SWISS FEDERAL INSTITUTE OF TECHNOLOGY
ZURICH

SEMESTER PROJECT

Modelling approach of a large scale district for the final objective to analyse the self-consumption of PV-produced electrical energy

Author:
Sabine PYTHON
MSc IBS

Supervisors:
Danielle GRIEGO
Prof. Dr. Gerhard SCHMITT

October 30, 2018

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Declaration of originality

The signed declaration of originality is a component of every semester paper, Bachelor's thesis, Master's thesis and any other degree paper undertaken during the course of studies, including the respective electronic versions.

Lecturers may also require a declaration of originality for other written papers compiled for their courses.

I hereby confirm that I am the sole author of the written work here enclosed and that I have compiled it in my own words. Parts excepted are corrections of form and content by the supervisor.

Title of work (in block letters):

Authored by (in block letters):
For papers written by groups the names of all authors are required.

Name(s): **First name(s):**

With my signature I confirm that
- I have committed none of the forms of plagiarism described in the 'Citation etiquette' information sheet.
- I have documented all methods, data and processes truthfully.
- I have not manipulated any data.
- I have mentioned all persons who were significant facilitators of the work.

I am aware that the work may be screened electronically for plagiarism.

Place, date **Signature(s)**

For papers written by groups the names of all authors are required. Their signatures collectively guarantee the entire content of the written paper.

Acknowledgements

Here I want to address a grateful "thank you" to Danielle GRIEGO for her insightful supervision, empathy, patience and support during the whole project.
Many thanks also go to Martin MOSTEIRO and Daren THOMAS for their technical support and even late-night intervention.

Contents

List of Figures

List of Tables

List of Abbreviations

CEA	**C**ity **E**nergy **A**nalyst
DHW	**D**omestic **H**ot **W**ater
HVAC	**H**eating, **V**entilation, and **A**ir **C**onditioning
PCS	**P**rojected **C**oordinate **S**ystem
PV	**P**hoto**v**oltaic

Chapter 1

Introduction

1.1 Context & Motivation

The 21st of May 2017, the swiss population accepted the "Energiestrategie 2050" (Leuthard and Thurnherr, 2017) aiming to the progressive dismantling of nuclear power plants in Switzerland. This loss in energy production should be replaced by a mix of renewable energies. The confederation's objective is to reach 4400 GWh by 2020 and 11400 GWh by 2035, excluding the production of hydropower plants (Energy, 2018). This requires on one hand a vast investment plan in renewable energy technologies, on the other hand a a smart planning strategy.

Renewable energies show daily and seasonal fluctuations, which can be counteracted by energy storage but also by producing the energy where and when it is needed. Indeed, buildings also show daily fluctuations in energy demand, which depend on the type of use and occupancy. Thus, one should connect different building types to match their demand curve to the production curve of the locally installed renewable energy technologies. Self-consumption is a useful concept when it comes to maximize the use of renewable energies as described by Luthander et al., 2015.

Connecting prosumer and consumer is also no new idea. Indeed, several research projects have been conducted on so-called decentralized or distributed networks. In this field, Orehounig, Evins, and Dorer, 2015 investigated the optimisation of the energy consumption based on the energy hub concept. Fazlollahi, Girardin, and Maréchal, 2014, Getman et al., 2015 and Marquant et al., 2017 focused on the clustering approach and computation.

These works are based on urban energy models, which has evolved to a research field on its own in the last decades as stated by Keirstead, Jennings, and Sivakumar, 2012. Reinhart and Davila, 2016 reviewed bottom-up modelling approaches, while Allegrini et al., 2015 reviewed and compared existing modelling tools. Frayssinet et al., 2018 reviews different urban energy simulation methods focusing on the computational approaches. Of course, developping those models are an important part of this research field. Fonseca and Schlueter, 2015 presented an integrated model for characterisation of spatiotemporal building energy consumption at the district scale, which has been further used to develop the City Energy Analyst software (Fonseca et al., 2016)

1.2 Scope & Limitations

For this project I took Wiedikon, a district in the city of Zurich, as a case study, containing approximately 6000 buildings. The district's buildings and their occupancy types are mapped in Figure 1.1. I simulated the solar potential and the demand with City Energy Analyst (CEA), a tool which is currently being developed at ETH Zurch in the Chair of Architecture and Building Systems by Fonseca et al., 2017. The aim of this simulation is to calculate the self-consumption ratio from the electricity demand and solar potential outputs. Since CEA had never been run in such a large scale, a further point of intereest is the runtime for different sample sizes.

Although some work has already be done in the Chair of Information Architecture with CitySim, we prefered to use CEA for this project. One of the main reason is the shorter runtime of CEA, indeed CitySim needs about 10 hours to simulate 1 day on a large district. Another important advantage of CEA is the large and geographically near developer team of CEA, whereas CitySim is maintained and supported by a limited amount of people. Thus, the support is faster and more efficient. Moreover, as an open source software, CEA has a higher probability to be developped further and to be used in future research.

This project focuses on the preparation of the database structure to work with CEA and a first investigation on the demand and solar potential profiles. In this report, I will describe the different modelling assumptions and the input data requirements of CEA. Further, I will explain the overall process, from the raw statistics to the demand and solar potential resutls. I will present the first results on a small case and to conclude explain the main learnings and potential of CEA.

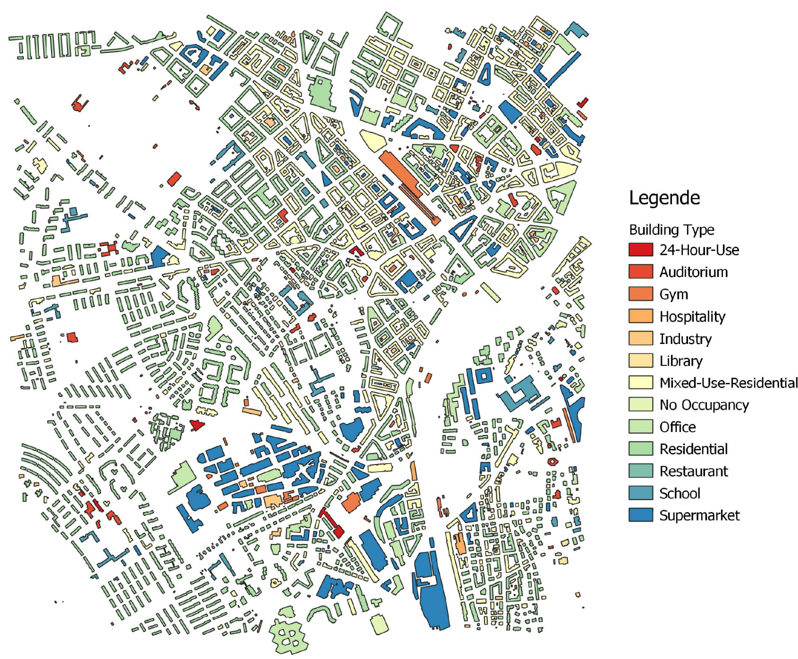


FIGURE 1.1: Building types of the whole district as in the statistics of the City of Zurich

Research Question

What is the best modelling apporach to simulate the electrical energy demand and production of a large district (6000 buildings) for the final objective to analyse the self-consumption at the community level?

Chapter 2

Method

2.1 Workflow

Figure 2.1 depicts the different databases (in squares) and the different tools (circles) used. One can notice that CEA itself contains different tools working with different input data. The ones shown in Figure 2.1 are the basic simulation tools needed to run further ones integrated in CEA, which are not depicted here. Indeed, CEA contains a vast choice of tools for various application for Urban Energy Systems application. Nevertheless, note that the order is of great importance. Indeed, some tools do need the output files generated by another tool. For example, the user needs to first run the *radiation* tool before the *demand* tool, since the lattest needs the solar radiation to assess the demand in lighting.

Source Databases

The first step of all new project is to gather and clean the source databases. The user has to make sure that the data sets are complete and that each geometry point has corresponding building properties. Further, it is necessary to develop an ID system to identify each building and fulfilling the CEA requirements, i.e. letter + numbers. This is also helpful in case debugging is needed.

Primary Databases

This source databases must in a second step be processed in the CEA structure. This concerns the format of the input files (Shapefile, DataBaseFile) but also the type of the input elements themselves (integer, float, etc.). The naming of the files and of the headers must also be set according to the CEA system. These requirements can be found in the online CEA documentation. The folder structure used in CEA is also given. Nevertheless, the user can here use the tool named *create_new_project* which will create the folder structure with the input databases. In case the user is not used to the DataBaseFile format, CEA also contains a tool to convert excel files to the desired DataBaseFile.

Secondary Databases

The third step consist in creating the missing secondary databases. This is easily done by running the *data helper* tool. Note that this tool does not notice whether the input elements have the correct type and could so produce wrong or empty files. I would therefore advice to check the secondary databases before going to the next step.

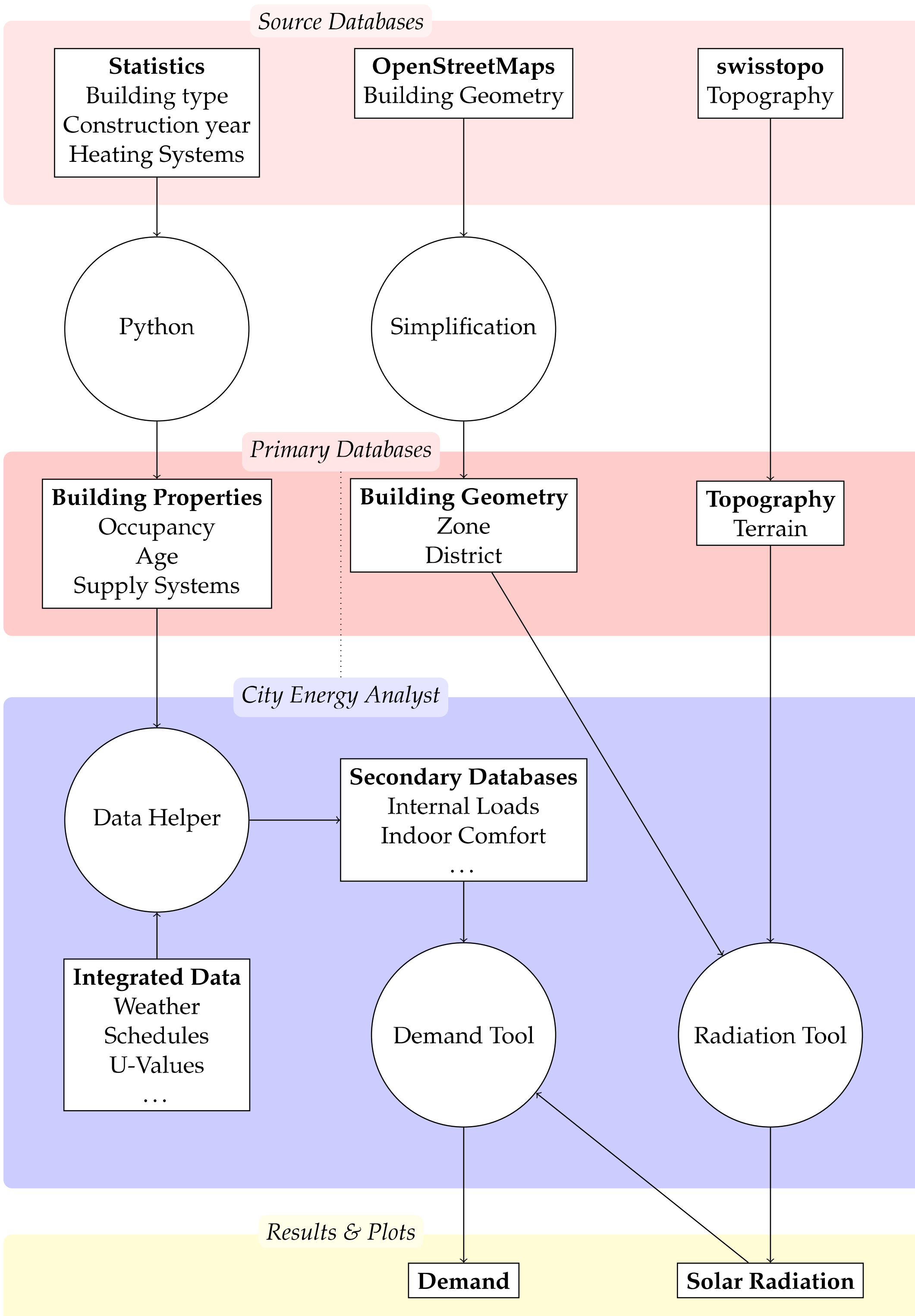


FIGURE 2.1: CEA workflow from source databases to simulation results.

Radiation Tool

Any simulation has to begin with the *radiation* tool. Out of the building geometry, the topography and the weather files, this tool calculates the hourly insolation at certain sensor surfaces in W/m^2. Depending on the size of the zone the runtime can last from few minutes to several hours. The runtime of the *radiation* tool will be further investigated and discussed in the next chapters.

Demand Tool

The demand tool processes information contained in the primary and secondary databases to compute the hourly demand of each zone. The demand output is separated in the different load types, i.e. heating, cooling, electricity, DHW. This tool is generally faster than the *radiation*, but no investigation has been undertaken to analyse to effect of the zone size on the *demand* runtime.

Plots

A plot tool is already part of CEA. The user can select the data to be plotted in the configuration editor under the tab called *plots*. The plots are web-based and have some interactive features. For example, the user can select the time range by displacing a cursor.

2.2 Data Processing

In this section I explain how I processed the data into a CEA readable structure. Further, I justify the different assumptions a made to simplify the model and to meet the CEA requirements.

To reduce the complexity of the model and so reducing the simulation time, the geometry originating from OpenStreetMaps has been simplified. The nearly 6000 buildings were clustered in 2000 zones, each zone corresponding to a group of buildings sharing facades. In this way, the number of polygons has been reduced without loosing the overall geometry.

To model the properties of the district of Wiedikon, I used the statistics published by the City of Zürich. Since the categories of the statistics do not exactly correspond to the ones integrated in CEA, the data has been processed with Python and brought to a readable format for CEA. The requirements of CEA and the processing approach are described in the sections below.

2.2.1 CEA Data Requirements

CEA has strict requirements on the format of the input files as well as for the type of the input data. These requirements can be looked up in the online CEA documentation. The user should also make sure that the coordinates system of the zone and district geometries corresponds to the system used for the terrain. Moreover, this should be a projected coordinate system (PCS) for CEA to work correctly. Further, note that CEA will not automatically notifiy the user if the data does not fit its requirements. Thus the user should check thoroughly each input before processing it with CEA, even more if the case is large and takes a longer time to simulate.

CEA defines three categories of input data: integrated, primary and secondary. The integrated databases are the schedules and building properties, which are already contained in CEA. The primary databases must be supplied by the user, according to a strict structure and naming. The occupancy distribution, the construction and renovation years, the topography and the zone geometry are primary databases.

Secondary databases can be set by the user, but can also be generated from CEA using the data helper tool. Indeed, based on the primary databases and on integrated database, CEA defines the supply and technical systems, the internal loads, the indoor comfort and the restrictions. Note that the data helper tool does not recognise whether a secondary database has already been created by the user. Thus, if not set otherwise in the configuration editor, the case specific database will be overwritten by CEA with generic assumptions.

2.2.2 Model Assumptions

Occupancy

The general occupancy types used by CEA differ from the ones used by the Statistics Office of the City of Zurich. I defined a translation key giving to each archetype of the statistical database a corresponding occupancy type from CEA (Table 2.2).

Recall, that to simplify our model and reduce the computation time, we clustered buildings sharing a wall to a zone. This means that buildings with different occupancy schedule are considered as only one. Fortunately, in contrary to CitySim, CEA accepts a percentage for each occupancy type. These ratios are based on the gross floor area of each archetype in the building zone.

Supply Systems

The supply systems input contains the energy carriers for heating, cooling, electricity and domestic hot water (DHW). I could adapt from the statistics the heating systems to the CEA code for each building zone (Table 2.4). But, there are no statistical database about the cooling and electricity supply systems. Since cooling system are quite rare in Switzerland, I assumed no cooling system for the entire district. Since I want to investigate the PV potential of the district, I defined the electricity supply of the whole district to be the typical swiss consumer energy mix for the basic model.

The Statistics Office of the City of Zurich does not record the DHW supply systems, but the Federal Statistical Office published some results about the DHW systems in Switzerland (Federal Statistical Office, 2018). As shown by 2.3, it appears that no system dominates the other, thus assuming the same supply system for DHW in the whole district would lead to too big discrepancies with reality. To respect the statistics as much as possible despite the lack of information about the individual buildings, I assigned a random DHW supply system to each building zone according to the statistical distribution. This means, a DHW supply systems with a high percentage in the swiss statistics will have a higher probability to be picked and assigned to a building zone. In this way, the overall distribution approximates the statistical federal distribution. Nevertheless, some bias could appear because the DHW supply systems are assigned per building zone, without taking the gross floor area of into account. Moreover, the number of the Federal Statistical Office are themselves are based on a sample, not on the whole swiss building stock, and the office does not publish if the percentage relate to the number of buildings/systems or on the gross floor area they supply.

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

TABLE 2.2: Key for the occupancy from the statistics of the City of Zurich to the CEA convention.

Age

Here CEA needs the year of construction of the building and the year of renovation of different building elements (roof, windows, partitions, HVAC, envelope) to derive the U-values of the different building elements (walls & roofs, windows, basement). From the statistics of the City of Zurich, we know the construction year and a

Primary Energy Source (en)	(dt)	
Oil	Heizöl	26.7%
Gas	Gas	16.7%
Electricity	Elektrizität	32.7%
Wood	Holz	4.0%
District Heating	Fernwärme	2.3%
Solar Thermal Collector	thermische Solaranlage	2.9%
Heat Pump	Wärmepumpe	13.1%
Other Energy Source	Andere Energieträger	0.9%
No Energy Souce	Kein Energieträger	0.5%

TABLE 2.3: Federal statistics of primary energy sources for domestic hot water in Switzerland.

Statistics types	CEA types
Kein Energieträger	none
Keine Angaben	none
Heizöl	oil-fired boiler
Kohle	coal-fired furnace
Gas	natural gas-fired boiler
Kombi-öl/Gas	natural gas-fired boiler
Elekrizität	electrical boiler
Holz	wood-furnace
Wärmepumpe Erdsonden	heatpump - soil/water
Wärmepumpe Luft	heatpump - air/air (COP 2.7)
Wärmepumpe Niedrigtemperaturige Abwärme	district heating heat pump - water/water
Wärmepumpe Andere	heatpump - water/water
Fernwärme	district heating Kerichtverbrennung CHP
Anderer Energieträger	None

TABLE 2.4: Key for the heating systems from the statistics of the City of Zurich to the CEA convention.

general renovation year, without knowing which building component(s) have been renovated or replaced.

The lack of documentation on the types of renovation prevent a modelling on statistical base. Indeed, statistics on this topic began in 2000 and have been in analyzed in a report published by the City of Zurich (Bauliche Erneuerungen in Zahlen, January 2016). Despite this recent results, the report focuses on data that could be used to customize the default data of CEA (for example if it CEA results appear too far from expected values), but not to improve the model of the input data. Thus, for the sake of simplicity, I assumed that the renovation year apply for all components (roof, windows, partitions, HVAC, envelope).

District & Zone

In CEA, the zone is the analysed sector, whereas the district also includes the surrounding buildings, which are not in the scope of simulation but still influence the analysed zone. Note that CEA and our model do not have the same definition of zone. For CEA, zone refers to the scope of simulation and analysis. In our model, a zone is a cluster of buildings sharing walls. From this point on, *zone* will be used in the CEA understanding.

The user has to be carefull when defining the zone and district. Indeed, all the buildings contained in the zone must also be in the district. Moreover, the *radiation* tool cannot handle underground buildings with no height above ground. Therefore, for the sake of simplicity, I deleted these buildings from both the zone and the district. Another important point is to set a Projected Coordinate System (PCS).

Topography

The terrain input is particularly important for the radiation simulation. Indeed, the height of the buildings, as well as hills or mountains, reduce or increase the incoming solar radiation. Even if the district of Wiedikon seems mostly flat, this is not always the case. Further, this part of the city of Zurich is gretly affected by Uetliberg, a steep hill dominating Wiedikon by almost 500 m. This is why the terrain spreads beyond the district boundaries to include the relief of Uetliberg as shown in Figure 2.2.

Since the topography is an important factor in the radiation calculation, the resolution of the input probably also plays a significant role in its runtime. Figure 2.3 depicts the topography for three different resolution, the smaller the mesh size, the higher the resolution. These files were downloaded from the geodata4edu website supplied by swisstopo.

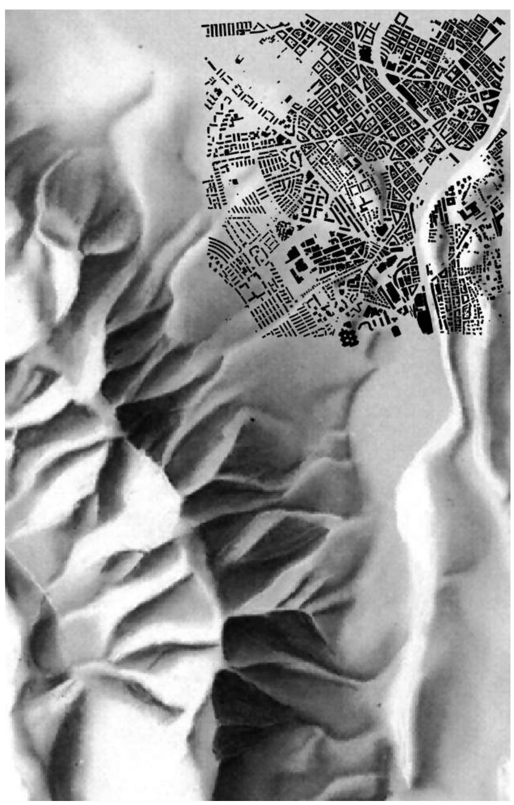
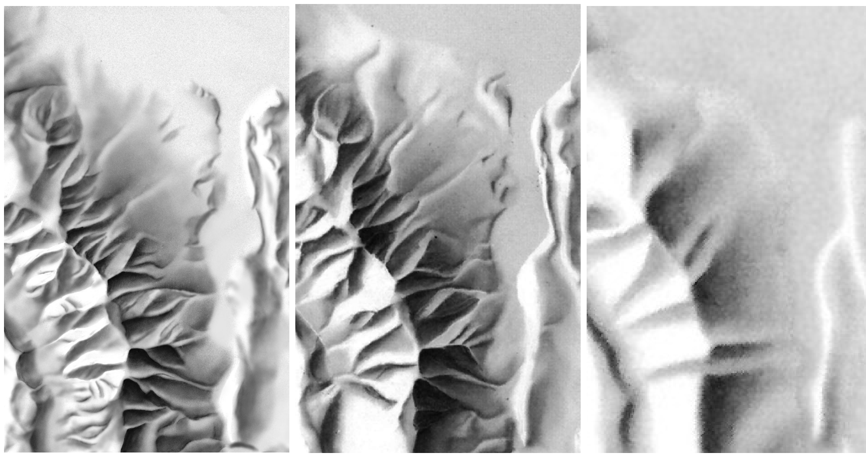


FIGURE 2.2: Topography (100mx100m) of the district of Wiedikon including Uetliberg.



(a) (b) (c)

FIGURE 2.3: Topography with resolution of (a) 50mx50m (b) 100mx100m (c) 200mx200m.

2.3 Sample Selection & Simulation

In this project, I investigate the influence of the zone size on the runtime of the *radiation* tool. The zones were cropped is such manner, that the smallest sample would be in the middle of the overall case study and the larger samples would grow around it. I selcted several "small" samples Figure 2.4 maps the diffrent samples, in this figure, each larger sample contains the smaller ones.

For the different samples, I defined for each zone size a larger district, often corresponding to the zone of the larger building. The zone sample and its corresponding district size are shown in Table 2.5. Because the 50 buildings zone is not completely surrounded by the 100 buildings sample, I assigned it the next larger sample, i.e. 500 buildings sample. It is indeed important that the zone is completely surrounded by the district, since the shading effect of the surrounding plays a major role in the *radiation* calculation.

Zone size	10	50	100	500	1000	1650
District size	100	500	500	1000	1650	1947

TABLE 2.5: Samples and their corresponding zone and district sizes

CEA crashed with the default parameters when running the *radiation* tool for 1000 buildings. For CEA to be able to simulate such a large sample, the *n-buildings-in-chunk* parameter has been reduced from 100 to 10. This would probably affect the runtime of the *radiation* tool. However, it is still unclear how this parameter would affect the results of the simulation.

2.4 Self-consumption scenarios

Using the electricity demand and the solar potential output from CEA, I analysed the self-consumption of 4 different electricity sharing scenarios. I assumed a PV efficiency η of 25% and a roof coverage r of 40% to calculate the produced electricity. The self-consumption is the ratio between the consumed solar energy over the produced solar energy as shown in equation 3.1. I chose the building Z0030 as the

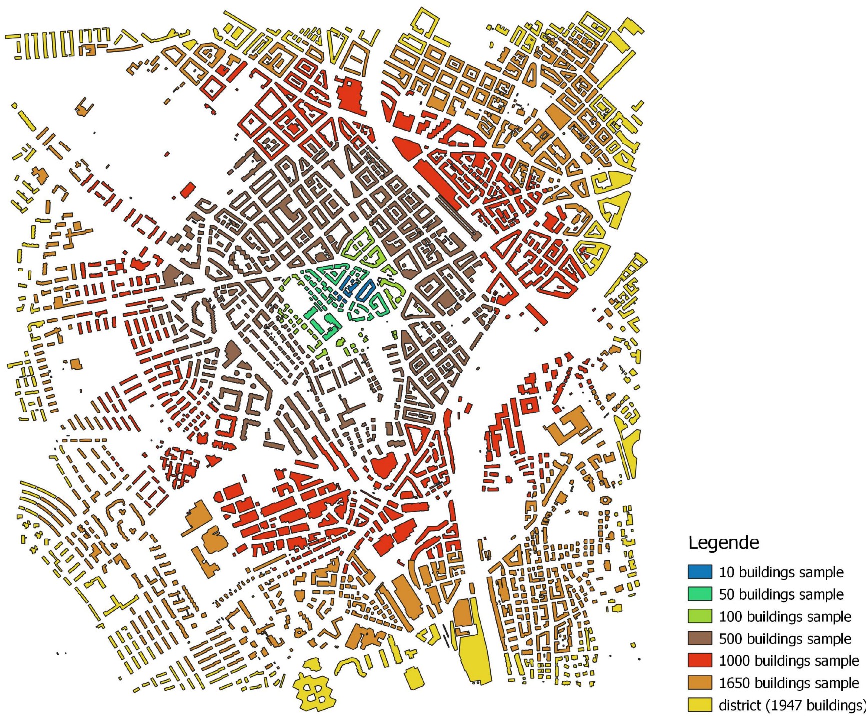


FIGURE 2.4: Map of the different sample sizes

PV electricity producer. To increase the self-consumption over the neighborhood, I added a group of residential buildings and a group of school buildings as consumer. Figure 2.5 maps the chosen buildings.

$$\text{self-consumption} = \frac{E_{sol,cons}}{E_{sol,prod}} \tag{2.1}$$

$$E_{sol,prod} = \eta \cdot r \cdot I_{sol} \cdot A_{roof} \tag{2.2}$$

The first scenario considers only the prosumer building, the second one adds the school complex. The third scenario takes as consumer only residential buildings, Z0030 and its near neighboors. The fourth scenario includes all the school and residential buildings considered in the previous scenarios. Table 2.6 summaries the scenarios and the considered buildings.

Scenario	Z0030	School	Residential
1	×		
2	×	×	
3	×		×
4	×	×	×

TABLE 2.6: Self-consumption scenarios.

FIGURE 2.5: Map of the building included in the different electricity sharing scenarios.

Chapter 3

Results

3.1 Runtime

CEA had never been run with district containing more than 400 buildings. This is why I was particularly interested in its runtime when running the *radiation* tool for different zone sizes. The resolution, or granularity, ot the terrain has also been taken into account, e.g. the terrain with a 100mx100m mesh has a higher resolution than the 200mx200m terrain. Table 3.1 resumes the results in minutes . A dash mean that the simulation has not been run for these parameters. I did not use the terrain PK50 for zones with more than 10 buildings, because the difference at this size between PK50 and PK100 are already notable.

Zone size	10	50	100	500	1000	1650
District size	100	500	500	1000	1650	1947
50mx50m	7.66	-	-	-	-	-
100mx100m	3.75	17.23	31.61	310.47	642.28	-
200mx200m	-	-	28.99	285.69	477.77	1123.26

TABLE 3.1: Runtime of the *radiation* tool in minutes different zone sizes and terrain resolution.

Figure 3.1 shows the influence of the topography granularity on the runtime. Indeed, here one can see that the resolution of the terrain makes a significant difference only above 500 buildings. Furthermore, the evolution of the runtime with the zone size does not seem to be exponential, which would mean that simulation with more than 1650 buildings should run in an acceptable and maybe even predictable time range. Nevertheless, this effect could also due to the fact that some parameters had to be change to scale the simulation from 500 to 1000 buildings. Indeed, CEA crashed with the default parameters when running the *radiation* tool for 1000 buildings because the threshold of sensors had been exceeded. For CEA to be able to simulate such a large sample, the *n-buildings-in-chunk* parameter has thus been reduced from 100 to 10.

3.2 Demand & Solar Potential

Self-consumption is the ratio between the consumed and produced energy. Thus to maximize the self-consumption the energy should be consumed exactly when it is produced. This concept is particularly important in the case of non-controllable renewables like wind and solar energy. Indeed, PV generated power is highly dependend on the sun and weather, whereas the consumption depends on the occupant's

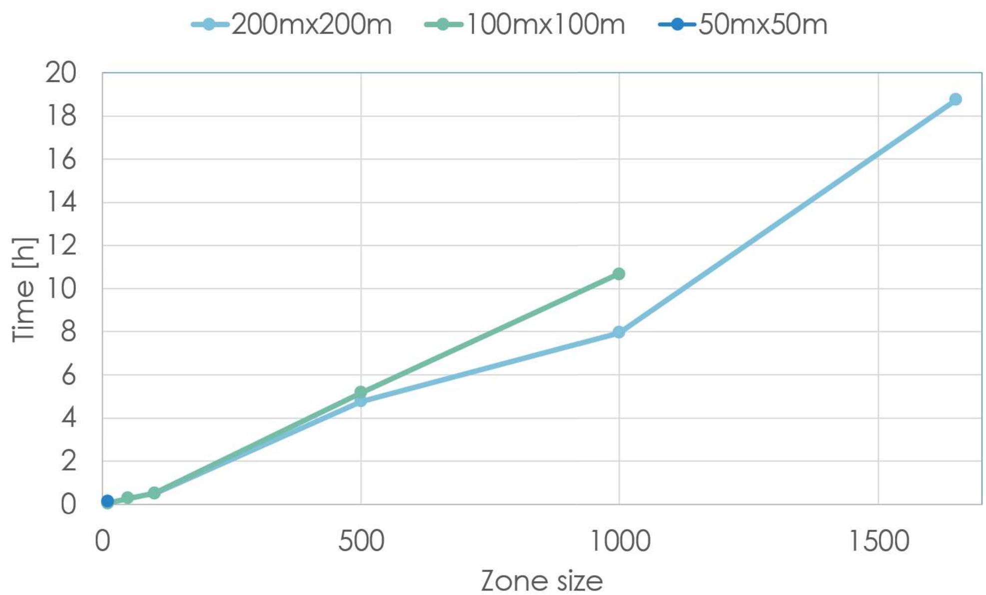


FIGURE 3.1: Runtime of the *radiation* tool in hours plotted against the number of buildings in the different zone samples.

habits. Therefore, the production and consumption profiles can be substantially different and thus reduce the self-consumption. This mismatch between production and consumption happens on three levels, the spatial, the daily and the seasonal levels.

3.2.1 Spatial Distribution

Figure 3.3 and Figure 3.2 show resptectively the electricity demand density ($kWh/m^2/year$) and the solar irradiation ($kWh/m^2/year$) of the 50 buildings sample. Note that the values of Figure 3.2 represent the yearly average of the solar irradiation on the roof of each building and not the potential PV production. By comparing these two figures, one can see that the demand distribution and the solar potential distribution do not correspond to each other. This perfectly depicts the spatial mismatch between the high potential PV electricity producer and the high consumption buildings. By developping a PV and electrictiy sharing system at the district level, the load and the production could be optimized to maximize the self-consumption. Visual results as Figure 3.3 and Figure 3.2 could help the urban planners to select appropriate buildings to be integrated in an PV community or energy hub.

To understand the radiation distribution pattern, let us have a closer look to the height of the buildings, which is shown in Figure 3.4. Indeed, one could assume that the higher the building, the more solar radiation it receives. However, the radiation and the building height maps do not show the same distribution. An interesting case is the highest building of the zone, in the southern most part. This building reaches 27m but has a low solar potential, despit its height and orientation. This can be explained by the steep hill bording its south façade and probably shading this building during most of the day. This hill is clearly visible in Figure 2.2 (a).

A comparison between the electricity density depicted in Figure 3.3 and the building type in Figure 3.5 shows that the occupancy type of the building only plays a minor role in the yearly electricity demand. The school complexe in the south part of the zone is a good example: it is composed of four buildings but each of them has a different electricity demand density. As explained by Aksoezen et al. (2015), the building age should be an important indicator for the energy demand, which does also include heating loads. Looking at the construction and renovation years depicted in respectively Figure 3.6 and Figure 3.7, we see that the age or renovation year are not highly correlated to the the electricity demand in Figure 3.3. This makes sense as the age mostly influences the heating loads and not the electrcity demand. This means that the electricity demand depends on a superposition of parameters and that a simple look at the building stock statistics is not enough to determine the electricity sharing potential.

3.2.2 Temporal Distribution

The Figure 3.8 and Figure 3.9 depict the weekly radiation and demand curves in respectively winter (January) and summer (July). These graphs have been exported from CEA. The electricity demand curve shows a relative constant load over the whole year, but it fluctuates in the hourly range. Indeed, each day is ruled by three peak hours: morning, noon and evening. This pattern is due to the strong representation of residential buildings in the 50 buildings sample. Indeed, dwellings are mostly occupied during the meal times.

In contrast to the electricity demand, the solar radiation strongly fluctuates over the year, with a peak in summer and a valley in winter. Furthermore, the hourly oscillations are stochastic since the radiation strongly depends on the cloudiness. Note that the radiation on the roof is the most affected by the season change, since it decreases of approximately 70% from summer to winter, whereas the radiation on the façades "only" diminishes of approximately 50%. Moreover, the time range of radiation is longer in summer than in winter.

Comparing the time evolution of the radiation and electricity demand, one can see that the curves mismatch in the peaks and duration. There would be theoretically enough radiation to supply the overall electricity demand, but these mismatches restrict the power supply times. Therefore, a diversification of buildings types and demands are needed to shift the peak to approach the solar radiation curve.

3.3 Self-Consumption

In this part, I will present the self-consumption results for the four scenarios defined in the method chapter. Using the electricity demand and the solar potential simulated by CEA per building and the equation 3.1 I calculated the hourly self-consumption ratio. Due to the night hours there is no PV power production and thus also a zero self-consumption during most of the year. Indeed, the yearly average stays in the range of 1.5% to 4.4% for all scenarios. Excluding the night hours, the yearly mean reaches a self-consumption between 3.1% to 8.6%. Table 3.2 summaries the two kinds of average for all scenarios.

$$\text{self-consumption} = \frac{E_{sol,cons}}{E_{sol,prod}} \tag{3.1}$$

Results explained by boxplot of SCR; tried to correlate with buildings and time of day/ season

Figure 3.10 shows the yearly distribution of the self-consumption for the four scenarios. As said before the mean is quite low for each scenario. Nevertheless, the distribution of the outliers varies strongly. One can see that the PV potential of the building Z0030 is too high for its own consumption, as it can use approximately 80% of its production at its best. Adding more consumers increases slightly the average and enlarges the high probability domain. The outliers of the scenarios 2,3 and 4 map in Figure 3.10 a similar pattern, whereas their density in the fourth scenario is higher than in the two other ones. This is especially true for the higher self-consumption ratios. This means that the fourth scenario has more high self-consumption hours. Further, one can see that the school complex has a strong effect on the outliers, while the increase in average is still low compared to the first scenario. On the other hand, the third scenario has a large effect on the average, probably due to its higher outliers density between 85% and 100%.

It has to be noted that the hours with the highest ratio are the first and last hours of the day, also winter days show a higher self-consumption as depicted in Figure 3.11. This can be explained by the low PV production during winter, sun rise and sun set, while there is still electricity demand from the users. Thus, a self-consumption of 100% means that all produced electricity is directly consumed, but it could also mean that the demand is not fully covered by solar energy.

	Scenario	Self-cons. average over all hours	Self-cons. average over day hours
1	Z0030	1.5 %	3.1 %
2	Z0030 & School	2.4 %	4.8 %
3	Z0030 & Residential	3.7 %	7.3 %
4	Z0030 & School & Residential	4.4 %	8.6 %

TABLE 3.2: Self-consumption average of the different electricity sharing scenarios.

FIGURE 3.2: Total solar radiation density in $[kWh/m^2/year]$ of the 50 buildings sample

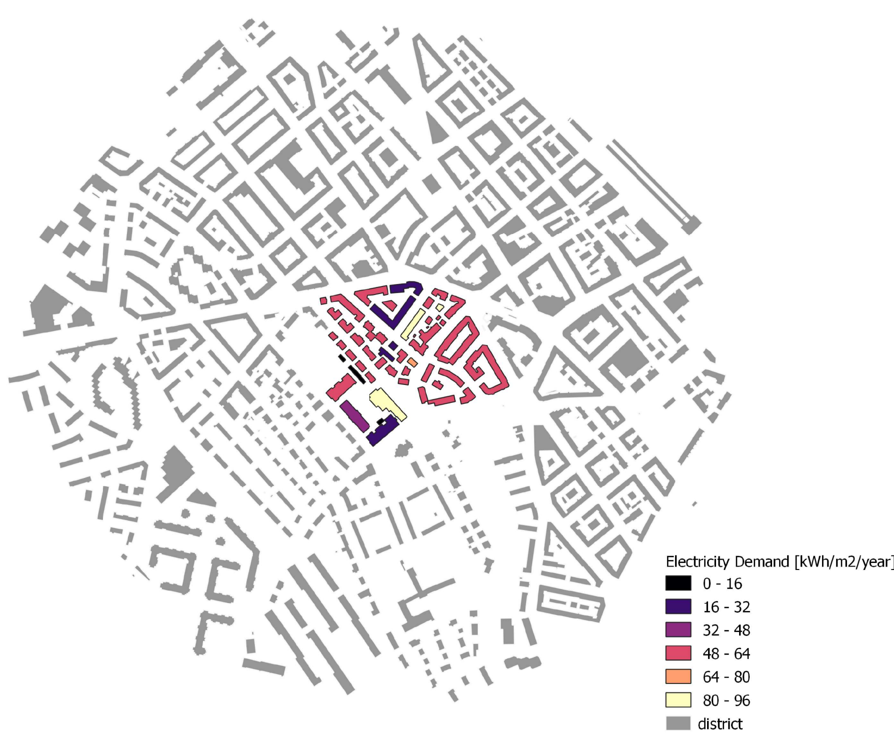


FIGURE 3.3: Total electricity demand density in $[kWh/m^2/year]$ of the 50 buildings sample

FIGURE 3.4: Building height in [m] of the 50 buildings sample

FIGURE 3.5: Building types of the 50 buildings sample

FIGURE 3.6: Construction year of the 50 buildings sample

FIGURE 3.7: Renovation year of the 50 buildings sample

FIGURE 3.8: Radiation and demand curves of the 50 buildings sample from January 1 to January 8.

FIGURE 3.9: Radiation and demand curves of the 50 buildings sample from July 1 to July 8.

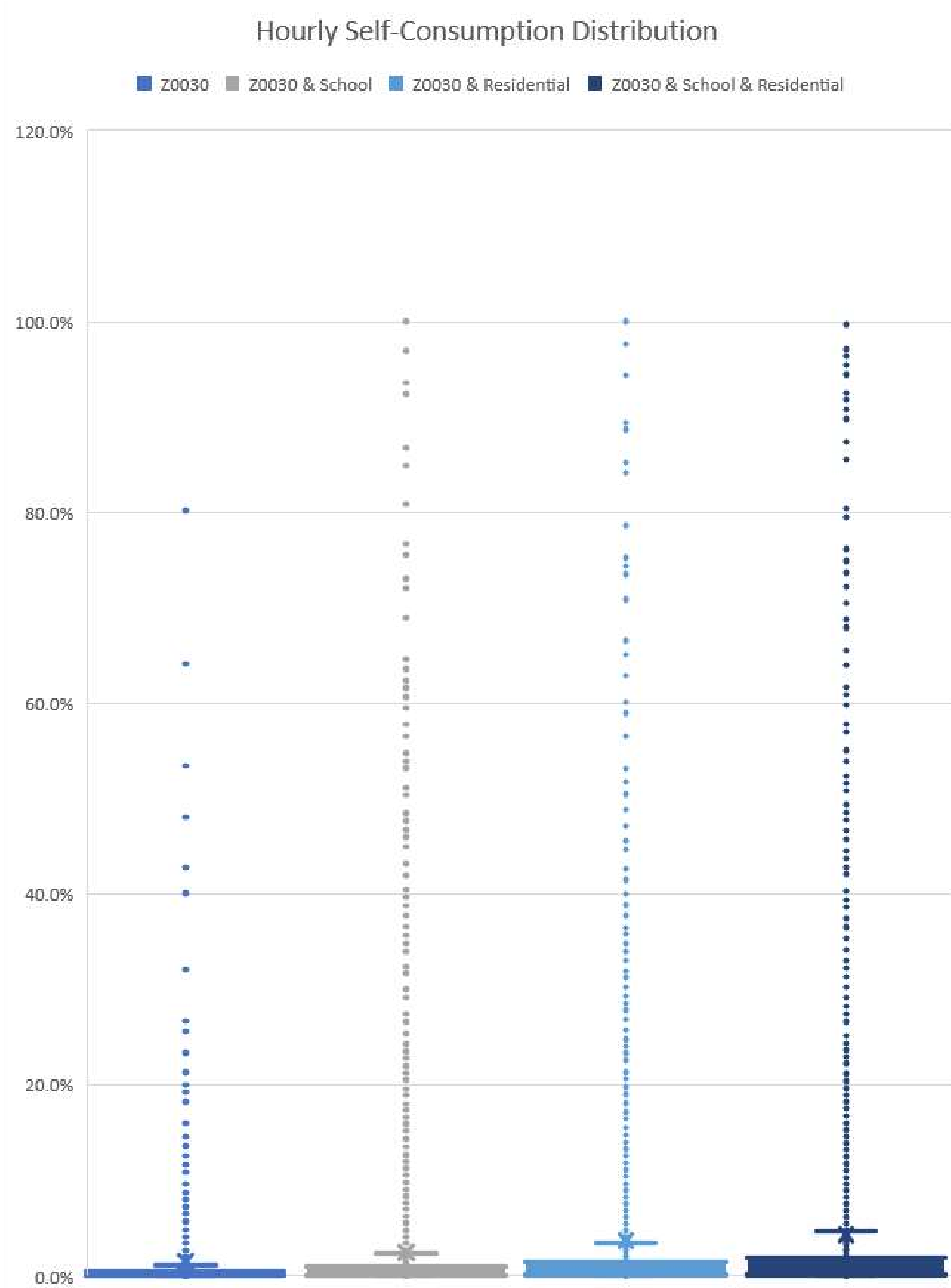


FIGURE 3.10: Hourly self-consumption yearly distribution of different electricity sharing scenarios.

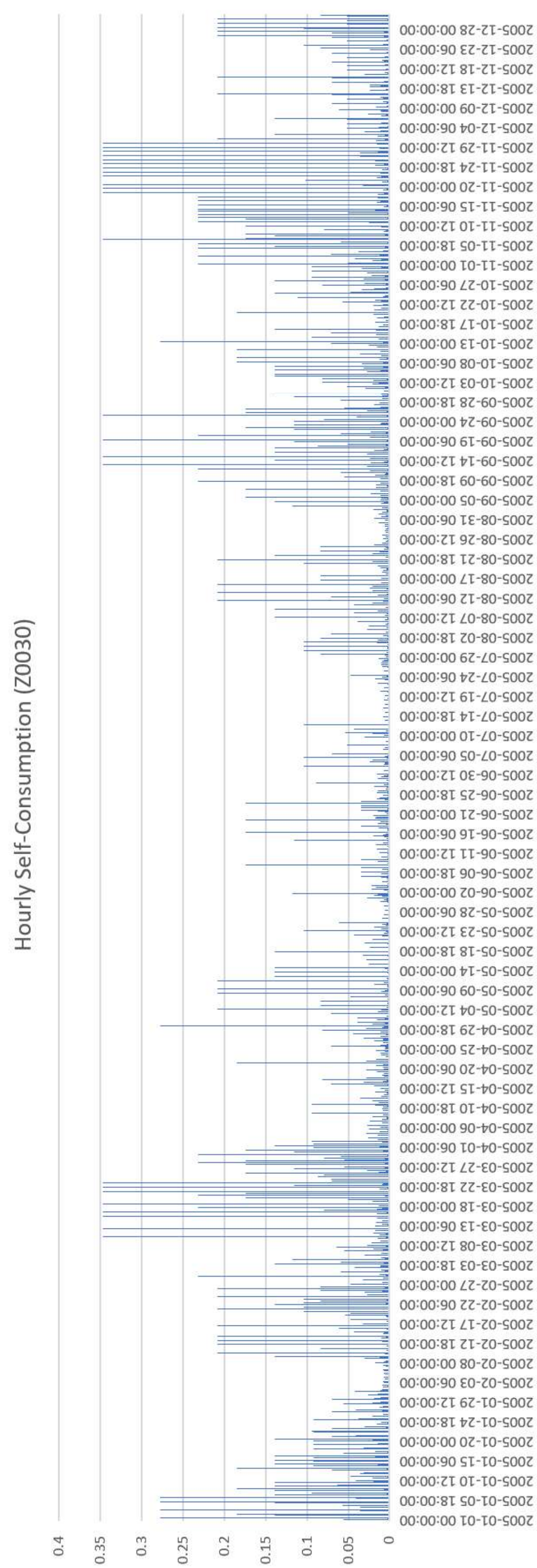


FIGURE 3.11: Hourly self-consumption over the year for the first scenario.

Chapter 4

Discussion

4.1 Runtime & Self-Consumption

The runtime analysis presented in this report gives a first understanding for the *radiation* tool. It seems that CEA handles increasing scale well, indeed the relation between the size and the runtime is almost linear. However, the observation scope includes only 6 different scales, thus lacking on samples, especially on the large scale level, to assess the time management of the *radiation* tool. Furthermore, the *n-buildings-in-chunk* parameter had to be reduce for the samples with more than 500 buildings, e.g. the runtimes for the large scales are hardly comparable to those of the small scales.

In this project I also approached a basic self-consumption analysis on different community scenarios. Note that the prosumer and consumer buildings has been chosen arbitrarly. I observed, that the prosumer alone would never reach 100% self-consumption ratio, while this is reached as soon as more consumers are added to the grid. The more consumers, the higher the average over the whole year, although it stays under 10% for all scenarios. I also observed that the highest self-consumption ratios are met at the first and last hours of the day as well as during winter, when the radiation potential is lower. It has to be noted that for this calculation I assumed all roofs to be flat and that I did not take into account the infrastructure limitations. One has to point out that the self-consumption results are too low to be realistic. This is probably due to the wrong calculation of the solar power production. Indeed, I calculated it directly from the solar radiation, without taking the conversion to electricity into account. Taking the results from PV simulation tool from CEA would be the correct way to proceed.

4.2 Learnings

In this section I will explain the different lessons learned at a process and personal level during this project. Indeed, several tools I used were new to me and also the scale of the project was a first-try for the CEA team.

As explained in the previous sections, CEA has strict requirements concerning the input files. Therefore, first listing the requirements and then thoroughly verifying the own databases is a non-negligible step. In this way, errors can be spotted in the early process and save a lot of time for the simulation part. This verfication step should include:

- Correct format and naming of the input files (Shapefile, DataBaseFile, Tagged Image File) as stated in the CEA documentation
- Correct type of the input data (integer, string, float, etc.) with Notepad or similar software as stated in the CEA documentation

- Corresponding and overlapping coordinate system for the zone, district and terrain
- All zone buildings included in the district
- No buildings with 0 floors above ground in the zone and district inputs for the *radiation* tool
- Correct structure of the project folder

To a new CEA user who wishes to simulate a large scale district I would recommend to first test it on a smaller sample, e.g. 10 to 30 buildings. Even if preparing a second project could seem laborious and time-consuming, I think this additional verfication would help to check the correctness of the input files in only few minutes and finally save time and avoid frustration at the larger scale. Moreover, is it easier to spot the error on a smaller sample, because there are less buildings to check and correct, thus the iteration steps are shorter and the verification faster. It is important to document every change during these iterations to implement them later on the larger scale project. When the small sample works flawless, all the corrections can be integrated to the large scale project at once based on the "verification report".

If, despite all the verification steps, the user still encounters problems with its simulation, I highly recommend to publish a so-called "issue" on the GitHub platform. There the maintainers can support the user in a conversation way. This process has the advantage to keep track of the evolution of the issue. Moreover, these discussions are public so that future users with similar issues can easily find an appropriate answer without having to describe their own problem and waiting for an answer.

4.3 Potential of CEA

Weaknesses

After my first experience with CEA and setting up my own case study, I would say that this tool is not mature enough for users without a technical support at proximity. I will explain why in this section. As explained in the method chapter, CEA has very strict requirements concerning the input database. Some of these are listed in the online documentation. However, some occured as the simulation crashed because of not adequate input files. In most cases, CEA would not notify where the error lies, so that the developpers who helped me and I had to search for the knot. For this search to be successful, a deep understanding of CEA is needed. This is why I think setting up a large project which completely complies with CEA in a reasonable time frame without the near help of the technical team is nearley impossible. However, this would be made easier with a more complete and intuitive documentation.

Another drawback of CEA, is its limited integrated database. Indeed, it includes data for exclusively Switzerland and Singapore. A user wishing to simulate a district in another geographical or climatic region, would have to adapt or even replace these inputs. But since CEA is an open source software based on GitHub, the choice of location could grow with time.

Strengths

CEA is a powerful tool when it comes to simulate large urban models. In a reasonable amount of time, researchers and planners can access valuable results in the form of plots and tables. It also contains a large choice of tools for diverse research or planning purposes, ranging from simply PV potential to 2000W society assessement.

Note that CEA is an open source software, this means that literally anyone could help developing it. This is a great advantage, since CEA could be further maintained and developed after the research project of the Chair of Architecture and Building Systems at ETH Zurich is completed. Furthermore, new tools and new databases could be add to enlarge its scope. Another advantage is the peer-to-peer support that can be given through the GitHub platform.

Chapter 5

Conclusion

5.1 Runtime & Self-Consumption

The runtime analysis presented in this report gives a first understanding for the *radiation* tool. It seems that CEA handles increasing scale well, with almost linear relation between size and runtime. Nevertheless, further research is needed to investigate the effect of the *n-buildings-in-chunk* parameter on the runtime and on the final results. It would also be interesting to analyse the behavior of CEA with even larger districts.

In this project I also approached a basic self-consumption analysis on different community scenarios. I noted, that the prosumer alone would never reach 100% self-consumption ratio, while this is reached as soon as more consumers are added to the community microgrid. The more consumers, the higher the average over the whole year. This stays under 10% for all scenarios because of the wrong PV power production calculation. I also observed that the highest self-consumption ratios are met at the first and last hours of the day as well as during winter, when the radiation potential is lower.

5.2 Key Learnings

Here are listed my key learnings on the process and personal levels:
Process

- CEA is "monolingual", it would not understand input files if not in the right format
- List requirements
- Thorough verification of input files
- Support on GitHub

Personal

- Documentation at every step
- Asking for help is ok
- Nobody wants to mess with geometry files
- " Fail small, fail fast, fail cheap" credo
- New skills in CEA, QGIS and GitHub

5.3 Potential of CEA

After my experience with CEA, I would summarize its weanesses and strengths in the following way:
Weaknesses

- Strict requirements
- Incomplete and unstructered documentation
- Limited location choice

Strengths

- Open source
- Broad choice of tools
- Integrated plots

Bibliography

Aksoezen, Mehmet, Magdalena Daniel, Uta Hassler, and Niklaus Kohler (2015). "Building age as an indicator for energy consumption". In: *Energy and Buildings* 87, pp. 74–86.

Allegrini, J., K. Orehounig, G. Mavromatidis, F. Ruesch, V. Dorer, and R. Elvins (2015). "A review of modelling approaches and tools for the simulation of district-scale energy systems". In: *Renewable and Sustainable Energy Reviews* 52, pp. 1391–1404.

Energy, SFOE Swiss Federal Office of (2018). *Energy stragtegy 2050 once the new energy act is in force*. http://www.bfe.admin.ch/energiestrategie2050/index.html?lang=de&dossier_id=07008. Online: accessed 05-October-2018.

Klemeš, Jiři, Petar Sabev Varbanov, and Peng Yec Liew, eds. (2014). *Clustering urban areas for optimizing the design and the operation of district energy systems* (24th European Symposium on Computer Aided Process Engineering – ESCAPE 24, June 15–18, 2014). Budapest, Hungary: Elsevier B.B, pp. 1–6.

Federal Statistical Office, FSO (2018). *Energy sources for hot water, 2017*. https://www.bfs.admin.ch/bfs/de/home/statistiken/bau-wohnungswesen/gebaeude/energiebereich.html. Online: accessed 10-September-2018.

Fonseca, J.A., T.-A. Nguyen, A. Schlueter, and F. Marechal (2016). "City Energy Analyst (CEA): Integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts". In: *Energy and Buildings* 113, pp. 202–226.

Fonseca, Jimeno A. and Arno Schlueter (2015). "Integrated model for characterization of spatiotemportal building energy consumption patterns in neighborhoods and city districts". In: *Applied Energy* 42, pp. 247–265.

Fonseca, Jimeno A., Daren Thomas, Shanshan Hsieh, Martin Mosteiro, Bhargava Krishna Sreepathi, Fazel Khayatian, Kian Wee Chen, Gabriel Happle, Zhongming Shi, Amr Elesawy, and Arno Schlueter (2017). *The City Energy Analyst 2.6 (Version v26)*. Zenodo. http://doi.org/10.5281/zenodo.1098896.

Frayssinet, Loïc, Lucie Merlier, Frédéric Kuznik, Jean-Luc Hubert, Maya Milliez, and Jean-Jacques Roux (2018). "Modeling the heating and cooling energy demand of urban buildings at city scale". In: *Renewable and Sustainable Energy Reviews* 81, pp. 2318–2327.

Getman, Dan, Anthony Lopez, Trieu Mai, and Mark Dyson (2015). *Methodology for Clustering High-Resolution Spatiotemporal Solar Resource Data*. NREL/TP-6A20-63148. National Renewable Energy Laboratory, U.S. Department of Energy Office of Energy Efficiency & Renewable Energy.

Keirstead, James, Mark Jennings, and Aruna Sivakumar (2012). "A review of urban energy system models: Approaches, challenges and opportunities". In: *Renewable and Sustainable Energy Reviews* 16, pp. 3847–3866.

Leuthard, Doris and Walter Thurnherr (2017). *Bundesratsbeschluss über das Ergebnis der Volksabstimmung vom 21. Mai 2017: Energiegesetz [EnG]*. https://www.admin.ch/opc/de/federal-gazette/2017/4865.pdf. Online: accessed 05-October-2018.

Luthander, Rasmus, Joakim Widén, Daniel Nilsson, and Jenny Palm (2015). "Photovoltaic self-consumption in buildings: A review". In: *Applied Energy* 142, pp. 80–94.

Marquant, Julien F., Ralph Evinsa, L. Andrew Bollinger, and Jan Carmeliet (2017). "A holarchic approach for multi-scale distributed energy system optimisation". In: *Applied Energy* 208, pp. 935–953.

Orehounig, Kristina, Ralph Evins, and Viktor Dorer (2015). "Integration of decentralized energy systems in neighbourhoods using the energy hub approach". In: *Applied Energy* 154, pp. 277–289.

Reinhart, Christoph F. and Carlos Cerezo Davila (2016). "Urban building energy modeling: A review of a nascent field". In: *Building and Environment* 97, pp. 196–202.