Modelling of “Zusammenschlüsse zum Eigenverbrauch” (ZEV) (self-consumption communities) in Bern and assessment of their economic profitability.

Master thesis
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handed in by
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2021

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Abstract

In the Bernese tariff system, a self-consumed kWh is more valuable for the owner of a decentralized PV system than a fed-in kWh. This is because of the difference between the relatively low feed-in tariff and the higher tariffs for grid electricity. The return on investment of a plant depends on self-consumption. In 2018, the legal basis for "Zusammenschlüsse zum Eigenverbrauch" (ZEV, self-consumption communities) was created, which are intended to increase self-consumption by combining different load profiles and thereby promote self-production. In this thesis, a data set for the city of Bern is created, with which the PV potentials and load curves can be simulated in hourly resolution for the individual buildings with the help of the City Energy Analyst. With a multicriteria optimization model, different hypothetical ZEVs are simulated in a case study. Based on the findings of a preliminary study, a building cluster in the Lorraine area of Bern is selected, which includes several residential buildings and a large retail type building. The model calculations show that residential buildings alone or ZEVs consisting only of residential buildings do not exploit their full PV production potential if costs are minimized. A one-time subsidy of 30% of the PV installation costs increases the optimal PV capacity for residential buildings, the retailer is expanding to its full potential even without it. By combining the types of use, the full potential of the cluster in the case study can be exploited even without subsidy. Thus, the results encourage the connection of residential houses and businesses, as this represents the social optimum in the model.

Contents

Acronyms

BAU business as usual

CEA City Energy Analyst

ewb Energie Wasser Bern

FiT feed-in tariff

GWR Gebäude- und Wohnungsregister

IPCC Intergovernmental Panel on Climate Change

kW kilowatt

kWh kilowatt-hour

kWp kilowatt-peak

OSM OpenStreetMaps

PV photovoltaics

SCR self-consumption rate

SSR self-sufficiency rate

ZEV “Zusammenschluss zum Eigenverbrauch”

1 Introduction

With the Paris Agreement of 2015, Switzerland, together with the other participating countries, have committed themselves for the first time to reducing greenhouse gases. The agreement stipulates that all parties must make efforts to hold *"[...] the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change."* (Paris Agreement, Art. 2.1(a), UNFCCC, 2015).

The Intergovernmental Panel on Climate Change (IPCC)[1], has issued a special report on "Global warming of 1.5°C" (IPCC, 2019). One of the key findings with a high level of confidence in the report is, that man-made global warming can be halted by achieving and maintaining net zero global anthropogenic CO_2 emissions and declining net non-CO_2 radiative forcing.

Among human activities, the energy supply sector is the most greenhouse gas-intensive (Bruckner et al., 2014). The IPCC (ibid.) defines the energy supply sector as the sum of all the steps taken from energy production, conversion, distribution and storage to the end user. Based on this definition, the IPCC concludes that the energy supply sector was responsible for about 35% of man-made greenhouse gas emissions in 2010. It should be noted that the sector's annual emissions growth rate almost doubled in the period 2000-2010 compared to the decade 1990-2000 (ibid, p. 516).

This strongly suggests that any pathway leading to the maximum 1.5°C warming target can only work with a change in the energy system. In the Special Report, the authors highlight three characteristics they elaborated and which apply to all pathways to meet the Paris agreement:

> *"(i) growth in the share of energy derived from low-carbon-emitting sources (including renewables, nuclear and fossil fuel with CCS [Carbon (Dioxide) Capture and*

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[1] The United Nations‘ body for assessing the science related to climate change.

> *Storage; note from the author]) and a decline in the overall share of fossil fuels without CCS [. . .],*
>
> *(ii) rapid decline in the carbon intensity of electricity generation simultaneous with further electrification of energy end-use [. . .], and*
>
> *(iii) the growth in the use of CCS applied to fossil and biomass carbon in most 1.5° C pathways [. . .]." (IPCC, 2019, p. 144)*

The electricity sector is of particular importance in this respect, as can be seen from point (ii). All scenarios calculated by the IPCC to achieve significant emission reductions, so-called deep emission cuts, involve electricity replacing other fuels in the end-use sector to a significant extent. The reasoning is, that it is assumed that the decarbonization costs in the electricity sector are lower compared to the rest of the energy supply (Bruckner et al., 2014).

It is evident, that the energy transition towards a CO_2-neutral electricity supply is crucial in the fight against climate change, but there are hurdles to overcome. In IPCC's Fifth Assessment Report (AR5) the authors name the following obstacles:

> *"The principal barriers to transforming the energy supply sector are mobilizing capital investment; lock-in to long-lived high-carbon systems; cultural, institutional, and legal aspects; human capital; and lack of perceived clarity about climate policy [. . .]." (IPCC, 2019, p. 144)*

The above-mentioned challenges also exist to a certain extent in Switzerland. Nevertheless, with its many reservoirs and hydroelectric power plants, which act as giant batteries, Switzerland is in a very comfortable position to achieve transformation in the electricity sector. Gunzinger (2018) shows that, from a technical point of view, the shift to 100% renewable energies in Switzerland is possible. Furthermore he shows that, with skillful investment and implementation, the transformation could even be economically profitable.

In political reality, steps are now being taken. In the wake of the nuclear catastrophe in Fukushima, Japan, in 2011 Switzerland plans the dismantling of nuclear power plants and their replacement by renewable energies as part of the Energiestrategie 2050 (Energy Strategy 2050) [2][3]. The electricity sector of Switzerland is intended to change drastically: By 2035, 11.4 TWh of electricity should be produced from non-hydro renewable energies. This would be an increase of 423% compared to 2019 (BFE, 2021). According to Remund (2017), solar energy transformed with photovoltaics (PV) is considered to have the greatest potential, with a total sustainable potential on Swiss roofs of 24.6 TWh per year[4].

So far, however, the penetration of PV in the Swiss market has been relatively low compared to countries in the EU-28 (BFE, 2018).This is partly due to the fact that PV-systems have mainly been installed on single-family houses. Indeed, in 2018, single-family house systems accounted for 71% of all installations Hostettler (2019). In order to promote the penetration of renewable energies, the so-called “Zusammenschluss zum Eigenverbrauch” (ZEV) (German for self-consumption community) is now authorized under the 2018 Swiss Energy Act[5]. This means that electricity marketing is no longer reserved for energy suppliers alone. Homeowners or neighborhoods are also able to sell the electricity they produce to other tenants and neighbors. Such agents are called “prosumers” Hirschhausen (2017). In principle, the new Act applies to all forms of self-produced energy. It is important to note that this thesis only examines ZEV with PV. Consequently, other technologies are not considered when ZEVs are mentioned.

The advantages that these self-consumption communities are intended to have are twofold. First, ZEV PV-systems should be cheaper per unit than individual installations, because they take advantage of economies of scale. And

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[2] Schweizerische Bundesverfassung (BV; SR 101): Art. 89, Abs. 2.

[3] Energiegesetz (EnG; SR 730.0): Art. 2

[4] Sustainable potential means that the technical, economic and societal limits have been taken into account. Protected buildings, for example, are excluded from this. The technical potential is even greater. (Remund, 2017)

[5] Energiegesetz (EnG; SR 730.0)

second, the real advantage of a community-system is the combination of different consumption profiles (Roberts et al., 2019). The reason is the following: an inherent disadvantage of solar power is, of course, that production depends on the sun. However, power consumption profiles of individual households are usually such that they have a greater need for electricity during the night than during daylight. If different households are combined, then the possibility of consumption profiles complementing each other increases, thereby increasing the self-consumption of a system (Schill et al., 2017).

EnergieSchweiz (2021, p.6, in English SwissEnergy)[6] defines self-consumption as follows: *"Self-consumption means the direct consumption of electricity at the same time as production at the place of production or the simultaneous storage and subsequent consumption at the place of production."* According to Mehta et al. (2019), increased self-consumption is essential in the current Swiss context of relatively low feed-in tariffs (FiTs) in order to make a PV system financially viable. This is because one kilowatt-hour (kWh) of self-generated electricity is sold at the respective feed-in tariff, which is currently a fraction of what is paid for electricity from the utility. In other words, the new legislation intends to create incentives for ZEV and thus a higher level of self-consumption. This seems promising in the context of the Swiss Energy Strategy 2050, but its effectiveness is yet to be evaluated.

This thesis aims to get further insight into this form of prosumage. A georeferenced data set for the municipality of Bern is created, which can be fed into the City Energy Analyst (CEA) model, an energy system model described in subsubsection 3.2.1. From this, the energy consumption and the PV potential can be simulated for each building. Since the computing capacity for this work was limited, only a part of the Lorraine quarter of Bern was simulated. However, the basis for the whole municipality is laid. In order to understand whether enabling ZEVs can fuel the further expansion of solar en-

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[6] The Swiss Federal Office of Energy SFOE introduces on their website, "SwissEnergy is the federal government's central platform for energy efficiency and renewable energy." (SFOE, 2021, Retrieved from : `https://www.bfe.admin.ch/bfe/en/home/swiss-federal-office-of-energy/the-swissenergy-programme.html`)

ergy in Switzerland, their economic viability under current costs and tariffs is investigated. For this purpose, a simpel optimization model is built. With that hypothetical ZEVs are simulated and the costs, the PV production and the remaining grid consumption are optimized. These results are compared with the situation without ZEV. In the process, the three-stage research question is to be answered.

Does the current regulatory environment in Bern, Switzerland, offer the possibility to operate ZEVs with solar power production profitably? Which building characteristics are conducive to the formation of a ZEV? Do the regulatory incentives promote the expansion of PV on the roofs of Bern and thus promote the energy transition?

The scope of the analysis is limited to the city of Bern in terms of regulation and spatially to the inner part of the Lorraine district. Furthermore, only the PV potential of roofs is taken into account, as no comprehensive data is available on the costs of solar cells on facades in Switzerland.

The thesis is structured as follows. In the next section 2 contextual information can be found. The first part, subsection 2.1, outlines the regulation and tariffs relevant for this thesis regarding ZEVs and PV. In subsection 2.2, a brief overview of selected literature is provided. With the multicriteria optimization in subsection 2.4 and self-consumption and self-sufficiency in subsection 2.3, some applied concepts are theoretically introduced. In section 3 the empirical strategy is formulated. First the optimization model (subsection 3.1) is introduced and second (subsection 3.2) the process for the consumption- and production-profile simulation with CEA is shown. The section 4 then provides an overview of the data sets used. Data described in subsection 4.1 to subsection 4.4 is used for the simulation with CEA. subsection 4.5 and subsection 4.6 then contain the basics for the cost assumptions for the PV and storage optimization. section 5 presents the case studies in which the developed tools were used. The results obtained are shown in section 6. Strengths, possible shortcomings and outlook for further research can be found in section 8. Finally, the conclusion in section 9 summarizes the most important takeaways.

2 Background

This chapter provides contextual information relevant for this thesis. First, the regulatory environment regarding the formation of ZEVs is presented. Second, an overview of literature dealing with ZEVs or similar structures is provided. This is followed by a theoretical introduction to self-consumption and self-sufficiency. Finally, the multiobjective optimization is briefly outlined theoretically.

2.1 Regulations concerning ZEVs

This subsection provides an overview of the conditions that must be met for a ZEV, and the regulations that apply to electricity tariffs and subsidy instruments.

2.1.1 Definition of a ZEV

EnergieSchweiz (2021) has published a guide to self-consumption where the framework for "prosumage" is explained. In principle, there are two options for decentralised energy production with self-consumption in Switzerland. With and without ZEV. As this work is limited to ZEVs, the other option is not discussed. In the guide, EnergieSchweiz (2021) summarises the most important legal provisions for a ZEV[7]:

- A ZEV represents a single customer in the sense of the Electricity Supply Act (StromVG). This means that a ZEV has a single connection point to the grid, where the network operator measures feed-in and feed-out. The customer relationship with the grid operator only goes as far as this point; the ZEV itself is responsible for everything that lies beyond the connection point. The ZEV is also free to choose its own legal form.
- Owners of adjacent properties can join together. Properties that are only separated from each other by a road, a railway line or a watercourse are

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[7] The detailed regulations can be found in the Energy Act, EnG, and in the Energy Ordinance, EnV. (SR 730.00 and SR 730.01)

considered to be adjacent as long as the owner of the separating structure agrees.

- The electricity production capacity must be at least 10% of the connected power [W]. Installations that are only operated for a maximum of 500 hours per year are not taken into account in determining the production output.
- If the ZEV consumes more than 100 MWh/year, it may participate in the free electricity market.

These provisions also shape the conditions under which possible ZEVs are searched for in the simulations.

2.1.2 Tariff regulations

The regulatory framework for energy supply is defined at federal level. Power supply to private households, self-consumption and ZEVs are then implemented at municipal level with the local grid operator. In the city of Bern, this is the Energie Wasser Bern (ewb).

Article 15 of the Federal Energy Act of 30 September 2016 (EnG)[8], stipulates that local grid operators are obliged to accept and appropriately remunerate electricity from renewable production in their grid area. This obligation applies if the annual production of the installation does not exceed 5000 MWh minus self-consumption or if the installed capacity does not exceed 3 MW. According to the law, the negotiation of the remuneration is the responsibility of both contracting parties, i.e. the network operator and the prosumer. If there is no agreement, the EnG states that the price paid by the network operator must be based on the costs avoided by the network operator for the acquisition of equivalent energy.

In this thesis ewb's tariffs are investigated. They are decided according to the EnG. All of ewb‘s tariffs can be found in the Systematic Collection of Bern City Law (SSSB); the FiT are regulated in the "Tarif über die

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[8] Energiegesetz vom 30. September 2016, as of 01.01.2018 , EnG; SR 730.0

Stromrücklieferung”[9] and the electricity prices in the “Tarif über die Stromlieferung”[10]. The exact tariffs at the time of this work are listed in subsection 4.6.

The price that may be charged for the electricity produced within a ZEV is also regulated and described in (EnergieSchweiz, 2021). However, in this thesis it is only considered whether the ZEV increases the welfare for the participating group as a whole and not how the possible profits and costs are distributed. This is why the ZEV internal tariff can be neglected.

2.1.3 Non-recurrent remuneration

Photovoltaic systems of all sizes are subsidized throughout Switzerland by the “Einmalvergütung” (EIV, non-recurrent remuneration). This is promoted at the federal level by Pronovo. With the EIV, system operators of photovoltaic systems receive a one-time investment contribution. A basic contribution and a performance contribution per installed kilowatt (kW) are remunerated. The one-time payment covers a maximum of 30% of the relevant investment costs of reference plants at the time of commissioning (Swisssolar, 2021). For simplicity, it is assumed in the case study of this thesis that the subsidy reduces the specific investment costs of a PV system by 30%.

2.2 Current research on ZEV and related concepts

As community PV-systems are a rather new phenomenon, there are few studies on this topic. Some of them, wich also serve as models for the present work, are briefly discussed in the following section.

Roberts et al. (2019) conducted a comprehensive study on the potential of community PV systems in Australia. Although Australia has a very high penetration of individual PV-systems on single-family homes, there is a lack of incentives and regulation to exploit the potential of residential apartment

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[9] SSSB 742.306

[10] SSSB 742.305

blocks. They evaluate apartment building load data, review the legislative environment, evaluate the solar potential, and then create a techno-economic model to simulate electricity flows and financial outcomes of apartment blocks with PV-systems. This research now allows owners to assess which form is reasonable for a community PV-system.

Using the City Energy Analyst software, Mehta et al. (2019) created a model for a district in Zurich which simulates the solar potential and the respective building consumption. On this basis, he created an agent-based decision model and simulates the circumstances under which agents decide to implement an individual or a community PV system, or no system at all. Roberts et al. (2019) provide a tool to analyze the economic viability of a ZEV. Their study includes several technical implementation variants. As the regulatory conditions are not yet very advanced in Australia, the authors restrict the decision bases to the technical and economic aspects. Mehta et al. (2019), on the other hand, operate in the regulatory environment of Switzerland and uses decision theories to investigate the behavior of individual agents. However, they simplify the technical hurdles by ignoring any possible network adjustments and thus also neglects a part of the costs. Spiller et al. (2020) examine various tariff structures for the Chicago metropolitan region with the aim of creating incentives for the broadest possible private investment in DER (distributed energy resources). They find that investments in PV are extremely tariff-dependent. At the same time, they also find that private investment in batteries and private PV is not optimal at current capital and electricity costs in the Chicago market environment. Günther et al. (2019) note that as of 2019, solar prosumage is still very little used in most markets. They therefore analyze solar prosumage with an open source power system model that includes prosuming agents. In their study they apply their model for different scenarios consistent with the German energy strategy for the path to 2030. In contrast to Spiller et al. (2020), they find that for Germany solar prosumage becomes profitable without subsidies in different scenarios. They conclude that with a suitable tariff structure for FiT and the retail market, the energy transition can be promoted and at the same time future system costs could be relieved. This is mainly because the networks, or at least their further expansion, are relieved by prosumage. Fina (2017) investigates the economic efficiency of photovoltaic systems in multi-storey residential buildings in Austria. It looks at case studies for such a building with German and Austrian retail tariffs. For this purpose, it carries out multicriteria optimisations, which allow the optimisation objectives to be given different weights. In this way, the trade-off between cost minimisation and grid minimisation can be represented. It shows that synergy effects exist when different consumption profiles can be combined. However, it also shows that the economic efficiency is strongly dependent on the end customer electricity prices. For example, her study shows no or only little savings potential with Austrian tariffs, while a PV system is always worthwhile with German prices. Fina's (2017) approach also serves as a model for the optimisation model presented in this thesis.

2.3 Self-consumption and self-sufficiency

Two of the most frequently mentioned concepts in the literature to describe decentralized energy systems are self-consumption and self-sufficiency. Thats why they are briefly introduced here. Luthander et al. (2015) visualize the self-consumption rate (SCR) and the self-sufficiency rate (SSR) in buildings and the idea behind the maximization of them as can be seen in Figure 1 and the equations (1) and (2).

$$self-consumption\ rate\ =\frac{C}{B+C} \tag{1}$$

and

$$self-sufficiency\ rate=\frac{C}{A+C} \tag{2}$$

In their review they also deliver the formulation witch is used in this thesis (Luthander et al., 2015, p. 82). At time t , the load is $L(t)$ and the self-

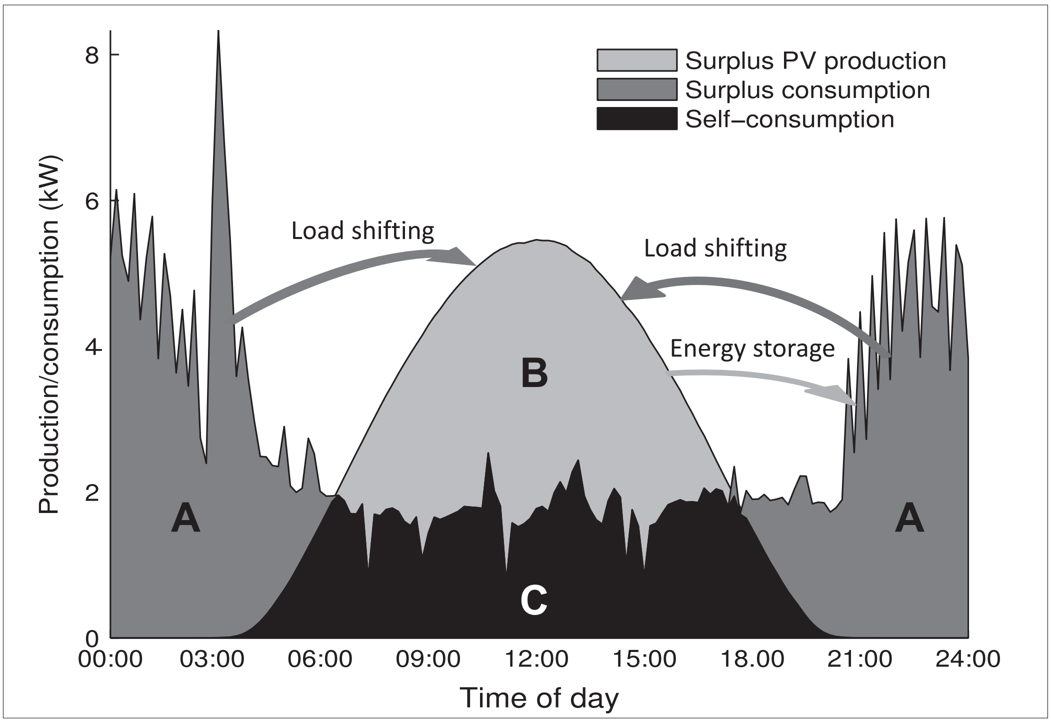

Figure 1: Schematic outline of daily net load (A + C), net generation (B + C) and absolute self-consumption (C) in a building with on-site PV. It also indicates the mechanics of the two main options (load shifting and energy storage) for increasing the self-consumption.
Source: Luthander et al. (2015, p. 82)

produced PV power is $PV(t)$. The self-consumption is given by

$$M(t) = min\{L(t), P(t)\} \tag{3}$$

In other words, as long as the demand is greater than the production, the whole production is consumed in the house. When production exceeds demand, in-house consumption is simply equal to demand. If a battery is considered, the definition can be extended to

$$M(t) = min\{L(t), P(t) + S(t)\} \tag{4}$$

A negative $S(t)$ here means that the battery is charging and a positive one, that it is discharging.

From this the definitions for the self-consumption rate and the self-sufficiency rate follow:

$$\phi_{SC} = \frac{\int_{t=t_1}^{t_2} M(t)dt}{\int_{t=t_1}^{t_2} P(t)dt} \tag{5}$$

$$\phi_{SS} = \frac{\int_{t=t_1}^{t_2} M(t)dt}{\int_{t=t_1}^{t_2} L(t)dt} \tag{6}$$

Luthander et al. (2015) state that a typical integration period is one year, which is sufficient to compensate for seasonalities and short-term volatilities. This also corresponds to the study period of this thesis.

2.4 Multicriteria Optimization

multicriteria optimizations are problems that have more than one objective function (Martins and Ning, 2021). A multicriteria optimization offers the advantage that it can investigate the previously mentioned trade-off between full exploitation of the potential and economic optimization, i.e., cost minimization.

Where a single optimization minimizes (or maximizes, but in this thesis the convention to formulate optimizations as minimization problems is adopted) an objective function

$$minimize\ f(x) \tag{7}$$

the multicriteria optimization expands to a problem with multiple objective functions (Martins and Ning, 2021).

$$minimize\ f(x) = \begin{bmatrix} f_1(x) \\ f_2(x) \\ \vdots \\ f_{n_f}(x) \end{bmatrix},\ where\ n_f \geq 2 \tag{8}$$

The difference to the single optimization is that in general the trade-offs mentioned above exist and not all objective functions can be minimized at the same time. The exception would be if the objective functions were separable, i.e. they depend on different design variables and can be minimized independently of each other. However, this is not the case here, so it will not be discussed further.

If not all objective functions can be optimized simultaneously without trade-offs, which is the case here, the concept of Pareto optimality must be used. Pareto optimal is a state in which no outcome of one objective function can be improved without worsening the outcome of another. Improving here means being closer to the individual optimum of the individual objective function. In the case with two objectives, as is the case in this work, the two functions can be spanned in a 2D coordinate system, the design space. The two axes then correspond to the respective objective functions. A point in this surface that is better than another in at least one objective function and not worse for the other dominates the other. All points that are not dominated by any other point are called non-dominated and are Pareto-optimal. The set of all these points is called Pareto-set, described as a function also Pareto-front. Figure 2 shows the Pareto set schematically for the case with two objective functions. This Pareto-front now describes the trade-off between the two objectives.

The goal of a multicriteria optimizations is to find the Pareto front. Since in many cases there are potentially infinitely many points on the front, the procedure usually corresponds to an approximation to the set. In the biobjective case, the Pareto front is a line in the space between the ordinates of both objective functions.

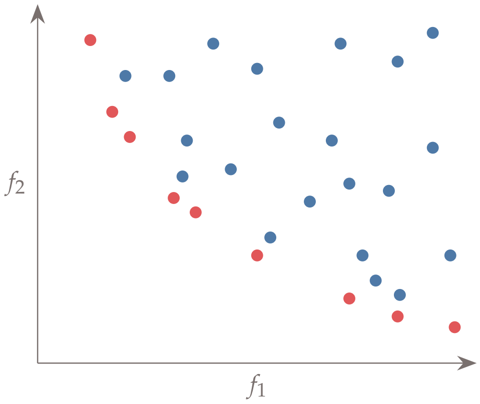

Figure 2: Example of a Pareto set. All the evaluated points are plotted against the two minimization objectives. The red points are non-dominated and thus in the pareto-set.

Source: Martins and Ning (2021)

There are many ways to solve multi objective optimizations. The method used in this work is the weighted sum method. It can be said that it is no longer a multiobjective optimization in the true sense. This is because the two objective functions are combined in a new linear objective function and each is given a weight. This new objective function is then optimized. The Pareto-front can then be approximated by changing the weights for different optimization processes. The method can be formulated in this way:

$$\bar{f}(x) = \sum_{i}^{N} w_i f_i(x) \tag{9}$$

Commonly, the weights are normalized to 1 so that $\sum_i^n w_i = 1$.

In the bi-objective case this reduces to:

$$\bar{f}(x) = w f_i(x) + (1 - w) f_2(x) \tag{10}$$

The weighted sum method is very popular because it is relatively simple to use and easy to understand. However, it also has some disadvantages. For example, the Pareto front can only be found at convex areas, for non-convex courses this method will not be able to approximate the whole front. Another disadvantage is that the choice of even spaced weights does not lead to equal distribution on the Pareto front. Thus, the choice of weights is not always reasonable to clarify.

For the sake of simplicity and comprehensibility, it is assumed that the weighted sum approach is sufficient for this thesis and approximates the Pareto front sufficiently well. In the following, the optimization problem used in this thesis will be set up.

3 Empirical strategy

In order to investigate the economic efficiency of ZEVs with PV, different hypothetical ZEVs in the neighbourhood of Lorraine are assumed and modeled. It is then examined whether the ZEV is more economical compared to the individual houses in total and whether higher PV capacities are optimal due to the merger. However, it is not investigated whether an agent would decide ex ante to participate in the ZEV. Based on load and PV production profiles, the size of the PV system is optimized for the respective ZEV; in the study with storage, the storage capacity is also optimized. The load and PV potential data are also obtained from model simulations. subsection 3.2 describes this preparatory simulation. In the following subsection 3.1, however, the optimisation model is presented first. The model formulation was taken from Fina (2017) and slightly adapted to my input data. The model adjustments were made considering the fundamental electricity model of Pierre Buisson used in teaching in the lecture Power Market Fundamentals (Axpo Solutions). The model for this thesis was written in Python with jupyter notebook for the implementation with Gurobi. Gurobi is a solver for mathematical optimization problems.

3.1 Optimization modell

The chosen model has two objective functions that are combined into one as a weighted sum. A short introduction to the weighted-sum approach can be found in subsection 2.4. In the following, the model is presented and the variables are explained. The respective units are given in square brackets after the variable. The optimization problem is defined as

$$\min_{PV, KW, S^{max}} \quad V = wC + (1-w)A, \quad w \in [0,1] \tag{11}$$

C and A correspond to the two different goals of cost minimisation and self-sufficiency, also called autarky. w represents the weighting factor with which the priority of a goal can be defined. $w = 1$ means in the present case that only the costs are minimised and the autarky goal is omitted. The reverse is true for $w = 0$. Values in between mean combinations of the goals with the chosen priorities. The repeated changing of the weights and renewed execution of the blended optimisation leads to the finding of points in the Pareto set and thus to the approximation of the Pareto front.

The observation time frame is given by the input data. These are available for one year in hourly resolution, which results in $H = 8760$ time steps.

$$C = \sum_{t=0}^{H} e_t^g \cdot p_t^g + PV\left[(I_0^p \ \cdot \ R_p \ + \ c_{o\&m})KW - p^f \cdot \sum_{t=0}^{H} e_t^f\right] + I_0^s \cdot \ R_s \ \cdot \ S^{max} + \epsilon \tag{12}$$

$$A = \sum_{t=0}^{H} e_t^g \tag{13}$$

C represents the cost function. e_t^g [kWh] corresponds to the grid electricity demand of the considered object in the annual hour t. p_t^g [CHF/kWh] is the grid electricity tariff in hour t, the tariff is time-dependent to represent the double tariffs during a day. The first sum therefore corresponds to the annual costs for grid electricity.

PV is a binary variable, if $PV = 1$ a PV system exists, if $PV = 0$ it does not. This variable controls the inclusion of the cost components that depend on the installation of PV. $c_{o\&m}$ [kilowatt-peak (kWp)] are the specific operating costs of a PV system. Here, for example, the cleaning costs and inverter costs are taken into account. KW [kWp] is the peak power of the installed PV system. Multiplied by the specific costs, the capacity-dependent investment costs result. I_0^p [CHF/kWp] represents the specific investment costs of a PV system. Since the period under consideration is one year, an annuity factor R must be included to convert the present value of the capital costs into a constant annual amount (annuity).

$$R = \frac{r \ \cdot \ (1+r)^T}{(1+r)^T - 1} \tag{14}$$

In there r is the risk-adjusted reference interest rate and T the assumed lifetime of the installation in years. In the cost function, a distinction is made between the annuity factor R_p of the modules and R_s of the storage, as these can have different lifetimes.

p^f [CHF/kWh] is the sales price for the electricity fed back into the grid, the FiT. Multiplied by the PV electricity fed back into the grid e_t^f, this results in the revenue from decentralised production, which can be deducted from the costs. I_0^s [CHF/kWh], the specific storage costs multiplied by S^{max}, the maximum storage capacity in kWh, and R_s result in the annuity of the storage costs. The model allows for storage without production. But for storage to be built in that case, the time differences in the electricity tariff would have to be large enough to make the storage of grid electricity worthwhile. A rational grid operator will not offer such tariffs.

ϵ finally is a fallback term, representing all other factors that may have direct influence on the costs, regardless of the existence of PV or the grid power. Such as costs incurred per connection point when connecting a ZEV.

A denotes the goal of self-sufficiency. Maximum self-sufficiency can be expressed in terms of minimimal grid consumption e_t^g [kWh], which is why the sum of hourly grid power consumption is minimized here.

The optimization of the presented objective function must not violate the following constraints.

$$s_t^{out} + e_t^g + e_t^s = L_t \tag{15}$$

$$s_t^{in} + e_t^f + e_t^s = KW \cdot u \cdot P_t \tag{16}$$

$$KW \leq MA \cdot PV \tag{17}$$

$$S_{t-1} - \frac{1}{n} s_t^{out} + n \cdot s_t^{in} = S_t \leq S^{max} \tag{18}$$

$$S_1 = S_H = 0 \tag{19}$$

$$KW, e_t^g, e_t^s, e_t^f, s_t^{in}, s_t^{out}, S_t \geq 0 \tag{20}$$

$$t = 1,\ 2,\ ...,\ H$$

L_t corresponds to the hourly electricity consumption profile. Constraint 15 states that the power consumption in kWh of each hour must be covered either by grid purchase, self-production or battery discharge. e_t^g is the purchased, e_t^s the self-produced and s_t^{out} the discharged amount in kWh. Constraint 16 ensures that the produced PV electricity in kWh is at any time either stored in (s_t^{in}), fed into the grid (e_t^f) or self-consumed (e_t^s). P_t is the profile of the PV production potential on the roof, this is given in kWh/m^2. KW is the size of the system in kWp. With the factor u [m^2/kWp] the PV production is converted into kWh. Constraint 17 states that the peak power of the plant must not exceed the maximum possible peak power allowed by the roof area (MA [kWp]). Constraint 20 specifies that the state of charge of the battery S_t cannot exceed the maximum storage capacity. S_t is equal to the state in the previous period minus the discharged electricity s_t^{out} or plus the stored electricity s_t^{in}. The storing and retrieving is subject to losses, n corresponds to the efficiency. The storage is said to be empty at the beginning and end of the optimization (Constraint 19). For all endogenous variables, the nonnegativity constraints hold.

Business as usual scenario The business as usual (BAU) scenario assumes that no PV is considered at all, the binary PV variable and S^{max} are set to 0 and the annual costs reduce to

$$C_{BAU} = \sum_{t=0}^{H} p_t^g \cdot e_t^g + \epsilon \tag{21}$$

The non-negativity conditions still hold. As all electricity demand must now be met by gridpower only, the other constraints simplify accordingly:

$$e_t^g = L_t \tag{22}$$

These costs are the basis for the comparison of the economic efficiency with the scenarios in which PV is built.

P_t, the PV production profile and L_t the electricity consumption profile are the input data for the model introduced in this subsection 3.1. The assumptions about the model parameters which were made for the optimizations in the preliminary study and in the case study can be found in the Appendix. The In the next subsection 3.2, it will be shown how these were simulated using the CEA.

3.2 Simulation of the load and PV data

As mentioned before, the goal in using the CEA software is to obtain hourly data on the expected electricity production from potential PV systems (P_t in Equation 16) and hourly data on the expected electricity consumption (L_t in Equation 15) from the individual buildings. It is necessary to simulate these data, because there are no hourly electricity consumption data for Bern available for a larger scale. The reason for this is that currently the vast majority of electricity meters are still only read every six months. This data situation will only change with the increased use of smartmeters in the future.[11] To create the hourly PV power generation potentials for a whole year, the data on the typologies of the houses, spatial data of Bern and weather data for a year were needed. The datasets are described in section 4. The rest, i.e. the creation of the model for the electricity generation with PV and also that for the electricity consumption, is done by the CEA. For this work, apart from the own input data, the default settings of CEA was used, which can be found in the GitHub repository[12]. The following sections describe the simulation

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[11] The Electricity Supply Ordinance states that by the end of 2027, 80% of all metering devices in a network area must comply with the requirements of Articles 8a and 8b. This means, among other things, recording 1/4-hourly data for at least 60 days. The remaining 20% may remain in use until the end of their functional capability. (StromVV; SR 734.1: Art. 31e)

[12] `https://github.com/architecture-building-systems/CityEnergyAnalyst/tree/master/cea/databases/CH`, (Fonseca et al., 2021), last checked, 30.10.21.

model.

3.2.1 City Energy Analyst

The CEA software package (Fonseca et al., 2021) is, as the developers (Fonseca et al., 2016, p. 1) themselves describe,

> *"[. . .]a computational framework for the analysis and optimization of energy systems in neighborhoods and city districts. The framework allows analyzing the energy, carbon and financial benefits of multiple urban design scenarios in conjunction to optimal schemes of distributed generation."*

The first step of the analysis is to collect the underlying data. As one of the developers of the CEA itself, Fonseca (2019) says, collecting geospatial data on the built environment and energy infrastructure is a very laborious process that has sometimes taken up to a year. To enable a start of the analysis within a shorter time, the CEA team has developed data helper tools.

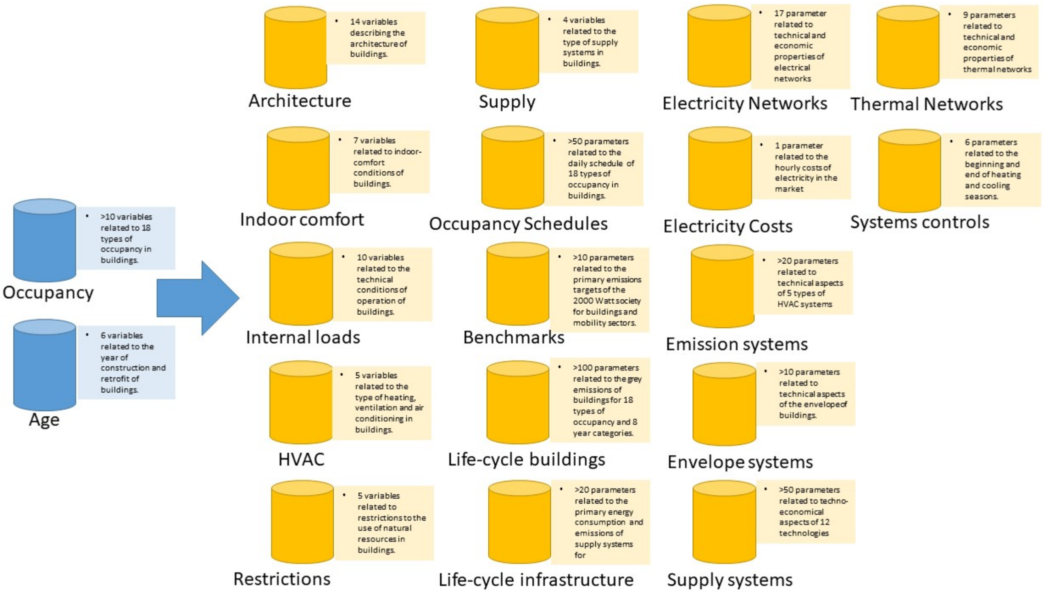

Figure 3: CEA Databases
Source: Fonseca (2019).

The heart of these tools is an open source database from which techno-economic aspects for the buildings in the investigated zone can be obtained. The developers have compiled them according to the latest state and best knowledge (Fonseca, 2019). The database is representative for buildings and settlements in Switzerland. What is left to the user to do, is creating his or her own “typology” database. This needs to contain the year of construction or renovation and types of occupancy of the individual buildings. The type of occupancy can be chosen out of 18 predefined standard use types in the CEA database. Together with the age the type then provides the inputs for the determination of the variables from the 17 CEA internal databases. Figure 3 shows an overview of the CEA internal databases. All data, those provided by CEA in a standardized way too, can be collected and fed in by the user. It quickly becomes clear that, depending on the data situation, a variety of different investigations can be carried out. In this work, however, in order not to go beyond the scope, only the aforementioned typology inputs are userdefined and then the comprehensive CEA data basis is used.

Python (2018) explains the whole CEA workflow based on the modelling of Wiedikon in Zurich. The flowchart in Figure 4 visualises the process. The squares are databases and the circles tools. All data in the source database square are collected by the user. As can be seen in Figure 4, spatial data is needed as primary input in addition to the typology data. These consist on the one hand of the terrain topography of the area to be investigated and on the other hand of the geometries of the structures standing on it. The topography plays an important role especially in the case of energy production by solar energy, because otherwise shadings are calculated incorrectly. The geometry of the buildings determines not only the potentials for PV generation, but also the magnitude of the processes taking place in them. CEA, for example, assumes an occupation scheme per type of occupancy and more or less visitors/occupants depending on the size and number of floors. In addition, of course, the geometry is also crucial for the solar potentials.

CEA provides also a tool to create spatial data. So it‘s possible to do an analysis even if one does not have all the data. However, these helpers are

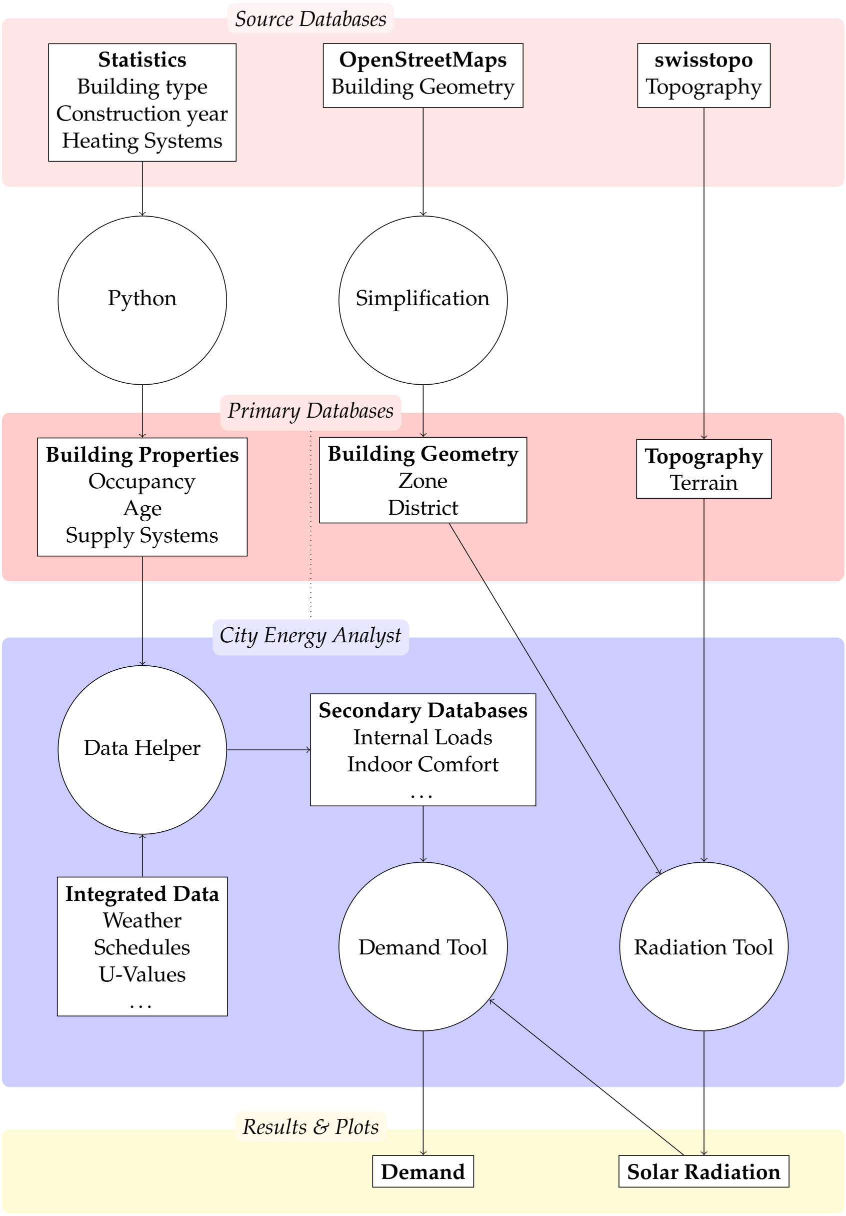

Figure 4: CEA workflow
Source: Python (2018).

currently very rudimentary. For example, for the topography, CEA simply creates a flat surface for the entire study area. For building geometries, CEA obtains building floor plans from OpenStreetMaps (OSM) and extrudes block models from them. For the simulation of PV potentials this is not suitable, since OSM has in majority no height information to the buildings. Where no information is available, an average height is simply assumed. In Bern, this is unfortunately the case for the most part, which is why a better data source was sought for this thesis.

Therefore data preparation is one of the most important and time-consuming steps. Using ArcGIS and R, the characteristics of the Gebäude- und Wohnungsregister (GWR) - in English Federal Register of Buildings and Dwellings - are linked to the spatial data of the buildings. The next chapter 3.2.2 describes this process in detail.

The inputs for the simulation are then the primary databases: As building properties the occupancy and age of the buildings in the analyzed zone are integrated in a dataBase format. The building geometry is defined for the buildings in the zone of analysis and a buffer zone (district) to account for possible shadings. These are inserted in a shapefile format. Finally, the terrain of the district is taken account of through a raster file. In the online CEA documentation (Fonseca, 2019) the exact types, names and order of the inputs can be found and must be strictly adhered to. Although the CEA documentation is quite extensive, not all necessary or useful information is available in a manual. So a large part of the process was trial and error, browsing threads on internet forums and deciphering error messages.

The final output data from the CEA used in this thesis are, first, the electricity consumption and PV production profiles in kWh and hourly resolution for each simulated building in the zone. The former correspond to L_t in the optimization model presented in subsection 3.1. The PV production profiles are still converted to kWh/m^2 for this work to obtain P_t. If a ZEV is assumed, the consumption and PV data are simply merged.

$$L_t = \sum_{i=1}^{Z} e^{g}_{t,i} \tag{23}$$

and

$$P_t = \frac{\sum_{i=1}^{Z} P_{t,i} \cdot Area(i)}{\sum_{i=1}^{Z} Area(i)} \tag{24}$$

for hour t and buildings $i = 1, ..., Z$ which form the ZEV.

3.2.2 Model building process

To prepare the building geometry a tool was created with the model builder from ArcGIS Pro, which combines the data from the different sources. This with the goal that the buildings and their according information, are as accurate as possible according to the current state of the sources. And that the CEA can still read them in. Figure 6 shows the flowchart of the tool in the ArcGIS Pro model builder.

With the first tool everything is projected to the same coordinate reference system. Compatible with CEA is WGS 84[13]. Since no joins are possible with 3D features in ArcGIS, a 2D footprint of the city model is also made.

In the second tool the next steps follow. First the zone shapefile is connected with the typology database of CEA. Then the GWR data set is added to the same layer, so that this layer now has the floor plans of the houses and for each house the CEA typology and GWR data. This is possible because the GWR dataset was transformed into a spatial point layer using QGIS.

Now the *building class*, the *year of construction and renovation* can be transferred from the GWR data set to the typology data frame. To make the model more accurate, another step could be to transfer the heating and hot water system information from the GWR to CEA's HVAC database. However, these are not widely available for Bern, so this was not done here.

After the necessary typology information is read from the GWR, the tool connects the footprint of the city model with the previous layer. Based on this, it then calculates the heights of the individual buildings. These complete the building geometry variables for the zone file of CEA together with the GWR floor attribute. The next two stages address features that CEA cannot handle. They delete all buildings that are less than 3 meters high and change the number of floors above ground to greater than or equal to one, since CEA cannot simulate buildings with 0 floors above ground or floors less than 3 meters high.

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[13] Reference system as basis for coordinates, swisstopo, https://www.swisstopo.admin.ch/en/knowledge-facts/surveying-geodesy/coordinates/reference-system.html, last checked 31.08.21.

The few buildings that still have a height/floor ratio of less than 3 can then be easily changed by hand in the CEA application.

Now the zone layer is complete with all desired information, all excess attributes are removed and the layer can be exported as a shapefile. The same applies to the typology dataframe. All desired information is complete and only needs to be put into the required database format. To make this work, the CEA-generated typology database is read in again and the calculated values are simply transferred into the fresh table. This is necessary because CEA uses column names that start with numbers, which were actually not compatible with the naming convention of Python and thus ArcGIS. So it was impossible to name columns with a number in ArcGIS. With the re-import this problem is circumvented. In Figure 5 the four layers that contain the input data for CEA can be seen. Below then the study area created by CEA with the simplification of the building geometry is shown. For this model and the input weather year, CEA simulates the irradiance, the PV potential (or other technologies if desired) and the energy demand using the internal database. All this in hourly resolution for a whole year for each individual building. The data basis includes the entire municipality of Bern. However, simulating such a large model with the available computing capacity would not be productive. For the case study, therefore, a district was sought that can be simulated in a practicable time and seems suitable for ZEVs. The suitability criteria are broadly defined. First, a visual inspection of the solar irradiance was performed via Sonnendach.ch. The condition was that the majority of the houses achieve a suitability of “good”. On the other hand, a visual search was also made for a neighborhood that, despite having a majority of residential buildings, also had a diverse mix of uses. With the help of ArcGis, the building use types of the GWR were made visible. The choice fell on the inner Lorraine, since the area can be well delimited between the Aare and the Nordring and, in addition to good irradiation values, also contains the desired use types. The modeled district is shown in Figure 12 in section 5.

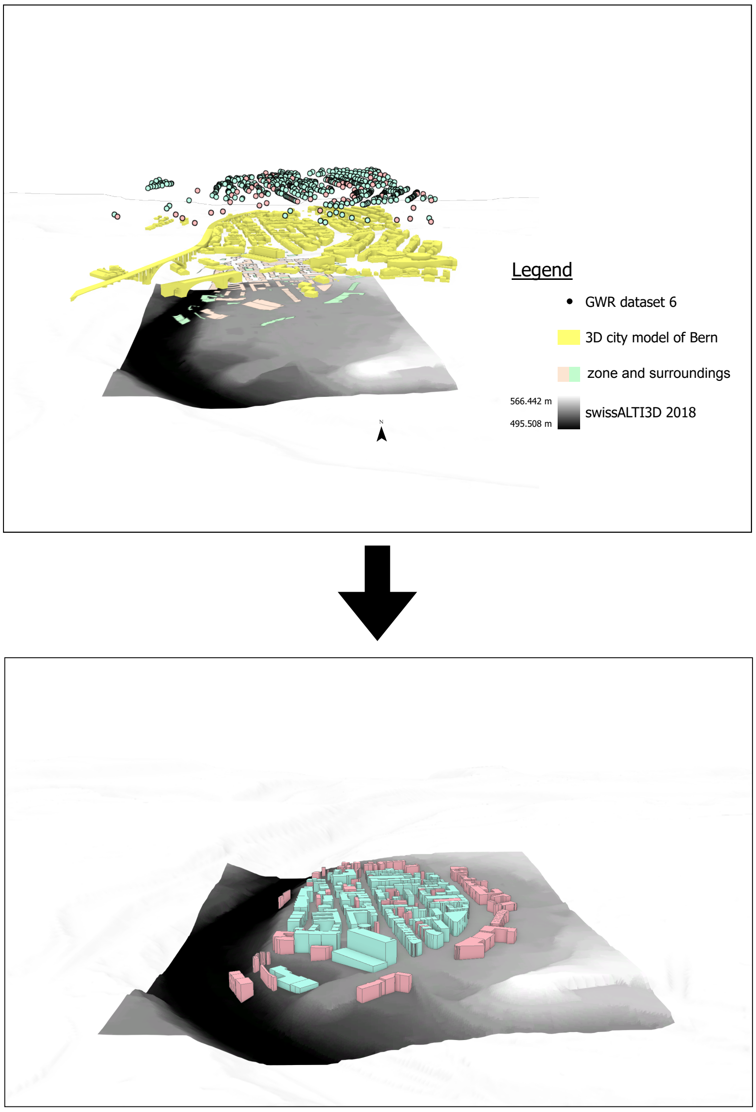

Figure 5: Above: Visualisation of all input datasets georeferenced and projected on WGS 84 - elevated for better distinction. **Below:** Visualization of the finished building model from CEA. Blue are the buildings for which the PV potential and electricity consumption are simulated. Pink are the surrounding buildings for which no output is generated, but which are still modeled for the irradiance simulation

Source: swisstopo, Geoinformation Stadt Bern, OpenStreetMap. Own visualization with ArcGIS.

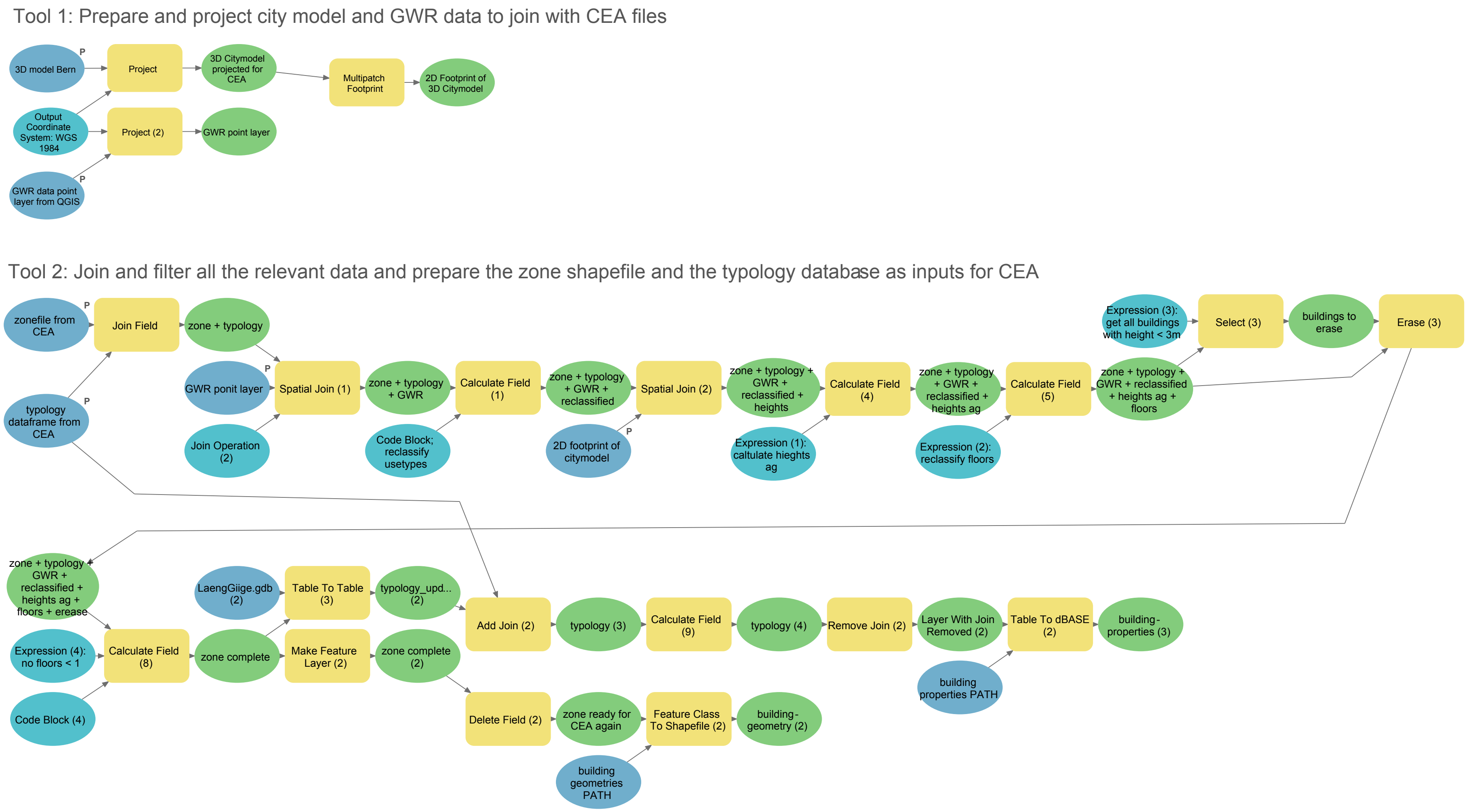

Figure 6: Flowchart of the tools for preparing input data for the CEA. Created with the model builder in ArcGIS Pro. *Source:* own visualization.

4 Data

The following section provides short descriptions for the data used in this thesis. The first four subsections consider inputs for the CEA software. The last three are the basis for the cost assumptions in the optimization model.

4.1 Weather

Suitable weather data can be ordered from Meteotest. With their software Meteonorm they can create typical weather years for around the globe.[14] CEA requires these in the standardized EPW (EnergyPlus Weather) format. The parameters provided in the .epw file determine the solar and atmospheric influences, which makes them indispensable for the simulation of PV power and energy demand. The documentation of CEA(Fonseca et al., 2021) shows which parameters are used by the CEA and in the documentation of Meteonorm (Remund et al., 2020) the production of each can be read.

4.2 Topography

The Federal Office of Topography swisstopo offers swissALTI3D. This is a high resolution digital elevation model for the whole of Switzerland in grid sizes of 0.5-2m. For this thesis a section of the DEM of Bern in the resolution of 2x2 meters was used. The data must be in raster format TIFF and projected to the WGS 1984 32 S coordinate reference system in order to be used in the CEA. The raster file of Bern also had to be cut into smaller areas, since the CEA could not read in a terrain of the entire size of the municipality. The documentation (swisstopo, 2018) has further informations on the DEM and shows how the elevation data were obtained.

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[14] https://meteonorm.meteotest.ch, last checked 31.08.21, Meteonorm is a is a product by Meteotest AG, Bern.

4.3 Building typology

The CEA records the typology description of each building in a dbf-database. This typology table defines the blue inputs from Figure 3. The user can specify the standard of construction, age and use. Those inputs then create the yellow secondary databases with the data helper tool. These data are obtained from the Federal Register of Buildings and Dwellings (GWR). The attributes number of floors, year or period of construction and building class are used in this thesis. Detailed information about the dataset can be found in BFS (2018).

4.4 Building geometry

As mentioned before, the CEA‘s tool for creating building geometries (the zone helper) from OSM is handy and you quickly have a study area at hand. However, the coverage of complete data in OSM for Bern is thin. For example, in the study area Lorraine the great majority of the houses have the same height and the same type when using the zone helper. Therefore it was quickly clear that better data had to be used. The documentation of the CEA gives exact information how the input files have to be structured and formatted. In practice, only one workflow containing different data sets worked for the simulation of the study site.

There are several 3D building models for Switzerland. Comprehensive for the whole country are the two datasets swissBUILDINGS3D 1.0 and swissBUILDINGS3D 2.0. The first one is a block model with a Level of Detail of 1 (LoD 1). This means the geometries of the buildings are simplified and cartographic generalization is practiced, i.e. individual buildings might be grouped into building units. Thus, the number of buildings does not correspond to reality. The second version has at least LoD 2 to LoD 3 and is therefore roof accurate, i.e. no longer simplified to a block. Although the floor plans of the buildings are adhered to in this model, rows of houses are still combined into one building geometry. For the city of Bern there is also a 3D model offered by the municipality, which is also at least roof accurate (LoD 2.5). The individual houses are only represented individually by the Bern model. However, it turned out that no data set can be used alone. On the one hand, the CEA cannot use roof-exact inputs and on the other hand, the houses in the swissBUILDINGS3D 1.0 and 2.0 datasets were grouped and thus oversimplified. Using these does not make sense, since it was intended to find out which houses should possibly combine to form a ZEV. For this, the individual houses are necessary as they are divided in reality.

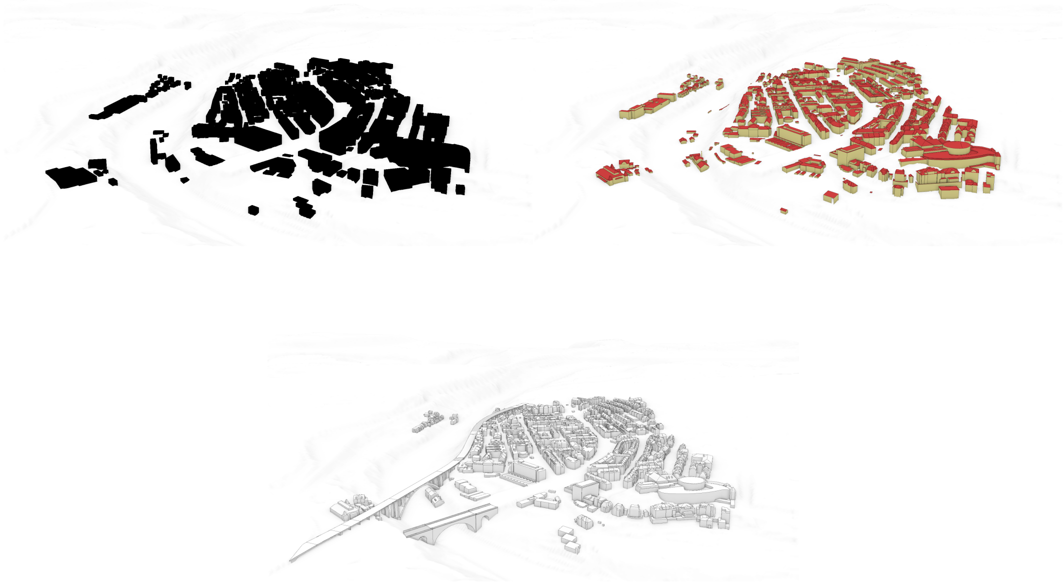
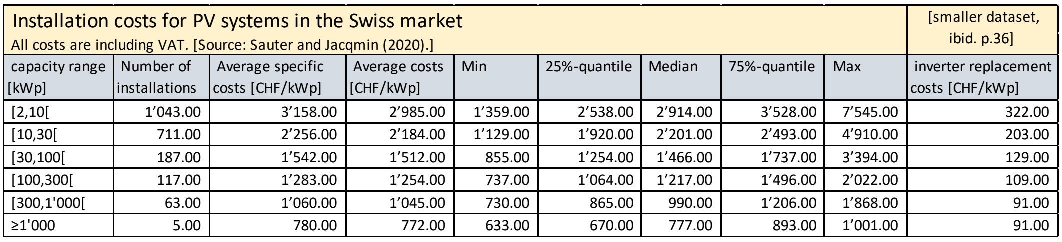


Figure 7: 3D building models
Source: swisstopo, Geoinformation Stadt Bern. Own visualization with ArcGIS.

A detour was found, which led again over the helpers of the CEA. With the zone helper tool, the area of investigation is marked out on OpenStreetMap. The CEA then creates the necessary shapefile with the building footprints and heights supplied by OSM. In this file, the heights are not correct at all, as OpenStreetMap lacks this information. But the floor plans are drawn for the individual buildings, as needed for the analysis, and the compatibility for further use in the CEA is given. Since the CEA extrudes the buildings in the simulation anyway (i.e. draws them as cuboids from the ground plans to the specified heights) and thus displays them without roof shapes, the higher LoD of the other data sets are of no use. However, the exact heights of these datasets are still needed.

4.5 PV costs

EnergieSchweiz has commissioned Planair to conduct an observational study of the Swiss PV market, which focuses on analyzing the costs of PV installations and not the volume of the market (Sauter and Jacqmin, 2020). The costs of the entire project are examined. For this purpose, the study is divided into two parts, the first deals with installation costs up to commissioning. The second covers all costs incurred by the developer and not invoiced by the companies involved in the installation. For this purpose, 2,347 projects were studied. The data is from 2019 and stems from invoices and quotes in that year. PV built on facades were not included. According to Energieheld[15] the cost of solar facades is c.a. 50% higher for the same output. The results are summarised below in Table 1.



Installation costs for PV systems in the Swiss market All costs are including VAT. [Source: Sauter and Jacqmin (2020).]									[smaller dataset, ibid. p.36]
capacity range [kWp]	Number of installations	Average specific costs [CHF/kWp]	Average costs [CHF/kWp]	Min	25%-quantile	Median	75%-quantile	Max	inverter replacement costs [CHF/kWp]
[2,10[	1’043.00	3’158.00	2’985.00	1’359.00	2’538.00	2’914.00	3’528.00	7’545.00	322.00
[10,30[	711.00	2’256.00	2’184.00	1’129.00	1’920.00	2’201.00	2’493.00	4’910.00	203.00
[30,100[	187.00	1’542.00	1’512.00	855.00	1’254.00	1’466.00	1’737.00	3’394.00	129.00
[100,300[	117.00	1’283.00	1’254.00	737.00	1’064.00	1’217.00	1’496.00	2’022.00	109.00
[300,1'000[	63.00	1’060.00	1’045.00	730.00	865.00	990.00	1’206.00	1’868.00	91.00
≥1'000	5.00	780.00	772.00	633.00	670.00	777.00	893.00	1’001.00	91.00

Table 1: Installation costs for PV systems in the Swiss markte for different capacity ranges

Source: Sauter and Jacqmin (2020).

4.6 ewb tariffs

The ewb envisages two FiT options for decentralised electricity production exclusively with photovoltaics. Firstly, the normal feed-in tariff (FiT) and then

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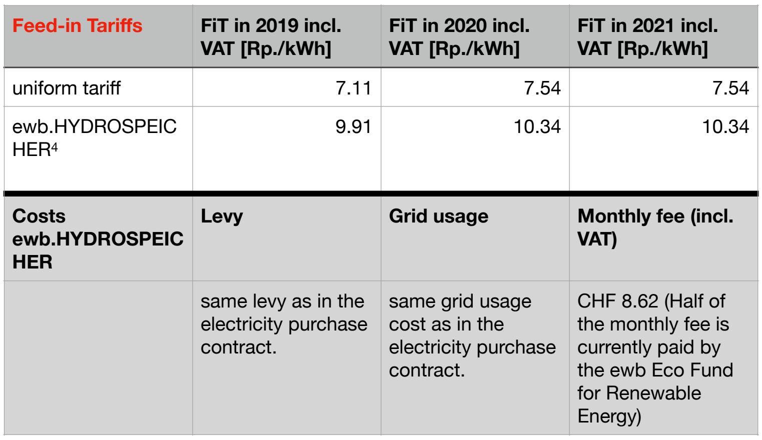
[15] https://www.energieheld.ch/solaranlagen/photovoltaik-loesungen/solarfassadevorteile-nachteile, last checked 31.08.21

a version with a “virtual battery”, where the utility stores up to 15 kWh in a storage lake. This is the ewb.HYDROSPEICHER product (see Table 2).[16] The first 15 kWh which are not consumed right away when produced are stored in the hydro storage. The further production is sold at the price of the ewb.HYDROSPEICHER FiT. When the PV system doesn‘t provide any electricity, the power from the storage is brought back. For this power the official levies and the grid usage are to be paid. Additionally there is a monthly fee for the whole product.



Feed-in Tariffs	FiT in 2019 incl. VAT [Rp./kWh]	FiT in 2020 incl. VAT [Rp./kWh]	FiT in 2021 incl. VAT [Rp./kWh]
uniform tariff	7.11	7.54	7.54
ewb.HYDROSPEICHER[4]	9.91	10.34	10.34

Costs ewb.HYDROSPEICHER	**Levy**	**Grid usage**	**Monthly fee (incl. VAT)**
	same levy as in the electricity purchase contract.	same grid usage cost as in the electricity purchase contract.	CHF 8.62 (Half of the monthly fee is currently paid by the ewb Eco Fund for Renewable Energy)

Table 2: ewb feed in tariffs
Source: Energie Wasser Bern (2020).

The electricity tariffs have been completely revised this year. There are now only three categories of grid usage in which ewb customers fall. Likewise, there is now only one uniform tariff for private households for new contracts. A double tariff (with peak and base hours) is only possible for customers in the Business grid usage class and above. There is no choice in the grid usage category; the customers category is determined by the electricity consumption and the power demanded. Table 3 shows the three categories of electricity tariffs valid from 01.01.2021 on. For comparison, the ewb.NATUR.Strom tariff for 2020 is shown below in Table 3. Before the standardisation, there were 15 subdivisions of the user categories.

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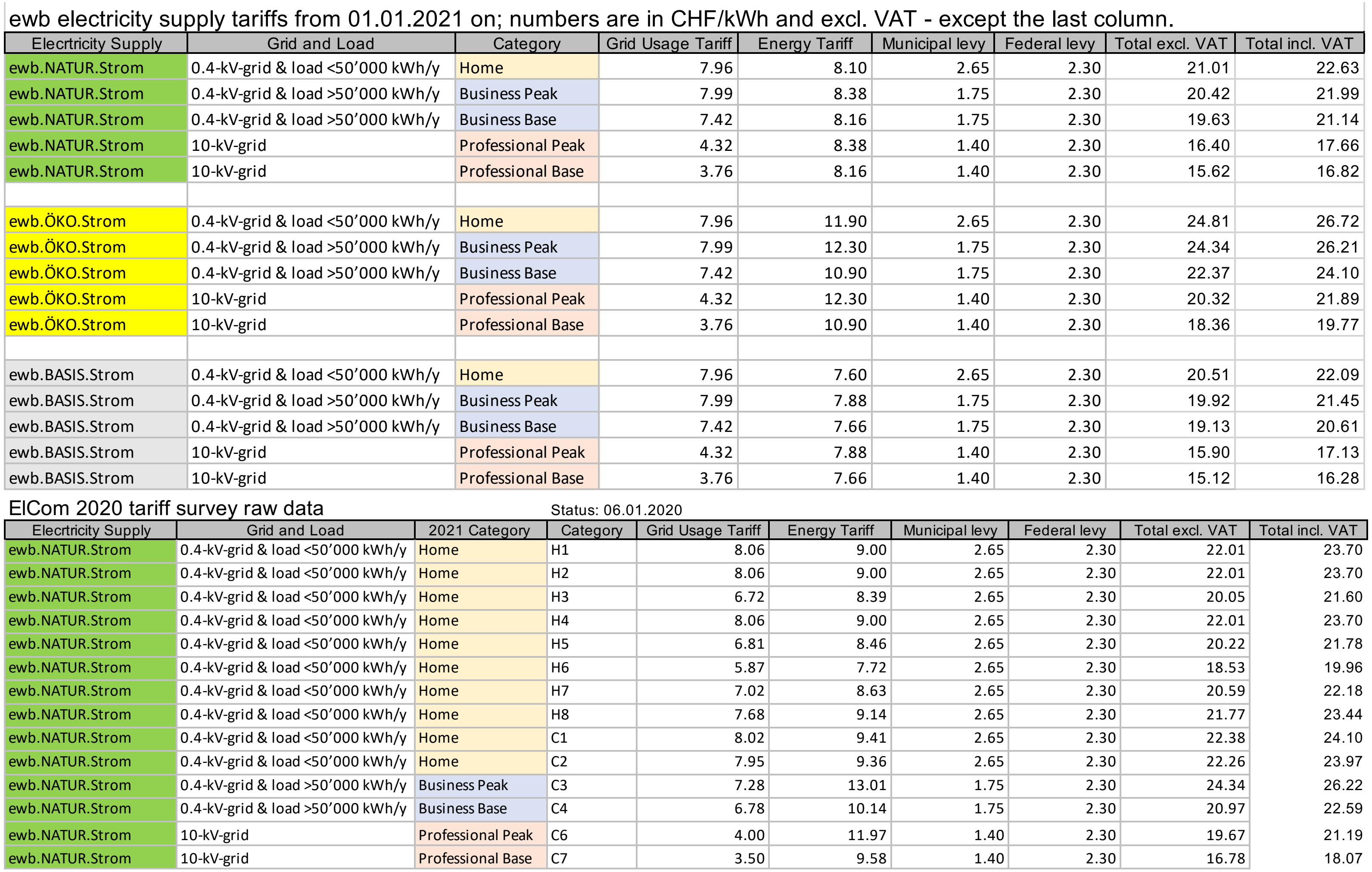
[16] In the uniform tariff, the guarantees of origin remain with the producer, while for the product ewb.HYDROSPEICHER, ewb takes over the guarantees of origin and pays for this with the higher tariff (SSSB 742.306). Whether a possible trade with the guarantee of origin is also an option for the prosumer cannot be clarified in the context of this work.



ewb electricity supply tariffs from 01.01.2021 on; numbers are in CHF/kWh and excl. VAT - except the last column.

Elecrticity Supply	Grid and Load	Category	Grid Usage Tariff	Energy Tariff	Municipal levy	Federal levy	Total excl. VAT	Total incl. VAT
ewb.NATUR.Strom	0.4-kV-grid & load <50’000 kWh/y	Home	7.96	8.10	2.65	2.30	21.01	22.63
ewb.NATUR.Strom	0.4-kV-grid & load >50’000 kWh/y	Business Peak	7.99	8.38	1.75	2.30	20.42	21.99
ewb.NATUR.Strom	0.4-kV-grid & load >50’000 kWh/y	Business Base	7.42	8.16	1.75	2.30	19.63	21.14
ewb.NATUR.Strom	10-kV-grid	Professional Peak	4.32	8.38	1.40	2.30	16.40	17.66
ewb.NATUR.Strom	10-kV-grid	Professional Base	3.76	8.16	1.40	2.30	15.62	16.82
ewb.ÖKO.Strom	0.4-kV-grid & load <50’000 kWh/y	Home	7.96	11.90	2.65	2.30	24.81	26.72
ewb.ÖKO.Strom	0.4-kV-grid & load >50’000 kWh/y	Business Peak	7.99	12.30	1.75	2.30	24.34	26.21
ewb.ÖKO.Strom	0.4-kV-grid & load >50’000 kWh/y	Business Base	7.42	10.90	1.75	2.30	22.37	24.10
ewb.ÖKO.Strom	10-kV-grid	Professional Peak	4.32	12.30	1.40	2.30	20.32	21.89
ewb.ÖKO.Strom	10-kV-grid	Professional Base	3.76	10.90	1.40	2.30	18.36	19.77
ewb.BASIS.Strom	0.4-kV-grid & load <50’000 kWh/y	Home	7.96	7.60	2.65	2.30	20.51	22.09
ewb.BASIS.Strom	0.4-kV-grid & load >50’000 kWh/y	Business Peak	7.99	7.88	1.75	2.30	19.92	21.45
ewb.BASIS.Strom	0.4-kV-grid & load >50’000 kWh/y	Business Base	7.42	7.66	1.75	2.30	19.13	20.61
ewb.BASIS.Strom	10-kV-grid	Professional Peak	4.32	7.88	1.40	2.30	15.90	17.13
ewb.BASIS.Strom	10-kV-grid	Professional Base	3.76	7.66	1.40	2.30	15.12	16.28

ElCom 2020 tariff survey raw data Status: 06.01.2020

Elecrticity Supply	Grid and Load	2021 Category	Category	Grid Usage Tariff	Energy Tariff	Municipal levy	Federal levy	Total excl. VAT	Total incl. VAT
ewb.NATUR.Strom	0.4-kV-grid & load <50’000 kWh/y	Home	H1	8.06	9.00	2.65	2.30	22.01	23.70
ewb.NATUR.Strom	0.4-kV-grid & load <50’000 kWh/y	Home	H2	8.06	9.00	2.65	2.30	22.01	23.70
ewb.NATUR.Strom	0.4-kV-grid & load <50’000 kWh/y	Home	H3	6.72	8.39	2.65	2.30	20.05	21.60
ewb.NATUR.Strom	0.4-kV-grid & load <50’000 kWh/y	Home	H4	8.06	9.00	2.65	2.30	22.01	23.70
ewb.NATUR.Strom	0.4-kV-grid & load <50’000 kWh/y	Home	H5	6.81	8.46	2.65	2.30	20.22	21.78
ewb.NATUR.Strom	0.4-kV-grid & load <50’000 kWh/y	Home	H6	5.87	7.72	2.65	2.30	18.53	19.96
ewb.NATUR.Strom	0.4-kV-grid & load <50’000 kWh/y	Home	H7	7.02	8.63	2.65	2.30	20.59	22.18
ewb.NATUR.Strom	0.4-kV-grid & load <50’000 kWh/y	Home	H8	7.68	9.14	2.65	2.30	21.77	23.44
ewb.NATUR.Strom	0.4-kV-grid & load <50’000 kWh/y	Home	C1	8.02	9.41	2.65	2.30	22.38	24.10
ewb.NATUR.Strom	0.4-kV-grid & load <50’000 kWh/y	Home	C2	7.95	9.36	2.65	2.30	22.26	23.97
ewb.NATUR.Strom	0.4-kV-grid & load >50’000 kWh/y	Business Peak	C3	7.28	13.01	1.75	2.30	24.34	26.22
ewb.NATUR.Strom	0.4-kV-grid & load >50’000 kWh/y	Business Base	C4	6.78	10.14	1.75	2.30	20.97	22.59
ewb.NATUR.Strom	10-kV-grid	Professional Peak	C6	4.00	11.97	1.40	2.30	19.67	21.19
ewb.NATUR.Strom	10-kV-grid	Professional Base	C7	3.50	9.58	1.40	2.30	16.78	18.07

Table 3: Above: ewb’s electricity purchase tariffs for all its products valid from 01.01.2020. NATUR is the standard product and consists of 100% renewable energy. ÖKO and BASIS can be selected as alternatives. ÖKO is made up of 100% solar power and BASIS is made up largely of nuclear power and a small proportion of hydroelectricity. **Below:** For comparison; ewb’s NATUR tariff valid in 2020 before the usage categories were renewed and the tariffs were more standardised.

Sources: (ElC, 2021), (ewb, 2020) and SSSB 742.305.

5 Stylized facts

This chapter presents the case studies that were conducted to answer the research question. The study area was modeled as explained in the subsection 3.2.

Selection of the area is done on the basis of the solar potential using the solar register city map of Bern (Solarkataster Bern)[17]. Since the preliminary study (see subsection 5.1) gave further evidence that an association of residential houses and houses with business use by day seems to be profitable, the second criterion in the process of identifying synergies of complementary consumption profiles are the building types. A suitable cluster of such buildings was selected in the research area to conduct the case study introduced in subsection 5.2.

5.1 Preliminary study

The economic viability of an installation plays a major role in the spread of PV, and this in turn depends on the self-consumed share of the electricity produced according to Luthander (2018). The aim is to combine different consumption profiles that complement each other and thus increase on-site consumption. This reduces both the PV grid feed-in and the purchase of grid electricity, which minimizes costs in the current tariff situation according to Mehta (2017). This preliminary study is to identify what types of buildings could complement each other.

CEA's team has defined 18 standard use types for buildings. Using the ArcGis tool presented in subsubsection 3.2.2, these were mapped to the corresponding GWR use classes in the study area. Based on the assumption that a merger is more profitable if the surplus of one party is consumed by the other instead of exported to the grid, the 18 building types are examined for complementary consumption profiles in a first preliminary investigation. Following the model of Fina (2017), the sample pearson correlation from elec-

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[17] `https://map.bern.ch/stadtplan/?grundplan=stadtplan_farbig&koor=2600668,1200332&zoom=2&hl=0&layer=Solarstrom&subtheme=CatUmwelt`, last checked 30.10.21.

tricity consumption to PV production is calculated (see Equation 25). A high correlation suggests high self-consumption, because this means that electricity consumption is high when production is also high. A correlation of 1 would mean that the two curves are exactly the same and the linear relationship would be perfect (Piot, 2019). A correlation of 0 means that there is no linear relationship between the level of irradiation and consumption.

$$r = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2(y_i - \overline{y})^2}} \tag{25}$$

The intuition is that houses with low correlation coefficients should be connected to houses with high coefficients. This is because a low coefficient indicates that production surpluses are more frequent. Where correlations are high, on the other hand, it is more likely that peak demand cannot be served by self-produced electricity.

In order to calculate the correlation and attribute it to the type of use, the 18 types were simulated in CEA with as equal conditions as possible. A simulation with own building geometries and without surroundings was not possible with CEA at this time. Therefore, a row of houses with floor plans of the same size as possible was chosen and the height was equalized for the simulation. In order to create nearly equal conditions for the houses in the simulation, a flat terrain was assumed and the surrounding houses were simulated as low as possible. Since this is a preliminary study, this simplification is acceptable. The simulation for the preliminary study was run twice because the row of houses consisted of 9 buildings. In each round, one half of the 18 occupancy types of CEA was assigned to one house each. Figure 8 shows a vizualiation of the model. Detailed information about the assumptions on all types of occupancy can be found in the CEA databases in the GitHub repository (Fonseca et al., 2021).

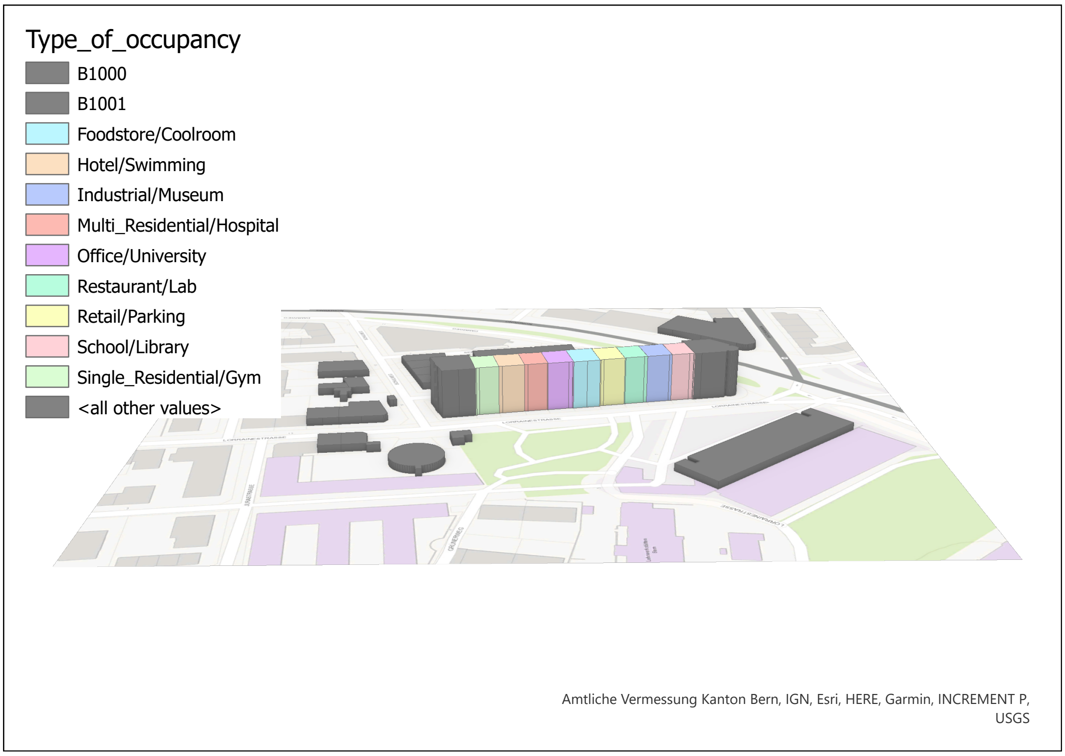


Figure 8: Visualization of the model used in CEA to compare the different types of occupancy.

Source: Own visualization with ArcGIS Pro

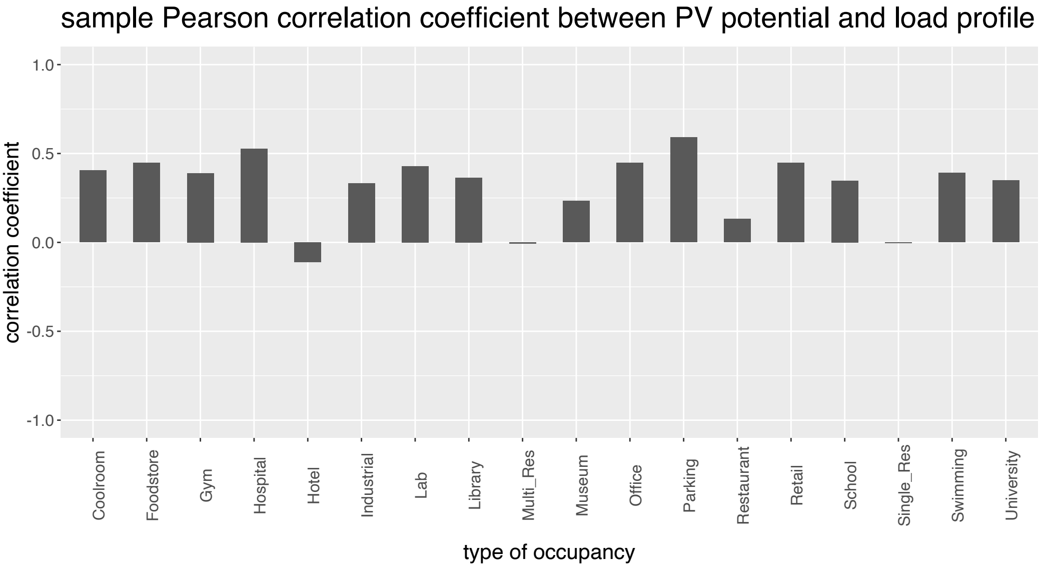
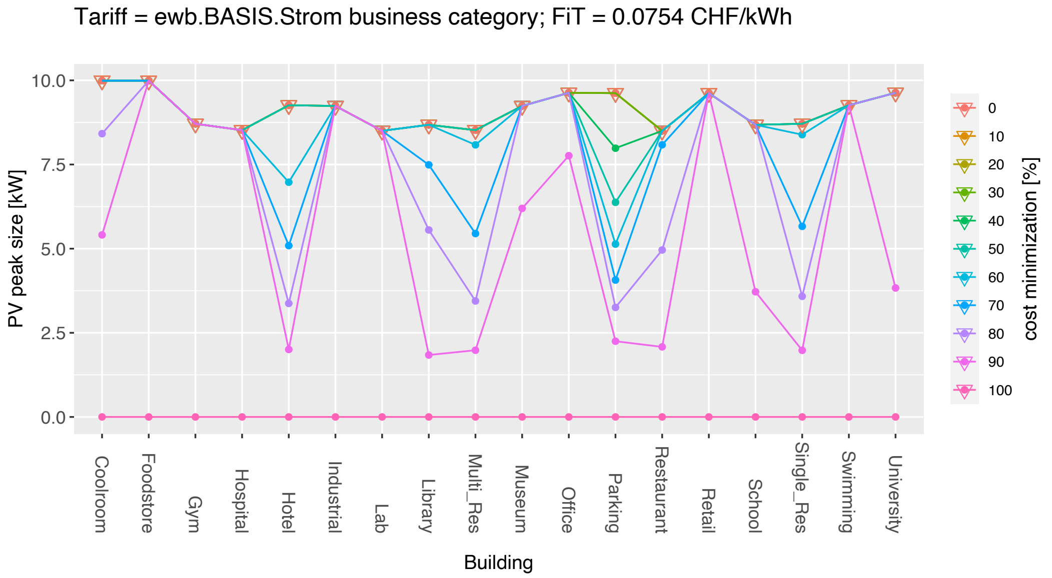


Figure 9: Visualization of the sample Pearson correlation between the curves of the PV potential and the load over the simulated time period for the 18 types of occupancy.

Source: Own figure

It can be seen well that types of use, which are designed for living or overnight stays show the lowest correlations. This is to be expected, since most people work during the day and the residential locations are therefore little used. In particular, this overview shows that PV installations on residential buildings or hotels are probably the least economical to operate, at least in the present simulation. Interconnections for self-consumption between residential buildings and buildings where commercial activities are carried out seem to make sense. The purpose of this preliminary study is to better assess the use types and verify the anticipation of which types might be complementary, without having to search for each use type in the available data for the community of Bern.

The optimization was then performed for all types of occupancy under the ewb default tariff option. The remaining assumptions can be found in the Appendix. The results are briefly discussed below.



Tariff = ewb.BASIS.Strom business category; FiT = 0.0754 CHF/kWh

Figure 10: Optimal PV peak sizes for the 18 model types of use with the ewb default prices, **FiT=0.0754 CHF/kWh and Basis tariff (see tables 2 and 3)**, and with different weights for the cost minimization objective. The **triangles** correspond to the maximum possible installed PV capacity.
Source: Own figure.

Figure 10 shows the optimized peak power under the ewb default tariff option. There is no storage possibility considered in the optimization.

For each usage type, the PV size results of 10 optimization runs are shown.

These 10 runs were each performed with a weight for the cost minimization target from 0 to 1 in steps of 0.1. The different weighted optimizations are represented by different colored lines. 100% cost minimization means here again that the autarky goal is completely neglected. Conversely, costs play no role at 0% weight and the optimization goal corresponds entirely to self-sufficiency. Thus, from 100 to 0, costs are allowed to grow increasingly. The triangles at the top correspond to the maximum PV peak size bounded by the roof area.

Looking at the bottom of the figure, it can be seen that it is not optimal for any type of occupancy to build a PV system with 100% cost minimization. That means, there is no potential for any type of use to save electricity costs by building a PV system compared to the situation without (BAU). With 0% cost minimization, i.e. 100% grid power consumption minimization, the maximum possible peak power would be installed in all buildings. Strikingly, the parking is the last type to reach the maximum peak power by reducing the degree of cost minimization to 20%. Despite the fact that the parking has the highest correlation of consumption and production hours. Investigating the PV and load the profiles made it clear why. The parking consumes so little electricity that it always has to feed in surplus, despite the high correlation. This is an indication that even high correlations should be treated with caution. It also seems crucial that the electricity can actually be used locally.

It is also noticeable that the optimal PV capacities of some types of occupancy make direct jumps from no PV system to maximum PV expansion. There, the BAU scenario is only slightly cheaper than a scenario with PV expansion and as soon as the cost minimization target is relaxed, PV becomes optimal. This can also be well illustrated by the (approximation of the) Pareto front. Figure 23 in the Appendix shows that these houses also have a very steep Pareto front. This is equivalent to a small price for a stronger grid current minimization. For the multiresidential type, the Pareto front is convex and the trade-off between cost minimization and grid minimization is greater.

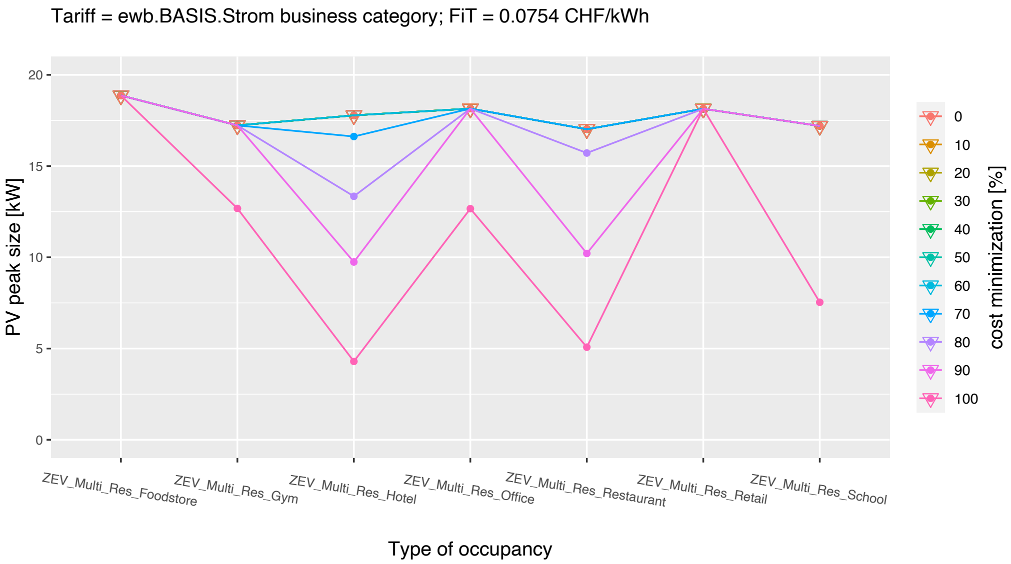


Figure 11: Optimal PV peak sizes for the seven combinations of different types of use with the ewb default prices, **FiT=0.0754 CHF/kWh and Basis tariff (see tables 2 and 3)**, and with different weights for the cost minimization objective. The **triangles** correspond to the maximum possible installed PV capacity.

Source: Own figure.

The next step is to show how the implementation of PV systems changes after the establishment of ZEVs between these use types. Since ZEVs with residential buildings are of particular interest in the context of Bern, the investigation will be restricted to combinations with the multi-residential type. As the choice of the neighborhood to be simulated fell on the inner Lorraine, six building types are examined in the following, which are also to be found in this district. These would be **Gym, Hotel, Restaurant, Foodstore, Office, Retail** and **School**.

Figure 11 displays that the installation of a PV system has a cost-minimizing effect for all of the seven hypothetical ZEVs. In other words, the annual electricity costs are lower with the integration of a solar power system than those costs in the business as usual scenario. As before, a smaller PV size is optimal for ZEVs with a hotel or restaurant compared to the other types of occupancy. In the case of a community with a foodstore or retail, on the other hand, the maximum possible PV expansion is optimal under each tariff considered. A merger with an office building or a school also seems promising. There, the maximum PV size is optimal from a 10%, respectively 20% relaxation of the cost minimization target towards self-sufficiency.

Based on these findings, a more realistic simulation was performed on the case study. This is introduced in the next chapter. The assumptions about the model parameters which were made for the optimizations in the preliminary study and in the case study can be found in the Appendix.

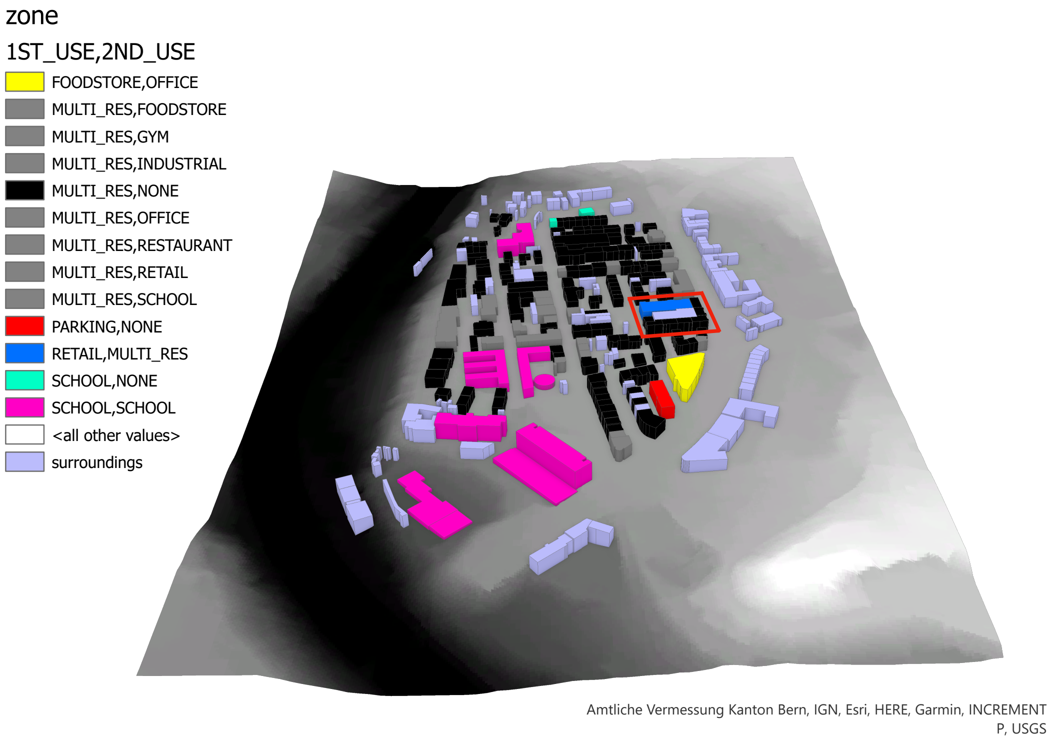
5.2 Case study

The simple preliminary study showed that the potential seems to be greatest for mergers between residences and businesses. This finding will now be tested in a case study using a more realistic model. The study area was modelled using the tools described in section 3 and the data in section 4. It is visualized in Figure 12. The colors are chosen to show buildings with a major occupancy that is not residential. After having looked at the different types of occupancy, the focus is now on ZEVs that can use the described synergies.

For the ZEV simulation, the building cluster framed with a red line was chosen. The chosen cluster contains large building with 80% retail use (*B1176*) and otherwise only multi-family residential buildings (*Buildings B1171-B1175, B177 and B1178*). First, the individual buildings are optimized and then four possible connections of the buildings within the clusters, which represent the hypothetical ZEVs.

The case study was designed to test the hypothesis that mergers in a residential city like Bern are most profitable when residential and commercial buildings are combined. With the four ZEV's the possible boundary cases of the cluster are to be represented. By that, the impact of size or composition of the ZEVs on the cluster are taken into account without having to simulate all combinations. This is to show how the size or composition of the ZEVs in the cluster affect the result without having to simulate all combinations.

To test how profitable a merger of only residential buildings is, two hypothetical ZEVs were chosen. Once a merger of only two adjacent apartment



Amtliche Vermessung Kanton Bern, IGN, Esri, HERE, Garmin, INCREMENT P, USGS

Figure 12: Different types of occupancy in the Lorrraine neighborhood. The buildings in the red square are used for the case study.
Source: Own figure

blocks as the smallest ZEVs, labeled *ZEV_2_MultiRes*. The other includes all apartment buildings, i.e. the largest possible residential merger of the cluster. It is called *ZEV_7_MultiRes*.

The last two ZEVs involve the retail block. *ZEV_Retail_1_MultiRes* consists only of the retail and one residential building. The other, *ZEV_Retail_7_MultiRes*, includes the whole cluster, i.e. the retail building plus the seven residential blocks. This is in order to get an impression of how the profitability changes with the number of buildings.

To simulate different ZEVs in this cluster, the load and irradiance profiles were combined as described in subsubsection 3.2.1. In the following section 6 the results are presented.

Based on the results, it can be shown that a pure ZEV from residential buildings is not very worthwhile and the possibility of storage does not increase the optimal PV output under the assumptions made. The one-time subsidy of 30% of the PV installation costs increases the optimal PV capacity for residential buildings, the retailer is expanding to its full potential even without it. By combining the types of use, the full potential of the cluster in the case study can be exploited even without subsidy.

6 Results

The results of the previously presented case study are explained below. In subsection 6.1 the results of the optimization of the individual buildings in the cluster are shown and compared with the results of the presented ZEV formations. In this chapter, no storage is allowed and only the results for 100% cost minimization are considered, since the focus is on economic efficiency. In subsection 6.2, the optimization results are shown for the best and worst performing ZEV when cost minimization is not the only objective. The results in subsection 6.3 lean on subsection 6.1. They additionally include the storage option in the optimization. Subsection 6.4 shows equivalently to subsection 6.2 the results when weight of the optimization objectives is shifted from cost-minimization to self-sufficiency, this time for ZEVs with storage as presented in subsection 6.3.

All results are shown for two cost scenarios. On the one hand, in the "standard" scenario, average specific PV costs from the litearur are assumed. On the other hand, in the "subsidy" scenario, a 30% subsidy on these installation costs is assumed, which is the maximum available in Bern at the time of this thesis.

6.1 Cost-minimization without storage

This chapter shows how much PV power is optimally installed while minimizing costs. First, Figure 13 shows the correlation coefficient for this cluster as well. As expected, the residential buildings show low to weak negative correlations between PV production potential and electricity consumption over the annual hours. The retail building, on the other hand, shows a medium-strong correlation of 0.45.

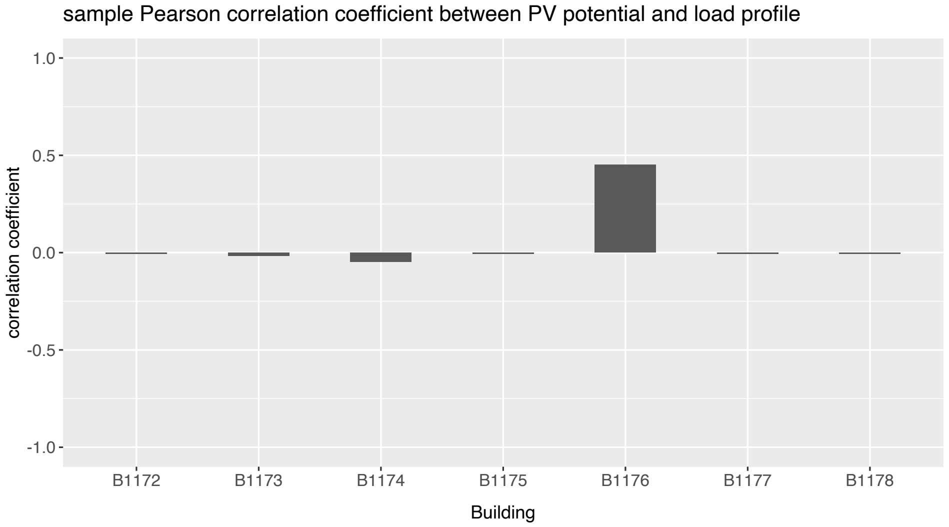


Figure 13: Visualization of the sample Pearson correlation between the curves of the PV potential and the load over the simulated time period for the buildings in case study 1.

Source: Own figure.

Now we look at which capacity is optimal for each building. Figure 14 shows on the Y-axis the PV potential of each building, constrained by the roof area, and on the X-axis how much of this potential is used at minimum cost. The difference in the types of use are apparent. The retail building clearly has the greatest potential and uses it to the maximum in both cost scenarios, which is why it marks the blue point at the top right. The red dots represent the residential buildings. Due to their much smaller size, they logically have significantly lower potentials. At the same time, however, they are only partially utilized. Without subsidy (the left part of the figure), a maximum of 1/3 of the possible PV power is cost-minimizing.

If the 30% subsidy is introduced, the pattern of distribution does not change as shown on the right in Figure 14. However, the cost-minimizing PV plant power almost doubles for each residential building. In any case, even for the best-suited residential building, there is still more than 30% unused potential. So it seems obvious that under the assumptions made for residential buildings, the maximum PV expansion is not economically optimal. This is where ZEV comes in, the basic idea of which is to promote PV expansion.

Therefore, the next paragraph takes the perspective of the social planner

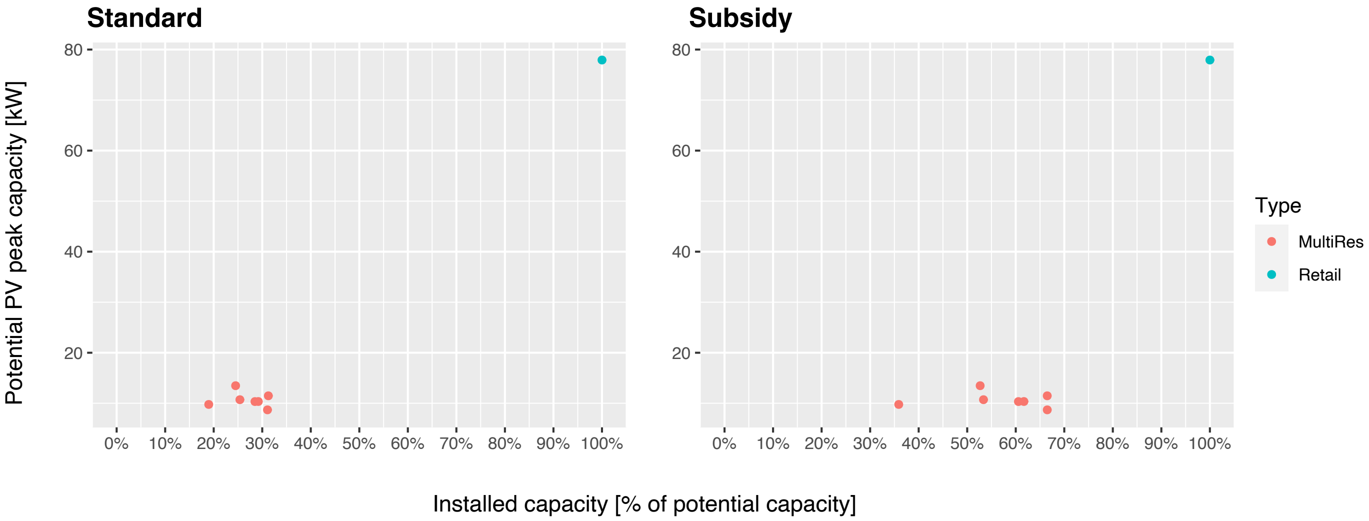


Figure 14: Potential vs. optimal PV peak sizes for the individual buildings in the investigated cluster with the ewb default prices, **FiT=0.0754 CHF/kWh and BASIS tariff** (see tables 2 and 3)
Source: Own figure.

and looks at the costs and PV expansion for the entire cluster when the ZEVs presented in the previous chapter are formed.

Socialplaner perspective

Figure 15 shows the annual cost in thousends of CHF and the installed PV power in kW on the left Y-scale and the self-sufficiency rate on the right Y-axes. The variables are always shown for the entire cluster. As mentioned before, the results are shown for the case without subsidy and the case with a subsidy of 30% on the PV installation costs. The maximum PV peak power potential of the whole cluster, i.e. when the entire roof area is utilized, corresponds to the result at *"ZEV_Retail_7_MultiRes"* (green bar on the far right of both plots). In absolute terms, it amounts to 152 kW.

The five different scenarios on the X-axis per bar chart correspond to the distribution of the buildings in the cluster into ZEVs or stand-alone. *"Individual Buildings"* thus represent the optimized cost, PV power and self-sufficiency rate (SSR) for the entire cluster when no ZEV is formed in it. *"ZEV_2_MultiRes plus remaining buildings"* represents the same variables for the whole cluster when two of the residential buildings (B1171 and B1172) form a ZEV in it and

Figure 15: Potential vs. optimal PV peak sizes for the individual buildings in the investigated cluster with the ewb default prices, **FiT=0.0754 CHF/kWh and BASIS tariff** (see tables 2 and 3)
Source: Own figure.

the rest are optimized individually. In the case *"ZEV_7_MultiRes plus remaining buildings"* the total costs, PV power and SSR are plotted for the cluster if all residential buildings are combined and only the retail is optimized individually. *"ZEV_Retail_1_MultiRes plus remaining buildings"* plots the same results assuming that the retail building with residential building B1176 is optimized as ZEV and the rest are optimized individually. *"ZEV_Retail_7_MultiRes"* finally represents the whole cluster optimized as a single ZEV.

The standard cost scenario shows, that it makes almost no difference in all variables whether the buildings in the cluster are optimized individually or ZEVs are formed with the residential buildings. Out of the three, the relative difference between the situation with the lowest total annual cost (*"ZEV_2_MultiRes plus remaining buildings"*) and the one with the highest (*"ZEV_7_MultiRes plus remaining buildings"*) is only 0.013%. The spread between the total PV capacity in the three cases where retail is no part of a ZEV is 0.124 kW or approximately 0.126%. These differences can be neglected. It can be said that if no ZEVs are entered between retail and residential buildings, the cluster reaches about 98.1 kW peak power, and thus 64.2% of the potential. The total annual electricity costs paid by the buildings in the cluster in this case amount to about 116'000 CHF.

However, as soon as a ZEV is formed which contains the retail building, the total installed PV power in the cluster increases. The installed power increases from about 98 kW when no ZEVs are formed to 108.2 kW, which means a 10.4% increase when the formed ZEV consists of the retail and an adjacent building (*"ZEV_Retail_1_MultiRes plus remaining buildings"*). Thereby the costs decrease slightly by 0.39%.

The full PV potential of 152.76 kW of the cluster is only exploited when all residential buildings are connected to the retail building. The installed PV power increases by 55.77 % compared to a ZEV-less scenario.

If the whole cluster is considered, 51% of the total potential is located on the retail building. It was already shown in the individual optimization that the retail building fully utilizes its PV potential, so this is fully exploited in any case. The residential buildings obviously do not build more power than in the individual optimization, i.e. less than 30% of the combined potential on the residential roofs. Thus, the increase of the optimal PV power in the overall area has the following reason: The fallow potential on the residential buildings is only economically used by the retail building through the day. Since the retail building is a very large consumer relatively to the other buildings, it can use the fallow potential of the entire cluster in a cost-minimizing way. For the retail building, this actually means that it has more roof space available to meet its electricity demand. In this sense, the additional electricity on the residential buildings is not produced for their residents, but for the retailer. If the investment costs within the ZEV are divided according to the electricity demand, returns are generated for all parties involved, as Table 4 shows. The self-sufficiency rate (SSR) of maximum 0.22, achieved by the *"ZEV_Retail_7_MultiRes"*, means that the share of self-produced electricity of the total consumption at full PV expansion is 22%. The corresponding self-consumption rate (SCR) of 93% shows that almost all of it is also consumed on site. Both SSR and SCR are at a maximum in this case while the costs are minimized. In contrast, SSR and SCR are low in the *"ZEV_7_MultiRes"*. This indicates that only a combination of the types of occupancy can use synergy effects in the present model. The high SCR from *"ZEV_Retail_7_MultiRes"* suggests that the retail consumer could still efficiently use potential from additional rooftops.

As displayed on the right, the 30% subsidy on the investment costs does not change the pattern. The orders of magnitude in the scenarios without ZEV with retail participation can again be regarded as identical. However, due to the subsidy, 22.7% more PV capacity is built over the entire cluster in all three aforementioned scenarios. Along with this, a saving of 3.2% can also be realized. Considering PV peak size, for the retail building there can't be any improvement, since it uses 100% of its potential already under the higher cost assumption. This means that the entire increase in built PV capacity happens on the residential buildings. In the individual analysis in Figure 14 it could already be shown that the subsidy roughly leads to a doubling of the PV utilization on the residential buildings.

The difference between scenarios with no or purely residential ZEVs in the cluster and the ones with ZEVs in which the retail building is involved decreases. But the cost and self-sufficiency maximizing scenario of the cluster (*"ZEV_Retail_7_MultiRes"*) does not change. There only the annual costs decrease by 4.7%. Therefore the subsidy only increases the return in this scenario, since the full potential is already exploited without it. This means that the retail building and the ZEVs containing it, would not need the subsidy under the assumptions made. Hence, from a social point of view, it seems optimal to connect the whole cluster. The decisive factor is the connection of the retail building.

From the perspective of the energy transition, the overall view is certainly decisive. Nevertheless, the next section aims to show whether the social optimum is also the most economical from a household perspective.

Household perspective

In order to present the household perspective, a simple calculation was made. The total costs of a ZEV are distributed to the participants weighted according to the electricity consumption. No distinction is made as to when the electricity is consumed. This corresponds to the assumption that the same tariff applies within the ZEV at all times. In reality, this may be true, but it does not have to be the case.

Table 4: Percentage change in yearly electricity costs from BAU to joining a ZEV for the participating households.

Standard

	ZEV_2_MultiRes	ZEV_7_MultiRes	ZEV_Retail_1_MultiRes	ZEV_Retail_7_MultiRes
B1171	-2.79	-2.42	-2.97	-4.01
B1172	-2.79	-2.42		-4.01
B1173		-2.41		-4.01
B1174		-2.42		-4.01
B1175		-2.41		-4.01
B1176			-3.37	-4.41
B1177		-2.42		-4.01
B1178		-2.43		-4.03

Subsidy

	ZEV_2_MultiRes	ZEV_7_MultiRes	ZEV_Retail_1_MultiRes	ZEV_Retail_7_MultiRes
B1171	-6.95	-6.33	-6.21	-8.45
B1172	-6.96	-6.33		-8.45
B1173		-6.33		-8.45
B1174		-6.33		-8.45
B1175		-6.33		-8.45
B1176			-6.60	-8.83
B1177		-6.33		-8.45
B1178		-6.35		-8.47

Compared to the BAU scenario, i.e. without ZEVs and PV plants, all ZEV variants are profitable for all participants. At the same time, the greatest individual cost savings are also made in the social optimum. In this case, annual savings of around 4% per building can be realized. The subsidy significantly grows the savings of each building. The largest ZEV would allow savings of over 8% per year, more than twice as much as without subsidy. Relatively speaking, the subsidy has an even stronger effect on the savings of ZEVs without retail. This is due to the fact that, as seen before, larger PV capacities are built there thanks to the subsidy. Qualitatively, however, the results are not changed.

The comparison to the individual optimization in Table 5 is interesting. The purely residential mergers are not more profitable than the individual optimization for all households. Most households are worse off in the ZEV, except B1174. As can be seen in the building properties in the appendix, B1174 is about four meter less high than the others. This causes it to be overshadowed, probably in hours where self-produced PV power would be consumed. That is why the negative correlation occurs. This leads to the fact that the building builds little PV in the single optimization, because its roof is unsuitable. But actually it could consume more at times when the sun is shining. The other buildings build in this sense for B1174. They receive less of the electricity produced by connecting B1174. Since the savings are from self-consumed electricity, they are worse off than in the single optimization. B1174, on the other hand, is better off because this building can reduce its grid consumption. The retailer also benefits because, based on its consumption profile, it can self-consume each additional kWh of PV electricity that the residential buildings do not use. However, the costs are distributed according to total consumption, which is not influenced.

Again, only the connection with the retail allows return for all, however in different amounts.

6.2 Cost-minimization and autarky without storage

This chapter shows the PV and cost development for two ZEVs when the goal of cost minimization is relaxed. *ZEV_7_MultiRes* was chosen because it is the worst performer from a household perspective and also does not provide much benefit from a social planner perspective. *ZEV_Retail_7_MultiRes* is shown because it is the most profitable from both perspectives.

The intention behind this is that not only the financial incentive can bring benefits. Behavioral economics has shown that individuals make decisions based on a wide variety of attitudes (Thaler, 2020). Ajzen (1991) shows in Theory of Planned Behavior how attidudes and subjective norms and perceived control are responsible for these intentions. Rogers et al. (2009) intro-

Table 5: Percentage change in yearly electricity costs from individual otpimization to joining a ZEV for the participating households.

Standard

	ZEV_2_MultiRes	ZEV_7_MultiRes	ZEV_Retail_1_MultiRes	ZEV_Retail_7_MultiRes
B1171	0.003	0.38	-0.18	-1.26
B1172	-0.01	0.37		-1.27
B1173		0.26		-1.38
B1174		-1.80		-3.40
B1175		0.42		-1.22
B1176			-0.49	-1.56
B1177		0.39		-1.25
B1178		0.33		-1.30

Subsidy

	ZEV_2_MultiRes	ZEV_7_MultiRes	ZEV_Retail_1_MultiRes	ZEV_Retail_7_MultiRes
B1171	0.02	0.69	0.81	-1.59
B1172	-0.04	0.63		-1.65
B1173		0.43		-1.84
B1174		-3.31		-5.49
B1175		0.75		-1.53
B1176			-0.88	-3.25
B1177		0.66		-1.62
B1178		0.54		-1.74

duce five adopter categories in the theory Diffusion of Innovation: Innovators, early adopters, early majority, late majority, and laggards. For innovators, for example, it is only crucial to participate in technological developments at an early stage, irrespective of other forms of benefit.

It can therefore be assumed that there are some households that place more weight on self-sufficiency than on cost when making their decision, for example, for ecological reasons.

Figure 16 shows for *ZEV_7_MultiRes* the optimization results of annual electricity cost (gray line and left scale) and PV size (yellow line and right scale) plotted over the weight of cost minimization. 100% means that only costs are minimized. At 0%, costs do not matter and grid power consumption is minimized, i.e., self-sufficiency is maximized. The black horizontal line shows at the left scale the business as usual costs, i.e. when no PV system is taken into account and only grid electricity is purchased.

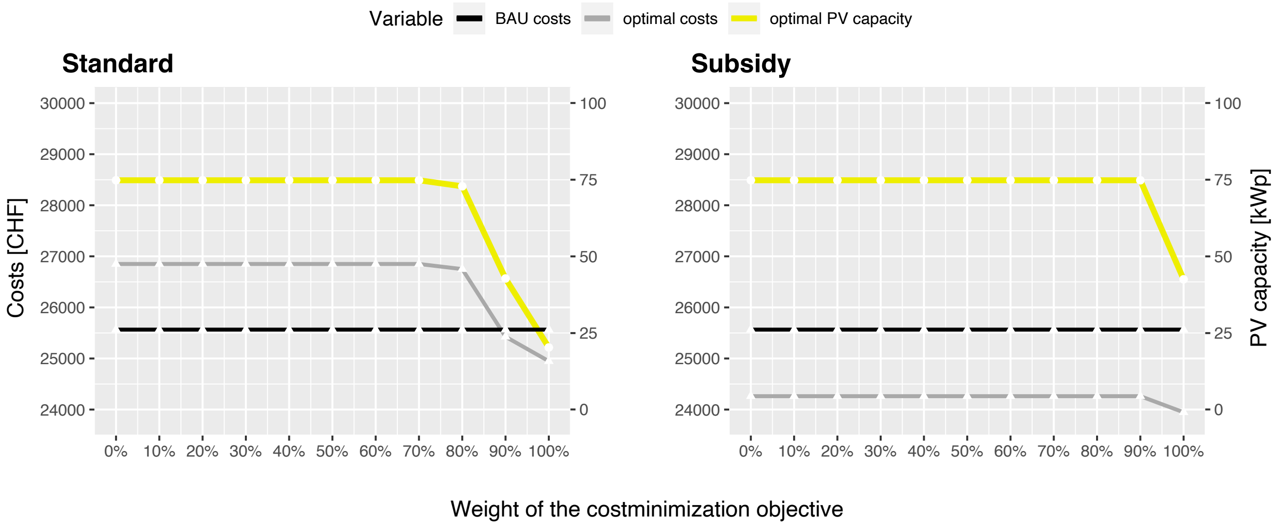


Figure 16: The optimized yearly electricity cost (left scale) and optimal PV peak sizes (right scale) for **ZEV_7_MultiRes** plotted over different cost-minimization degrees. The right plot is calculated with a subsidy on investment costs of 30%. Ewb defalt prices, *FiT=0.0754 CHF/kWh and BASIS tariff* (see tables 2 and 3) are considered.
Source: Own figure.

The standard case in the left plot shows that the savings for ZEV are just over 600 CHF/year with cost minimization. However, if the goal of cost minimization is already weighted with only 70% or less, the largest possible PV power, which the roof surfaces allow, is optimal.

The full exploitation of the potential leads to annual additional costs for the ZEV of just under 1300 CHF or 5% compared to Business as Usual. Compared to the cost-minimizing scenario, this corresponds to a difference in annual costs of about 7.6%.

In the right plot of Figure 16, depicting the case with a 30% one-time subsidy, the resulting costs of all optimizations are lower than if no PV system was built. With 100% cost optimization, a saving of 315 CHF per year is still possible compared to the lower weight. The tradeoff consists of about 43% of the maximum PV capacity. After that, already for all weights the full PV potential utilization becomes optimal and consequently the costs do not increase further. This results in an annual saving of at least 1304 CHF for the ZEV with the subsidy.

Figure 17 shows the same reasoning for the case of the most profitable merger *ZEV_Retail_7_MultiRes*. The plot shows only straight lines, since under the assumptions made and for the available PV potential, the two optimization objectives for this ZEV coincide. 100% cost minimization leads to minimum grid access and vice versa. Furthermore, the ZEV provides annual savings of about 5160 CHF or 4.3%. Consequently, the one-time payment simply reduces the annual cost of the ZEV. The savings thus increase to about 10450 CHF or about 8.75 %.

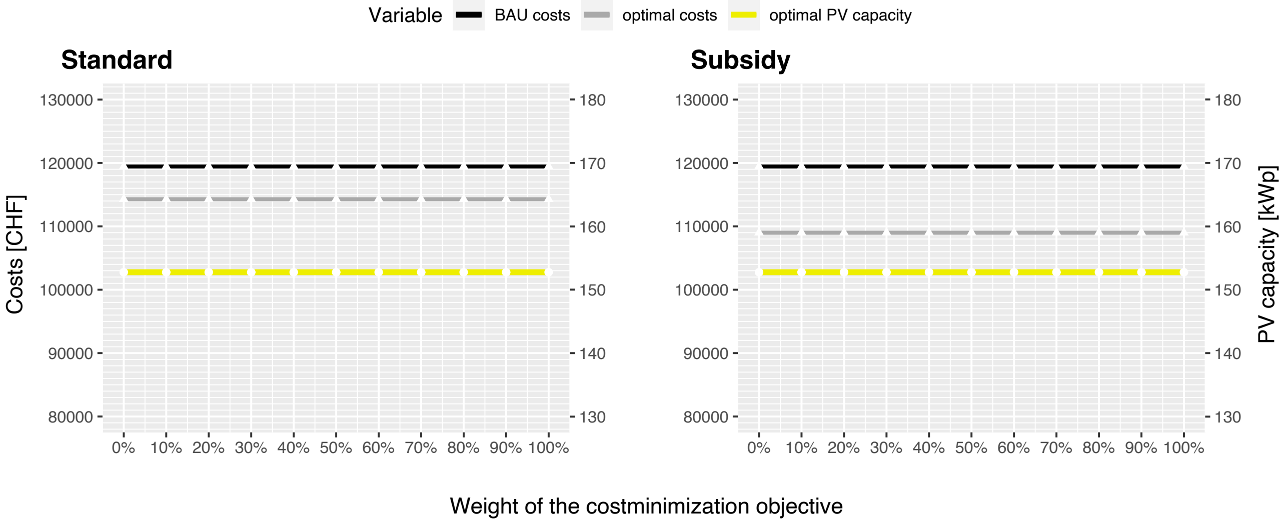


Figure 17: The optimized yearly electricity cost (left scale) and optimal PV peak sizes (right scale) for **ZEV_Retail_7_MultiRes** plotted over different cost-minimization degrees. Ewb defalt prices, *FiT=0.0754 CHF/kWh and BASIS tariff* (see tables 2 and 3) are considered.
Source: Own figure.

6.3 Cost-minimization with storage

In this chapter, the possibility of electricity storage is considered. In addition to the costs and the PV system, the potential storage size is now also optimized with regard to the objectives.

Individual building analysis

Figure 18 draws as before in subsection 6.1 on the Y-axis the PV potential of each building, constrained by the roof area, and on the X-axis how much of this potential is used at minimum cost. There is no difference to the graph in subsection 6.1. This means that at 100% cost minimization for the individual buildings no storage is built.

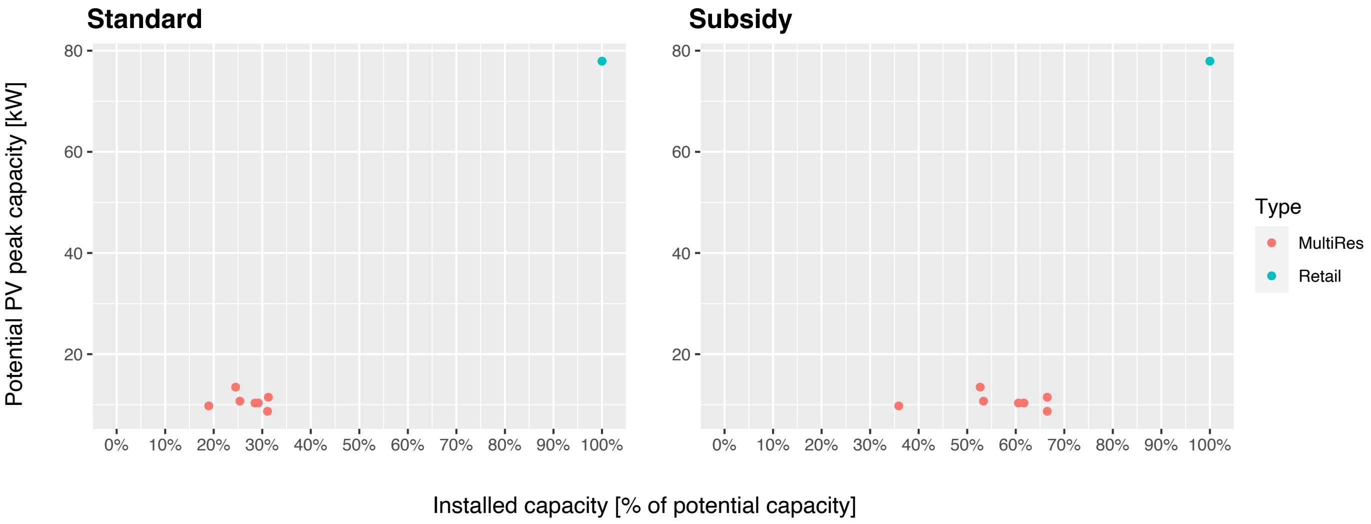


Figure 18: Potential vs. optimal PV peak sizes for the individual buildings in the investigated cluster with the ewb default prices, **FiT=0.0754 CHF/kWh and BASIS tariff** (see tables 2 and 3)
Source: Own figure.

Socialplaner perspective

Also when considering the simulated ZEVs in Figure 19, there is no difference to the previous study. Therefore, no additional cost savings or larger PV systems are possible with storage as long as the costs are minimized. The household view presented in subsection 6.1 does not need to be presented again here. Since no storage is built, nothing changes for all buildings under the assumptions made. Thus the next chapter shows the case, when not only cost-minimization is considered.

6.4 Cost-minimization and autarky with storage

A storage facility does not seem to have a cost minimizing effect under the assumptions made. Here again, it is shown how the results change when the prioritization of the cost minimization objective is changed in favor of the self-sufficiency objective.

Figure 19: Potential vs. optimal PV peak sizes for the individual buildings in the investigated cluster with the ewb default prices, **FiT=0.0754 CHF/kWh and BASIS tariff** (see tables 2 and 3)
Source: Own figure.

In Figure 20, it can be seen that as the emphasis on self-sufficiency increases, more storage capacity is built out. Until finally, when costs no longer play a role, costs and storage capacity rise to absurd heights. However, the main take-away message is, that storage is only built at all, at the moment or after the maximum PV power is installed. Hence, storage does not lead to a stronger expansion in PV in the presented model. By shifting the objective to self-sufficiency, storage is only used to increase this further. This means that storage does not lead to a stronger expansion in PV in the present model. By shifting the emphasis to self-sufficiency, storage is only used to increase this somewhat. This is done by storing the surplus production at certain hours instead of selling it. As can be seen in the graph, however, this is associated with additional costs.

Figure 22 again shows *ZEV_Retail_7_MultiRes*. Because the full PV potential has a cost-minimizing effect here, the storage also has no influence on the PV system size here. As soon as the costs have less weight than the self-

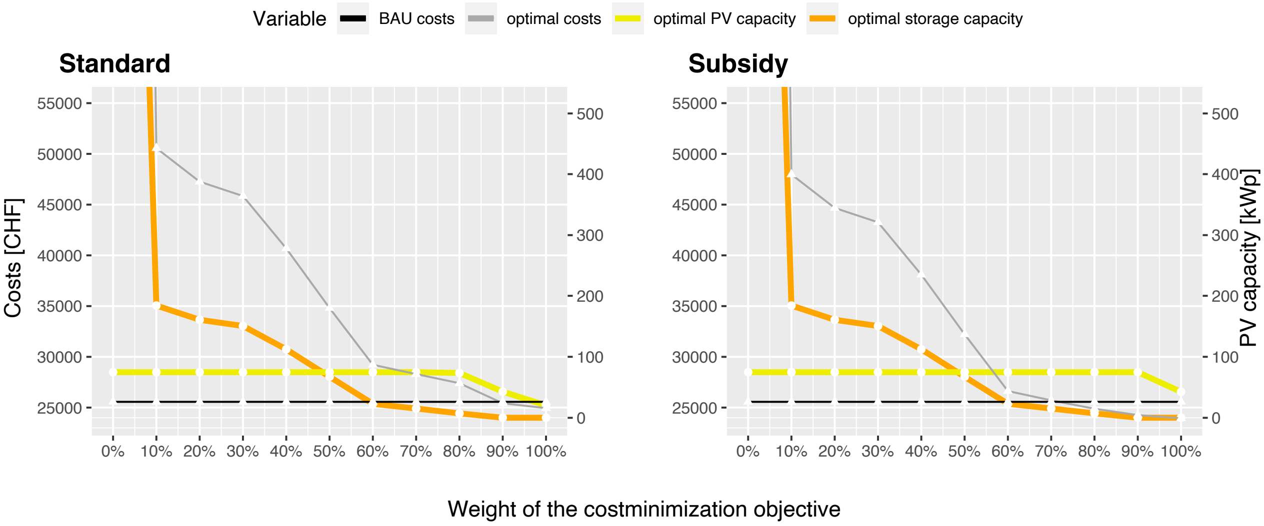


Figure 20: The optimized yearly electricity cost (left scale), optimal PV peak sizes [kW] and storage capacity [kWh] (right scale) for **ZEV_7_MultiRes** plotted over different cost-minimization degrees. Ewb defalt prices, *FiT=0.0754 CHF/kWh and BASIS tariff* (see tables 2 and 3) are considered.
Source: Own figure.

sufficiency, the investment in storage starts. However, absurdly high sums must be invested again for an extremely small increase in self-sufficiency. As expected, storage is rather useless when self-consumption is already high, since the purpose of storage is exactly to increase self-consumption.

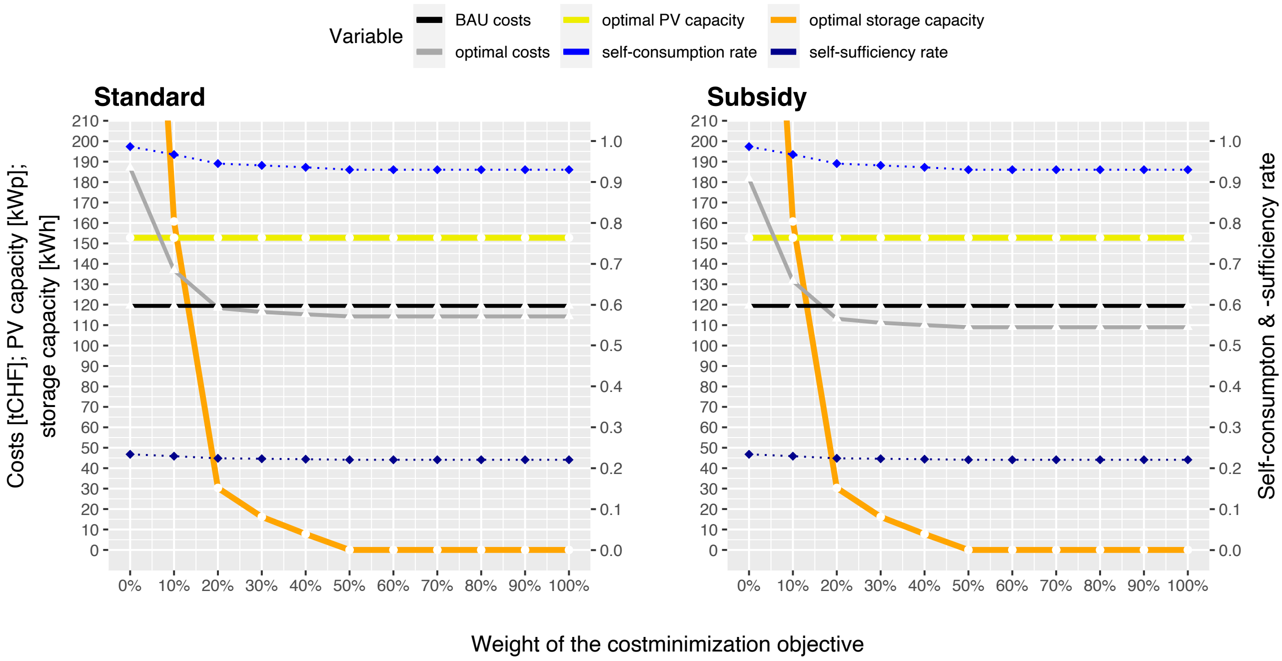


Figure 21: The optimized yearly electricity cost (left scale), optimal PV peak sizes [kW] and storage capacity [kWh] (right scale) for **ZEV_Retail_7_MultiRes** plotted over different cost-minimization degrees. Ewb defalt prices, *FiT=0.0754 CHF/kWh and BASIS tariff* (see tables 2 and 3) are considered.

Source: Own figure.

7 Sensitivity analysis

As Ellinger et al. (2003) point out, due to the statics in linear model simulations, it is important to investigate which assumptions have a large impact on the output. From an econometric point of view, this is important because the constancy of the output data assumed in these models is generally limited (Ellinger et al., 2003). There are several questions that can be addressed with a sensitivity analysis. According to Ellinger et al. (2003, p.99), the questions that can be answered with a sensitivity analysis are: *"What effects does the presumed inaccuracy of this or that model variable have on the optimality of the specified solution?"* Or also, according to Taschner (2017, p.123): *"How much does the result change if the input factor under investigation is systematically varied within a certain value interval or assumes a number of defined alternative values?"*

Taschner (2017) cautions, however, that even if sensitivity analysis made important contributions to identifying critical input factors, it is not able to describe the “real” uncertainty in a model. This is due to the fact that only one parameter is changed at a time, while the others remain fixed. In reality, however, this is not the case. Therefore, it remains to say that the sensitivity analysis provides information about the sensitivity of the model to changes in individual parameters, but it cannot determine the probability with which the values are correct.

The present model is a mixed-integer linear program (MILP). For linear programs, the theory of sensitivity analysis is mature, for those containing integer programs, research is still ongoing (Jia and Ierapetritou, 2004). Different approaches, which can be found in the literature, as they are presented for example from Jia and Ierapetritou (2004), are too complex for this work. Therefore, the one-at-a-time perturbation, the simplest version of the sensitivity analysis, is used. Thereby, the output changes are analyzed as one paramteter is perturbed at a time (Jia and Ierapetritou, 2004).

Figure 22 shows the results regarding the optimal PV system size of this one-at-a-time perturbation for the four hypothetical ZEVs. The changes are made at 100% cost minimization. In each case, the following five objective function coefficients were changed individually: the electricity tariff, the feed-in tariff, the specific investment cost of the PV installation, the specific operating cost, and the costing input.

Shown on the X-axis is the magnitude of the percent change in optimal PV system size when the parameter listed on the Y-axis is either increased or decreased by 10% from the default scenario. Dark gray bars indicate results for an increased parameter, light gray for a decreased parameter. The bars still show the percentage change in optimal PV power as a number.

Two findings are evident: First, the optimal PV power for ZEVs with retail participation does not change for any variations. Secondly, ZEVs consisting exclusively of residential buildings respond relatively strongly to changes in tariff or specific investment costs. The latter effect could also be shown earlier

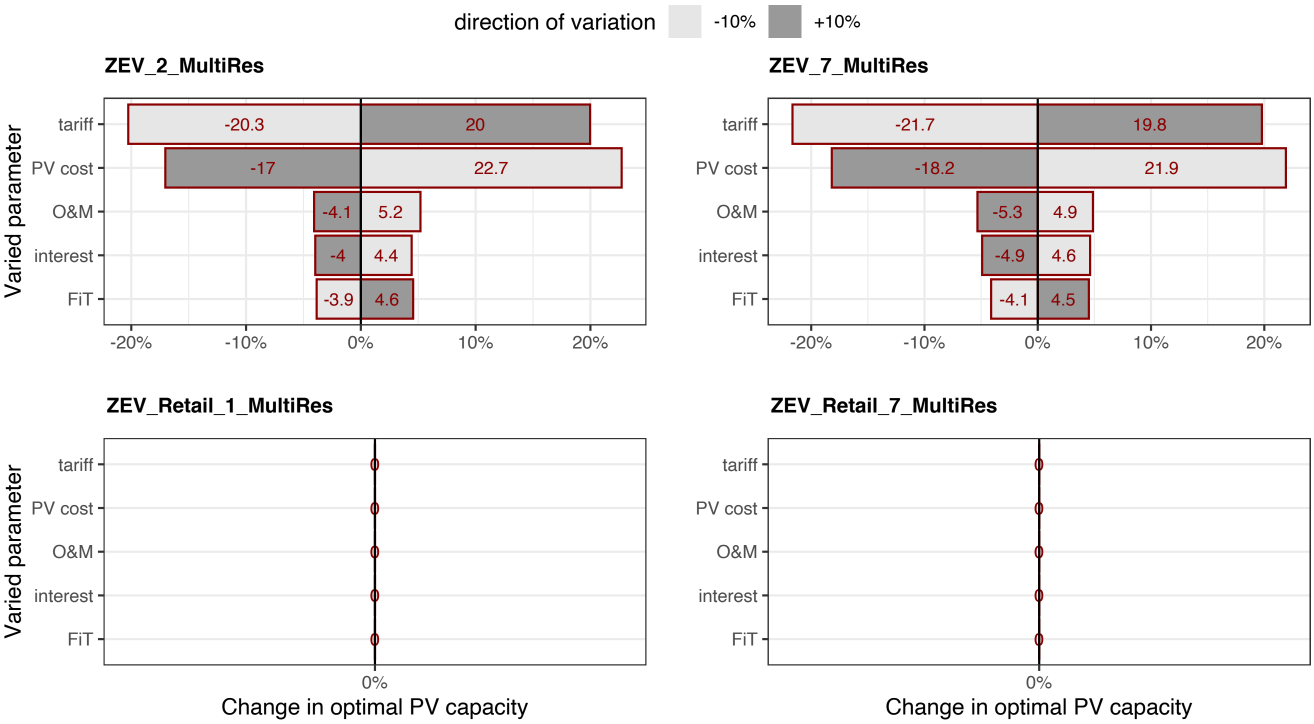


Figure 22: Change of the optimal (100% cost-minimization) PV power compared to those resulting from standard assumptions with ewb defalt prices, *FiT=0.0754 CHF/kWh and BASIS tariff* (see tables 2 and 3) are considered.
Source: Own figure.

in the case study when investigating the subsidy. An increase of the electricity tariff by 10% leads to an increase of the PV peak power of about 20% in both residential ZEVs. Almost to the same extent, a 10% decrease leads to a further increase in peak PV capacity of slightly more than 20%. If the costs are reduced by 10%, the size of the optimal PV system for the residential ZEVs increases by 22.7% and 21.9%, respectively. The effect is slightly less strong in the other direction. 17% and 18.2% smaller systems are optimal with a 10% increase in specific investment costs.

However, the PV system size reacts underproportionally to changes in the remaining parameters. As described before, the analysis does not show how likely the assumptions about the parameters are. However, it does show which assumptions are critical. In the present work, a real tariff was used, so this assumption should not be improbable. However, the assumption that the retailer has the same tariff as the households is probably not true, as will be discussed in the next section. But the sensitivity analysis also just shows that the retailer is not sensitive to any parameter. At least not in the varied order of magnitude. Based on this analysis, it is of course still not possible to say how the results will change if the retailer gets a significant lower electricity tariff.

A 30% change in investment costs was examined in the case study, whereby the residential buildings also reacted strongly with an expansion of the PV systems. It is possible that an even larger increase in investment costs would also change the results if the retailer is involved. However, this should be ruled out in view of the steadily decreasing PV module costs.

Finally, it can be said that the optimization results certainly depend strongly on the selected tariff and investment cost assumptions. What seems to be very robust, however, is the statement that the use of synergy effects between the residential buildings and the retailer minimizes the costs and maximizes the PV expansion. This result was not qualitatively changed by any variation.

8 Discussion

After presenting the results, one main finding stands out. Large daytime consumers, such as the retail building in the case study, should join together with residential buildings to form a ZEV for economic reasons and share PV power production. In doing so, they would also maximize the utilization of the PV potential. The reasoning is straight forward. Large daily consumers would maximally invest in PV and fill their total roof area, but this does not yet cover their daily needs. Residential buildings leave potential fallow. The cost and benefit maximizing step would be that the residential buildings make their roof potential available to the day consumers against compensation. This is also the rationale behind the ZEV regulation. The split yield corresponds to the compensation. The problem is that in reality this is not observed. According to the SFOE, the municipality of Bern has a utilization of the available potential of 2.7%[18].

I see two main reasons for this. The first is transaction and coordination costs. After discussions with a solar contractor, there is reason to believe that in practice there are diverse coordination and transaction costs, which were not considered in this model. Because of the relatively small amount of electricity expenditures per household, the return on investment as an absolute amount is probably too small in many cases for residential residents to want to incur the expense of joining forces. A simple calculation can show the consideration: An average Swiss household electricity bill is of 932 CHF for the year 2020 (The Federal Council, 2019). The maximum return from the case study of a ZEV member compared to individual optimization is 5.49% per year. In absolute terms, the savings for the above mentioned average household in this house is 51.2 CHF/year. It seems plausible that in reality the household's coordination costs exceed this amount. Especially since the extreme example was chosen here and the profits as well might be even smaller. For a rational

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[18] Swiss Federal Office of Energy (SFOE), *Electricity production plants in Switzerland*, `https://www.uvek-gis.admin.ch/BFE/storymaps/EE_Elektrizitaetsproduktionsanlagen/`, last checked 14.11.2021.

large daily consumer, however, these returns should be attractive. This leads to the second possible reason why the results of the model cannot be observed in reality.

In the model, the same tariffs were assumed for all participants (buildings), so that the effect of the different usage types is not disturbed. In reality, large electricity consumers, such as the retail building from the case study, benefit from the liberal electricity market. Due to competition, they are likely to receive significantly lower electricity prices than households. These lower electricity prices reduce the rate of return and also for the large daily consumers, the incentives do not seem to be sufficient in reality to significantly drive the PV expansion.

However, the results suggests that the subsidy has the desired effect, especially for households, and leads to a higher utilization of PV potential. In order to drive the expansion further, this seems to be necessary at the state of the art electricity prices. On the other hand, based on the sensitivity analysis, it could also be argued that electricity tariffs should be increased to drive PV expansion. This could be done by introducing a CO_2 tax. Thus, the tariff increase would happen via the internalization of external effects of non-renewable energies. PV production itself would not be affected, or only to a relatively small extent. This is certainly a direction that can be further explored.

Analysis of transaction and coordination costs could also be fruitful. In a further investigation, these could be modeled with the error term in the presented model.

But besides, the results of this thesis must be taken with a grain of salt because of the small sample size. It is clear that a case study of such a small sample is not significant. The case study must rather be seen as an application example of the developed tools. Further, the simplifications made are also strong. For example, the buildings modeled as blocks do not reflect the predominant house shape for large parts of Bern. Furthermore, the coarse hourly resolution of load and PV data leads to a probable overestimation of self-consumption. Coarse because in the energy market, supply and demand must be balanced at every moment. This makes the energy market unique but also means that power flows in hourly resolution are a gross simplification of reality. As Luthander et al. (2015, p.14) states: *"In general, the self-consumption and thus also the revenue for PV systems without batteries are overestimated when using hourly resolution of PV electricity production and household load profiles. This is due to the sub-hourly variability that is evened out in the hourly values. Especially the load profiles are sensitive to the temporal resolution since the variability in the household load is often larger than the variability in the PV power production."*

In addition, the data in hourly resolution do not correspond to real measured values but are the result of a model simulation. It must be remembered that the assumptions made by CEA are based on average values. Even if the occupancy model is stochastic, not too big differences between simulated buildings of the same type can be expected (Romero, 2019). However, it can be assumed that these averages are relatively good suited for the buildings studied, since for multi-family buildings the total load consists of all individual load profiles combined anyway. In reality, the differences in consumption are also likely to be smoothed within the building, as shown by the results of Fina (2017). But still, even if the CEA development team has created the underlying databases to the best of their knowledge and using the latest technology, real houses and ZEVs in Bern can of course differ significantly from the simulation. For a next study it would therefore be appropriate to calibrate the model created with the CEA with real measured data.

Regarding the market environment in Bern, it can be said that under the assumptions of this thesis Energie Wasser Bern with subsidy supports the spread of decentralized electricity production. As mentioned before, it was not possible to investigate the role played by the tariffs of large daily consumers. However, since the free market plays here, the municipality's utility company and the municipality itself probably have little leeway. Another field would certainly be to investigate what incentives are set by other Swiss utilities for the expansion of ZEVs, since the freedom of the respective electricity suppliers to set their own tariffs is relatively large.

It is clear that the framework of a master's thesis always leads to simplification and the results correspond to this. The purpose is also more about the learning process. In this sense I think that the value of this work lies mainly in the elaboration of a workflow. A workflow for the assessment of ZEVs in Switzerland in places where real electricity and PV potential data are lacking. With this work it was shown how publicly available data can be used to create a model of larger parts of a city for simulating ZEVs. Finally, the optimization model introduced allows the financial assessment based on the calculation of the annual electricity costs. Those different tools can also be used for further investigations and can be further refined as desired.

9 Conclusion

In this thesis, a data set for the city of Bern is created, with which the PV potentials and load curves can be simulated in hourly resolution for the individual buildings with the help of the City Energy Analyst. For the thesis the Lorraine, neighborhood in Bern, was simulated. From this model, a building cluster consisting of seven residential buildings and a large retail store was selected for a case study. A multi-criteria optimization model was used to first calculate the cost-minimizing PV size of the individual buildings in the cluster and then for four hypothetical ZEV formations. The analyses were performed with and without one-time remuneration. The model shows that residential buildings in individual optimization do not exploit the full PV potential. Also a pure combination of residential buildings does not increase the PV expansion. Further, the possibility of storage does not increase the optimal PV output under the assumptions made. The one-time subsidy of 30% of the PV installation costs increases the optimal PV capacity for residential buildings, however the retailer is expanding to its full potential even without it. By combining the types of use, the full potential of the cluster in the case study can be exploited even without subsidy. Thus, the results encourage the interconnection of residential houses and large daily consumers. However, the significance is certainly limited by the input data of the optimization. The load and PV profiles were simulated with a highly simplified building model. The sensitivity analysis showed that the residential use type is strongly sensitive to tariff or investment cost changes. However, the main conclusion that residential and the large daily consumer (retailer) in a ZEV both minimize costs and maximize PV deployment is robust for the variations made.

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A Appendix

A.1 Model assumptions preliminary study

PV system

T_{panel} $= 20\ years$

P_{panel} $= 0.16\ kWp$

$T_{inverter}$ $= 10\ years$

cost parameters [19]

r $= 1.75\ \%$

p_t^g = ewb.BASIS in the business category (see Table 3)

p^f = ewb FiT of 0.0754 CHF/kWh (see Table 2)

I_0^p $= 2256\ CHF/kWp$

$c_{o\&m}$ $= (4.6 + 14.20)\ CHF/kWp$ (for cleaning and inverter replacement)

ϵ $= 0\ CHF/a$

MA is shown in Table 6 below.

Table 6: Maximum PV potential limited by the roof area and the power of a panel for every type of occupancy in the preliminary study.

Hospital	Gym	Swimming	University	Parking	Coolroom
8.52	8.71	9.26	9.63	9.62	9.99
Lab	Museum	Library	Multi_Res	Single_Res	Hotel
8.5	9.24	8.68	8.52	8.71	9.26
Office	Retail	Foodstore	Restaurant	Industrial	School
9.63	9.62	9.99	8.5	9.24	8.68

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[19] The specific investment costs are chosen for the PV peak capacity according to Table 1.

A.2 Model assumptions case study

PV system

T_{panel} $= 25\ years$

P_{panel} $= 0.16\ kWp$

$T_{inverter}$ $= 10\ years$

$T_{storage}$ $= 10\ years$

cost parameters[20] [21] [22]

r $= 1.75\ \%$

p^g_t = ewb.BASIS in the business category (see Table 3)

p^f = ewb FiT of 0.0754 CHF/kWh (see Table 2)

I^p_0 $= 2319\ CHF/kWp$

I^s_0 $= 1310\ CHF/kWh$

$c_{o\&m}$ $= 23.95\ CHF/kWp$ (for cleaning and inverter replacement)

ϵ $= 0\ CHF/a$

MA is shown in Table 7 below.

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[20] The specific investment costs chosen are the average of the costs for all roof sizes occurring in the case study according to Table 1. The same applies to the OM costs. The expected lifetime was taken from the same source.

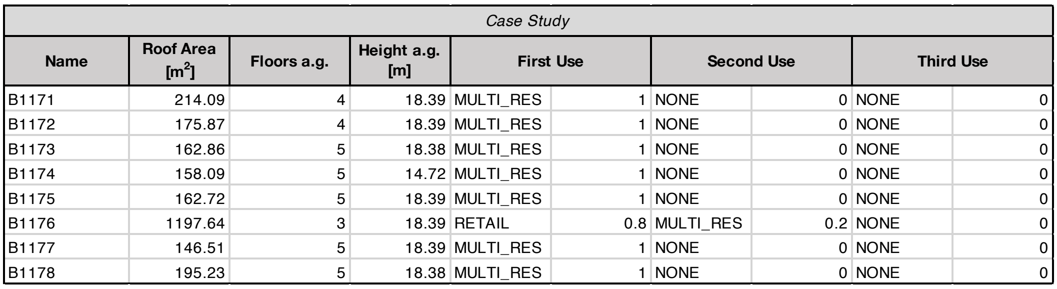
[21] The selected investment costs of a battery correspond to the average of the costs calculated by Perch-Nielsen et al. (2020) for large and small batteries. The expected lifetime was taken from the same source.

[22] The choice of the interest rate is based on the calculation of the calculation interest rate according to Art. 35 KPFV of the Federal Department of the Environment, Transport, Energy and Communications DETEC.

Table 7: Maximum PV potential limited by the roof area and the power of a panel for every building and ZEV of the case study.

B1171	B1172	B1173	B1174
13.48 kWp	10.71 kWp	10.34 kWp	9.77 kWp
B1175	B1176	B1177	B1178
10.35 kWp	77.93 kWp	8.7 kWp	11.48 kWp
ZEV_Retail_1_MultiRes	ZEV_2_MultiRes	ZEV_7_MultiRes	ZEV_Retail_7_MultiRes
91.41 kWp	24.19 kWp	74.83 kWp	152.76 kWp

A.3 Building properties case study



Case Study									
Name	**Roof Area [m^2]**	**Floors a.g.**	**Height a.g. [m]**	**First Use**		**Second Use**		**Third Use**	
B1171	214.09	4	18.39	MULTI_RES	1	NONE	0	NONE	0
B1172	175.87	4	18.39	MULTI_RES	1	NONE	0	NONE	0
B1173	162.86	5	18.38	MULTI_RES	1	NONE	0	NONE	0
B1174	158.09	5	14.72	MULTI_RES	1	NONE	0	NONE	0
B1175	162.72	5	18.39	MULTI_RES	1	NONE	0	NONE	0
B1176	1197.64	3	18.39	RETAIL	0.8	MULTI_RES	0.2	NONE	0
B1177	146.51	5	18.39	MULTI_RES	1	NONE	0	NONE	0
B1178	195.23	5	18.38	MULTI_RES	1	NONE	0	NONE	0

Table 8: Building properties of the model used in the case study to simulate the annual hourly PV production and load profiles for each building.
Source: Own table.

A.4 Pareto sets

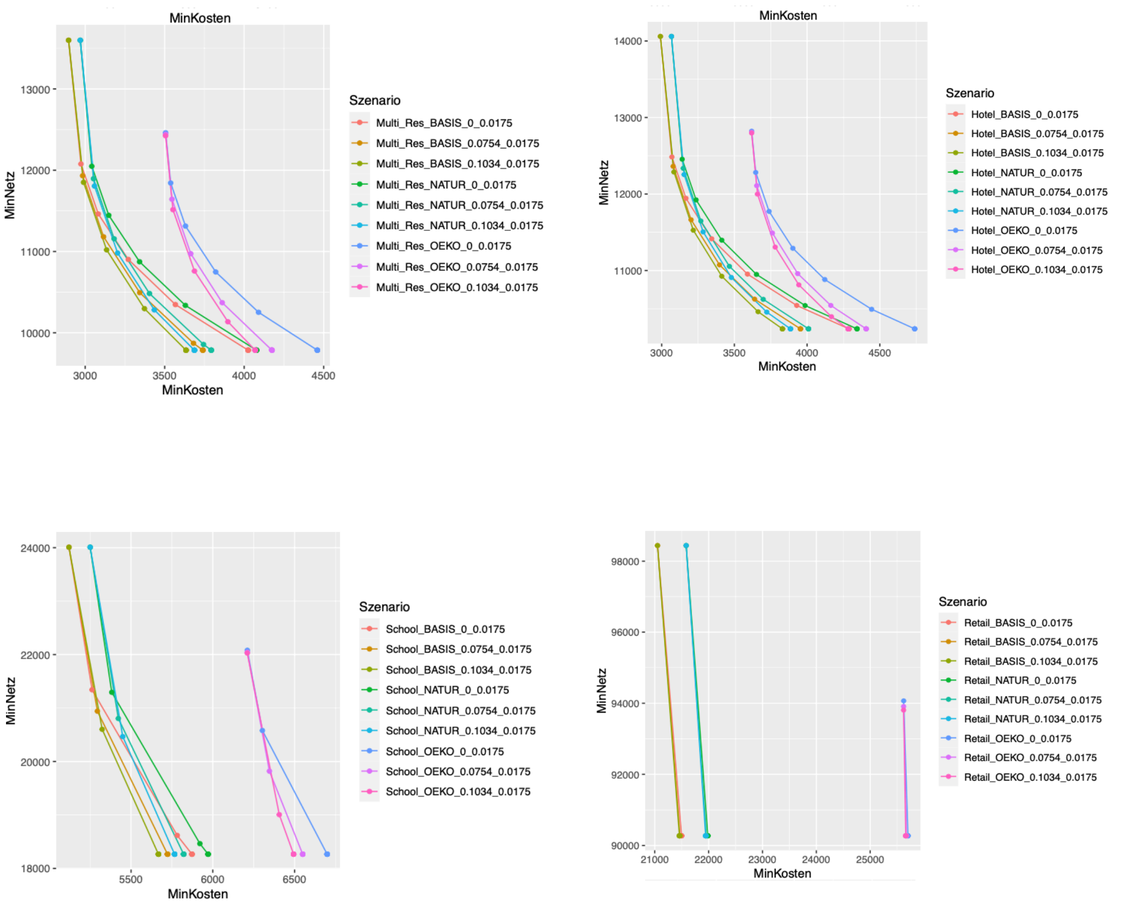


Figure 23: Four selected Pareto fronts showing the difference in tradeoff cost vs. self-sufficiency between heavy daytime or nighttime electricity users.
Source: Own figure.

Declaration of consent

on the basis of Article 18 of the PromR Phil.-nat. 19

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Registration Number: 12 - 127 - 635

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Bachelor ☐ Master ☐ Dissertation ☐

Title of the thesis: Modelling of „Zusammenschlüsse zum Eigenverbrauch“ (ZEV) (self-consumption communities) in Bern and assessment of their economic profitability.

Supervisor: Prof. Dr. Doina Radulescu

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