demands of 721 of 1437 building blocks are over the 100 MWh level. Such big building blocks are free to purchase electricity on the wholesale market if they form a ZEV (legal entity required), but it is unclear how many actually do so as owners simply transfer electricity charges to tenants and participating on the wholesale market requires expertise which the owners may not themselves possess/afford or even value. Hence the scenarios are segregated primarily by demand sizes - one with the building population smaller than 100 MWh annual demand, and another with all buildings irrespective of the 100 MWh criteria.

Since the objective of this thesis is to analyze the impact of the new self-consumption regulation on individual and community adoption, it makes sense to segregate scenarios based on whether these regulations are in place (reality) or not (hypothetical). Hence the scenarios are also distinguished on the basis of allowing/disallowing ZEV formation, all other variables kept the same. This can show the influence of the new regulation in assisting ZEV formation.

Scenarios:

1. **Buildings below 100 MWh annual demand - Model 'A'**
   In this scenario, only the 716 building blocks having annual demand smaller than 100 MWh are included. ZEVs formed must also not exceed the 100 MWh annual demand limit. Table 2.6 shows the building stock for this scenario, which is also the population of agents.

Table 2.6: Model 'A' building stock

Building Type	Number of Buildings	No. of buildings that can form a community
Residential	526	423
Commercial	143	109
Public	47	34
Total	716	566

This scenario makes it possible to somehow compensate for the CEA aggregation of buildings by only keeping the relatively smaller buildings in the simulation - all of whom purchase only through EWZ. This is closer to reality as the buildings exist independently and not as buildings blocks, even when they are aggregated, the electricity price levels do not change. So the only limitation here is that the potential PV sizes are oversized due to large roof areas available.

There are 2 cases under the ‘Model A’ scenario:

(a) **no-ZEV - only Individual PV Systems**
This case serves as baseline for a comparison with cases which allow for ZEV formation.

(b) **ZEV - Individual and Community PV Systems**
ZEV formation is allowed. This case can show how many buildings opt to form communities over individually adopting PV and demonstrate the effect of the ZEV regulations.

2. **All buildings in Alt-Wiedikon - Model ‘B’**
In this scenario, all 1437 building blocks in Alt-Wiedikon are included. Table2.7 shows the building stock for this scenario, which is also the population of agents.

Table 2.7: Model ‘B’ building stock

Building Type	Number of Buildings	No. of buildings that can form a community
Residential	1053	894
Commercial	291	226
Public	93	68
Total	1437	1188

Again, there are 2 cases under the ‘Model B’ scenario as well, differentiated on the basis of price levels:

(a) **Retail Electricity Prices**
The rationale behind this case is assuming that the large buildings are just aggregated for this work (CEA building block aggregation) but in fact owners opt for separate bills for the apartments within them, and hence the electricity price is always at the EWZ-set retail level.

(b) **Wholesale Electricity Prices**
The other extreme case is if these building owners indeed buy on the wholesale market already, or if they choose to, then how PV adoption would be affected.

The best approximation to reality will be a mix of the above two cases as some buildings might opt to purchase on electricity on the wholesale market while others may stick to purchasing from EWZ at retail prices.

2.6 Model Calibration

An agent-based model can have a variety of inputs, some also with different weights, as is the case in this work. If these weights are arbitrarily assigned, the results can mean anything, and any derivation from results is vague. In order to have a meaningful interpretation of results, a validation of the ABM becomes necessary. This is essentially trying to fit the simulation curve to a historical curve (what actually happened in the past) by finding the best possible weights for the different variables used in the ABM through a sensitivity analyses to reach the least possible root mean square error (RMSE).

Historical PV adoption data in Switzerland, while available since 1991, was not segregated for urban regions until 2015 and the latest available installation data was of 2016. Community PV systems have no mention anywhere. 2 years of high quality data was not enough for model validation. Hence, the models were calibrated to fit to historical, low resolution country level adoption data (scaled for the size of the population considered) projected into the future for 5 years until 2022. This was based on the assumption that adoption levels will follow a similar rate of increase in the near future. Table 2.8 shows the historical data until 2016 from [2], and a linear extrapolation into the future until 2035. Using the number of buildings in Switzerland and Alt-Wiedikon, a scale factor (ratio of the number of buildings in Switzerland to the number of buildings in the Model) is applied to derive the historical adoptions and the future projection for the Alt-Wiedikon district, for both Models A and B. Since Model A and Model B have a difference in the number of agents and their associated PV system sizes, they were calibrated separately. Both were done by disallowing ZEV formation, since the data available is for the old policy case in which no ZEVs were explicitly allowed.

From Table 2.8, the projected level of adoption in 2035 for Switzerland is 7.485 GW, indicating that the adoption trend from 2013-2016 is on track to reach the Swiss targets for 2035 (approximately 7 GW). **Hence the projected historical data is also considered to be the target for 2035.**

Table 2.8: Historical and Extrapolated Solar PV Adoption Data - Swiss level, Model B and A level

		Switzerland 1.738 Million Buildings		Model B 4701 Original Buildings (1437 Building Blocks)			Model A 1287 Original Buildings (716 Building Blocks)		
	Year	Cumulative Adoption (MWp)	Yearly Adoption (kWp)	Cumulative Adoption (kWp)	Yearly Adoption (kWp)	Calibration Data (kWp)	Cumulative (kWp)	Yearly Adoption (kWp)	Calibration Data (kWp)
Historical Data	2013	753.11	-	2036.78	-		557.61	-	
	2014	1058.14	305.03	2861.73	824.95		783.46	225.85	
	2015	1391.50	333.36	3763.30	901.57		1030.29	246.82	
	2016	1661.47	269.97	4493.43	730.13		1230.17	199.89	
Extrapolation of Historical Data	2017	1980.67	319.20	5356.69	863.26		1466.51	236.34	
	2018	2286.51	305.84	6183.84	827.15	**827.15**	1692.96	226.45	**226.45**
	2019	2592.35	305.84	7010.99	827.15	**1654.30**	1919.41	226.45	**452.90**
	2020	2898.20	305.84	7838.14	827.15	**2481.46**	2145.86	226.45	**679.35**
	2021	3204.04	305.84	8665.30	827.15	**3308.61**	2372.32	226.45	**905.80**
	2022	3509.89	305.84	9492.45	827.15	**4135.76**	2598.77	226.45	**1132.26**
	2023	3815.73	305.84	10319.60	827.15		2825.22	226.45	
	2024	4121.57	305.84	11146.75	827.15		3051.67	226.45	
	2025	4427.42	305.84	11973.91	827.15		3278.12	226.45	
	2026	4733.26	305.84	12801.06	827.15		3504.57	226.45	
	2027	5039.11	305.84	13628.21	827.15		3731.02	226.45	
	2028	5344.95	305.84	14455.36	827.15		3957.47	226.45	
	2029	5650.79	305.84	15282.51	827.15		4183.92	226.45	
	2030	5956.64	305.84	16109.67	827.15		4410.37	226.45	
	2031	6262.48	305.84	16936.82	827.15		4636.83	226.45	
	2032	6568.33	305.84	17763.97	827.15		4863.28	226.45	
	2033	6874.17	305.84	18591.12	827.15		5089.73	226.45	
	2034	7180.01	305.84	19418.27	827.15		5316.18	226.45	
	2035	7485.86	305.84	20245.43	827.15		5542.63	226.45	

The different weights to be calibrated are the weights for the 4 attributes of the TPB, as shown in Equation 2.9: attitude toward the behaviour, subjective norms (or, peer effects), perceived behavioural control and the neighbour persuasion. Since the ranges of these variables are between 0-1 and the first three are considered to be an integral part of the TPB, those weights are made to add up to 1. To begin with, these are considered to be equal to each other i.e. one-third. The neighbour persuasion is a secondary effect and accounted for separately. Literature has shown that persuasion/passive peer effects from unknown neighbours is not considered very important with respect to adopting a new technology, and hence the weight for this variable is kept low (0.1) to begin with. The threshold of the intention function (2.9) is kept at a level of 0.5 to begin with, and kept constant. This is because a value of 0.5 on a scale of range 0-1 is the least biased value, and other weights are adjusted in reference to this value of the intention.

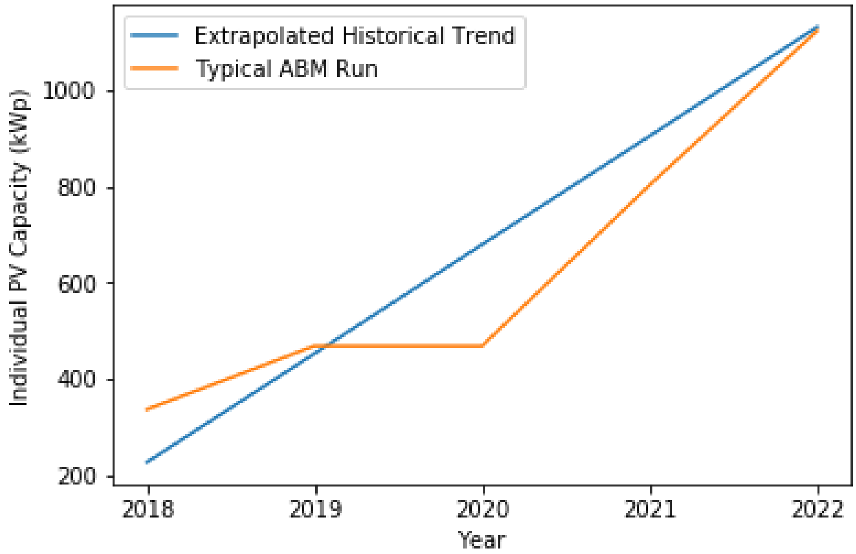
In order to fit the historical projection, it was necessary to allow buildings to adopt even if the NPVs of the PV system were negative. This represents the innovators and early adopters category from Rogers' adopter categories [12]. The degree to which agents were allowed to have a negative NPV was limited by a negative 0 to 10% of the investment costs of their PV systems.

Table 2.9 shows the weights of the agents, the negative NPV allowed and the RMSE of the final calibrated models A and B. Appendix 6.5 details the calibration process further.

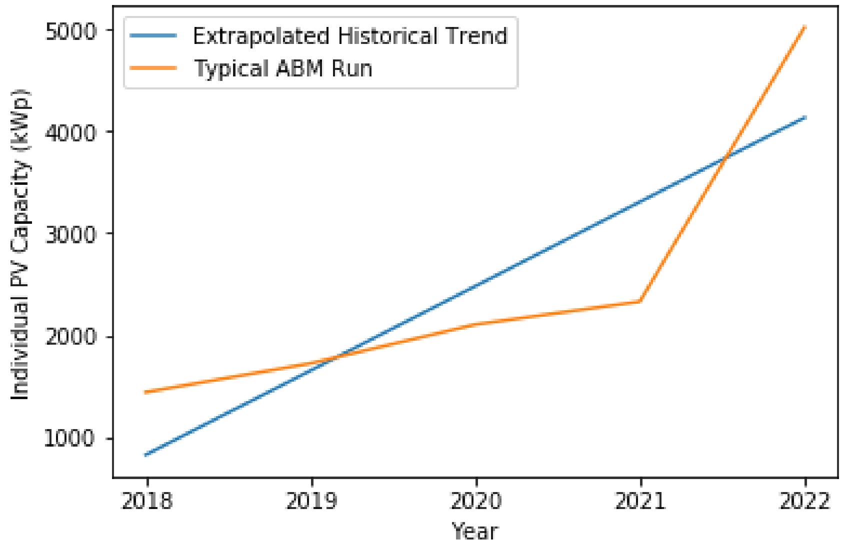
Table 2.9: Calibrated Weights

Weights	**Model A**	**Model B**
Attitude	0.39	0.25
Peer Effects	0.31	0.42
Perceived Behavioural Control	0.3	0.33
Neighbour Persuasion	0.1	0.1
Negative NPV Factor	-0.05	0
RMSE	**116.279**	**673.00**

Figure 2.12 shows the adoption and historical projected trend curves with the calibrated values, and these are the best fits achieved for the 2 models.



(a) Model A



(b) Model B

Figure 2.12: Best fits for Models A and B

2.7 Assumptions

This section explains the most important assumptions in this work.

- PV system sizes are assumed to occupy the maximum available roof sizes from the CEA building data. This is done in order to make the decision making process easier. If the PV size would not be fixed, it would be too computationally intensive to calculate NPVs of the different possible system sizes for each agent each year of the ABM simulation run and then have the agent decide to adopt. And, it would be more difficult with ZEVs as the range of possible PV system sizes would be even more.

- PV system sizes for ZEVs (which consist of more than one building block) are considered to occupy the sum of the roof sizes of all component building blocks.

- A big assumption in this work is due to the CEA aggregation of buildings into building blocks, which increases rooftop and hence PV system sizes, and reduces the resolution of the model. This aggregation leads to large electricity demands and large PV systems, leading to very positive NPVs for the PV systems, an uncommon occurrence as usually individual PV systems are small (less than 30kWp). This also means that the effect of economies of scale when forming communities is reduced.

- In this work, individual adoptions are defined as adoptions by one building block, and community adoptions are adoptions by more than one building block. It is important to note than the individual adoptions may consist of more than one building in the building block, and hence be a community system in reality.

- Cooperation costs for forming a ZEV are assumed to be only the capital costs of extra smart meter installations. Administrative costs, costs of time, talking to other people and coming to a conclusive decision are very difficult to find/estimate and hence left out.

- Since the policy states that building owners cannot charge tenants participating in a ZEV more than what EWZ charges for the retail electricity, the tenants do not stand to lose any money in case they join the ZEV. On the other hand, tenants can gain if the price the owner charges is less than the EWZ price. Hence it is assumed in this work that all tenants in the building will join the ZEV in case the owner decides to install solar PV on the rooftop. This also alleviates the need for modelling tenants and the decision-making power lies with the building owners in the current scope of the model. Hence, the fact that some apartments may be owned by people other than the building owner was also disregarded, although the apartment owners might have a stronger say in what happens on the building property than the tenants.

- In terms of the agent-based model, some variables were kept constant while others were varied during the 18 year simulation period between 2018 and 2035.

- Constant:
  * Population of the agents - as the number of building owners are equal to the number of buildings and it is assumed that no new buildings are constructed in this district and no buildings are demolished.
  * Environmental Attitude of the agents - while it would be very interesting to vary the environmental attitudes of agents, especially with rising activist movements in Europe currently, they are kept constant for ease of understanding ABM results.
  * Peer Network of the agents - it is assumed that each agent has a fixed peer network and that this does not change over the course of time.
  * Electricity Prices - kept constant since it is difficult to estimate how the local utility will change prices in the future, and past prices have stayed within a very small range.
  * Subsidies - assumed to be constant until they run out in 2030 as it is assumed that the policy does not change in this time period.
  * Feed-in Tariffs - assumed to be constant as the local utility has kept these constant for the past 4 years, and it is unclear how these might evolve.
  * Members of the ZEV - it is assumed that the plots made with the help of the regulations (section 2.2) do not change, hence the possible member choices an agent has for ZEV formation do not change.
- Variable:
  * PV Prices - assumed to be linearly falling, as explained in section 2.3. Consequently, NPVs and profitability indices of the agents linearly increase at the same rate.
  * Peer Effects - as more agents adopt solar PV systems, peer effects on the agent increase.

2.8 Methodology Overview

Figure 2.13 gives an overview of the methodology of this work.

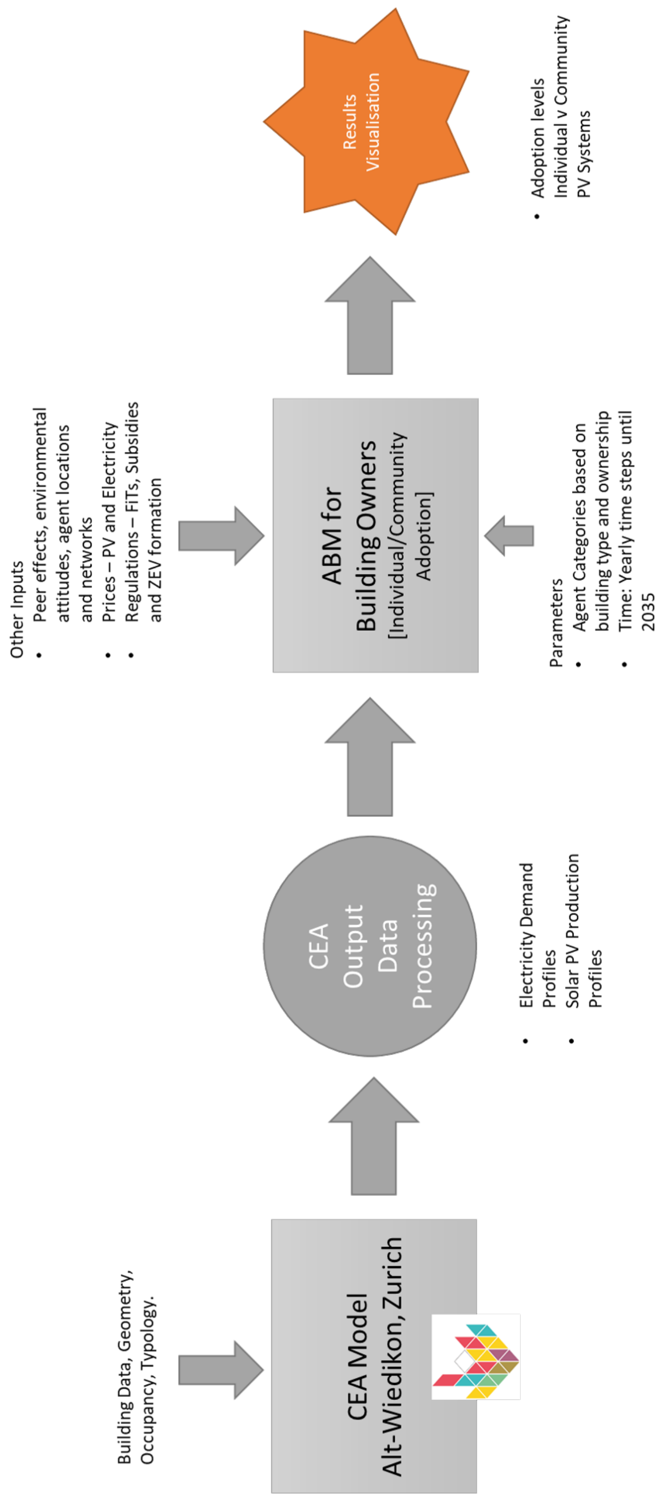


Figure 2.13: Overview of the Methodology

Results

In this chapter, the results of the ABM are presented, segregated according to the scenarios.

3.1 Buildings below 100 MWh annual demand - Model 'A'

3.1.1 Case: no-ZEV

This case is an extension of the old regulations, with the only difference being that subsidies are now available to PV systems of all sizes between 2kW - 50 MW. Figure 3.1 shows the evolution of PV system adoption in this case.

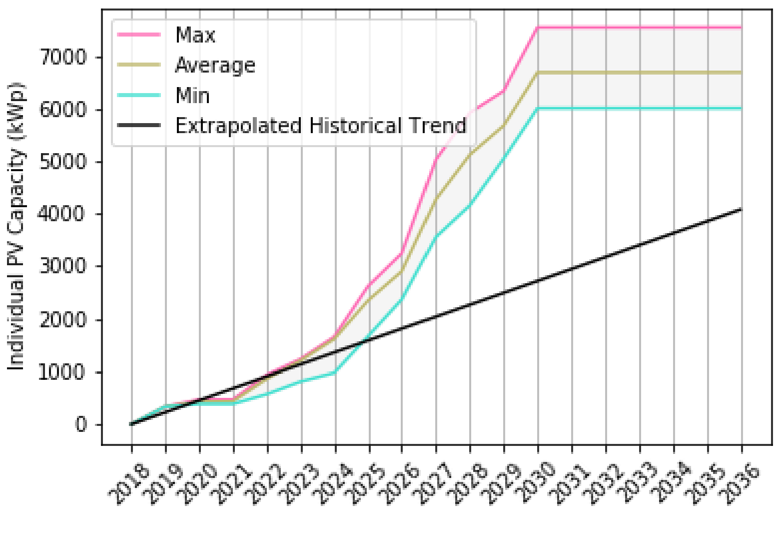


Figure 3.1: Adoption in the no-ZEV scenario

For the first 5 years until 2023, the level of adoption follows the historical trend. This is also explained by the fact that the calibration was done for this time period. Post 2024, the adoptions increase dramatically. This is because of slowly increasing peer effects and falling PV system prices which leads to higher NPVs. The higher NPV of agents has 2 effects - it brings down the NPV within the acceptable limit of -5% of investment costs for agents who were previously crossing the intention stage but not adopting; and an increased profitability index which increases the PBC (perceived behavioural control) attribute and allows more agents to cross the intention stage and contemplate installing an individual or community PV system in stage 2 of the adoption process. Figure 3.2 shows this for an example agent. Over the years, the intention (yellow) slowly increases, mainly due to the increasing PBC attribute (increasing NPV and hence increasing profitability index). In 2026, the intention is still lower than the threshold of 0.5 and the agent has still not adopted solar PV. In 2027, the neighbour persuasion increases to 0.33 i.e. a third of the neighbours in the plot of this agent have crossed the intention threshold already. Also, subjective norms increase from 0 in 2025 to 0.1 in 2027, which means that some peers in this agent's network have already installed solar PV in the last 2 years. These events coupled together cause the agent's intention to cross the threshold of 0.5. Since the NPV of this agent is also greater than -5% of the investment costs, it adopts an individual solar PV system. The agent is then taken out of the simulation, which explains the flattening of agent attributes post 2027 in Figure 3.2.

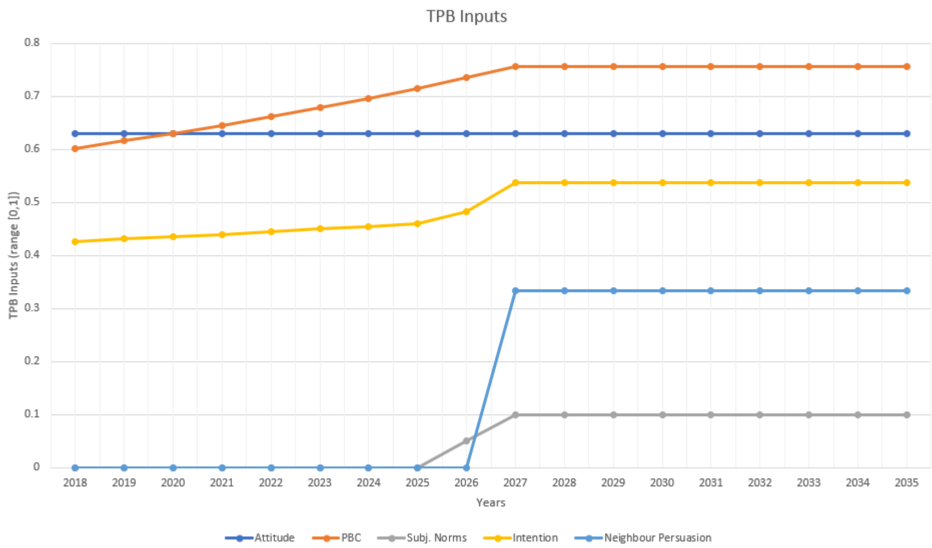


Figure 3.2: Variation in agent attributes over the years, for an example agent

Coming back to the macro-level, the adoption trend shows that adoption balloons post 2024 and increases on average at a gross rate of 830 kW/year. However, in general there are no adoptions post 2030 (selected ABM runs do show adoptions, but those are 1-2 agents adopting in 2035 when falling PV prices again help increase the NPV). This is due to the fact that the investment subsidies are not available post 2030 which causes NPVs (and hence the profitability index) to fall, and they do not recover enough by 2035. Figure 3.3 shows the effect of the removal of the investment subsidies on the (scaled) profitability index of a typical building. This indicates that in order to keep up the adoption, either the subsides must be continued, or other measures such as changes in the level of feed-in tariffs might be necessary. In spite of this flattening of adoption post 2030, the results indicate that even in the lowest level of adoptions the projected historical trend is exceeded by at least 1500 kW.

Figure 3.3: Profitability Index of a typical Agent over the Years. Intention (Yellow) is the weighted sum of attitude, PBC, Subjective Norms and Neighbour Persuasion.

3.1.2 Case: ZEV

It is this scenario which helps understand the effect of the new regulation by allowing the formation of ZEVs. Figure 3.4 shows the average of all ABM runs - the trend is very similar to the one in the no-ZEV scenario. And Figure 3.5 shows the individual and community adoption levels separately, to highlight the huge difference between them.

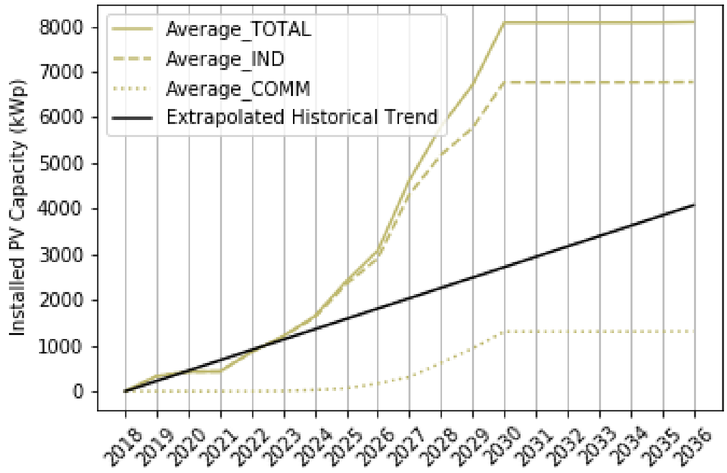


Figure 3.4: Average Adoption level segregated by System type

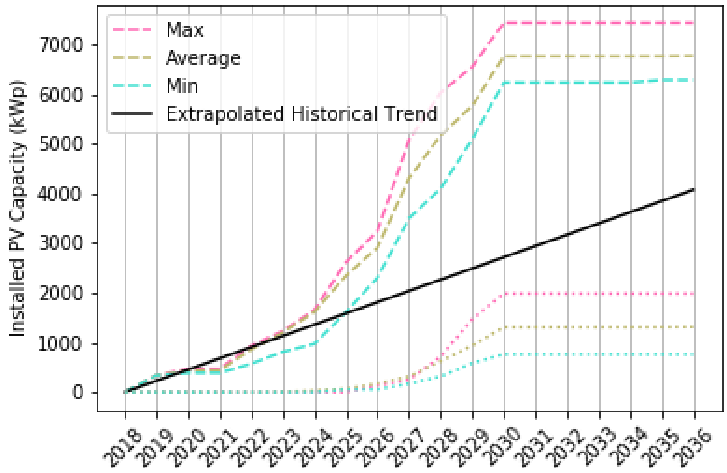


Figure 3.5: Individual and Community Adoption in the ZEV scenario. Dashed - Individual; Dotted - Community

Clearly, the total number of adoptions is approximately twice that of the projected trend. However, almost 85% of this is made up of individual PV systems, and only about 15% of the installed capacity is through a ZEV. This is somewhat counter-intuitive, as ZEVs tend to be larger than individual PV systems and more profitable through economies of scale. The explanation lies in the sizes of the PV systems considered - since the CEA energy model used aggregated building blocks aggregated from buildings sharing a wall with each other (section 2.1.1), the roof sizes of the buildings for the ABM were pretty large, leading to very large PV system sizes considered by the agents for adoption. This meant that NPVs of the PV systems, even individually, were good enough to ensure adoption, and the benefit of the ZEV's economies of scale was only applicable to a few buildings. It is very important to note that the 'individual' adoptions are infact adoptions by individual building blocks, which may consist of more than one building. In reality, such systems would be community systems shared by different buildings. However, there are a some ZEVs formed and hence the total adoption level in this scenario is greater than the no-ZEV scenario by almost exactly the amount of community PV systems installed. The ZEV regulations do help in increasing the total installed capacity by making it feasible for more buildings to install solar.

Taking a typical ABM run to observe how adoption differs across the different agent types, it is seen that commercial and public building owners proportionately adopt more than residential building owners - refer Figure 3.6. This is because commercial and public buildings are larger than the residential ones, hence have larger roof sizes on which larger and more profitable PV systems can be installed.

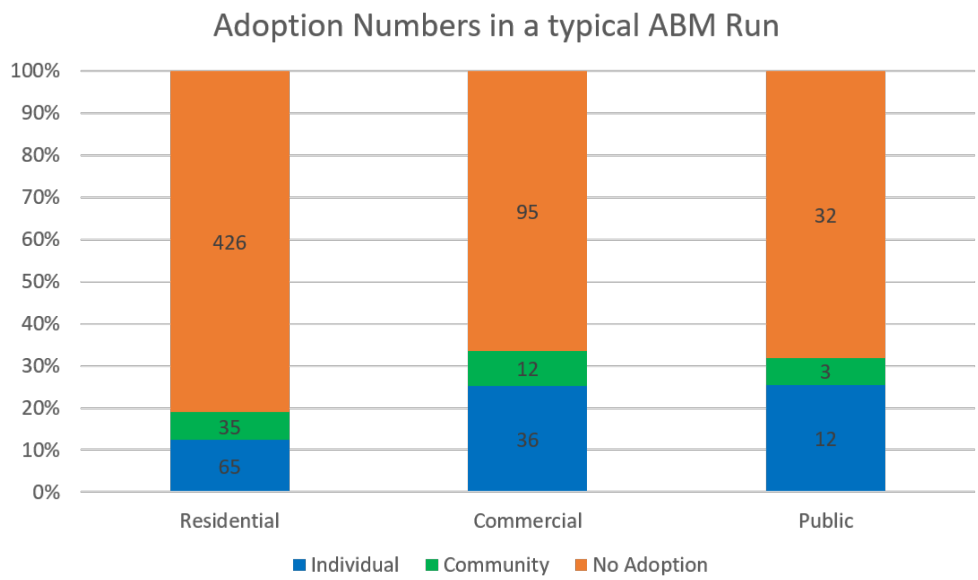


Figure 3.6: Adoption in a typical ABM Run

It is interesting to see the type of buildings opting to form ZEVs and the exact reason and year of formation. The time-scope of ZEV formation is quite different from individual PV adoption - delayed by about 8 years. It is only in 2025-2026 that the first ZEVs are formed. The reason is the decision-making process used in the ABM coupled with the resolution of the underlying energy model. The formation of a ZEV is contingent on a number of things falling into place - not only must an agent must cross the intention stage, there must be at least one other agent within it's list of possible ZEV members (refer section 2.4) which should cross the intention in the same year. This isn't enough - the possible ZEV must not have an annual demand greater than 100 MWh (as explained in section 2.5), and must have a positive NPV for each member of the ZEV. Also, the share of the NPV in the ZEV must be greater than an individual PV system's NPV for the agent which initializes the formation (the Energy Champion of the community). Even though a majority of agents can form a community with another agent, the chances of agents crossing the intention stage together are low. Since the individual PV system NPVs are already very positive for most agents, those which do cross the intention in the early years of the simulation readily adopt individual systems as none of their possible ZEV members have an intention to adopt.

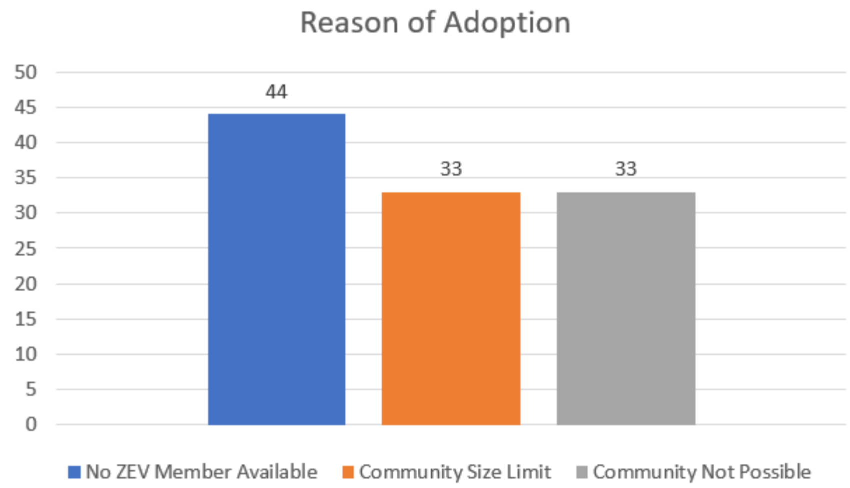


Figure 3.7: Reasons of Individual Adoption

The graph in figure 3.7 shows the main reasons of solar PV adoption in a typical ABM run for this scenario in which 110 agents adopt individual PV systems while 50 agents opt to form 22 ZEVs. As is clear from the figure, most agents end up adopting individual PV systems because no other agent was available to form a ZEV with (blue bar), or because the potential ZEV being formed was larger than 100 MWh of annual demand and hence disallowed (orange bar). The ones that do form a ZEV are also later in the simulation period as these are the agents with smaller PV systems which depended on decreasing PV prices and increased peer effects in order to cross the intention stage in the first place. Of the 22 ZEVs formed consisting of 50 individual buildings and 1444 kW installed capacity in this typical ABM run, the average individual PV capacity of these buildings was only 29 kW, and 48/50 buildings had a PV capacity of less than 41 kW. This indicates that all of these were smaller buildings which came together to form the ZEVs; and achieved an average ZEV capacity of 65 kW per system, thereby taking advantage of economies of scale. Figure 3.8 shows the different types of communities formed - only 6 are 'Mixed' communities, i.e., involve different building types, whereas 16 consist of similar building types. This highlights the restrictive nature of the ZEV regulations - most possible ZEV formations are with the adjacent building, which are quite often of the same typology. Relaxing the ZEV regulations could allow for greater choices of ZEV formation and potentially better complementing of load profiles in the ZEV.

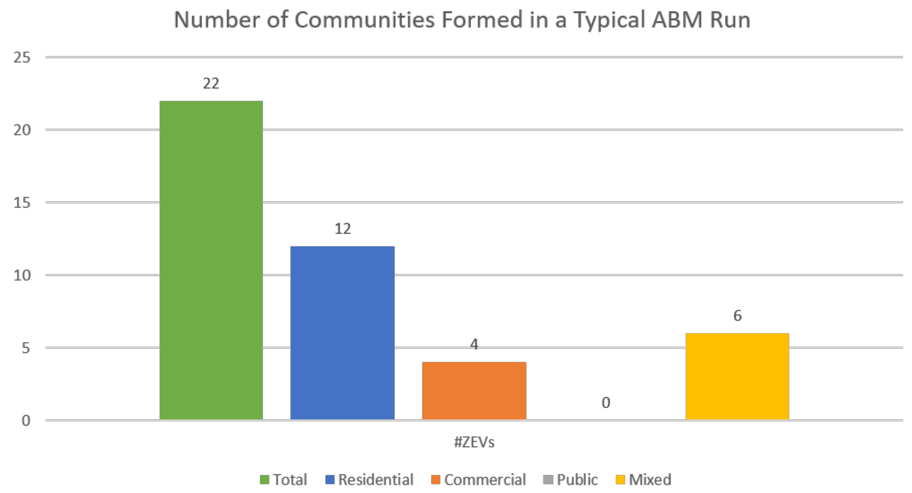


Figure 3.8: Number and type of ZEVs/Communities formed in a typical ABM Run

3.2 All Buildings in Alt-Wiedikon - Model 'B'

3.2.1 Case: Retail Electricity Prices

Figure 3.9 shows the results of this scenario at retail electricity prices. The solid lines indicate total adoption levels, which are on average about 3 times greater at the end of the simulation period than the projected trend, 48000 kW vs 14800 kW. This level of adoption far exceeds the expectations of the regulators, at least in this specific district of the city, but still only provides about 8.4% of the district's electricity demand.

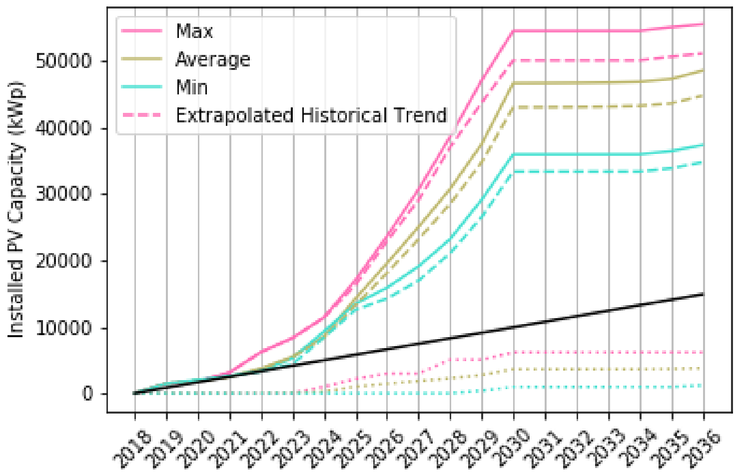


Figure 3.9: Retail Prices: Installed PV Capacity, segregated by Total (solid line), Individual (dashed), Community (dotted)

The shape of the adoption curve is similar to the ones in the reduced buildings scenario, with adoption slowly increasing until 2023 and then taking off rapidly, at an approximate rate of 5000 kW of installed capacity per year. Again, similar to the Model A scenario, it is the individual PV systems driving the adoptions - they are 90% of all installed capacity.

Community PV adoption, while greater in absolute installed capacity than the reduced buildings scenario, is again not really taking off. The reasons remain the same - large buildings adopt individual systems themselves as NPVs are positive or in an acceptable negative range, and there are no agents to form a ZEV with when an agent crosses the intention stage.

3.2.2 Case: Wholesale Electricity Prices

Figure 3.10 shows the results of this scenario at wholesale electricity prices. The solid lines indicate total adoption levels, which are on average about 3.5 times smaller at the end of the simulation period than the projected trend, 4000 kW vs 14800 kW. This is because of the assumption that all buildings having an annual demand greater than 100 MWh purchase electricity on the much cheaper wholesale market, making the NPVs of PV systems negative. Hence the number of agents crossing the intention stage is greatly reduced in the first 6 years of the simulation and a flat adoption curve is obtained. As PV system prices keep falling, the economics of PV systems start becoming interesting to agents and adoptions increase, only to be halted by the subsidies being phased out in 2030. Adopters are primarily those buildings with annual demands less than 100 MWh, as their PV systems help replace the expensive retail electricity.

Community adoptions rarely occur - the maximum community adoption at the end of the simulation period is 2 communities with an installed capacity of 110 kW. This is due to the same reasons previously explained in 3.2.1.

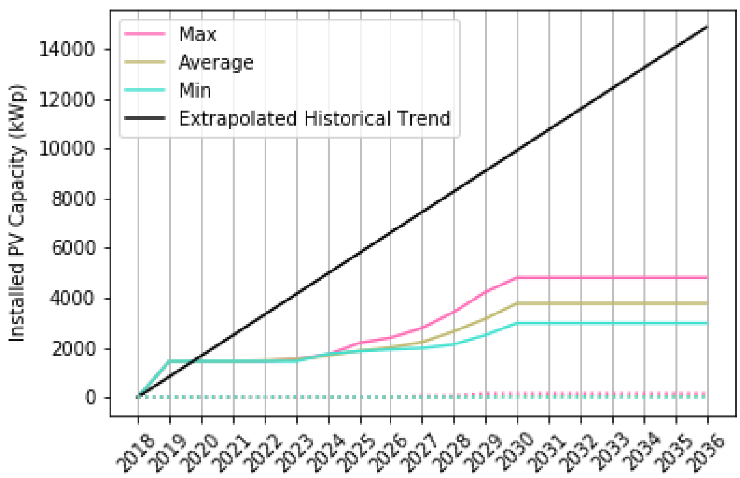


Figure 3.10: Wholesale Prices: Installed PV Capacity, segregated by Total (solid line) and Community (dotted)

3.2.3 Learnings from Model 'B'

A crucial learning from these two cases of retail/wholesale prices in the Alt-Wiedikon scenario is the huge impact of the prices in the adoption levels. In reality, one can expect a combination of these cases and end up somewhere in between the adoption levels - some large buildings (especially ones owned by building cooperatives/Genossenschafts like Woko [46] or Livit[47]) with annual demands greater than 100 MWh may be purchasing from the wholesale market, but other large buildings owned by family-businesses may not have the necessary knowledge of and skill-set required to participate on the wholesale market. This is crucial for policymakers, as policy can focus differently on buildings and building cooperatives based on the sizes of their demands.

Discussion

4.1 Implications for Policy

The different cases across ‘Model A’ and ‘Model B’ lead to similarly shaped adoption curves, although the magnitudes are quite different. Except in the ‘Wholesale Prices’ case of Model B, the projected historical trend (which is in line with the required future levels of PV) is always exceeded by at least 1.5 times by the simulation results. This gives an initial sense that the policy is doing well in terms of meeting required targets by the end of the simulation period, 2035. However, accounting for the Wholesale Prices case of Model B gives a different picture - adoption levels fall short of the target by about 3.5 times. In reality, the adoption levels may lie somewhere in between the Retail and Wholesale Price cases of Model B, as only few large building owners may buy at wholesale electricity prices but others may continue to buy at retail prices. Estimating the proportion of building owners opting for either price level is out of the scope of this work, and the best estimation is that adoption targets will most likely be in between the levels of the Retail and Wholesale price cases and exceed the targets.

As evident, wholesale prices bring down the feasibility of PV systems drastically. Legally, a ZEV is required to have at least 10% of demand as installed capacity on site. Large mergers exceeding the 100 MWh annual demand limit can install the smallest (and cheapest) PV system to comply with regulations and take advantages of wholesale prices, a potential loophole in the current policy which can lead to a high number of ZEVs with small PV systems but not enough installed capacity to reach the 2035 targets. However, accessing the wholesale electricity market is not straight-forward and requires expertise, which building owners may not possess/value. Policymakers must pay attention to the different adoption dynamics with changing electricity prices.

A clear indication from all cases is that as soon as the subsidies are halted in 2030, adoptions almost cease. This implies the massive importance of the subsidies, and that PV system prices by 2030 do not fall much to make adoption feasible without the subsidies. Since in the simulations the adoptions increase sharply post 2024 and exceed targets (except Model B - case Wholesale prices), the amount of subsidy provided could be reduced and the duration extended to ensure a smoother and continuous growth in adoption levels of solar PV which do not abruptly halt in 2030. Other measures can include an increase in the level of feed-in tariffs to keep PV systems economically feasible.

The high rate of increase in adoptions post 2024 is not only due to falling PV prices; increasing peer effects also play a role. Policy can look into spending money on more information campaigns and help increase peer effects to increase adoption levels. A similar argument stands for the environmental attitudes of the population - creating more awareness can potentially lead to similar adoption levels but at lower expenses on subsidies. A detailed sensitivity analyses on the inputs of the TPB with survey data from a sample of the population can be useful to identify the more relevant criteria for decision-making, which can then be targeted by the policy. For instance, people in Switzerland may not care too much about the profitability of their PV systems but rather about their status among peers, and hence may install PV even if it is a loss-making investment. In such a case, policy can focus less on subsidies and more on the social aspects around PV installations, such as competitions among communities for greater installed PV capacity or subsidizing organizations assisting the public to install solar PV, like Solar Community Organizations (SCOs) in the US [32].

The results also indicate that adoptions are driven by individual and not community PV systems under the definition of this work. The aggregation effect negated the effect of economies of scale, but also meant that most individual adoptions (one building block) were in fact aggregations of many individual buildings, i.e., communities in reality. Although the aggregation effects overlook difficulties in cooperation and group decision-making, the results do indicate that it clearly makes economic sense to have larger PV system sizes through community PV systems. Policy can be tuned to assist community PV formations more, such as by funding contractors and PV organizations to act as mediators/project planners for joint community PV systems between neighbouring buildings and consider them as a single building block for a ZEV, as considered in this work.

A secondary reason for low community PV adoption is also the policy which does not allow ZEV formation across public property and usage of the distribution grid. If these are relaxed, there can be many more possible combinations between buildings which can take advantage of complementary load profiles. Of course, the level of relaxation of this restriction is highly dependent on the distribution grid operator (EWZ in Zurich) for reasons of technical grid stability - a study on the dynamics of electric power flow with ZEVs can help inform the policymaker to what extent the current restrictions might be relaxed.

4.2 Limitations and Future Work

While this work includes a comprehensive model and analysis, many limitations exist with respect to the resolution of the input data and existing data for model validation. This section includes these limitations and how they can be addressed in future work.

A major limitation of this work is the aggregation of buildings into building blocks for energy modelling in the CEA. Building sizes were quite large, much larger than reality. This meant large annual demands (more than half of the buildings in the district had annual demands larger than 100 MWh), large roofs and consequently large PV sizes. This led to very positive NPVs for a majority of buildings/agents, and the results showed that adoption levels exceeded targets. In reality, such large PV system sizes (larger than 100 kWp) on rooftops are uncommon and need collaboration with neighbouring buildings to have a large roof space to install such PV systems. By virtue of aggregation, the collaboration component was pre-included without any cooperation costs and without the increased number of agents deciding together which can be more complicated. These points together meant individual PV adoptions by the large buildings was very easy. It is important to note that these 'individual' adoptions are actually aggregations of multiple buildings and are hence community and not individual adoptions. The simplest solution to these problems is an increased model resolution with data on each building separately, and ideally even apartments within the building. However, it quickly becomes very computationally intensive to do so with district scale energy modelling.

Another limitation of this work is the lack of a proper data-set to validate the ABM. ABMs must preferably be validated with historical data in historical contexts over an extended period of time, which can become difficult in case of models exploring diffusion of new technologies, such as in this case. Future work can hopefully have access to more years of adoption data, both individual and community, to validate such a model.

The decision-making mechanism in this work can be improved in a number of ways. During the decision-making process, as described in 2.11, agents which have crossed the intention stage but are unable to form a ZEV with other agents move on to adopt an individual PV system if the NPVs are favourable. This is what leads to more individual systems in the first few years of the simulation as not many agents cross the intention stage simultaneously. The use of an agent attribute such as having a more individual/social mindset can allow agents to neglect adopting individual PV systems and instead go over the process again the next year in hope of finding other agents to form a ZEV with. A memory attribute also goes hand in hand with this - the agent can be programmed to have a memory and have it affect the adoption decision in the later years of the simulation.

Community formation in this work is contingent on one agent making the decision. If a community PV system is possible and the NPV of the system in positive, the agent which initiated the adoption process is termed as an 'Energy Champion' and decides for all other agents involved in the community. This is unlikely in reality, as other agents would have their own opinions and would try to negotiate based on their own values and beliefs. A ranking system could be incorporated to account for the different values of other agents in the community, or a more complex decision-making process can model such behaviour.

Furthermore, in the current decision-making process, community PV systems are adopted if more than one agent within the plot passes the intention stage independently and then the community PV system's NPV is better than the individual PV system. The neighbour persuasion term in the TPB does try to account for influences from neighbour building owners within the same plot, but this influence is only for the agent to cross the intention stage. Post that, the agent decides based on NPVs only. In reality, neighbouring building owners might persuade a building owner to install solar PV together with them i.e. convince him/her to install PV even if they had not even considered it. Tenants of the building could also decide among themselves the need for solar PV on the building roof and try to persuade the building owner to install PV.

Some other changes in the decision-making mechanism can be to allow the individual PV adopters to later come together and form a ZEV to take advantage of increased SCRs. That is, multiple agents need not adopt a community solar PV system together but rather form one later if they wish to. Also, those agents which cannot install solar PV on their roofs could be termed as 'non-PV candidates' but still be allowed to join ZEVs - to determine the optimum ratio of prosumers to consumers in a community, similar to [48].These different ways of cooperation and decision-making to form a community PV system can be explored in future work.

The environmental attitude of the agents is kept constant in this work. However, in the recent past, an increasing number of activist movements and governmental organizations are stressing that climate change needs to be tackled quickly. The more such events take place, the more environmentally aware the population gets. One way to account for this would be to not keep the environmental attitude constant but rather vary it over the simulation period by accounting for planned future events and plans of governmental/non-governmental organizations.

There can be a greater differentiation between the different agent types used in this model, such as through different peer networks (commercial building owners know more commercial building owners) and different thresholds for PV adoption (commercial building owners may look for quicker return on investments or a minimum investment size). Also, a greater variety of agents than the 3 used in this work can be included in the ABM. Some obvious types can be including more stakeholders, such as the local electric utility, solar community organizations (SCOs), governmental organizations, corporations, PV system sellers, builders, and most interestingly, large Baugenossenschaften (Housing/Building cooperatives). These stakeholders can have their own objectives (sell maximum PV systems, install PV to develop a green image, etc.) and their attributes can be assigned differently to highlight differences in their objectives. Ideally, survey data would be the most accurate for this.

Some other aspects for future work include:

- Data collection - collecting agent attributes (environmental attitudes, peer networks, indicators considered most important for financial evaluation of investments, etc.) through surveys specifically targeted on the population being modelled and specifically for solar PV; collecting electrical grid distribution data and incorporating it to better identify which buildings can form a ZEV together.

- More scenarios:
  - PV system sizes can be varied (smallest to largest sizes, optimal sizes for each roof) instead of keeping them constant to see how sizes impact adoption levels.
  - The level of subsidies and feed-in tariffs can be varied to identify optimum levels, subject to other assumptions.
  - Relaxing ZEV regulations to allow a building to form a ZEV with any other building (slowly increasing the radius from adjacent buildings only to the entire district) can be very interesting to look into.
  - Allowing for greater dynamics in the model by allowing more variables to change over time - agent population, attitudes, peer networks and electricity prices.

Conclusion

In this thesis, a psychological decision-making theory was combined together with high resolution energy data and simulated with the help of an Agent-based model to explore the dynamics of solar PV adoption in Zurich's Alt-Wiedikon district. A key contribution of this thesis is the development of a decision-making methodology for the adoption of community solar PV systems, which has not been explored in previous research but is now important to consider with the increased emphasis on community solar in Switzerland and all around the world. During this work, various ways of accounting for the dynamics of multiple people involved in a decision were explored but left as possibilities for future work as they did not fit within the scope of work. A multitude of research topics could only be touched upon in this thesis, such as theories of cooperation and network theory, and opportunities exist to dive into each element of the thesis in much greater detail for future work, as already detailed in section 4.2.

The results obtained across different scenarios help indicate important policy implications regarding the latest policy incentivizing solar PV adoption in Switzerland - PV adoption targets look set to be exceeded beyond targets for 2035, driven by individual and not community PV systems under the definition of this work. A primary derivation from exceeding targets would mean policymakers can consider reducing the amount of subsidies provided, but extend the period of availability to counter the flattening of adoption post 2030. Also, policy can focus on aiding community PV formations through contractors and PV organizations to act as mediators/project planners to help people cooperate and take advantage of the economies of scale of larger PV systems. It is also seen how important electricity price levels can be to adoption levels, and policymakers must ensure that no loopholes exist which can adversely affect adoption.

Personal Reflections

Working for 6 months on this master thesis, some personal learnings and reflections are:

- New Software and Language - GIS, Python.
- New Skills - Interpreting policy and forecasting implications.
- Believing in a project and giving 200% to it is a very satisfying experience.
- Clear understanding of what the ‘Research Life’ holds - not so bad!
- Complicating research (and life) is easy, simplifying it is more difficult.

Appendix

6.1 Appendix A: Key Building Typologies Stadt Zurich to CEA

Taken from Sabine Python's Semester Project [33].

Statistics types	CEA types
Single family detached building	SINGLE_RES
Single family residential building extended	SINGLE_RES
Multifamily house with 2 apartments	MULTI_RES
Multifamily residential	MULTI_RES
Community-based residential buildings	MULTI_RES
Retirement home	MULTI_RES
Office Building	OFFICE
School house	SCHOOL
Kindergarten School	SCHOOL
University	SCHOOL
Other building for school purposes	SCHOOL
Museum and library	LIBRARY
Theater, concert, movie	LIBRARY
Assembly building, multi-purpose hall	LIBRARY
Church, mosque, synagogue	LIBRARY
Church hall	LIBRARY
Other Culture buildings	LIBRARY
commercial building	RETAIL
Wholesale and retail buildings	RETAIL
Restaurant	RESTAURANT
Hotel	HOTEL
Other building for hospitality	HOTEL
Short-term accommodation	HOTEL
Industrial building	INDUSTRIAL
Workshop building	INDUSTRIAL
Other building for industry	INDUSTRIAL
Agriculture, gardening and economy building	INDUSTRIAL
Sports Hall	GYM
Other buildings for sports	GYM
Train Station building	PARKING
Tram and bus station	PARKING
Garage (1-9 parking spaces)	PARKING
Garage (greater than 9 parking spaces)	PARKING
Warehouse/storage	PARKING
Other small building	PARKING
Residential with commercial use (mixed-use)	MULTI_RES
Hospitals and nursing home	HOSPITAL
Military, police and fire department buildings	HOSPITAL
Prison and detention center	HOSPITAL

6.2 Appendix B: OpenStreetMap Transport Data

Manual cleaning up through visual inspection was necessary to make the boundaries of the plots in Alt-Wiedikon.Basically, kept the main roads and public roads. OSM data downloaded from the internet had 22 types of roads, had to be filtered out/deleted to make making the communities easier

- Mostly the small paths, steps, tracks etc were removed
- Because of this, sometimes logical boundaries were deleted since the above deletion was performed via code. Hence manually checked again (by overlapping with OSM data and Google Maps) to make sure that the plots were according to the ZEV regulations. If not, manually added lines and created boundaries to ensure that the plots made sense.
- Since the energy model made by Sabine aggregated buildings into building blocks, many of the building blocks were going over roads etc (i.e. buildings with arches)
- So manually checked such zones and appropriately included/removed them from the plots made
- It meant that some buildings were going into 2 plots, made decisions to limit them to one plot only

Table 6.1 details the information kept and removed.

Table 6.1: OpenStreetMap Filtering Information of Roads

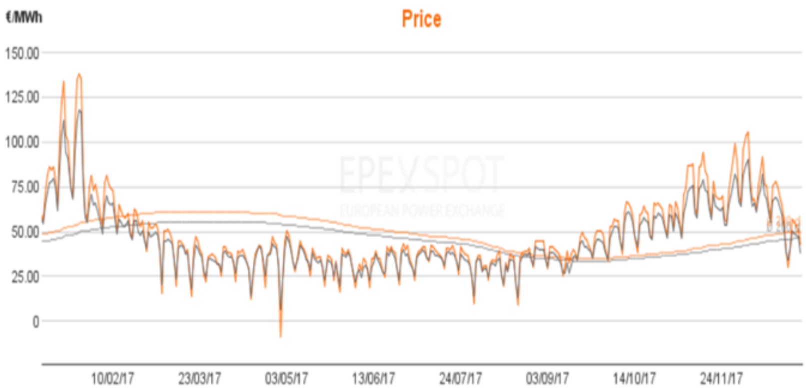
Road Type	**Description**
Construction	KEPT: judgement and google maps
Cycleway	Removed: extra lines next to proper roads like residential/primary/secondary
Footway	Removed: extra lines next to proper roads like residential/primary/secondary.
Living_street	KEPT: Proper roads
Motorway	Removed: Repetition of primary/secondary roads
Motorway_link	Removed: Repetition of primary/secondary roads
Path	Removed: No relevance to ZEV regulations. One of the following: private - like entrances to houses; foot - just for walking across unpaved paths/fields/gardens etc.; asphalt - these led inside complexes; bicycle paths
Pedestrian	Removed: Small paths within complexes, vehicles not allowed
Platform	Removed: Repetition primary/secondary take care
Primary	KEPT: Proper roads
Primary_link	KEPT: just a connection to the primary roads
Proposed	Removed: Repetition
Residential	KEPT: Proper roads
Secondary	KEPT: Proper roads
Secondary_link	Removed: Repetition with secondary
Service	KEPT: Proper roads
Steps	Removed: Similar to paths - irrelevant to ZEV regulations; also part of private or in between gardens/complexes
Tertiary	KEPT: Proper roads
Tertiary_link	Removed: Repetition to tertiary
Track	Removed: All out of area of consideration
Unclassified	KEPT: because they were proper roads
Blanks	KEPT: Railway lines/tram lines/admin boundaries etc.

6.3 Appendix C: Additional Data

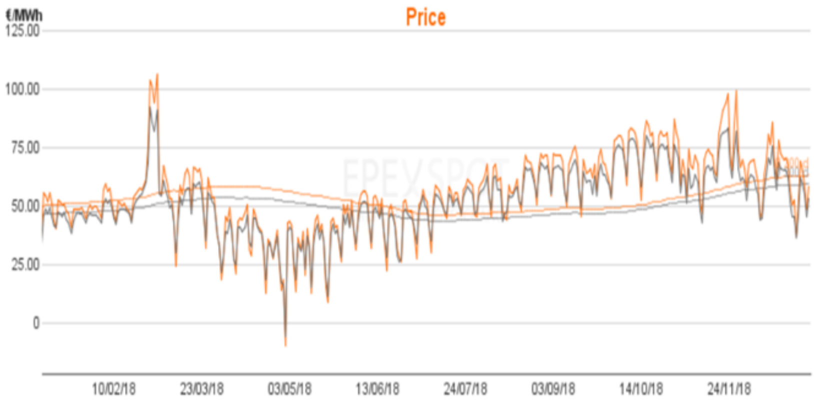
This appendix includes additional information related to the data and prices used in this thesis.

Wholesale Electricity Prices

Average wholesale price levels can be approximately taken as 60 CHF/MWh and 50 CHF/MWh for the peak and non-peak hours respectively. These are considered to not change during the simulation period.



(a) 2017



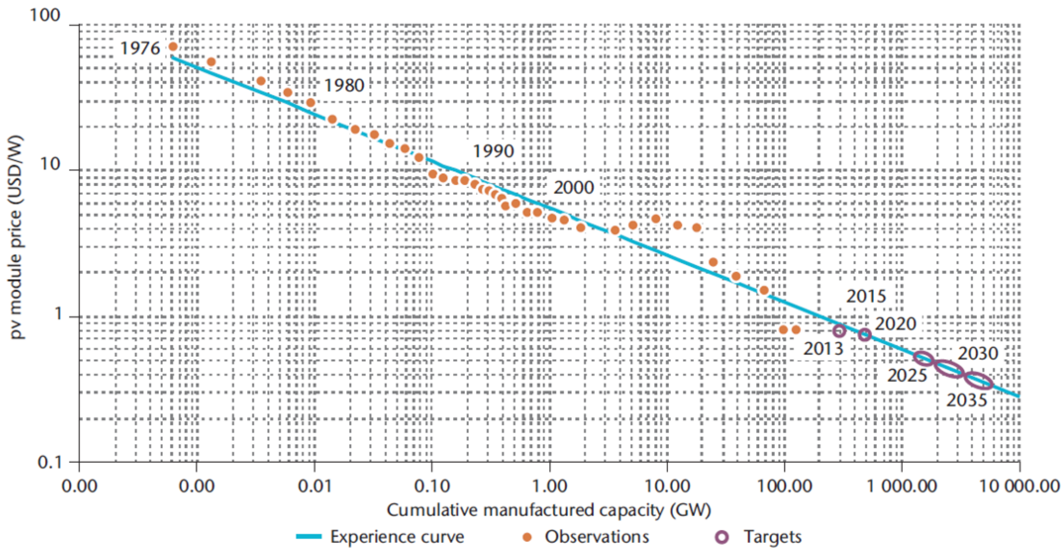
(b) 2018

Figure 6.1: Wholesale Electricity Prices in Switzerland, Epexspot [6]

PV Module Price Projections

These are taken from the IEA Technology Roadmap Solar Photovoltaic Energy 2014 [43].

Figure 10: Past modules prices and projection to 2035 based on learning curve



Notes: Orange dots indicate past module prices; purple dots are expectations. The oval dots correspond to the deployment starting in 2025, comparing the 2DS (left end of oval) and 2DS hi-Ren (right end).

KEY POINT: This roadmap expects the cost of modules to halve in the next 20 years.

Figure 6.2: PV Module Price Projections

6.4 Appendix D: Solar PV Production CEA v SFOE Data

The Swiss Federal Office of Energy (SFOE) have their own PV production estimates through the Sonnendach models [35], which account for roof orientation and tilt, and hence are more accurate than CEA which uses flat roofs for calculating the PV electricity produced. Since the SFOE data available was only with a yearly resolution, it could not be used in this work. However, a comparison with CEA data was useful to have a sense of magnitude difference between the CEA and SFOE data. R-squared of the CEA and SFOE data was very high at 0.933, indicating a good fit, Figure 6.3. However, the median difference, as seen in Figure 6.4, is about 10 MWh. This is equivalent to 3 households' yearly electricity demand, or the yearly generation of a 10 kWp of solar PV system. The CEA is thus underestimating the PV generated from solar PV systems installed on the roofs. However, CEA data is still used as it provided hourly resolution data, which was very important for SCR calculations.

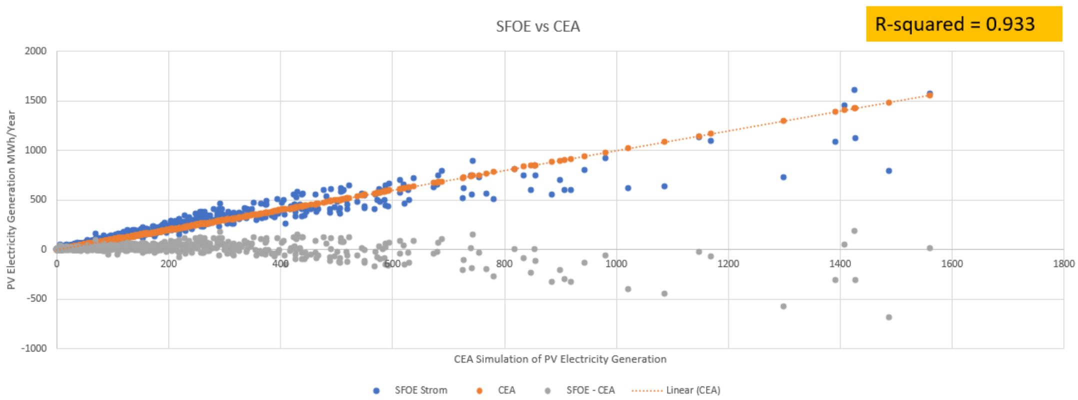


Figure 6.3: SFOE v CEA Data Fit

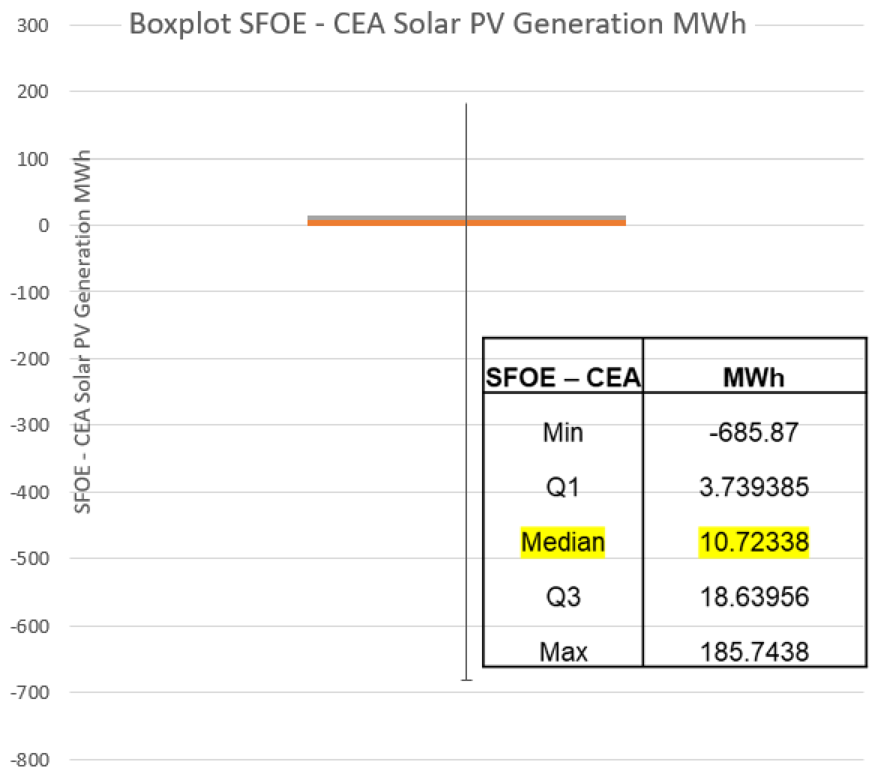


Figure 6.4: Boxplot of difference between SFOE and CEA Data

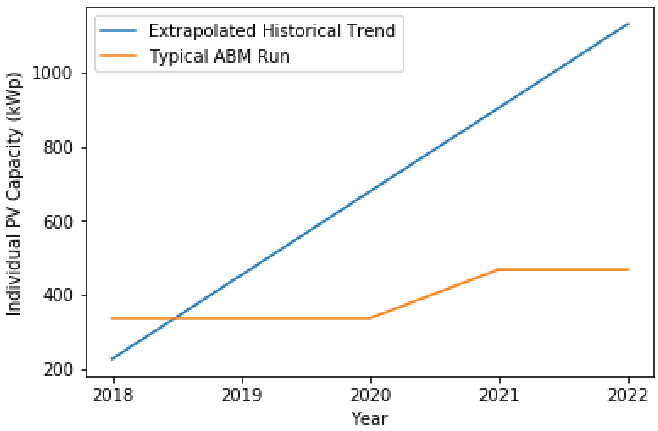
6.5 Appendix E: Calibration

This appendix includes additional information related to the calibration of the model, continued from section 2.6.

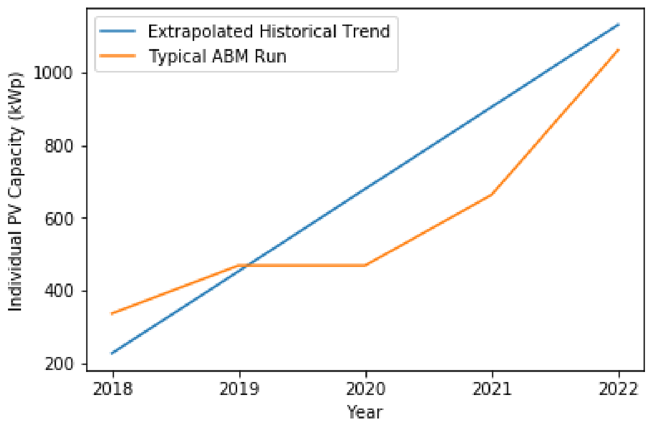
6.5.1 Model A Calibration

Starting with equal weights for attitude, peer effects and perceived behavioural control ($= 1/3$) and a weight of 0.1 for neighbour persuasion, the effect of negative NPV is seen to give the best RMSE fit at -5% of the investment costs. Figure 6.5 shows this.

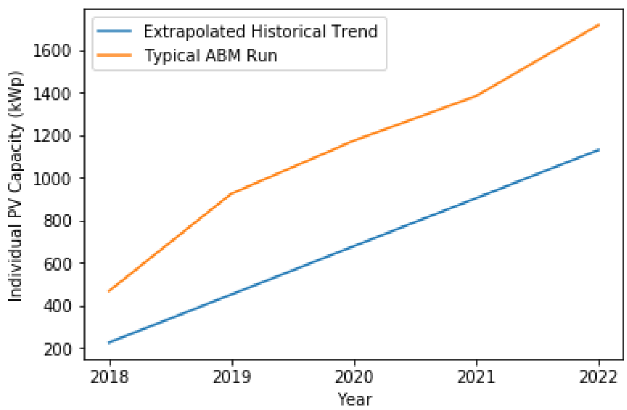
Since the negative NPV worked best at -5% of the investment costs, other weights were varied as shown in Figure 6.6 (not all iterations shown) to achieve the least possible RMSE.



(a) NPV$\geq 0, RMSE = 393.71$

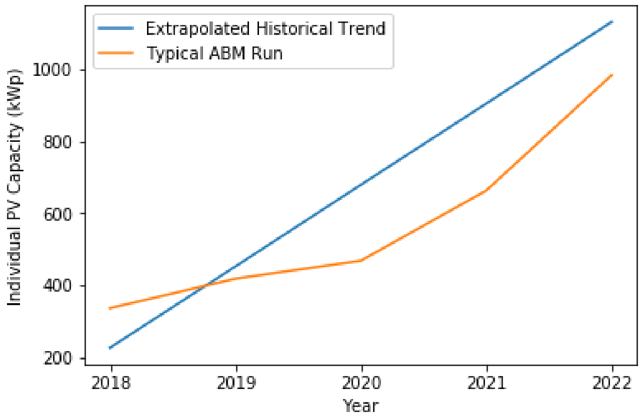


(b) NPV$\geq -5\% of Investment, RMSE = 155.24$

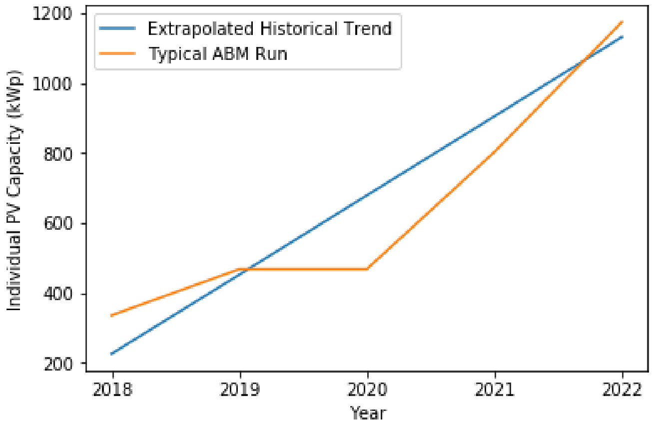


(c) NPV$\geq -10\% of Investment, RMSE = 469.94$

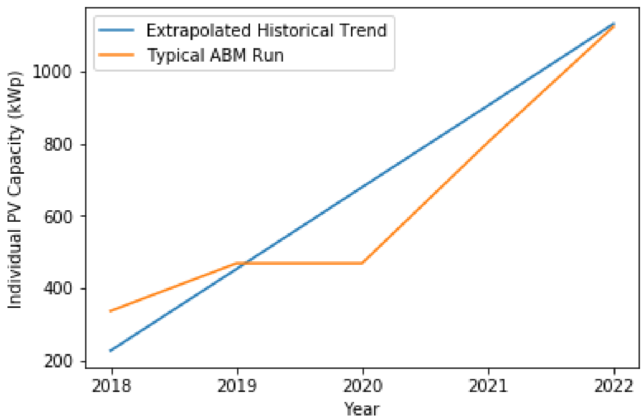
Figure 6.5: Model A: RMSEs for changing NPVs with fixed Attitude = 1/3, Peer Effects = 1/3, PBC = 1/3



(a) Attitude = 0.35, Peer = 0.35, PBC = 0.3, RMSE = 166.279



(b) Attitude = 0.4, Peer = 0.3, PBC = 0.3, RMSE = 117.584

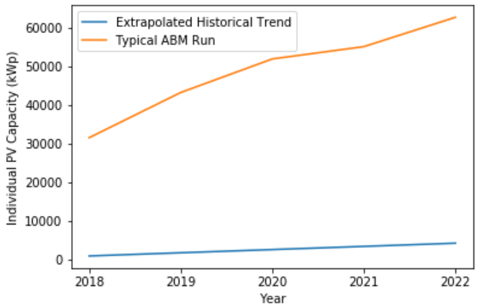


(c) Attitude = 0.39, Peer = 0.31, PBC = 0.3, RMSE = 116.056 - **LEAST RMSE**

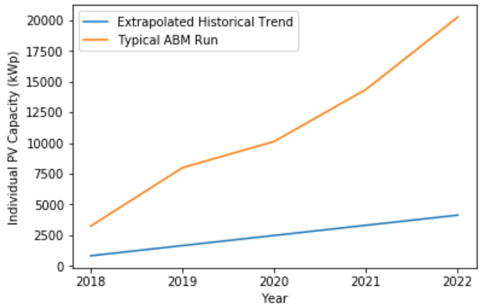
Figure 6.6: Model A: NPV fixed $\geq -5\% of Investment Costs$

6.5.2 Model B Calibration

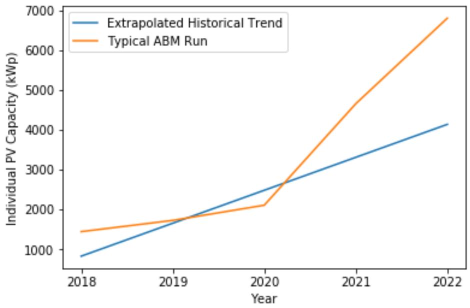
Starting with equal weights for attitude, peer effects and perceived behavioural control (= 1/3) and a weight of 0.1 for neighbour persuasion, the effect of negative NPV is not important for this model and the best RMSE fit is obtained with a positive NPV always. Weights were varied as shown in Figure 6.6 (not all iterations shown) to achieve the least possible RMSE.



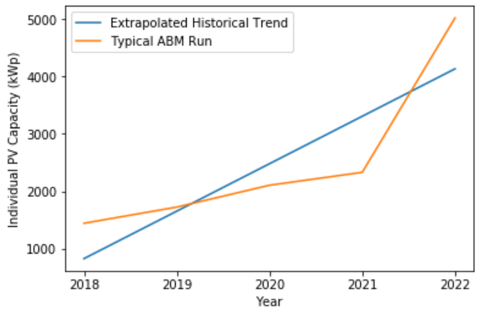
(a) Attitude = 1/3, Peer = 1/3, PBC = 1/3, RMSE = 47333.58



(b) Attitude = 0.27, Peer = 0.4, PBC = 0.33, RMSE = 9867.25



(c) Attitude = 0.27, Peer = 0.42, PBC = 0.31, RMSE = 1373.39



(d) Attitude = 0.25, Peer = 0.42, PBC = 0.33, RMSE = 673.00 - **LEAST RMSE**

Figure 6.7: Model B: NPV always positive

6.6 Appendix F: Github Repository

All relevant code and data of the master thesis is stored in this Github-Repository.

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