SWEET Call 1-2020: EDGE

Deliverable report

Deliverable n°	1.2
Deliverable name	Need for energy balancing by region for renewable energy system scenarios of Switzerland
Authors The authors bear the entire responsibility for the content of this report and for the conclusions drawn therefrom.	Nicolas Stocker, ZHAW, stkk@zhaw.ch Michael Wild, ZHAW, wimm@zhaw.ch Jürg Rohrer, ZHAW, rohu@zhaw.ch
Delivery date	May 2023

sweet swiss energy research for the energy transition

Table of contents

Summary

The accelerating decarbonization of the Swiss electricity system necessarily causes a shift towards a more decentralized electricity supply, while increasing adoption of electric mobility and heat pumps leads to a similar effect on demand. At the same time, despite ever-increasing predictability, future electricity generation is less controllable and more dependent on weather and the environment. Combined, these changes complicate the challenge of matching supply and demand at all times. Coupled with the desire to increase self-sufficiency and local production, solutions have to be found to balance local supply and demand. A broad range of technologies, concepts, and policies have to be evaluated to solve this issue in an optimal manner, with (local) storage and PtX being two amongst them.

The overarching goal of EDGE is to analyze the process of integrating very high shares of decentralized renewable energy into the Swiss energy system and thereby considering varying conditions in the regions of the Alps, Cities, and Midlands. The present report is the first in a series of three, together detailing the role of storage, and PtX-technologies in the EDGE-regions (Cities, Midlands, Alps). This first report is concerned with establishing the data basis and methodology for identifying the need for energy shifting. In this context, the difference in decentralized production and consumption in each analyzed geographical scope (municipality, canton, region) has to be met with an equal reaction – be that load shifting, demand side management, curtailment, storage, variable consumers (such as PtX), grid exchange, or others. The second and third report will contain updated and refined datasets, extensions to the analysis methodology, identification and selection of relevant technologies for energy/power shifting, as well as matching thereof with individual municipalities.

A top-down modelling approach was chosen to represent electric energy generation and consumption with a high temporal and spatial resolution. Based on the CH-wide scenario values detailed in the Energieperspektiven 2050+ (Scenario ZERO Basis), decentralized electricity production and consumption timeseries for a model year in 15-minute timesteps were synthesized for each Swiss municipality. This entails two steps: First, the spatial distribution of annual aggregate values on Swiss municipalities, and second, finding a relative timeseries. The multiplication of the two, together with the CH-wide target value, yields an absolute value timeseries, per municipality. The aggregation of all production and consumption timeseries yields a total difference per municipality (excess/deficit of production), thereby representing the electrical flow over the municipality boundary, absent all other means of balancing. This difference is characterized over different timeframes and geographical scopes to gain an understanding of the need for load/energy shifting.

Although an in-depth evaluation of the model will be provided in the subsequent report, the preliminary findings can be summarized as follows: Municipalities of the Alps-region demonstrate a higher electricity generation than consumption, while urban areas exhibit the opposite trend, and the Midlands present a balance between the two. The temporal patterns of electricity usage reveal that spring and autumn are quite similar, characterized by substantial daily and weekly fluctuations between excess power and power deficits. Aggregating production and consumption on a weekly basis during the summer period indicates a surplus in electricity production for most municipalities. Conversely, during winter, only a select few municipalities, predominantly located in the region of the Alps, experience an excess in locally generated electrical energy.

List of abbreviations

CCS	Carbon Capture and Storage
DSM	Demand Side Management
EP 2050+	Energy Perspectives 2050+ (Energieperspektiven 2050+)
EV	Electric Vehicles
FSO	Federal Statistical Office (Bundesamt für Statistik, BfS)
FTE	Full-Time Equivalent
GIS	Geographic Information System
GWR	Gebäude- und Wohnungsregister
NET	Negative Emission Technologies
PtX	Power-to-X
PV	Photovoltaics
SFOE	Swiss Federal Office of Energy (Bundesamt für Energie, BfE)
WtE	Waste-to-Energy

Acknowledgements

1   Introduction

This report aims to model the electricity consumption and generation timelines for distributed entities in all municipalities across Switzerland, within the context of a fully decarbonized scenario. The rationale behind this investigation is that the rise of electric mobility and heat pumps, coupled with decentralized energy generation, will cause substantial changes for electricity grids and measures for energy shifting. Further, local consumption of decentralized production can increase network resilience and regional energy independence, and cause a reduction in transmission losses, amongst other benefits. To address this challenge, several measures are being considered, including the implementation of local storage and the strengthening of networks.

Modelling the local, municipal-level generation and consumption of electric power over a model year allows to identify and characterize the flows across the municipal boundary. By conducting this analysis, one can gain valuable insights into the dynamics of local power generation and consumption and the ability to identify potential solutions to address the challenges posed by decentralized energy systems. The analysis in this report focuses on generation and consumption of electric energy because decarbonization happens to a large degree with electrification, thus making electricity a dominant form of energy usage in Switzerland in decarbonized future scenarios [1]. In addition, electric energy is ideal to be transported and it is extremely flexible to be converted to other forms of energy, thus allowing for easier links across spatial and technological boundaries (sector coupling).

This first report is intended to focus on the methodology, and data acquisition and processing. The modelling of production and consumption profiles for each municipality is a necessary prerequisite to identifying the need for load/energy shifting, in turn informing the need for storage, amongst others. As multiple opportunities for improvement of the data basis have been identified, this report will only present a limited analysis but serve as a basis for the next repots.

The second report (scheduled to be published in May 2024) will include a region-wise techno-economic realization of the previously calculated need for energy balancing by region using batteries, power-to-x, and demand-side management. It will focus on serving the calculated need for energy balancing with available technological solutions including economic considerations. The third report (scheduled to be published in May 2025) will feature the analysis on the facilitation of a decentralized renewable Swiss energy system with batteries, power-to-x, and demand-side management. It will focus on the synthesis of the findings in the previous report to determine the role of storage, power-to-x and demand-side management in a renewable Swiss energy system. Synergies between the three examined regions will be taken into account by considering of energy flows between the three regions.

The modelling target is a fully decarbonized Swiss electricity system. To this end, the scenario values of the Energieperspektiven 2050+ [1], scenario ZERO Basis (target year 2050) were chosen. For this analysis, a top-down approach was employed. For each individual category of decentralized electricity generation and consumption listed in the EP2050+ (e.g. rooftop PV or heat pumps), an aggregate annual value relative to the appropriate CH-wide value is generated for each municipality based on the best-available information – directly available historical data, future predictions, or bottom-up models. Similarly, an annual timeseries of relative values was found by either using data of historical years if no significant changes have to be assumed, aggregations of bottom-up models, or custom models. A detailed explanation of the data acquisition and processing is given in section 2. It is important to note that most generation and consumption curves are inherently flexible – that is, they depend on the surrounding network states and other factors to varying degrees. As a clear example, running hydro power plants in Switzerland vary their power output by up to around 40% within a single day to match demand. A (possible) introduction of dynamic tariffs would also flexibilize most categories of electricity consumption. Since these curves are deemed to be fixed when they are in fact flexible, this flexibility has to be accounted for when determining the means for meeting the need for load shifting, prior to all other considerations. However, at this stage it is beneficial to retain a technology-agnostic stance.

2 Methodology and Data Processing

For each municipality in Switzerland, a year-long separate timeseries of electricity production and consumption comprising different categories (see section 2.1) was produced in 15-minute intervals. Each final dataset is a multiplication of three components: (1) a relative timeseries describing how the load/production profile is distributed over the whole year (considering regional and local differences where possible), (2) the relative share of CH-wide annual load/production estimated or modelled in that municipality, and (3) a total CH-wide yearly load/production value (prediction, scenario values). The processing workflow for this methodology is presented in Figure 1 and a simplified scheme with example values is shown in Figure 2. This allows to generate local sequences of absolute values that collectively sum up to the predicted CH-wide values according to the scenario, while still retaining local differences.
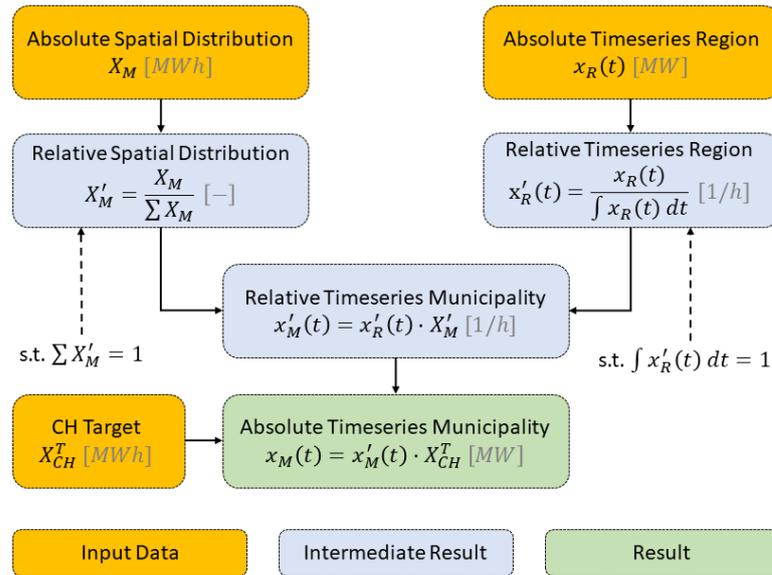

Figure 1. Data acquisition and processing workflow. From absolute spatial distributions and absolute timeseries (CH-wide, regional/cantonal, or municipal level), relative values are generated, the multiplication of which gives a relative timeseries per municipality that subsequently can be multiplied by a CH-wide target value to obtain an absolute timeseries per municipality, all of which add up to the target value.

The distribution of yearly values to each municipality as well as the municipal relative timeseries were obtained from various sources. It is important to note that some of the values used are sourced from bottom-up modelling of future scenarios (such as rooftop PV and electromobility), while others are derived from historical data (such as hydropower). All associations between sources and sinks of energy and municipalities are derived via geography, i.e. the physical location of an entity, as opposed to its location within the network topology. In practice, a facility can be physically located in a municipality while being connected to the distribution grid of another municipality. A number of technologies have been deliberately neglected: Nuclear, pumped and storage hydro, as well as fossil generation were not included in this analysis since they are not feeding in on a municipal level. Geothermal, PtX, and CCS/NET were neglected in this step because they are either irrelevant, it is very unclear how they will be implemented in the future, or they represent a flexibility that will be part of the later analysis. Note that as a result thereof, production and consumption are not inherently balanced on a national level, even though the scenario as a whole is. An explicit modelling of energy demand for cooling buildings in a separate category was neglected in this iteration, as it is not explicitly listed in the scenario parameters within the EP 2050+. However, the inclusion of this demand in a future analysis entails a relatively straight-forward adaption of the methodology used to find the consumption profile for heat pumps, and will be considered in a next step.
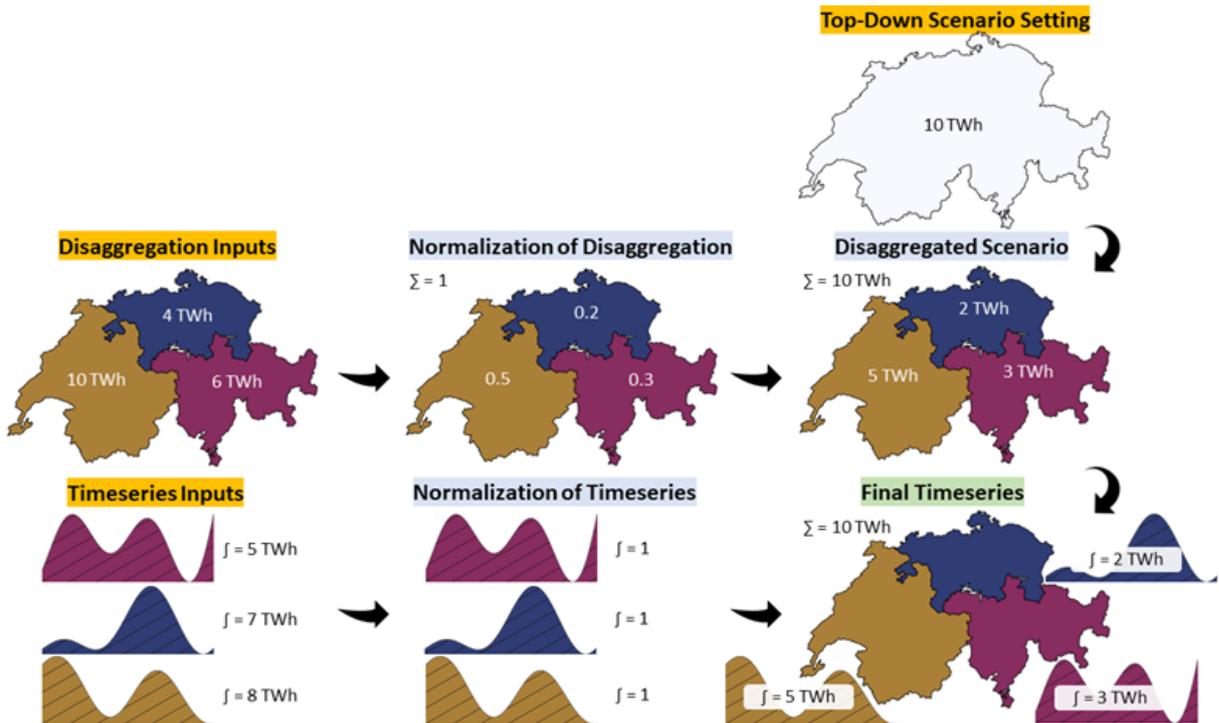
Figure 2. Modelling overview: interplay of top-down scenario settings, spatially disaggregated values, and timeseries with exemplary values. For each category (e.g. rooftop PV), there is a top-down setting, which is allocated to individual municipalities (here exemplarily represented by only three colored areas) based on relative distribution values obtained from processing publications and datasets with spatially explicit results. Timeseries for individual municipalities or groups of municipalities are normalized and then scaled with the yearly municipal value in order to generate yearly timeseries for each individual municipality. Figure 1 represents the same processing workflow as a mathematical procedure with the two figures having the same color scheme for input data, intermediate results, and results.

In the presented analysis, the official set and borders of Swiss municipalities as of January 1 of 2022[1] was used. Datasets of various sources from differing years were used to determine the disaggregation of electric energy production potentials, loads, and the temporal distribution i.e. the timeseries shapes. The datasets for potential disaggregation of wind power, biomass and biogas, rooftop PV timeseries, consumption disaggregation for electric mobility were already aggregated on a municipal level. These datasources originate from various years, thus using differing sets of Swiss municipalities. A GIS-based process was in these cases used to adapt the data to the common set of municipalities from 2022.

Wherever historical power timeseries were used, the preferred reference year is 2018. Thereby effects of the COVID19-Pandemic are not included, and weekdays/dates match with 2035 such that weekly effects (e.g. shifting load patterns on weekends) are taken into consideration.

2.1 CH-wide Scenario Values

The CH-wide scenario values were obtained from Energieperspektiven 2050+, scenario ZERO Basis. An addition has been made by further dividing PV production into five categories, namely rooftops, façade, infrastructure (roads, parking, highways, etc.), alpine, and agricultural PV. The relative share of each category was adopted from values found by Meteotest and Swissolar [2], adding an informed guess for the potential of Agri-PV not found in the aforementioned study. Although very high values for

---

Agri-PV potential have been found recently [3], current regulations limit the deployment of this technology to very select sites. The scenario values used in this study are listed in Table 1.

Table 1. Production and consumption annual scenario values used throughout this study. The shown values correspond to scenario ZERO Basis found in the Energieperspektiven 2050+, augmented with a more granular categorisation of photovoltaic generation.

Production	Scenario Value [GWh]	Consumption	Scenario Value [GWh]
PV cumulative, of which:	33'611	General Load	41'094
Rooftop PV	16'282	Electromobility	13'145
Façade PV	5'731	Heatpumps	9'008
Infrastructure PV	7'196		
Alpine PV	2'305		
Agri-PV	2'097		
Wind	4'324		
Biomass (Wood)	163		
Biogas	1'151		
Wastewater	107		
Waste-to-Energy (ren.)	671		
Small Hydro	1'306		
Running Hydro	17'241		
Total	58'574	Total	63'247

2.2 Decentralized Consumption

2.2.1 General Load

The term "general load" refers to the aggregation of all loads connected to the low and medium voltage grid in a municipality, excluding those from heat pumps and electric vehicles, which are subjected to dedicated modelling.

Load Spatial Disaggregation

For spatial disaggregation of the general load, available municipal-level data from the cantons of Lucerne[2], St. Gallen[3], Basel-Landschaft[4], and Aargau[5] and an additional Switzerland-wide dataset with selected municipalities[6] were used to fit a linear least-squares regression on the annual electricity consumption of a municipality, using municipal population and full-time equivalents (FTE) of the industrial and service sectors[7] as regressor (whereas the agricultural sector has shown to have no relevant impact). In total, Switzerland had 2148 municipalities in 2022, of which 504 (23.4%) publish publicly available electricity consumption data. Wherever possible, data of 2018 was used. These 504 observations of yearly consumption together with the known FTE by industrial sector were used in a log-log model,

$$\ln(C_g) \cong \beta_0 + \beta_1 \ln(FTE_{S2} + FTE_{S3}) + \beta_2 \ln(P) \tag{1}$$

---

[2] Energiespiegel Gemeinden, *https://uwe.lu.ch/themen/energie/Kommunale_Energieplanung/daten_zu_energie/energiespiegel_gemeinden*

[3] Netzabsatz Strom St. Gallen, *https://energiesg.shinyapps.io/stromverbrauchsg/*

[4] Energiedaten Gemeinden BL, *https://www.statistik.bl.ch/web_portal/8_4_2*

[5] Energieplanung Kanton Aargau, *https://www.ag.ch/de/verwaltung/bvu/energie/energieplanung*

[6] Cercle Indicateurs, https://www.bfs.admin.ch/bfs/de/home/statistiken/nachhaltige-entwicklung/cercle-indicateurs/staedte/alle-indikatoren/energie-klima/stromverbrauch.html

[7] Statent, *https://www.bfs.admin.ch/bfs/de/home/statistiken/industrie-dienstleistungen/erhebungen/statent.html*

where β_0 is the intercept, β_1 and β_2 the coefficients, C_g is the annual general consumption (in units of MWh), P is the population, and FTE_{S2} and FTE_{S3} are the full-time equivalents in the industrial and service sectors, respectively, for each municipality. The log-log model was selected with a comparison of several model formulations and their performance in a cross-validation analysis with the available data. It featured the best combination of performance and fulfilment of the four assumptions for linear regression with log-log modelling (log-log relationship, independence, homoscedasticity, normality). The linear regression yields the following results for the intercept and coefficients: β_0 = -3.355, β_1 = 0.704, β_2 = 0.164. The model features a p-value below machine accuracy, an adjusted R-squared = 0.916, and the intercept and both predictor terms feature p-values < 0.0012. Figure 3 shows a comparison of modelled and observed annual consumption values.

While the general model performance is good, the cross validation showed that there are some cases of bad prediction. In a vast majority of those cases, the obvious "culprit" is a single industrial plant with high consumption. The authors are not aware of openly available datasets that contain information in the granularity needed to correctly model such specific cases.
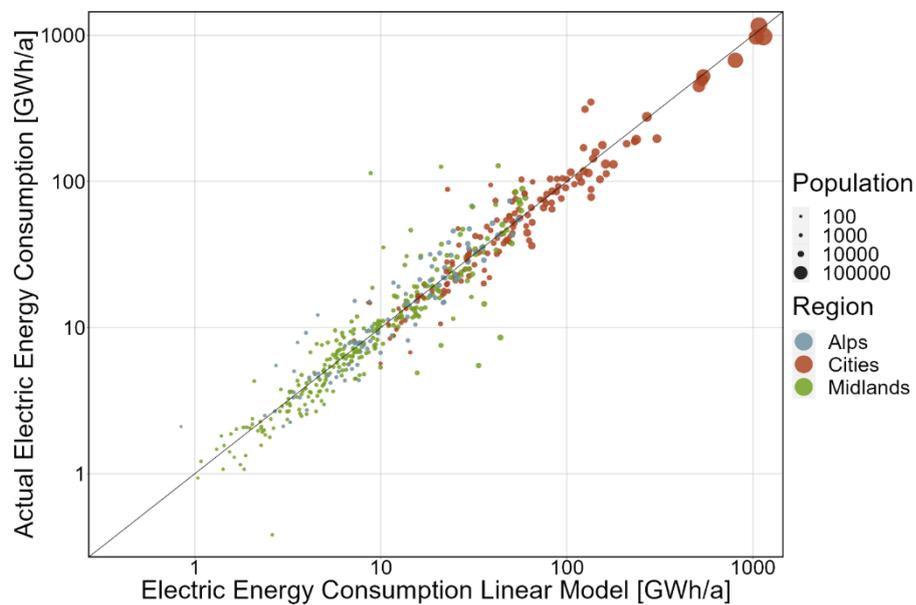

Figure 3. Observed vs. modelled yearly electric energy consumption (2018) for 504 municipalities with known consumption used for log-log modelling. The model features a p-value < 2.2*10^-16, an adjusted R-squared = 0.916, and the intercept and both predictor terms feature p-values 0.12% or less (see Equation 1 for its formula).

Applying the model for all municipalities without known general load, combined with known values, results in a complete set of municipal consumptions for Switzerland. The results are presented in Figure 4. Note that although absolute values are shown for reference, only relative values are relevant for further processing, later being scaled by the scenario values (EP 2050+), such that the sum of all municipalities corresponds to the scenario total value.
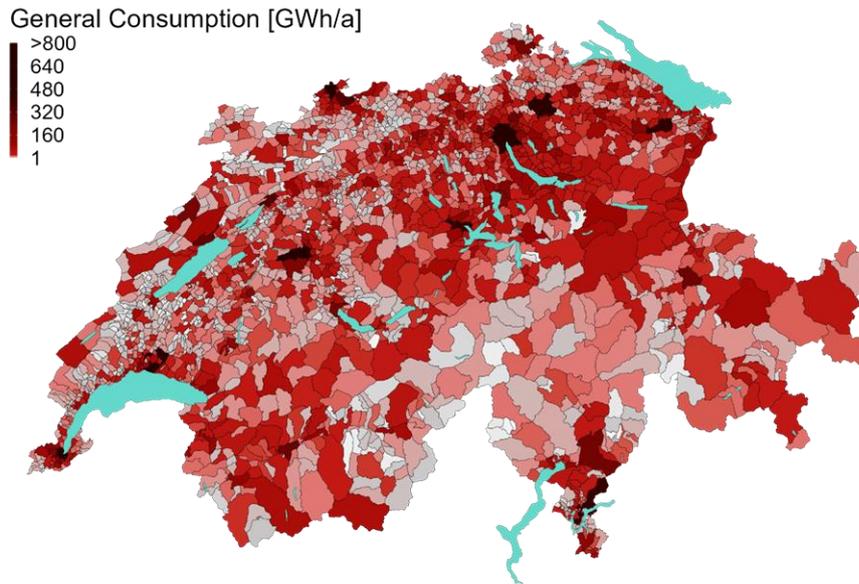
Figure 4. General electric energy consumption by municipality per year. 504 municipalities have known general consumption values, which originate from the years of 2017 to 2022. These measured values were directly used, while the remaining 1644 municipalities' consumption was calculated with a log-log model (Equation 1). The color scale is cut at 800 GWh/a but the values of Basel, Bern, Geneva, and Zurich are above this threshold with the maximum in Zurich at 2779 GWh/a.

Timeseries Modelling

Relative timeseries for each municipality were sourced from 15-minute interval data for general load and production made available by Swissgrid[8]. This dataset contains load curves for most cantons or combinations thereof. Each municipality is then assigned the relative load curve of their host canton or canton group – i.e. all municipalities within a canton (or grouping of cantons found in the Swissgrid dataset) follow the same relative general load curve, but with their individual absolute scaling given by the spatial disaggregation introduced at the beginning of this section. Figure 5 shows the relative load of three exemplary municipalities normalized to their respective maximum load, for the first full week (Monday – Sunday) of every quarter. Figure 6 shows all cantonal load curves exemplary for the month of June, normalized to their annual maximum.

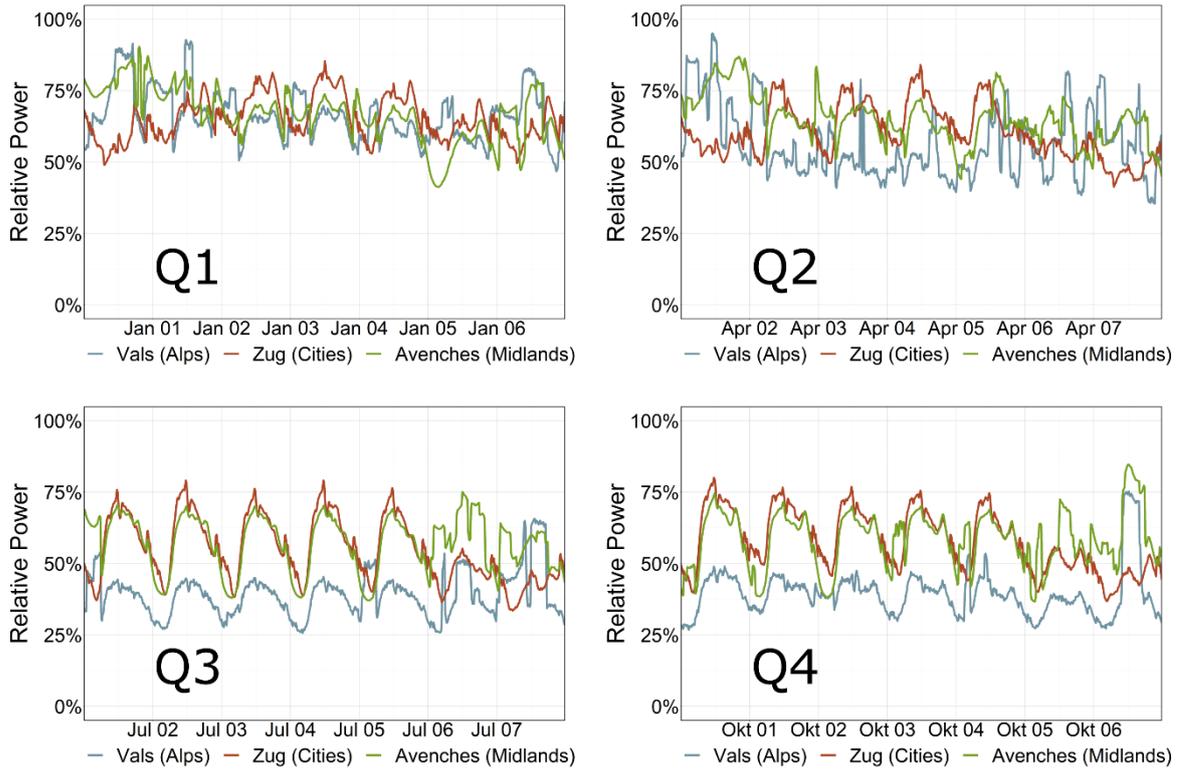[8] Swissgrid Energieübersicht 2018, *https://www.swissgrid.ch/de/home/customers/topics/energy-data-ch.html*

Figure 5. Relative load of three exemplary municipalities, normalized to their respective maximum load, shown for the first week of every quarter.
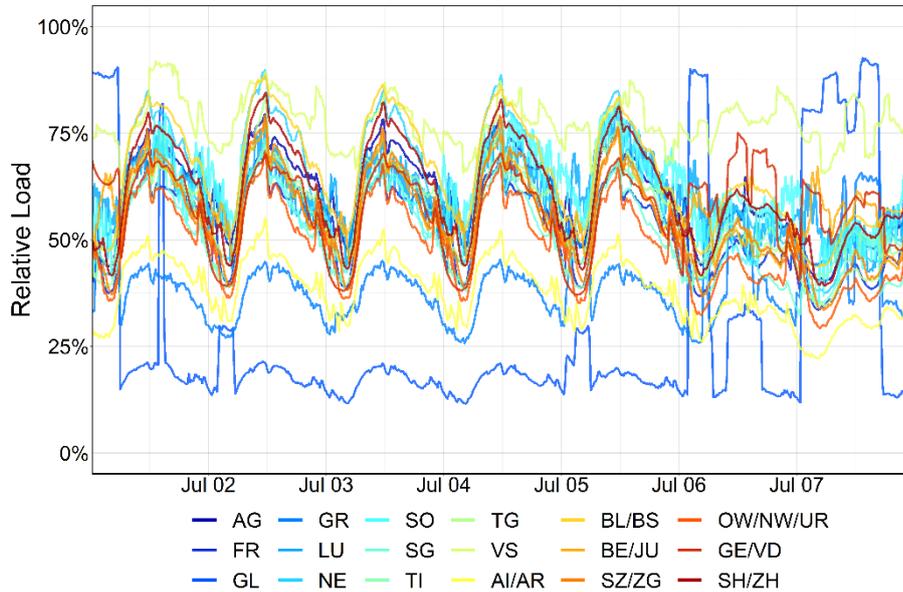

Figure 6. All cantonal load curves exemplary shown for the first week of July, normalized to their respective annual maximum loads.

Limitations: The timeseries data includes all consumption registered in a given zone. This includes loads for heat pumps and electromobility, as well as pumped hydro. Unfortunately, given the lack of more granular data, it is not possible to isolate general load in the sense of the Energieperspektiven 2050+ from the current datasets. The most visible impact is in the canton of Glarus, which experiences periodic load changes of up to 500% within a short timespan, possibly owed to a single pumped hydro power plant, Linth-Limmern.

2.2.2 Heat Pumps

Load Spatial Disaggregation

Modelling the electricity consumption of heat pumps on a municipal level involves multiple steps. From a total aggregated CH-wide heating demand, the annual consumption of a municipality is approximated by using an estimate of the current annual heating demand, which is provided by HSLU (implicitly assuming that the spatial distribution is not changing until the target year 2035). Figure 7 shows the spatial distribution of annual population-specific heating demand in Switzerland. Within each municipality, the current share of different heating systems is determined via the GWR dataset[9], using the total building area as weights. Figure 8 shows the current shares of fossil, solar, heatpump, and district heating systems in each municipality. The share of heating systems in the decarbonized target state is determined using the Energieperspektiven 2050+, using the available values for residential buildings[10]. The aggregated differences in CH-wide heating shares are equally distributed to the subset of non-renewable heating systems in each municipality, such as to account for already-existing renewable infrastructure, such as district heating networks. This in turn allows to calculate the total heat demand per municipality for each type of heating system, including heat pumps.
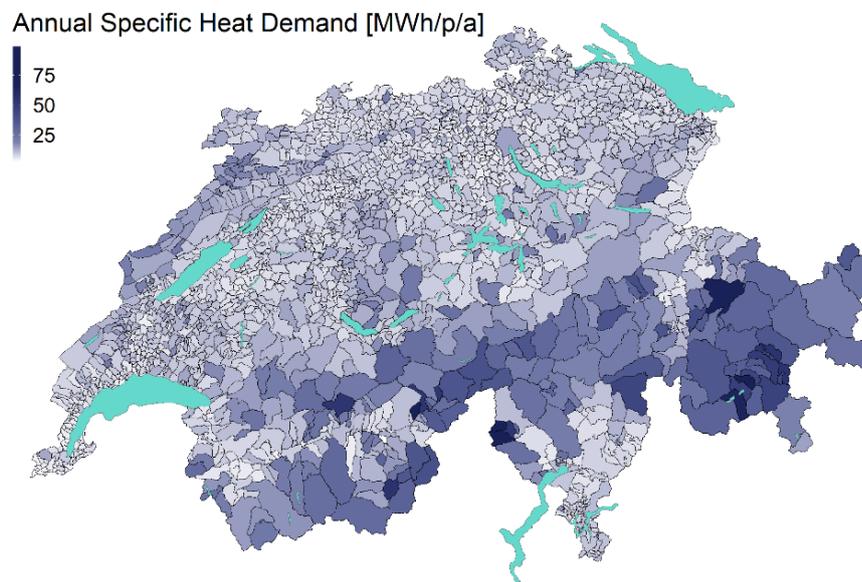

Figure 7. Specific heat demand (MWh/p/a) of municipalities in Switzerland. Data provided by Sarah Schneeberger (HSLU).

---

[9] Eidg. Gebäude- und Wohnungsregister (GWR), *https://www.housing-stat.ch/de/index.html*

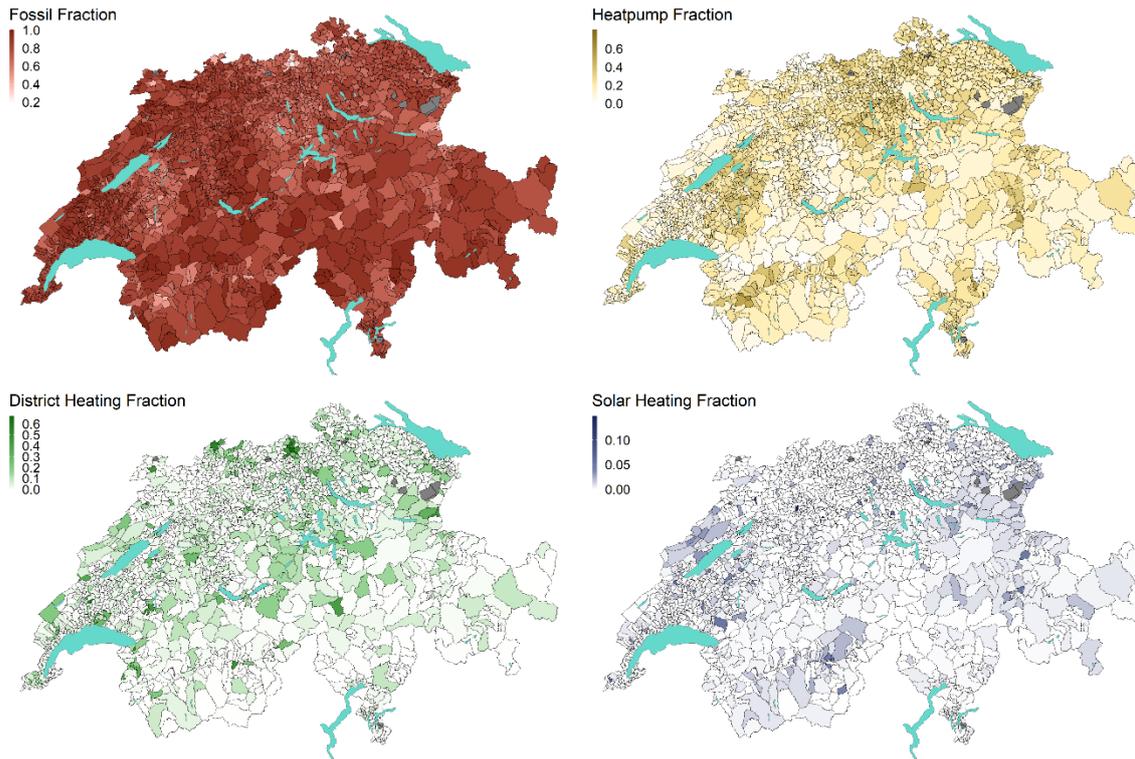[10] Section 7.4.3, «Raumwärme» (residential only)

Figure 8. Current relative fractions of fossil, heatpump, district heating, and solar heating systems in Swiss municipalities. Building-level data obtained from the Swiss building registry (GWR), weighted by building area.

Timeseries Modelling

To model the temporal aspect, a reference dataset containing 45 modelled air temperature profiles in 2035 is used[11], the locations of which are shown in Figure 10. For each municipality, the corresponding dataset is found by finding the minimum weighted distance $d_w = d_{hor} + 100 \cdot d_{vert}$ between municipality centroid and each model location. A correction factor of -0.0065 K/m is then used to account for elevation differences between municipality centroid and model location[12]. The local temperature profile is subsequently used to generate a heating degree timeseries[13], whereby a limit of 12°C of average daily temperature is used to determine whether a day falls within a heating period. The difference in exterior temperature and desired interior temperature (20°C) then scales the relative heating demand (excluding hot water), which in turn is scaled linearly by the heat demand covered by heat pumps in that municipality, found in the spatial disaggregation. Using the ratio of electricity consumption and heat demand (EP2050+), the electrical load curve associated with heat pump consumption for each municipality can be generated. Figure 9 shows the relative heat demand for the three exemplary municipalities of Vals (Alps), Zug (Cities), and Avenches (Midlands).

---

[11] Klimaszenarien fürs zukünftige Innenraumklima (MeteoSchweiz), *https://www.meteoschweiz.admin.ch/dam/jcr:c5f3078c-db13-4c34-b56d-bdf5f818b64f/Fachbericht_MeteoSchweiz_279.pdf*, Data available at *https://s.geo.admin.ch/94e9d38450,* Modelled Temperature «tre200» was used (air temperature 2m above ground)

[12] Decreases in temperature with altitude (MeteoSchweiz), *https://www.meteoswiss.admin.ch/weather/weather-and-climate-from-a-to-z/temperature/decreases-in-temperature-with-altitude.html*

[13] Methodology follows the definition of Heating Degree Days (Heizgradtage) given by MeteoSchweiz, *https://www.meteoschweiz.admin.ch/wetter/wetter-und-klima-von-a-bis-z/heiztag.html*
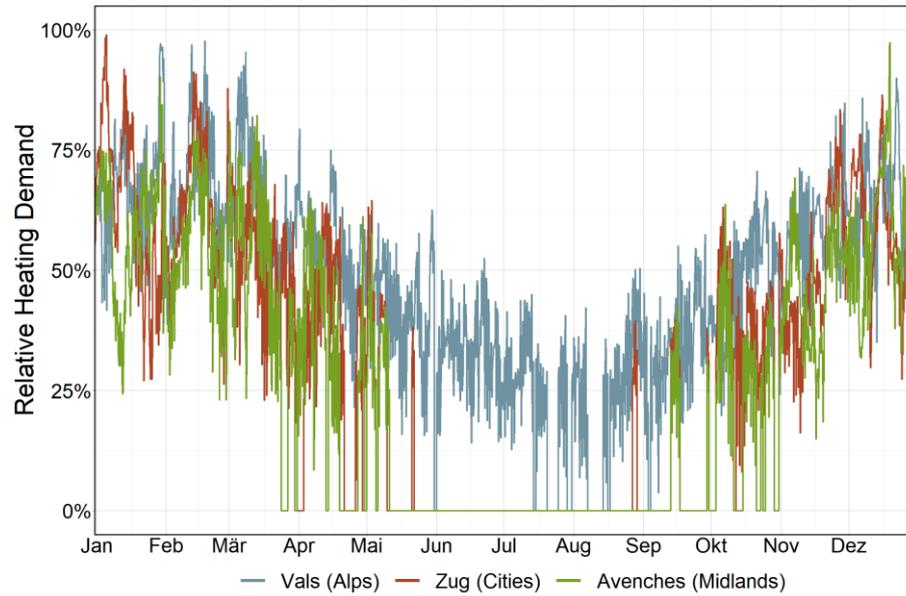
Figure 9. Relative heating demand in the exemplary municipalities of Vals (Alps), Zug (Cities), and Avenches (Midlands), downsampled to 4h-intervals for illustrative purposes.
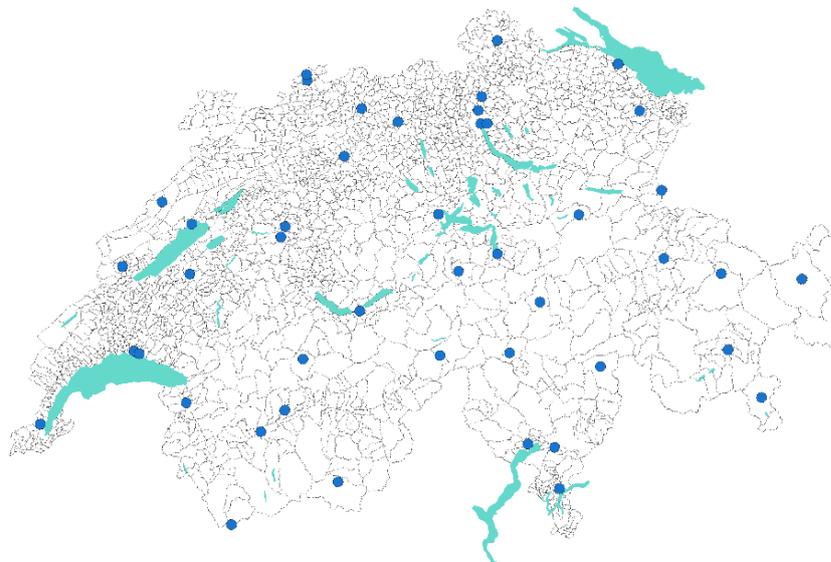

Figure 10. Locations of modelled temperature timeseries in a design reference year (DRY) based on the Swiss climate scenarios CH2018.

Limitations: The future relative distribution of heating demand is modelled after the current distribution – i.e. does not take into account demographic changes or region-specific developments. The current heating system distribution within a single municipality is based on data found in the building registry, directly inheriting its quality. Specifically, the sparse and systematic (non-)availability of energy reference area data necessitates using the building area as a proxy, thereby allowing for systematic errors. The future heating system distribution assumes a homogeneous replacement of remaining fossil heating systems. This does not account for the heterogeneous penetration of district heating networks, the availability of natural gas infrastructure, and other location-specific circumstances. The temperature dataset allocation uses a heuristic approach that aims to pair each municipality with the location most representing the local environment. However, different approaches and distance weights could be used at this point. The instantaneous electricity demand for heatpumps does not account for any thermal inertia of the associated buildings, other than the classification of heating days.

2.2.3 Electric Vehicles

In order to account for the substantial portion of future power consumption attributed to electric vehicles, a distinct category was established for their modelling.

Load Spatial Disaggregation

The power consumption caused by electric vehicles by municipality was provided by Marìa Parajeles (ETH Zurich). The energy required by municipality was calculated for the Swiss population of 2020, assuming a 100% electrification of cars, and a cold day of April. These values were subsequently scaled to reflect the annual electric energy consumption by electric vehicles, as illustrated in Figure 11. Note that as with all shown disaggregations, only relative values are used to in the subsequent processing steps, with absolute scaling being achieved by multiplication with the CH-wide scenario values (see Table 1).
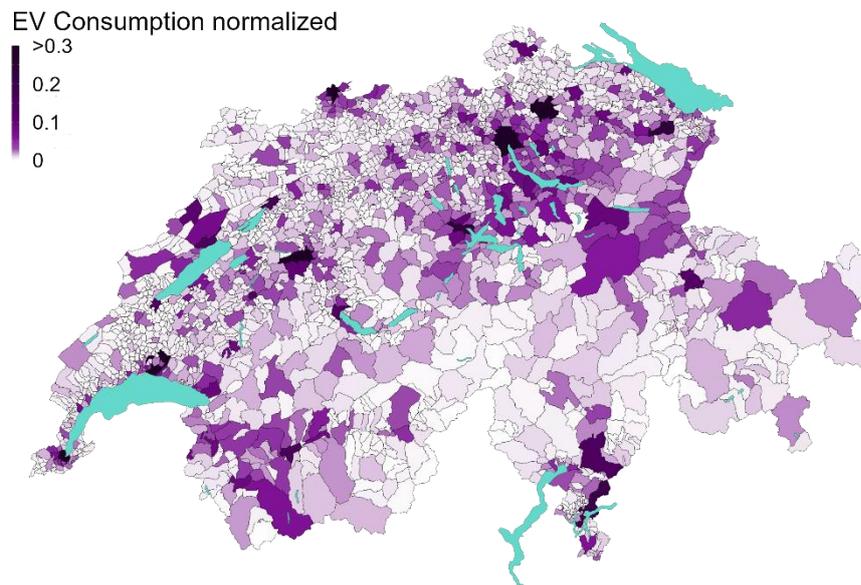

Figure 11. Annual normalized electric energy consumption by electric vehicles per municipality. Data for spatial distribution provided by Marìa Parajeles Herrera (ETHZ)[14]. All values were scaled to a value range between 0 and 1. Only the relative spatial load distribution is relevant within the presented methodology because for each category a top-down value is disaggregated based on the relative shares of municipalities. The color scale is limited to 0.3, with the values of Winterthur (0.31), Geneva (0.32), Bern (0.36), Basel (0.39), Lausanne (0.42), and Zurich (1) being above this threshold.

Timeseries Modelling

To construct the power consumption timeseries, established load profiles from literature [4] were employed. These load profiles account for differing population densities and charging types like home, work, and public charging. In this analysis, the individual load profiles were aggregated to yield specific time curves for each EDGE-region. The assumed composition of the load profiles for the EDGE-regions can be found in Table 2. As of 2022, more than 90% of charging in Switzerland happens at home or at

---

[14] EV consumption is part of the electrification integration in the Swiss region's research project for the SWEET EDGE consortium.

the work place [5]. Hence, a relative distribution of 50% for home charging, 40% for work charging, and 10% for public charging, based on the energy expended for charging, was adopted.

Table 2. EV load profile composition of EDGE-regions of timeseries provided by [4]. Naming of the different population density categories is identical to the original data source. Every density category features a separate timeseries for home, work, and public charging in [4]. For all regions a relative share of 50% home charging, 40% work charging, and 10% public charging was considered.

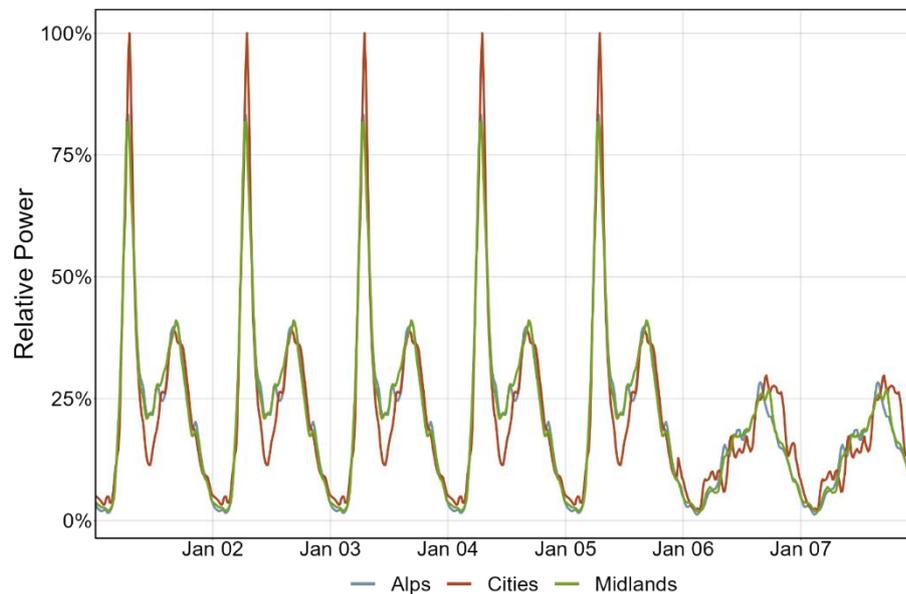| Density Category	Charging Type	Alps	Cities	Midlands
		Relative share of charging profiles composition		
Big City	Home	0	0.25	0
	Work	0	0.2	0
	Public	0	0.05	0
City	Home	0	0.25	0
	Work	0	0.2	0
	Public	0	0.05	0
Suburb City	Home	0	0	0.17
	Work	0	0	0.13
	Public	0	0	0.03
Town	Home	0.25	0	0.17
	Work	0.2	0	0.13
	Public	0.05	0	0.03
Rural	Home	0.25	0	0.17
	Work	0.2	0	0.13
	Public	0.05	0	0.03

Figure 12. Relative electric vehicles demand profiles by EDGE-region in an exemplary week. The profiles differ between weekdays and weekends otherwise they are repeated with identical shapes over the course of the year.

EVs possess significant potential for demand-side management and can serve as mobile batteries in vehicle-to-grid applications [6], [7]. Detailed modelling of future load profiles is therefore unlikely to yield meaningful insights, as the profiles of EVs are expected to be heavily influenced by demand-side and

battery management strategies. Therefore, the load profiles created as described in this paragraph with a weekly profile were used, as shown in Figure 12.

2.3   Decentralized Production

2.3.1   Running Hydro

The running hydro power plants have been localized using the WASTA dataset[15], where the installed capacity was sourced from as well. The distribution of specific facilities on to municipalities was achieved by analyzing the geometric overlap with municipal boundaries. Figure 13 shows the locations of all Swiss running hydro power stations, with marker sizes corresponding to the expected annual electricity production. Timeseries data was obtained from Energy-Charts[16] for 2018, assuming CH-wide production is distributed equally based on individual annual expected production (as of 2018) at all times. Figure 14 shows historical data for 2018, while Figure 15 shows the daily production profile for the first day of every quarter of that year. Currently, all listed running hydro power plants are included in the analysis, with the exception of five plants located outside Swiss borders (but included in the original dataset). As a future improvement, hydro power plants should be categorized according to the network level of their grid connection, with higher-voltage connections being dismissed to retain the decentralized aspect of the analysis. Further, inclusion of small hydro potentials[17] could be considered.
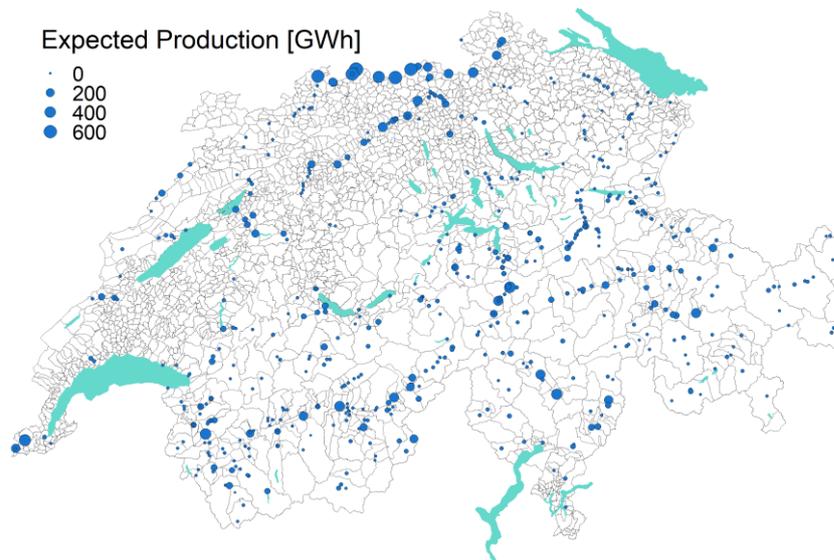

Figure 13. Running hydro power stations in Switzerland, with marker diameters proportional to annual expected production.

---

[15] Statistik der Wasserkraftanlagen (WASTA), *https://opendata.swiss/de/dataset/statistik-der-wasserkraftanlagen-wasta*

[16] Energy-Charts, *https://www.energy-charts.info/charts/power/chart.htm?l=de&c=CH*

[17] Kleinwasserkraftwerkspotentiale der Schweizer Gewässer (BfE), h*ttps://www.bfe.admin.ch/bfe/de/home/versorgung/statistik-und-geodaten/geoinformation/geodaten/wasser/kleinwasserkraftwerkpotentiale-der-schweizer-gewaesser.html*
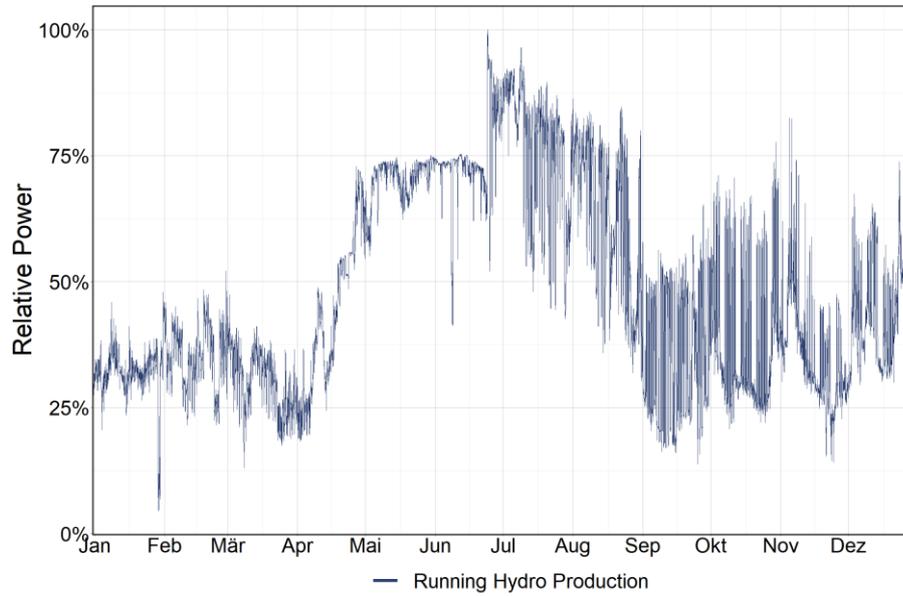
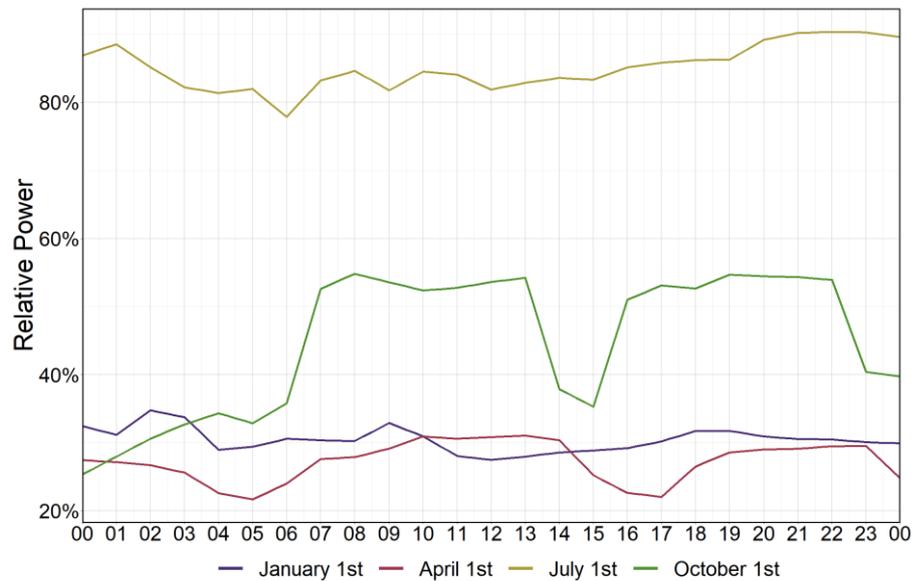Figure 14. Relative power of running hydro electricity production in 2018.

Figure 15. Relative power of running hydro electricity production in 2018, shown for the first day in every quarter.

2.3.2   Rooftop PV

Spatial Potential Disaggregation

The estimation of annual electric energy generation potential from rooftop photovoltaic systems is based on the findings of a study about Swiss rooftop photovoltaic potentials by Anderegg et al. [8]. This study presents reduction factors that can be applied to the available potential production values obtained from Sonnendach.ch[18], a database containing the potential production values for each roof in Switzerland. To establish these reduction factors, rooftops were categorized into different groups, and a statistically significant sample of rooftops was manually analyzed to calculate the reduction factor by comparing it

---

[18] *https://www.uvek-gis.admin.ch/BFE/sonnendach/?lang=de* and *https://opendata.swiss/dataset/solarenergiepotenziale-der-schweizer-gemeinden*

to the values from the Sonnendach database. The categorization of rooftops was based on combinations of tilt and categorized roof area. Applying the reduction factors to the whole Sonnendach database resulted in all Swiss georeferenced roof geometries and their individual electric energy generation potential with a rooftop photovoltaic system. To assign each rooftop geometry to a specific municipality, an intersection calculation was performed using a georeferenced dataset containing the borders of all municipalities. As a result, the annual generation potential for each municipality was determined. The outcomes of this analysis are presented in Figure 16.
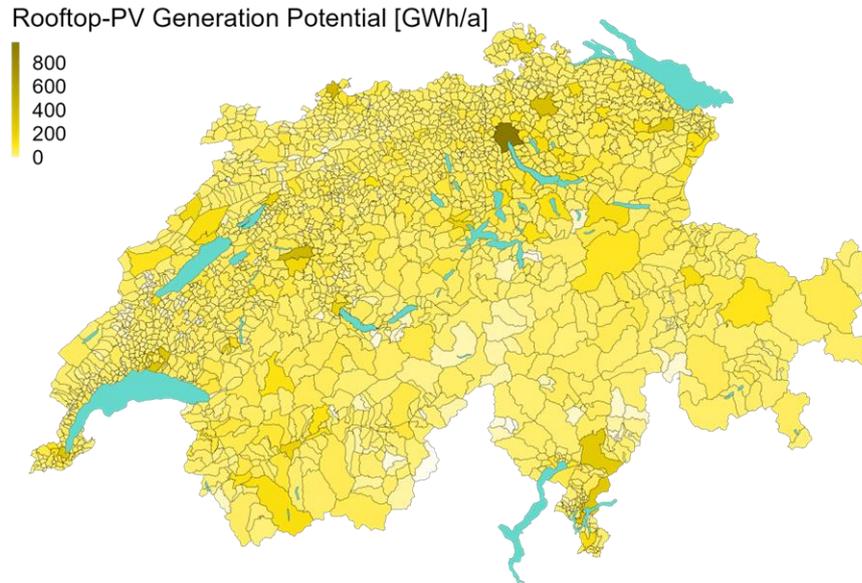

Figure 16. Annual electric energy production potential by rooftop PV per municipality. Results calculated applying reduction factors from [8] to the Sonnendach database.

Timeseries Modelling

Bucher and Schwarz [9] published specific PV generation profiles for each municipality in Switzerland assuming a Swiss-wide generation by PV of 30 TWh/a, utilizing historical weather data from 2004 to 2018. As a consequence, the production profiles of the municipalities are correlated due to their common dependence on general weather patterns across Switzerland (see Figure 17 and Figure 18). Specifically, the data from the "Anreize Winterstrom" scenario and the year 2018, which serves as the standard reference year, were utilized. The original data source provides a temporal resolution of 1 hour, which was increased to 15 minutes for the purposes of this study through linear interpolation. For the three

exemplary municipalities Vals, Zug, Avenches an overview of their yearly profiles is shown in Figure 19 and their monthly mean profiles in Figure 20.

A limitation of directly employing generation profiles aggregated on a municipal level is that they encompass both rooftop PV and façade PV systems. The presented methodology includes separate modelling for rooftop and façade PV, thereby requiring the use of distinct profiles.
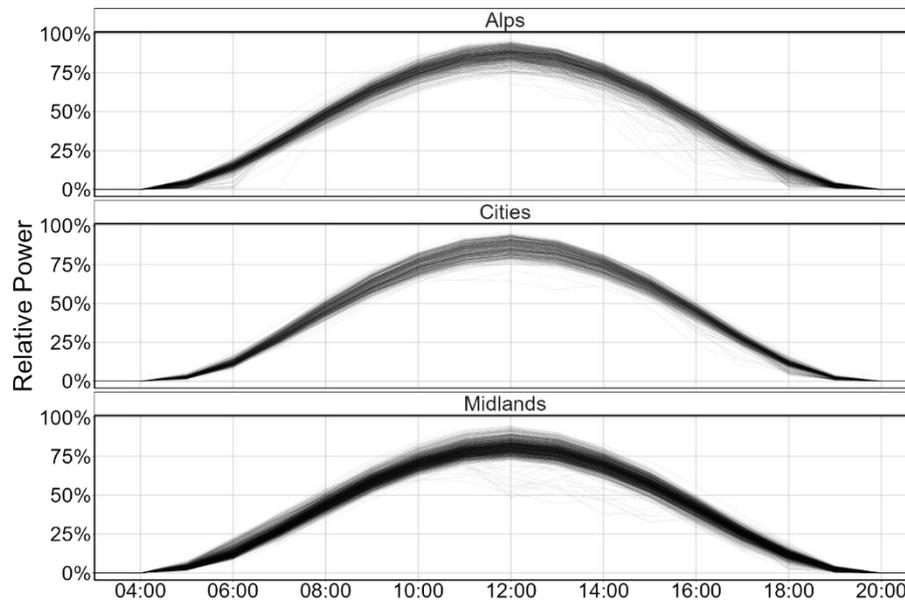

Figure 17. All municipal rooftop PV production profiles on July 1 (exemplary summer day) presented by EDGE-region. Profiles feature a temporal resolution of 15 minutes and are scaled so that their maximal value over the course of one year equals 1. Used timezone is Central European Summertime. The data originate from the real weather on 1. July 2018, which was a sunny day nearly all over Switzerland. Data source: [9]
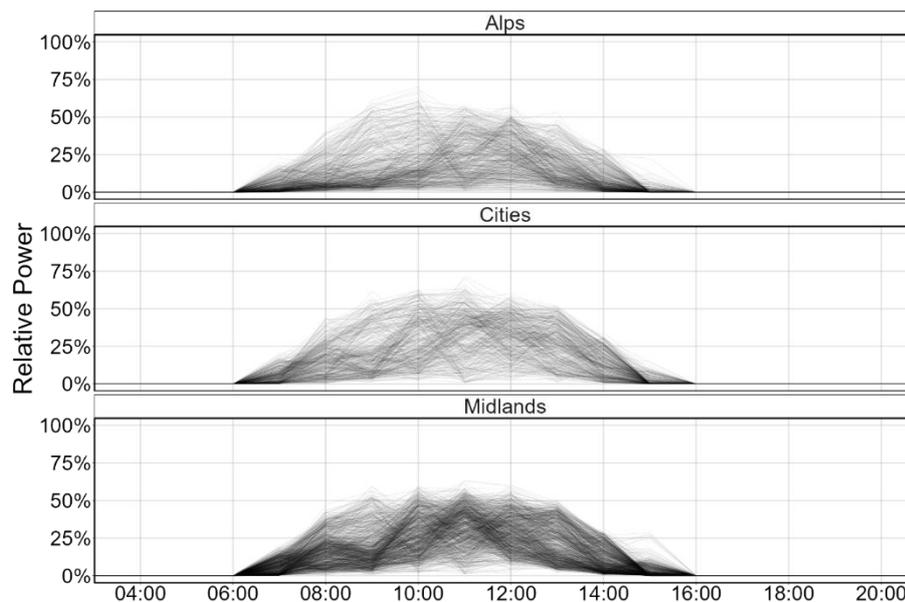

Figure 18. All municipal rooftop PV production profiles on December 1 (exemplary winter day) presented by EDGE-region. Profiles feature a temporal resolution of 15 minutes and are scaled so that their maximal value over the course of one year equals 1. Used timezone is Central European Summertime. The data originate from the real weather on 1. December 2018, which was mostly sunny with some clouds in certain locations. Data source: [9]
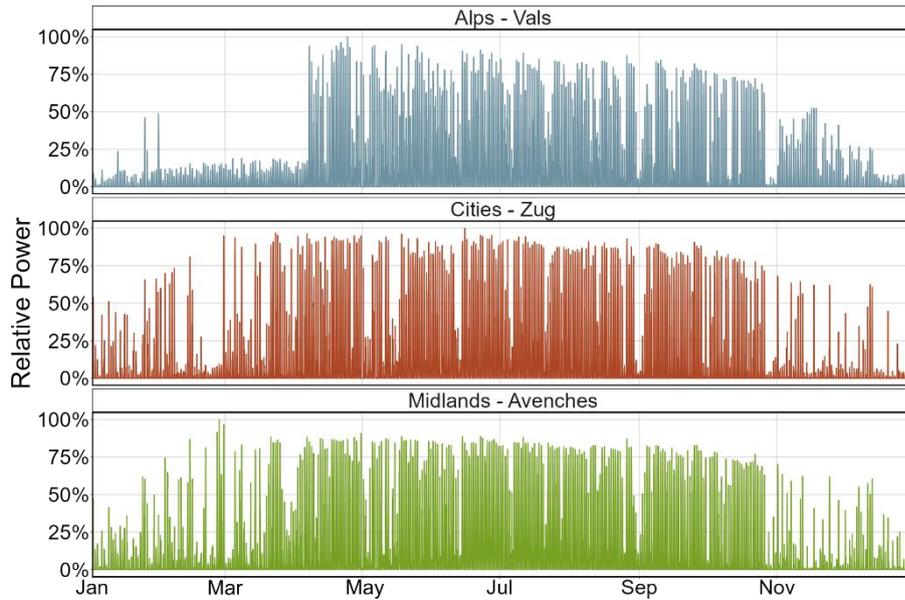
Figure 19. Yearly relative power generation profiles of Rooftop PV of one exemplary municipality per EDGE-region. Profiles feature a temporal resolution of 15 minutes and are scaled so that their maximal value over the course of one year equals 1. Data source: [9]
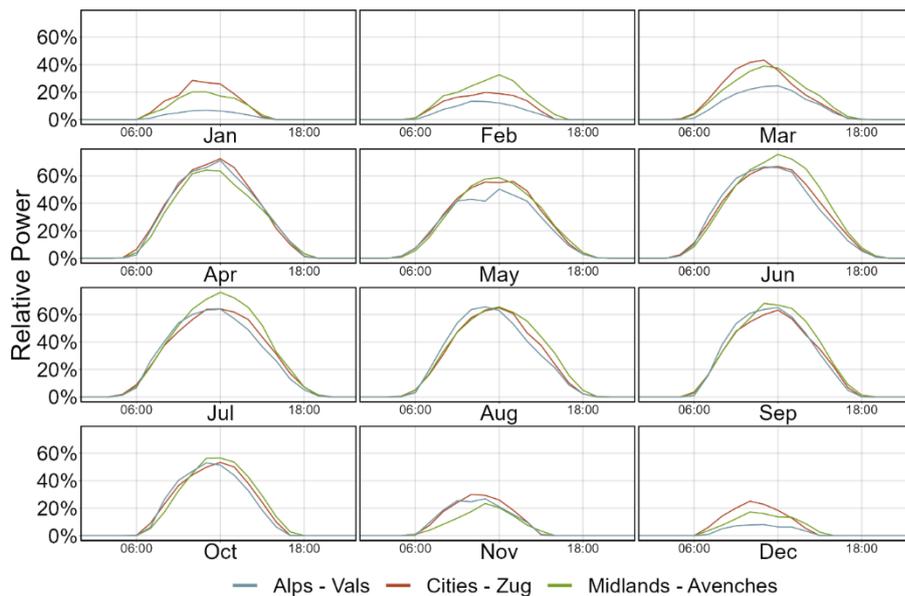

Figure 20. Mean monthly relative power generation profiles of Rooftop PV of one exemplary municipality per EDGE-region. Yearly timeseries were aggregated by taking the mean of identical times of the day over the course of each month. Profiles feature a temporal resolution of 15 minutes and are scaled so that their maximal value over the course of one year equals 1. Data source: [9]

2.3.3   Façade PV

Spatial Potential Disaggregation

The Sonnendach.ch database[19] contains the quantified annual generation potential attributed to PV systems for each façade in Switzerland. Anderegg et al. [10] proposed a general reduction factor for these potentials accounting for the facade components that impede the installation of PV modules. This

---

general reduction factor of 52.5% was applied to each façade potential value sourced from the Sonnendach.ch database. Identical to the methodology for rooftop PV, an intersection calculation between the dataset with the individual façade potentials and the borders of the Swiss municipalities yielded the annual façade PV potential by municipality. The results of this analysis are illustrated in Figure 21.
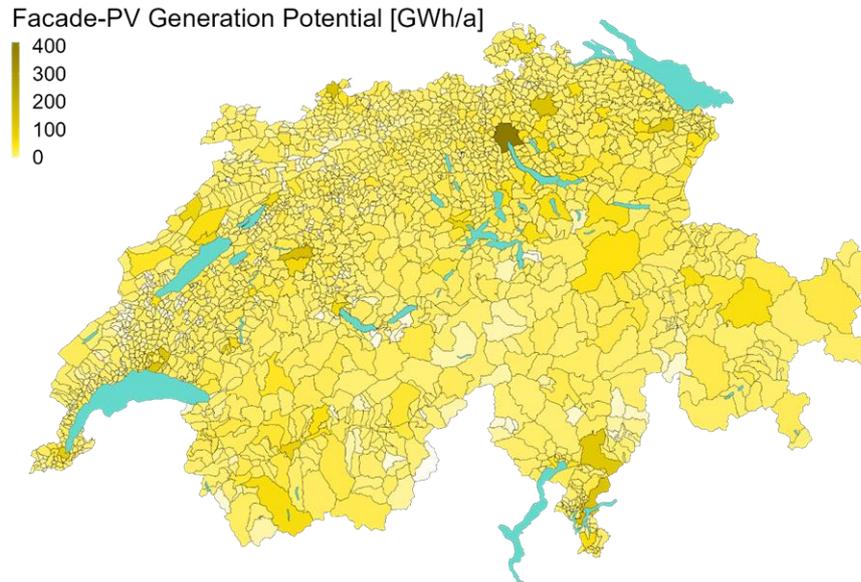

Figure 21. Annual electric energy production potential by facade PV per municipality. Results calculated applying reduction factors from [10] on the Sonnendach database.

Timeseries Modelling

The identical dataset, published by Bucher and Schwarz [9], served as the fundamental basis for the modelling of façade photovoltaic (PV) timeseries. To account for the distinct diurnal and seasonal production patterns of façade-mounted PV panels, the timeseries were modified by a dynamic factor. This factor was intended to emulate the consequences of the different tilt angle between rooftop and façade mounted panels.

This dynamic factor was derived from a calculation of direct irradiation for the individual locations of municipalities, the time of the year, including tilt and orientation of panels. For each municipality, the dynamic factor was computed for every timestep, approximated as a mean of the ratio between panels with a tilt of 90° (representing a facade) and 30° (representing a pitched roof) with orientations 110°, 145°, 180°, 215°, and 250° (where 90° denotes East, 180° South, and 270° West).

Profiles representing all 2148 municipalities for an exemplary summer and winter day are presented in Figure 24 and Figure 25, respectively. For three exemplary municipalities, one for each EDGE-region, an overview of their yearly profiles is shown in Figure 22 and their monthly mean profiles in Figure 23. Monthly averages display a combination of tilt and orientation of panels, location specific climate, and weather effects. An effect of this combination is apparent with mean profiles of February featuring lower values than months in summer, even though the yearly maximum generation occurs in February (for Zug and Avenches): February of 2018 had less sunny days than in the summer months, even though generation peaks with a vertical panel tilt occur during winter. It is evident that a reduced power production occurs in the winter months in Vals as an example municipality for the group of the Alps. The reduced production is due to snow coverage. This effect is an unwanted consequence of the employed modelling approach, which should actually not occur for façade PV because of the vertical tilt of panels.
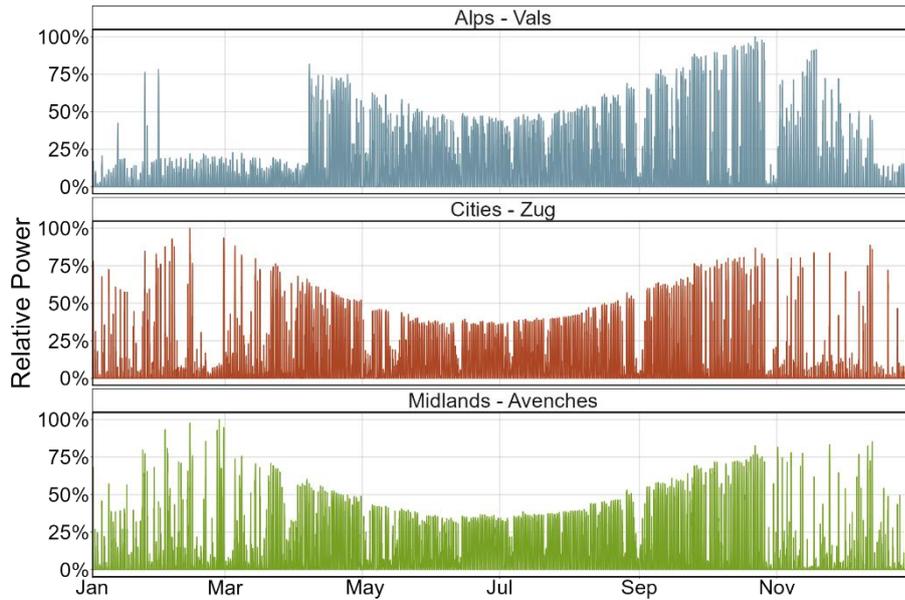
Figure 22. Yearly relative power generation profiles of façade PV of one exemplary municipality per EDGE-region. The municipality names are Vals, Zug, and Avenches. Profiles feature a temporal resolution of 15 minutes and are scaled so that their maximal value over the course of one year equals 1. Original data source: [9]; data adjusted to simulate the effect of vertical panels.
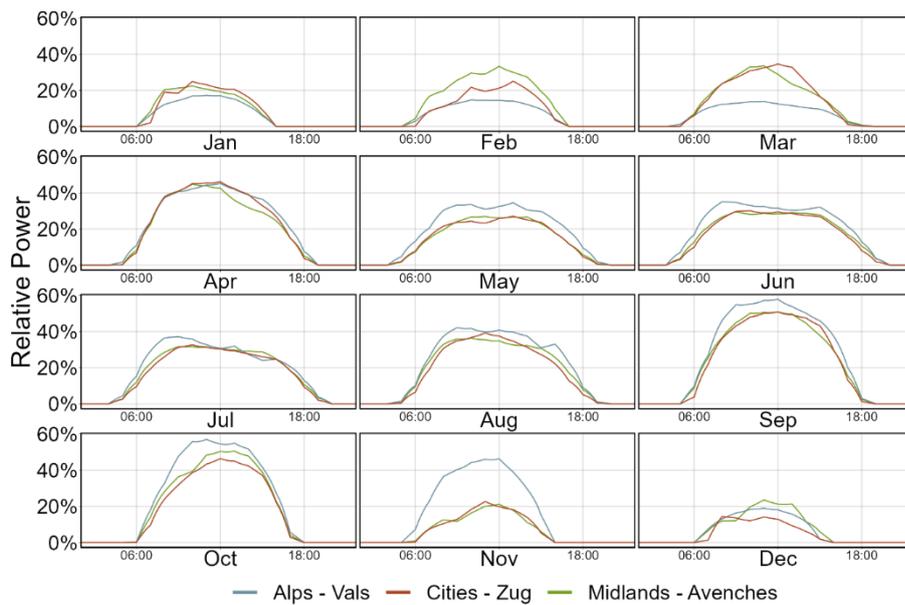

Figure 23. Mean monthly relative power generation profiles of façade PV of one exemplary municipality per EDGE-region. Yearly timeseries were aggregated by taking the mean of identical times of the day over the course of each month. Profiles feature a temporal resolution of 15 minutes and are scaled so that their maximal value over the course of one year equals 1. Original data source: [9]; data adjusted to simulate the effect of vertical panels.
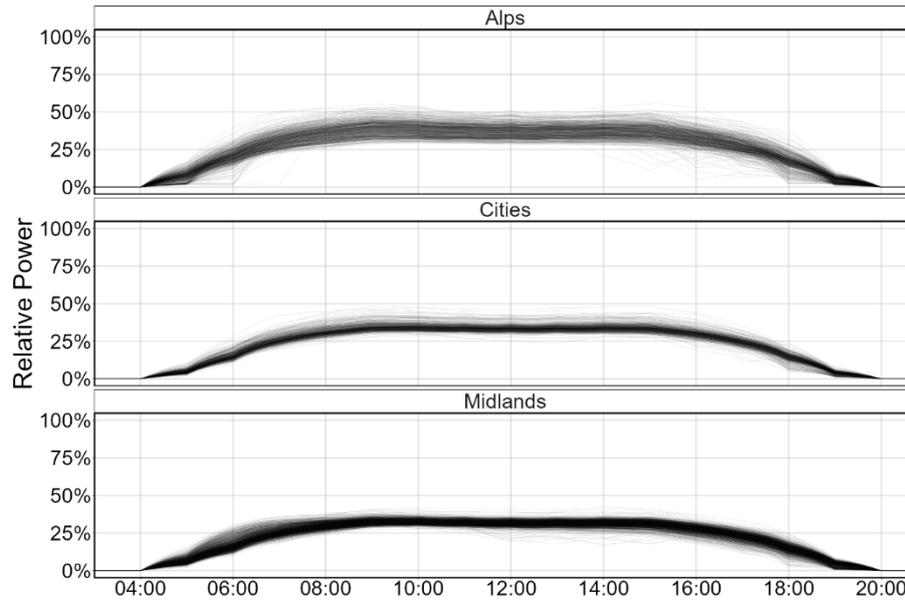
Figure 24. All municipal façade PV production profiles on June 1 (exemplary summer day) presented by EDGE-region. Profiles feature a temporal resolution of 15 minutes and are scaled so that their maximal value over the course of one year equals 1. Used timezone is Central European Summertime. The data originate from the real weather on 1. July 2018, which was a sunny day nearly all over Switzerland. Original data Source: [9]; data adjusted to simulate the effect of vertical panels.
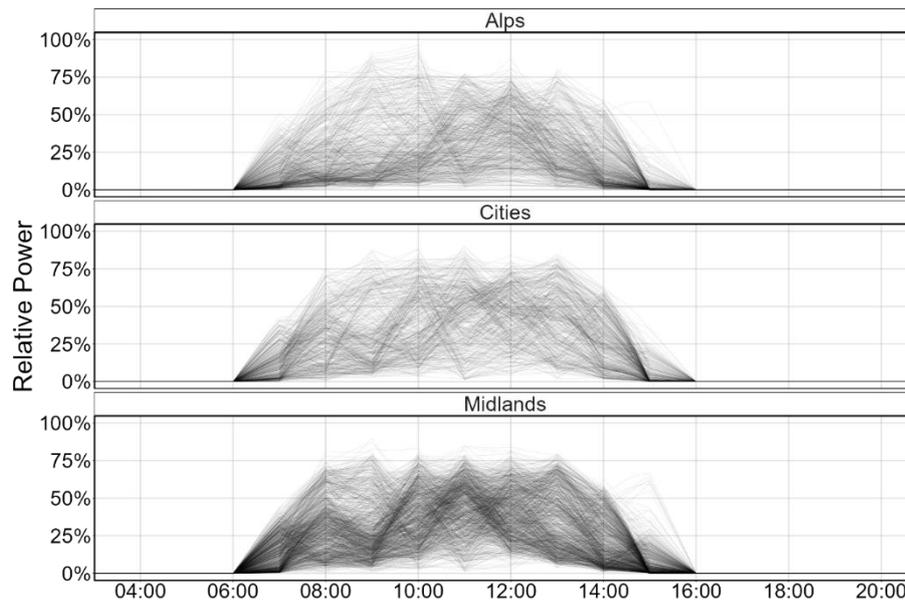

Figure 25. All municipal façade PV production profiles on December 1 (exemplary winter day) presented by EDGE-region. Profiles feature a temporal resolution of 15 minutes and are scaled so that their maximal value over the course of one year equals 1. Used timezone is Central European Summertime. The data originate from the real weather on 1. December 2018, which was mostly sunny with some clouds in certain locations. Original data Source: [9]; data adjusted to simulate the effect of vertical panels.

2.3.4   Agricultural PV

Agricultural PV or agrivoltaics (abbreviated also agri-PV) provides an enormous technical production potential for electric power but the socio-techno-economic potential remains to be identified. Future legislation and the design of subsidies both for the photovoltaic and the agricultural part are going to have a decisive impact on how the potential values.

Spatial Potential Disaggregation

The underlying dataset for the potential disaggregation of agricultural photovoltaics to a municipal level was created with the methodology described by Jäger et al. [3]. For this analysis, an enhanced dataset was obtained with courtesy of Dionis Anderegg (ZHAW). The dataset consists of georeferenced polygons of Swiss agricultural areas, which are compatible with agrivoltaics installations, and incorporates their corresponding electric energy production potentials. Three main improvements were made compared to the initial publication by Jäger et al. [3]: the underlying irradiation layer is more accurate, absence of a lower threshold for the specific power productivity for polygons to be included in the total potential, and a more comprehensive and succinct selection of agricultural polygon areas.

To allocate each agrivoltaic area to a designated municipality, an intersection calculation was conducted using a georeferenced dataset comprising the borders of all municipalities. As a result, the annual generation potential with agrivoltaics for each municipality was determined. The outcomes of this calculation are presented in Figure 26.
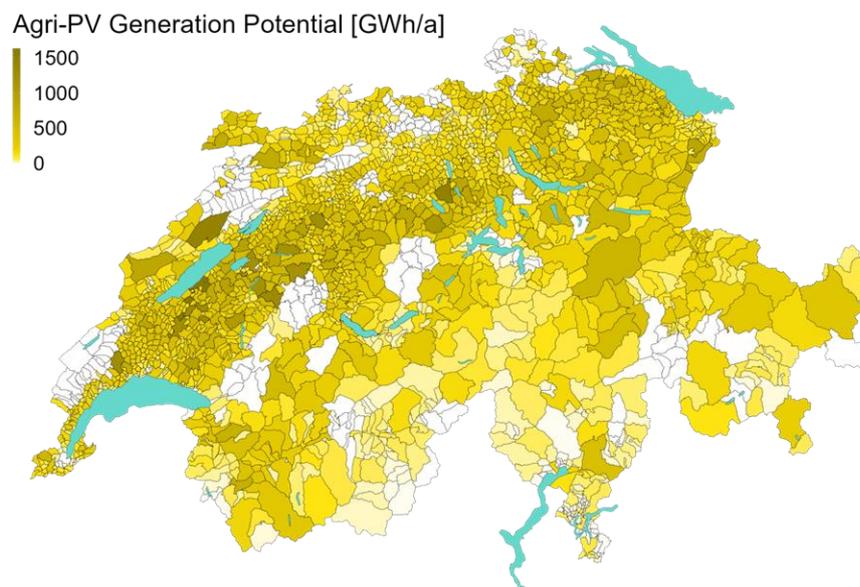

Figure 26. Annual electric energy production potential by Agri-PV per municipality. Nature reserves and similar protected areas are the predominant reason for most continuous areas of zero potential. Data source (updated dataset): [3]

Timeseries Modelling

Agrivoltaics is in Switzerland a new application of photovoltaics with the first systems being inaugurated at the time of writing this report. Its future development largely depends on the legislation and potential subsidies being put in place in the coming years. It is therefore difficult to foresee which types of systems are going to be implemented and which locations of the immense overall technical potential are going to be used. The uncertainty thus directly translates to the production timeseries profile. The temporal shape for each municipalities' production with agrivoltaics were therefore modelled to be identical to the profile with rooftop PV as described in section 2.3.2. This approach implies that agrivoltaic systems will have similar tilt angles like rooftop PV systems and can be motivated by the fact that all currently known agrivoltaic projects in Switzerland replace existing polytunnels.

2.3.5   Infrastructure PV

The term infrastructure PV is used as an umbrella term for PV systems on infrastructure other than classic roof and façade applications. Examples include locations along roads, on bridges, over parking spaces, over wastewater treatment plants, on noise barriers, etc.

Spatial Potential Disaggregation

The authors are not aware of studies, which quantify the potential of PV on infrastructure (roads, bridges, parking spaces, etc.) with a spatially explicit modelling. The infrastructure-PV potential is therefore assumed to be 5% of the potential on rooftops - based on expertise available at ZHAW, where work is ongoing to produce a study on the infrastructure potential in the canton of Zürich. Consequently, rooftop areas serve as a proxy for the existence of higher levels of infrastructure which can be used for PV applications. The relative potential distribution, which is the relevant factor in this step of our methodology, is therefore equivalent to the relative distribution of rooftop PV. The absolute annual generation potential by infrastructure PV per municipality is presented in Figure 27.
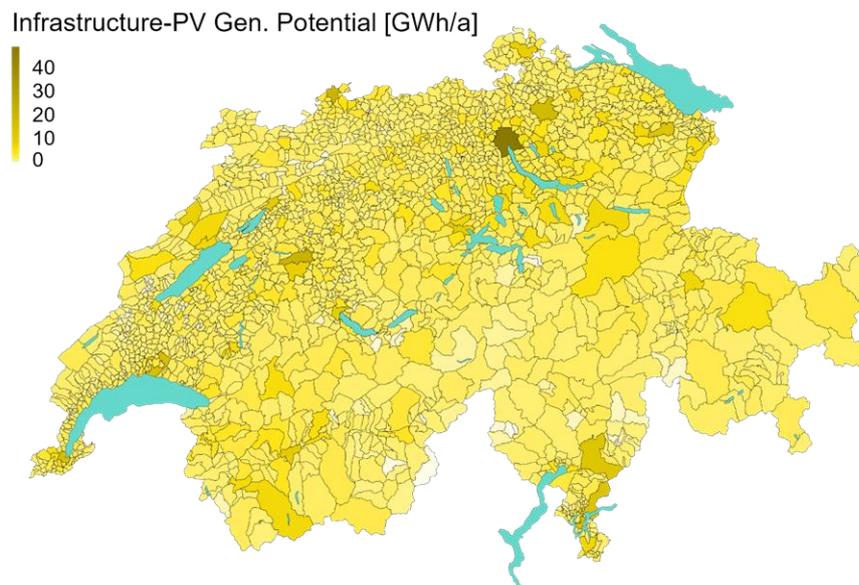

Figure 27. Annual electric energy production potential by infrastructure PV per municipality (assumption: infrastructure PV potential is 5% of rooftop PV potential).

Timeseries Modelling

A similar reasoning as for the potential disaggregation of agrivoltaics in section 2.3.4 can be stated: the effective future production timeseries of infrastructure PV depends on the relative shares of system types, which are not yet known. In addition, certain infrastructure PV applications have similar properties as rooftop PV in that there are existing substructures that influence a cost-efficient tilt and orientation of panels. Thus, the relative timeseries of infrastructure PV are assumed to be equivalent to the relative timeseries of rooftop PV (described in section 2.3.2).

2.3.6   Alpine PV

Spatial Potential Disaggregation

The generation potential disaggregation of alpine PV to the municipality level was calculated on the basis of a georeferenced dataset created in a Master Thesis[20] at ETH Zurich [11]. The data of the reference scenario of their study was used, which take into account the solar irradiance of locations but also their suitability under the legal limitations currently discussed by the Swiss parliament. The analysis excludes north-facing slopes and areas prone to rockfalls. In line with the currently discussed legislation, an altitude constraint has been imposed, taking into account only those locations with an elevation more than 1500 meters. Slopes steeper than 30° are deemed to be unsuitable. National Parks and other legally protected areas have been excluded. Further, in order to ensure a high share of winter production, sites must exhibit an energy yield greater than 500 kWh/kWp. Moreover, a lower threshold of 10 GWh/a has been placed on the energy production by one continuous solar park and PV systems are mandated to maintain a minimum distance of 100 meters from existing buildings.

The assignment of each alpine PV site to its respective municipality necessitated an intersection analysis with a georeferenced municipality dataset. This allowed for the quantification of the annual electric energy generation potential utilizing alpine PV per municipality (see Figure 28 for an illustration of the results).
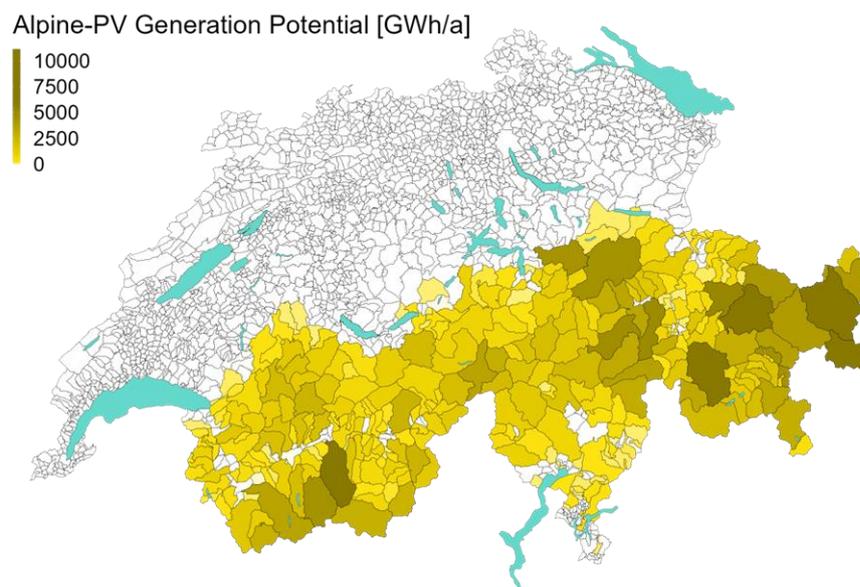

Figure 28. Annual electric energy production potential by alpine PV per municipality. The potential calculation includes the current status of new laws yet to be finalized. Among others, one criterion is an altitude above sea level of at least 1500 m, which excludes many municipalities in Switzerland entirely. Data source: [11]

Timeseries Modelling

The underlying data source for the temporal modelling of alpine PV consisted of five distinct alpine PV profiles. These profiles were derived from a combination of empirically measured data from an alpine PV pilot installation in Davos[21] as presented in [12], and simulated PV profiles from four selectively chosen alpine locations (Gondo, Arosa, Flims, Oberalp). All PV systems employed bifacial modules and tilt angles ranging between 70° and 90° to optimize the amount and yearly distribution of power

---

[20] Thesis supervision and data provision by Marius Schwarz, ETH Zurich

[21] Alpenstrom Davos project by group "Erneuerbare Energien" at ZHAW, https://www.zhaw.ch/de/lsfm/institute-zentren/iunr/oekotechnologien-energiesysteme/erneuerbare-energien/solarenergie/alpenstrom-davos/

generation (location specific tilt angles). The simulations were executed using the commercially available PVsyst software[22],[23]. The relative timeseries for alpine PV was computed as the temporal mean across all five profiles. Figure 29 and Figure 30 illustrate the resulting timeseries used for alpine PV power generation.
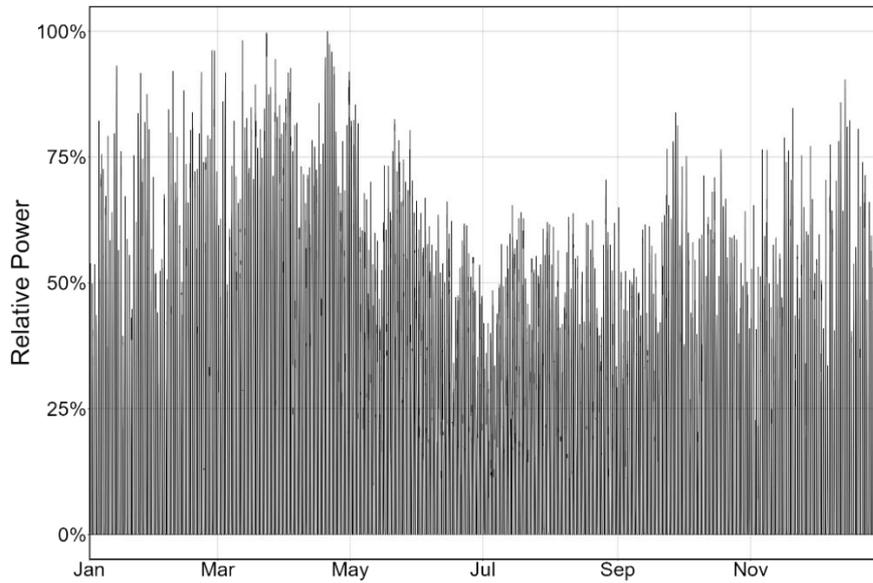

Figure 29. Year-long relative production timeseries used for alpine PV. All municipalities with alpine PV potential were modelled with an identical profile. It was derived as the temporal mean of the measurement timeseries from Davos and the four simulated profiles from Gondo, Arosa, Flims, and Oberalp to yield one year-long timeseries with a temporal resolution of 15 min.
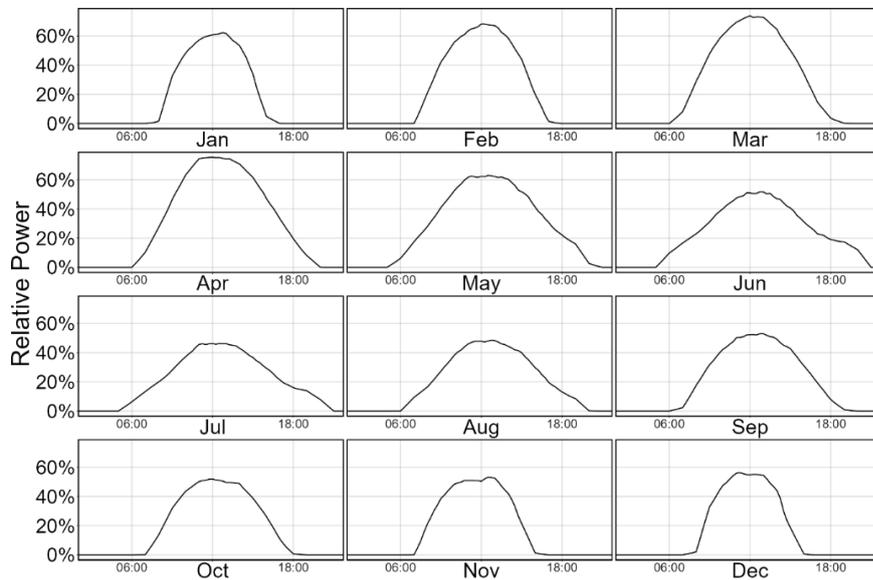

Figure 30. Mean monthly relative power generation profile of alpine PV. Each municipality features the same profile, which is then scaled with the respective yearly generation potential. Yearly timeseries were aggregated by taking the mean of identical times of the day over the course of each month. The profile features a temporal resolution of 15 minutes and is scaled to a maximum value of 1 over the course of one year.

---

[22] PVsyst, *https://www.pvsyst.com/*

[23] Simulations and data provisioning by Dionis Anderegg , ZHAW

2.3.7 Wind

The wind potential in Switzerland was sourced from a proprietary dataset provided by the Swiss Federal Office of Energy (SFOE). To model the production timeseries, data from the year 2018 from Energy-Charts[24] was used, assuming homogeneous production throughout Switzerland. Since this data is aggregated from a currently quite small sample (roughly 40 larger installations[25]), local effects are much more pronounced. However, that is not inherently detrimental to this analysis as the system boundary for the main analysis are single municipalities, for which such pronounced local effects are expected to be present as well. While Figure 31 provides a yearly overview of the modelled wind generation profile, Figure 32 illustrates four exemplary days in detail.
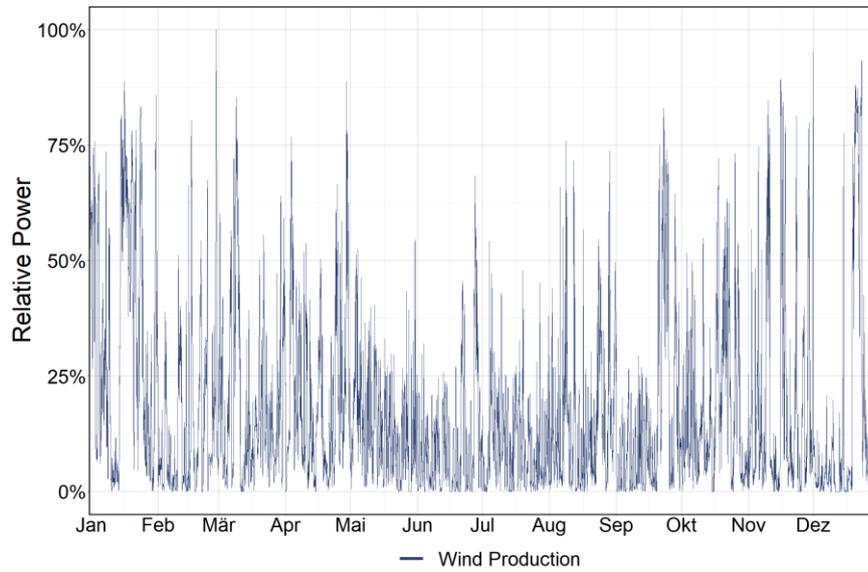

Figure 31. Relative power of wind electricity production in 2018 scaled to a maximum of 1. 2018 was used as reference year for historic data inputs, which serve as proxy for future profiles.
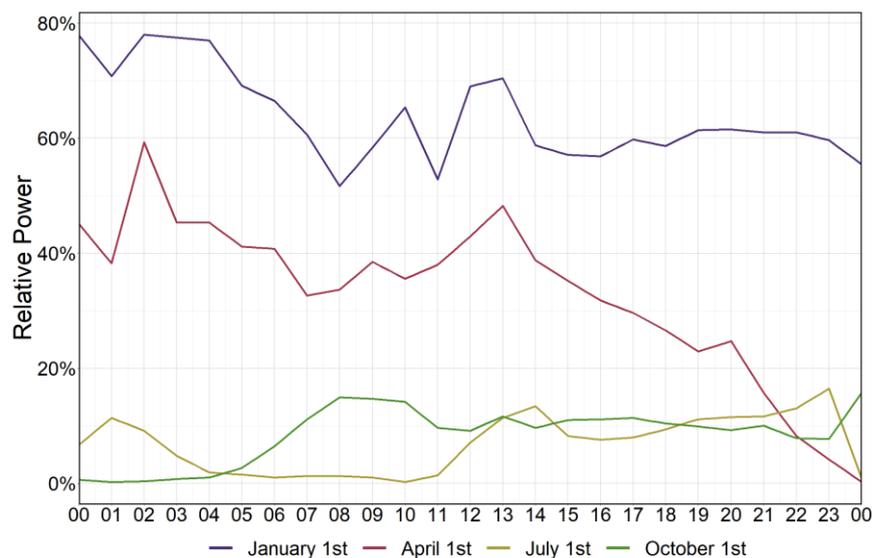

Figure 32. Relative power of wind electricity production in 2018, shown for the first day of every quarter, normalized to the yearly maximum.

---

[24] Energy-Charts, *https://www.energy-charts.info/charts/power/chart.htm?l=de&c=CH*

[25] Wind Energy, SFOE, *https://www.bfe.admin.ch/bfe/en/home/supply/renewable-energy/wind-energy.html*

2.3.8 Biomass (Wood)

Spatial Potential Disaggregation

The sustainable potential for energy generation via the employment of woody biomass at the municipal level was quantitatively established by the research of [13]. This dataset was created in the year 2017. Disparities have emerged to the set of municipalities of 2022, necessitating a standardization process, which was accomplished through the application of a GIS-based approach. Figure 33 visually represents the normalized spatial distribution of potential of energy from woody biomass in a renewable way. The primary energy potential of woody biomass and substrates to generate biogas were calculated in [13]. The share of heat generation from biomass is much bigger than electricity generation and electricity is often generated in a combined process with heat generation [14]. Large shares of the biomass potentials and their spatial distributions shown in section 2.3.8 and 2.3.9 are therefore not going to be used for electricity generation, which is the focus of this report. It is an implicit assumption that the relative distribution of the electricity generation potential is identical to the distribution of primary energy potential from biomass.
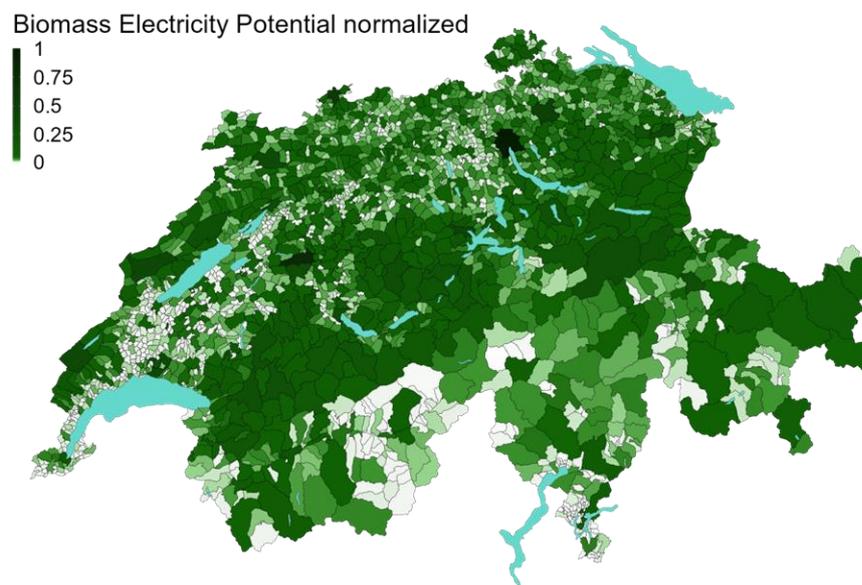
Figure 33. Relative potential of electricity production from biomass. All values were scaled to a value range between 0 and 1. Only the relative spatial potential distribution is relevant for the methodology because for each category a top-down value is disaggregated based on the relative shares of municipalities Apart from grown wood, waste wood is factored in as well, leading to high generation potentials in certain cities. Data source: [13].

Timeseries Modelling

The relative power production timeseries from biomass was assumed to be equivalent to the relative production timeseries of biogas (shown in Figure 35), for lack of a better alternative. Since the resulting absolute values are comparatively small, this simplification should not have a significant impact on the analysis.

2.3.9 Biogas

Spatial Potential Disaggregation

There are a multitude of distinct substrates that can be utilized for the generation of biogas, which can subsequently be transformed into electricity. Taken into account as sources for biogas for this report were manure, agri byproducts, greenwaste, household garbage, and organic waste. A comprehensive

analysis by [13] presents the sustainable potential for electrical energy production using agricultural residues, green waste, domestic refuse, and organic waste. This estimated sustainable potential was cumulatively combined with the sustainable potential derived from manure, which was determined via a more detailed investigation that took into consideration techno-spatial constraints, as proposed in [15] and detailed in a previous report in the context of the EDGE-project [16]. The results of this aggregation are visually presented in Figure 34.
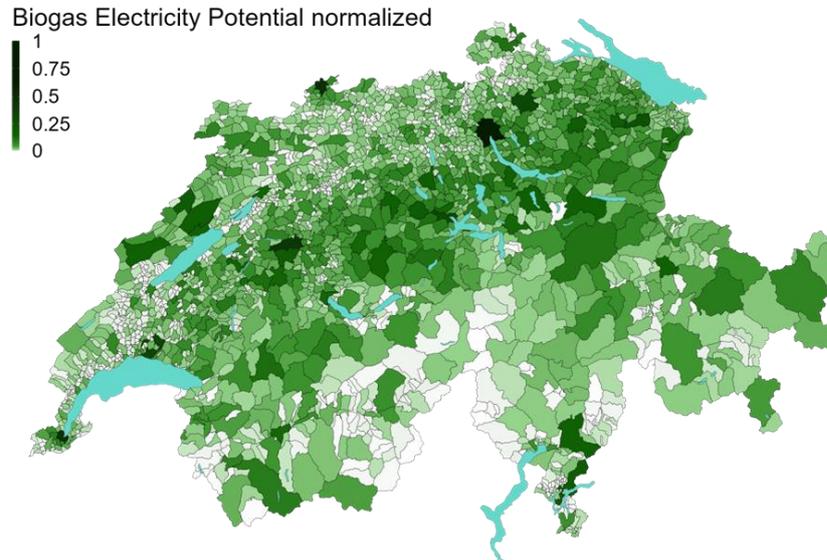

Figure 34. Relative potential of electricity production from biogas. All values were scaled to a value range between 0 and 1. Only the relative spatial potential distribution is relevant for the methodology because for each category a top-down value is disaggregated based on the relative shares of municipalities. Data source: [13].

Timeseries Modelling

Figure 35 shows the relative CH-wide production timeseries of biogas, which was obtained from Energy-Charts[26] for the year 2018. 2018 serves as reference year and proxy for future profiles for the hereby presented approach. Electricity generation from woody biomass and biogas for all municipalities was modelled with this timeseries. More daily details of the timeseries are shown in Figure 36.

---

[26] Energy-Charts, *https://www.energy-charts.info/charts/power/chart.htm?l=de&c=CH*
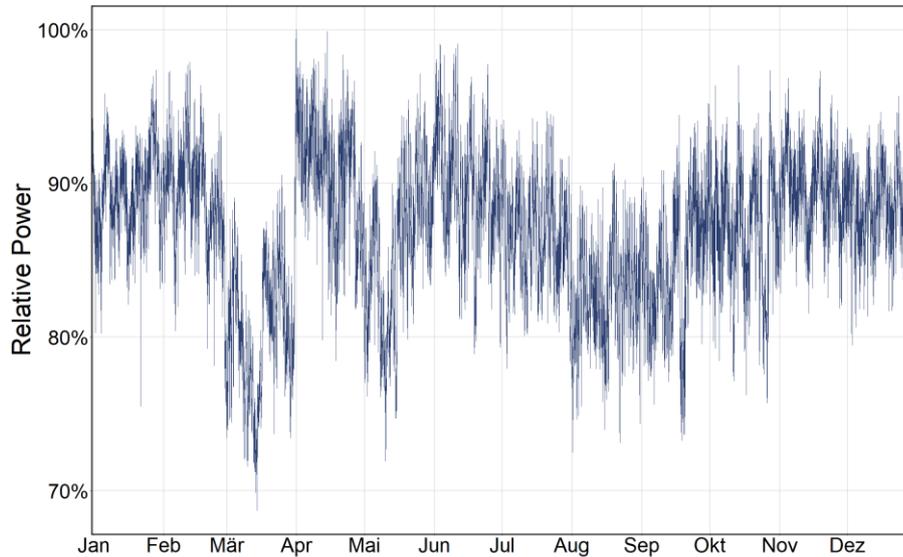
Figure 35. Relative power of biogas electricity production in 2018. 2018 was used as reference year for historic data inputs, which serve as proxy for future profiles. All municipalities are modelled with the same timeseries.
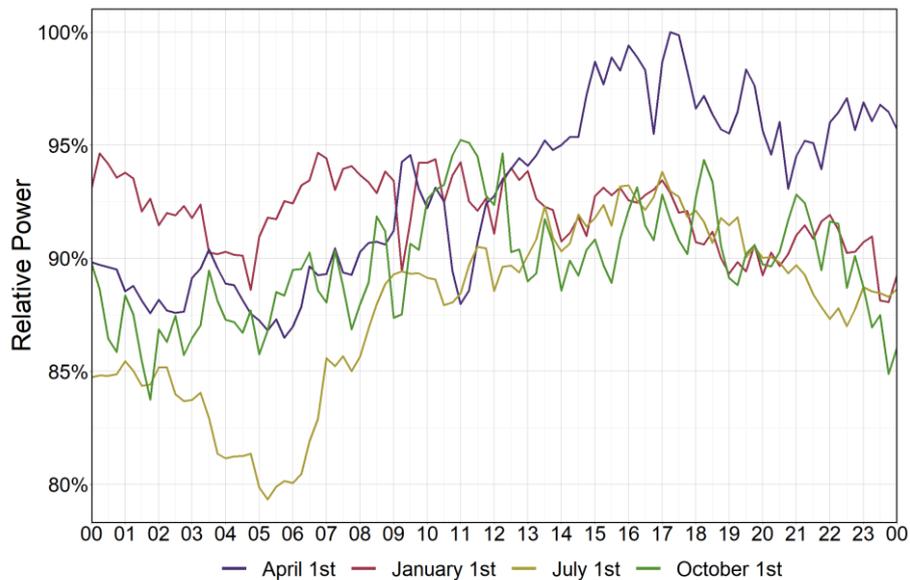

Figure 36. Relative power of biogas electricity production in 2018, shown for the first day of every quarter, normalized to the yearly maximum.

2.3.10 Waste-to-Energy

Waste-to-energy plants are included in a dataset from SFOE[27], which contains the yearly electricity production for each facility. Figure 37 shows the locations of all Swiss waste-to-energy plants, with marker sizes corresponding to their expected annual electricity production (renewable and non-renewable). Together with timeseries data from Energy-Charts[28] shown in Figure 38, a production timeseries is generated for each containing municipality, assuming that the CH-wide production is distributed equally according to individual (current) annual expected production at all times. Since the scenario values within the Energieperspektiven 2050+ are limited to the renewable fraction of WtE

---

[27] Kehrichtverbrennungsanlagen (KVA), *https://opendata.swiss/de/dataset/kehrichtverbrennungsanlagen-kva*

[28] Energy-Charts, *https://www.energy-charts.info/charts/power/chart.htm?l=de&c=CH*

(50%), the resulting absolute values are doubled to account for the non-renewable (but nevertheless decentralized) fraction.
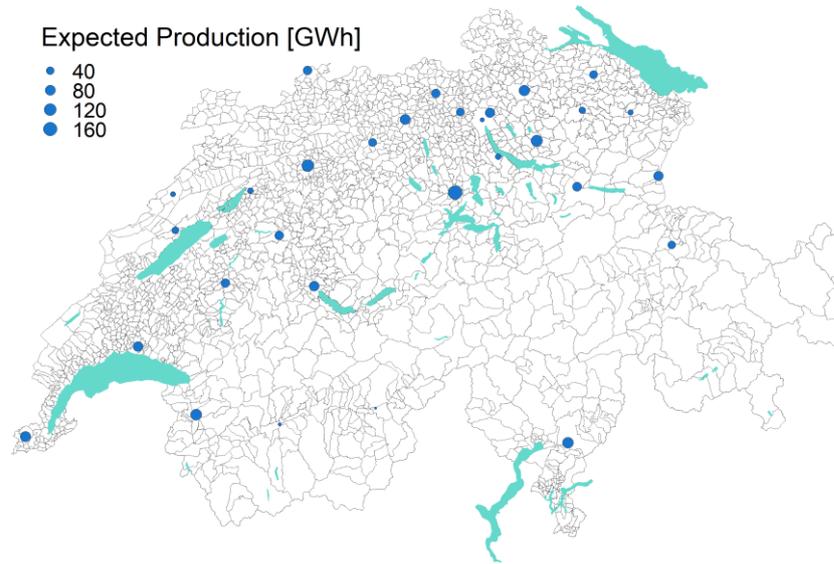

Figure 37. Waste-to-energy plants in Switzerland, with marker diameters proportional to annual expected production.
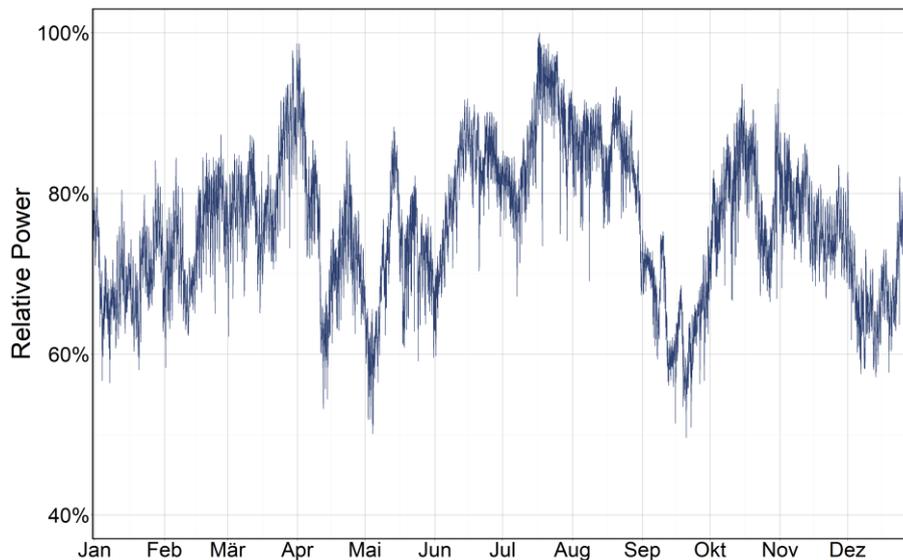

Figure 38. Relative power of waste-to-energy electricity production in 2018.

2.3.11 Wastewater

The locations of Swiss wastewater treatment plants are included in a dataset from the Swiss Federal Statistical Office (FSO)[29], which contains potentials for waste heat recuperation based on the number of consumers connected to each facility. The locations are shown in Figure 39. Here the assumption is made that biogas production and subsequent power production is directly proportional to the aforementioned potential. By using the CH-wide target number for biogas electricity from wastewater plants, a preliminary electricity generation potential is assigned to each facility. Subsequently, plants with a potential below 20kW$_{el}$ are discarded, since it is assumed that this is the lowest level at which

---

[29] Potential der Abwasserreinigungsanlagen für Wärmenutzung, *https://opendata.swiss/de/dataset/thermische-netze-warme-und-kalteangebot*

such an additional process step could be introduced in a financially prudent way. The remaining facilities, representing >98% of the potential, are then again scaled by the CH-wide target number. Timeseries data was obtained from Energy-Charts[30] for 2018, which matches the weekdays of 2035. The resulting relative values are shown in Figure 40.
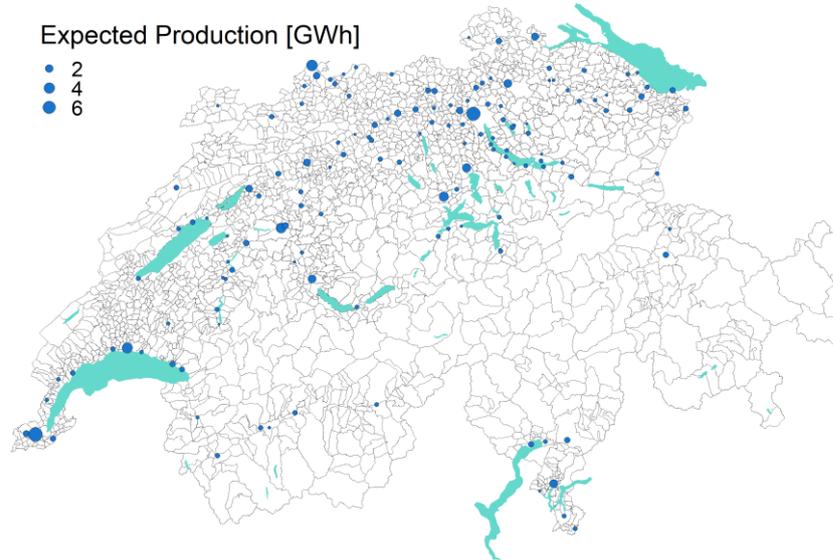

Figure 39. Wastewater treatment facilities in Switzerland, with marker diameters proportional to annual expected production.
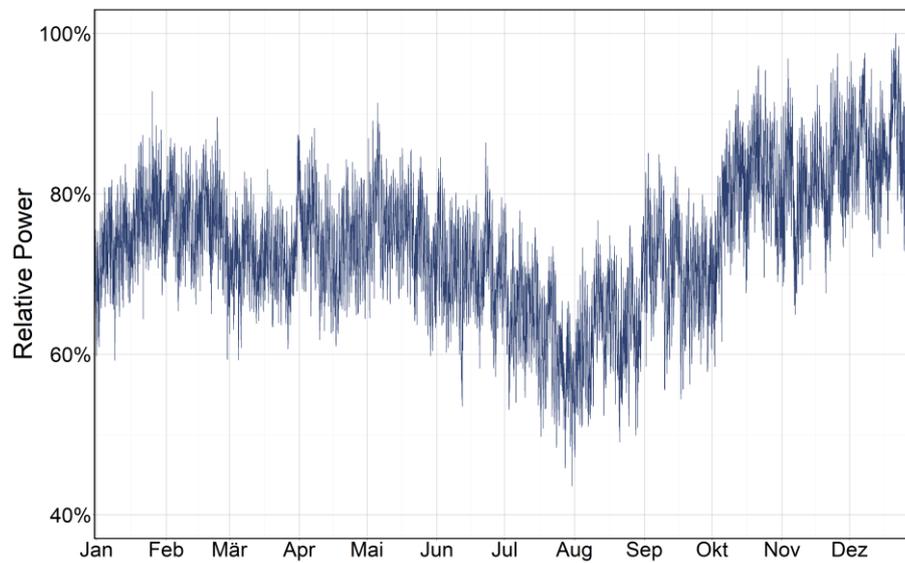

Figure 40. Relative power of wastewater biogas electricity production in 2018.

---

[30] Energy-Charts, *https://www.energy-charts.info/charts/power/chart.htm?l=de&c=CH*

3 Analysis Showcase and Results

As detailed in section 2, timeseries data for each decentralized generation and consumption category was produced on a municipal level for a fully renewable scenario (scenario ZERO Basis from EP2050+). In the following, this data is first presented exemplary for two municipalities. The examples were chosen according to the 10%/90% quantile of average annual differences in production and consumption (only considering municipalities in excess of 2000 inhabitants), namely Rolle VD (-6.72 MW) and Altstätten SG (+1.99 MW). The methodology, statistics and analysis are thereby demonstrated, before showing results for all three EDGE-Regions, and Switzerland as a whole. It should be noted at this point that within this report, the analysis is solely limited to showing the need for energy shifting, i.e. precisely characterize the deviation between supply and demand, on a municipal level and with an adequate temporal resolution. Further refinement of this analysis, as well as the techno-economic matching of this deviation with suitable technologies (storage, PtX, and other flexibility) is part of the next reports.

3.1 Data Processing and Analysis - Showcase

The production and consumption timeseries for a selected exemplary week in April for both sample municipalities (Altstätten & Rolle) are shown in Figure 41 and Figure 42, respectively. Positive values correspond to production, whereas negative values represent consumption. Within overarching categories (production, consumption), curves are stacked. The singular black curve represents the difference of instantaneous production and consumption, with positive values corresponding to surplus production.

The example of Altstätten SG shows a municipality with surplus local production, mainly driven by PV. Additionally, there is a sizeable potential for wind power, managing to fill gaps at least partially in PV production. As can be seen from the cumulative curve, surplus production spikes of up to 50 MW are to be expected. Conversely, the example of Rolle VD shows a municipality with a large deficit in local production. This is mainly driven by a large general load, and spikes caused by EV charging. Apart from PV, no other significant means of decentralized local electricity production is available.
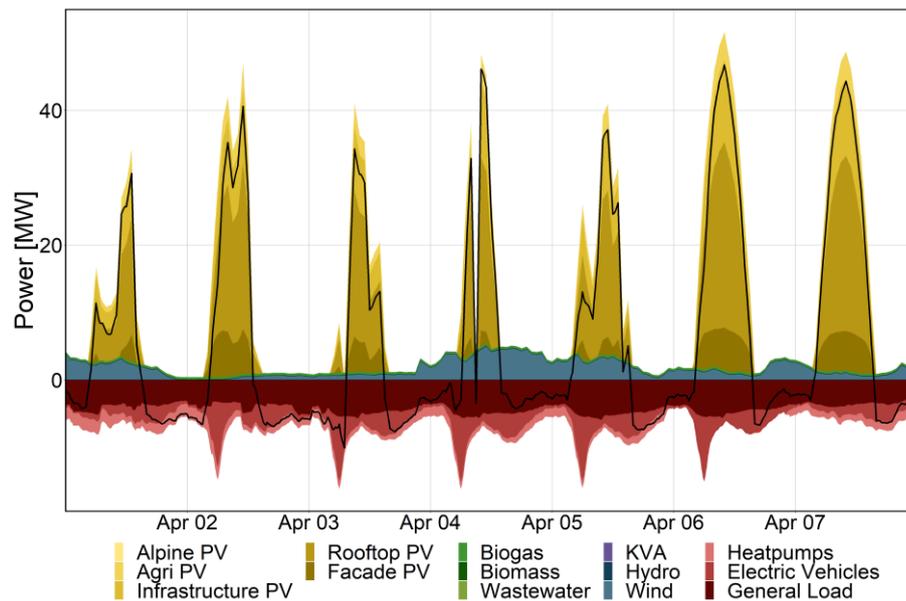

Figure 41. Decentralized Production and consumption profile in the municipality of Altstätten SG for a selected week in April. Positive values correspond to surplus production, curves are stacked within production and consumption categories.
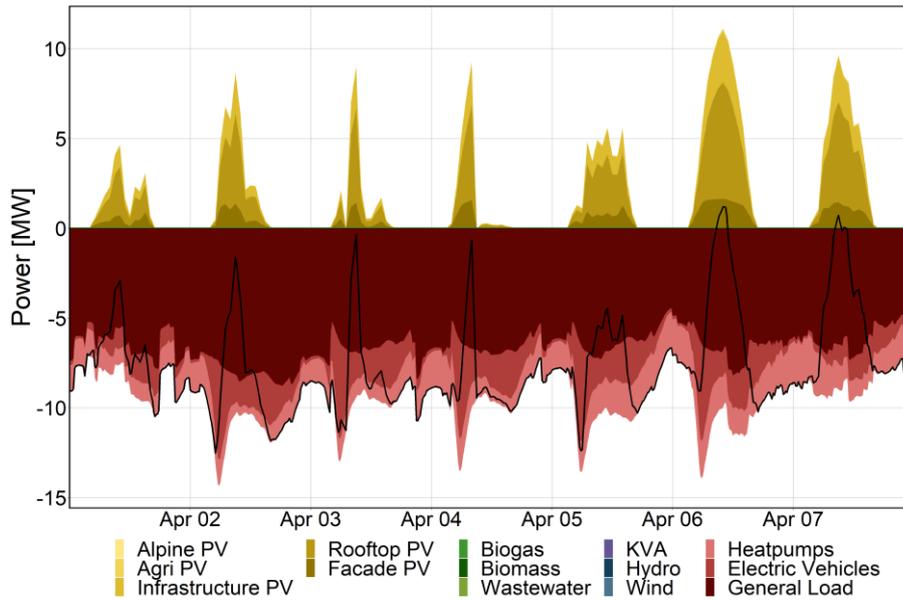
Figure 42. Decentralized production and consumption profile in the municipality of Rolle VD for a selected week in April. Positive values correspond to surplus production, curves are stacked within production and consumption categories.

Figure 43 shows the categorized consumption and production of Altstätten SG over the model year, aggregated by weeks. Figure 44 shows the same analysis for Rolle VD. While both municipalities exhibit characteristic consumption profiles, Altstätten boasts a decidedly larger potential for all forms of PV (with the exception of alpine PV), which is mainly augmented by wind power. Even though Altstätten is a net producer over a whole year, this analysis shows that there are still multiple timeframes within which consumption outweighs production – from intra-daily to periods of multiple weeks.
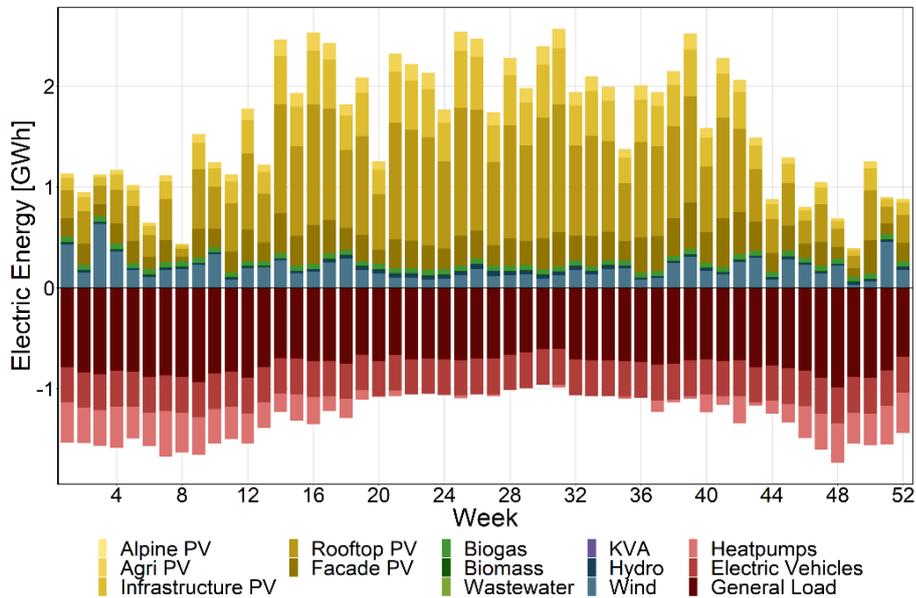

Figure 43. Decentralized production and consumption in the municipality of Altstätten SG for the whole model year, aggregated for each full week (Monday to Sunday). Positive values correspond to production.
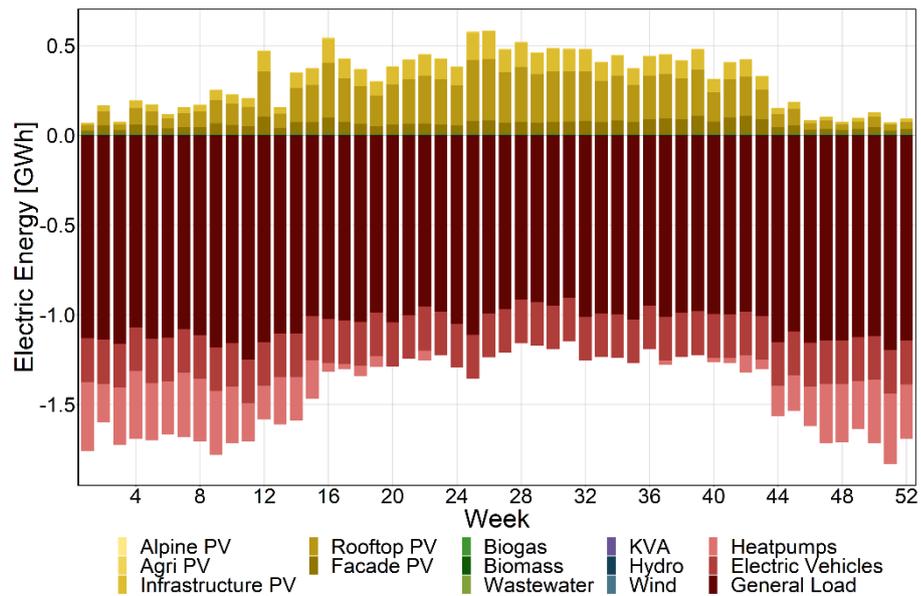
Figure 44. Decentralized production and consumption in the municipality of Rolle VD for the whole model year, aggregated for each full week (Monday to Sunday). Positive values correspond to production.

The range in power curves of the aggregated production, aggregated consumption, and the delta of the two aforementioned variables of all municipalities is enormous as evident from Figure 45, Figure 46, and Figure 47. While the biggest part of the observations remains in the one-digit range for both production, consumption, and their delta, a few municipalities feature much higher values. All three profiles show seasonal behaviour with production being higher in summer and consumption the other way around. The electricity production features more variability on the timescale of days in comparison to the consumption, where a weekly pattern can be observed. Among the delta-timeseries the profiles with the biggest values feature peaks of about three times the consumption compared to production. The biggest share of profiles lies in a narrow band between about 6 MW of local deficit or excess energy (see Figure 47).
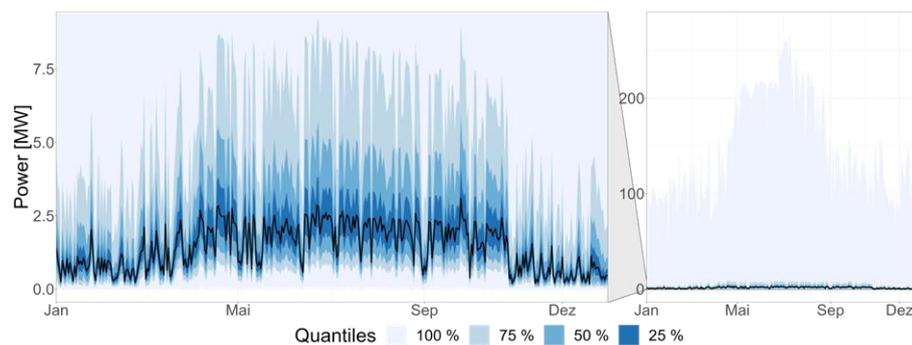

Figure 45. Quantiles of power generation of all municipalities over the course of the modelled year. For each timestep, the blue shades display the quartile of all power values. The median is shown as a black line. The left-hand side of the plot shows a zoom into the overall plot, which is shown on the right.
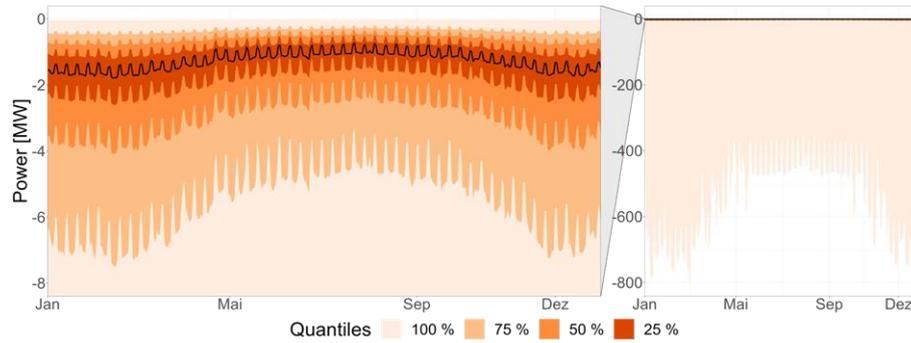
Figure 46. Quantiles of power consumption of all municipalities over the course of the modelled year. For each timestep, the red shades display the quartile of all power values. The median is shown as a black line. The left-hand side of the plot shows a zoom into the overall plot, which is shown on the right.
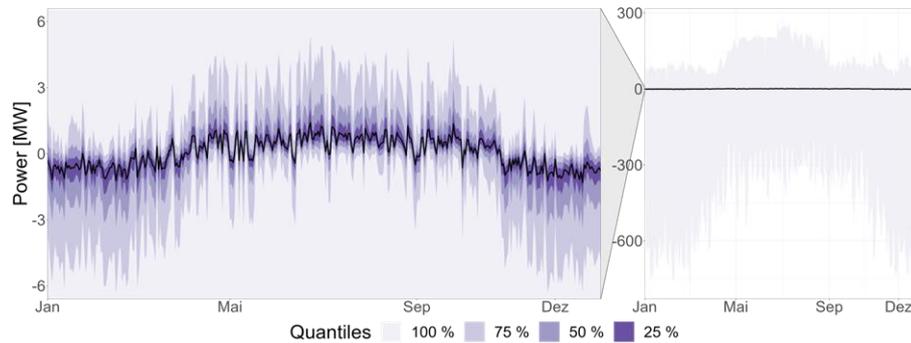

Figure 47. Quantiles of power delta between production and consumption of all municipalities over the course of the modelled year. For each timestep, the violet shades display the quartile of all power values. The median is shown as a black line. The left-hand side of the plot shows a zoom into the overall plot, which is shown on the right. Positive values represent an excess of generated power, while negative values mean that consumption is higher than generation.

3.2   Analysis: EDGE-Regions

As shown in section 3.1, there appear to be systematic differences between municipalities – influencing the way in which storage and PtX, or generally energy shifting applications, have to be deployed to minimize impacts on the grid. A group-wise analysis thus helps to reduce complexity and generalize findings. EDGE as a project introduces three regions in Switzerland, which differ in their underlying fundamentals in terms of energy production and usage. Figure 48 shows the exclusive classification of municipalities into the regions of Alps, Midlands, and Cities defined within the EDGE consortium [17]. It is based on a 9-category-classification presented in Figure 49, according to the mapping described in Table 3.
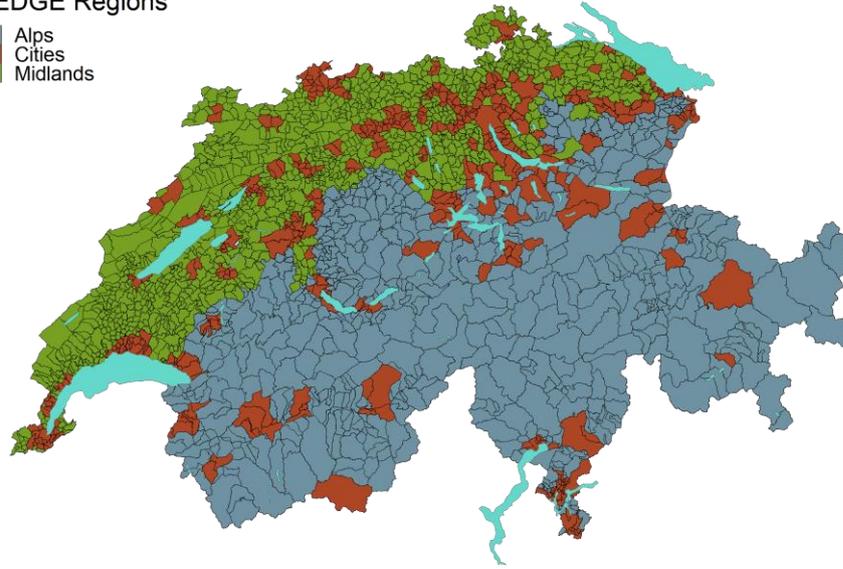
Figure 48. Classifications of Swiss municipalities into regions of Alps, Cities, and Midlands, according to EDGE methodology. 2022 is the reference year for the list and border definitions of municipalities.

Figure 49. Classifications of Swiss municipalities into combinations of a population density and a mountain types classifier according to EDGE methodology. 2022 is the reference year for the list and border definitions of municipalities.
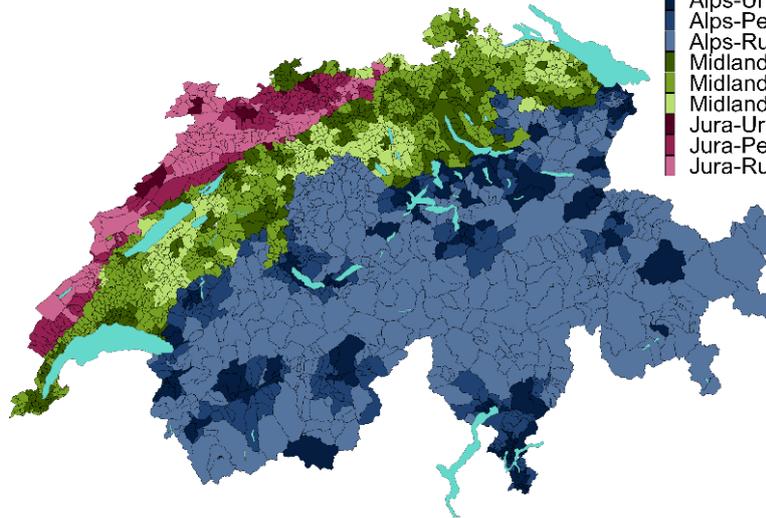
Table 3. Classifications of Swiss municipalities into regions of Alps, Cities, and Midlands, derived from a classification based on a combination of two official classifiers from the federal statistical office. The first classification by the federal statistical office is the "Gemeindetypologie" with nine categories, which was aggregated to the three main categories "Urban", "Periurban", "Rural". The second classification is named "Berggebietsregionen", which was simplified ("Schwarzwald", "Schwäbische Alb", and regions without classification are all classified as Midlands). These municipality classifications follow the EDGE-project-wide approach given in [17]. In accordance with the EDGE-project, the term "Midlands" is in this report used as a synonym for Swiss Plateau.

	Alps	**Midlands**	**Jura**
Rural	Alps	Midlands	Midlands
Periurban	Alps	Midlands	Midlands
Urban	Cities	Cities	Cities

An equivalent to the analysis shown in section 3.1 was conducted for municipalities aggregated by region. Figure 50 shows the decentralized production and consumption during the model year, aggregated for the three EDGE-regions, for each full week. The number of municipalities, population (and concomitantly infrastructure), and land area varies significantly for the three EDGE-regions, as listed in Table 4. Absolute-value comparisons of the three regions are therefore of limited value, depending on context. More illuminating, in general, are the differences in the ratio of electricity production and consumption, and their respective evolutions over the year. All regions exhibit a peak in production in summer, with consumption being highest in winter. While the group of alpine municipalities shows substantial overproduction over the course of the year, the Midlands are more balanced, and the group of the Cities feature an excess in consumption in comparison to production over the course of one year. Wind power is a relatively significant factor in the group of the Midlands, thus leading to a yearly production profile showing a smaller peak in summer. This is especially contrasting to the Cities-group, which (apart from running hydropower) relies mostly on generation by photovoltaics.

Table 4. Number of municipalities, population, and area by EDGE-region and BFS classification. The allocation from BFS classification to EDGE-region is according to Table 3.

| EDGE-region	BFS Classification	Number of Municipalities		Population in Thousand		Area in km²	
Alps	Alps-Periurban	572	221	1131	460	23561	4185
	Alps-Rural		351		671		19376
Cities	Alps-Urban	476	145	5467	1251	6827	3586
	Jura-Urban		15		113		225
	Midlands-Urban		316		4104		3015
Midlands	Midlands-Periurban	1100	571	2072	1223	10452	4476
	Midlands-Rural		249		500		2466
	Jura-Periurban		150		194		1498
	Jura-Rural		130		155		2012
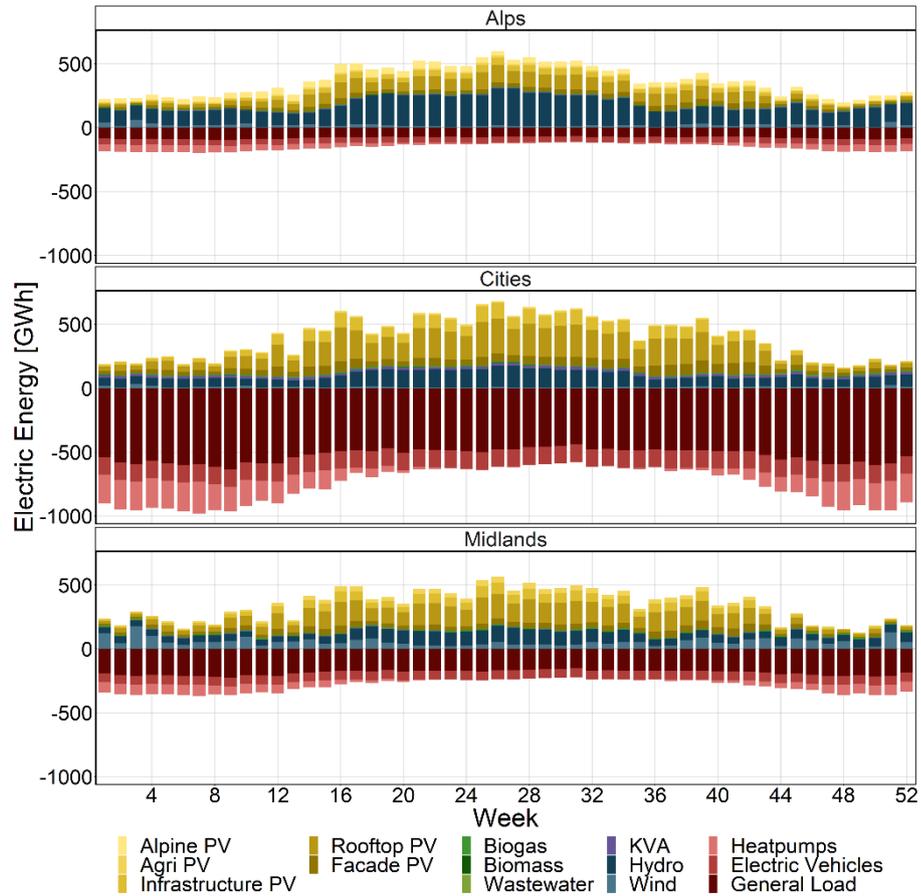
Figure 50. Decentralized production and consumption during the model year, aggregated for the three EDGE-regions, for each full week. Positive values correspond to production.

Figure 51 and Figure 52 show the annual decentralized electricity production versus consumption for all Swiss municipalities, grouped into EDGE-regions. They show quite clearly that on an annual basis, most cities are net negative (with some exceptions), alpine municipalities are net positive (again, with exceptions), and midlands municipalities fall somewhere in between. It can also be seen that the yearly amount of local consumption and generation is correlated but with a considerable number of exceptions. Figure 53 shows the same analysis, but with a focus on smaller municipalities (note that this plot is *not* logarithmic). It becomes evident that a considerable share of the total number of 2148 municipalities is low in population with a tendency to a net positive production. The regions of the Alps and Midlands are overrepresented in this group. Figure 56 shows the relation between aggregated production and consumption for each month, for each municipality, while Figure 54 and Figure 55 show the same information on a bi-seasonal and seasonal aggregation. Upon analyzing the data, it is evident that municipalities with large populations do not show an excess generation of electricity. When examining seasonal variations, autumn and spring are remarkably alike, exhibiting almost indistinguishable characteristics on this level of temporal aggregation. In contrast, winter presents a more pronounced energy deficit for most municipalities, signifying a substantial gap between energy production and consumption. However, summer is characterized by frequent instances of excess energy production. Finally, the variability in results among municipalities increases in winter compared to summer, meaning that the differences in terms of local power deficit or excess power among municipalities is season-dependent.
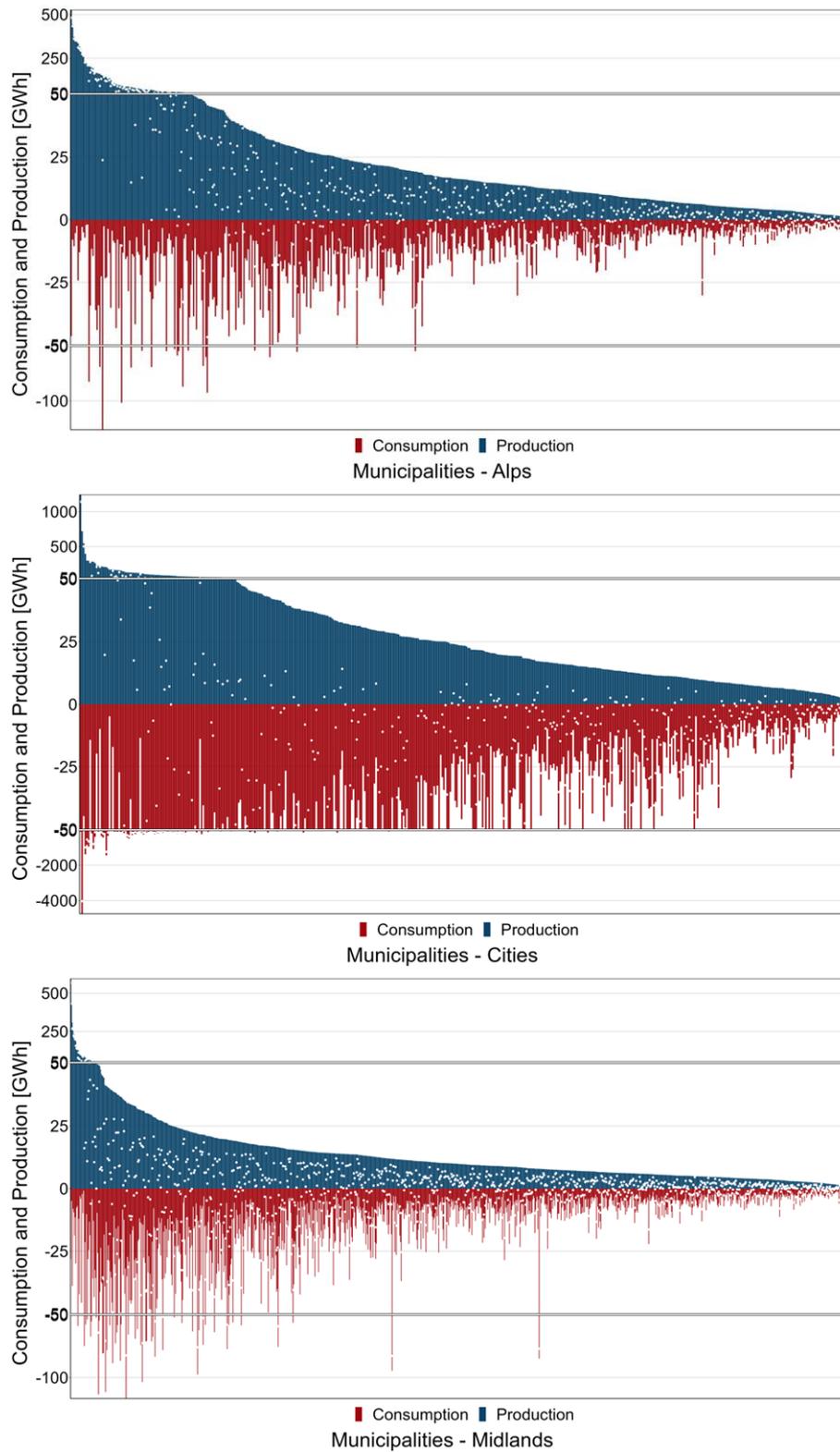
Figure 51. Yearly aggregation of produced and consumed electric energy by municipality divided into EDGE-region. The municipalities are ordered by electricity production in descending order. A white dot represents the difference between production and consumption. If it is positive a municipality generates more electric energy than it consumes over the course of the model year. Note that the y-axis is not continuous but features two breaks in each plot to cover the whole range of values. Most municipalities are classified as part of the Midland region leading to more bars in that subplot.

Figure 52. Annual decentralized electricity production vs. consumption for all Swiss municipalities, grouped into EDGE-regions (colors), scaled by population (bubble sizes). The diagonal line indicates net self-sufficiency on a yearly basis.
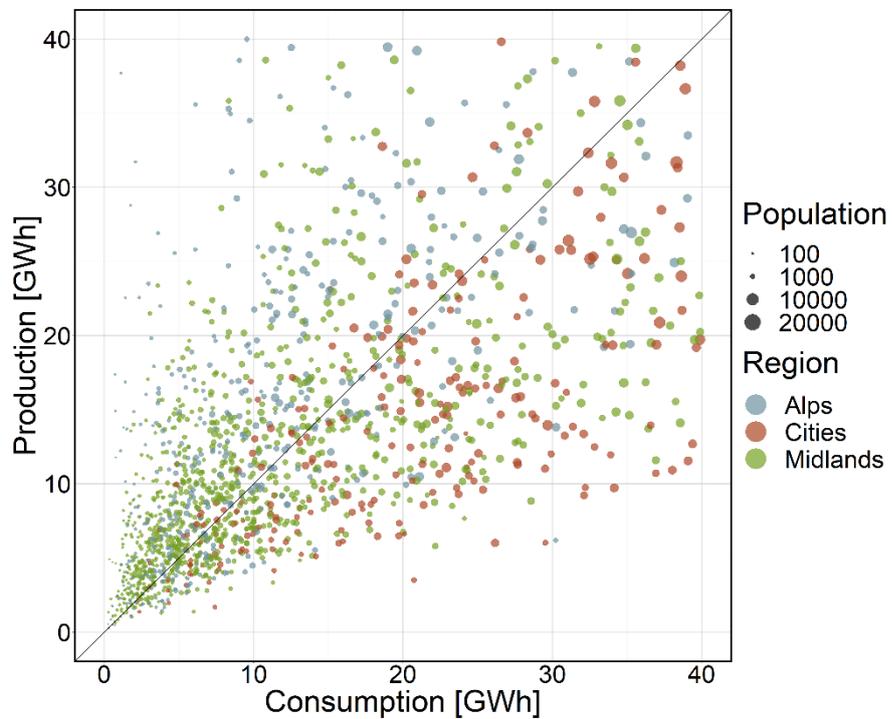
Figure 53. Annual decentralized electricity production vs. consumption for all Swiss municipalities with annual consumption and production below 40 GWh, grouped into EDGE-regions (colors), scaled by population (bubble sizes). The diagonal line indicates net self-sufficiency on a yearly basis.
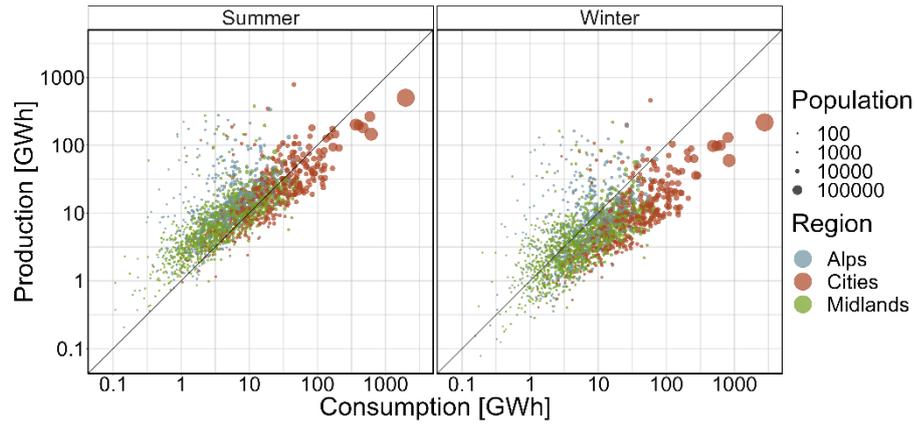
Figure 54. Biseasonal decentralized electricity production vs. consumption for all Swiss grouped into EDGE-regions (colors), scaled by population (bubble sizes), in summer and winter. The diagonal line indicates net self-sufficiency on a semi-annual basis. April to September is classified as summer, October to March as Winter.

Figure 55. Seasonal decentralized electricity production vs. consumption for all Swiss grouped into EDGE-regions (colors), scaled by population (bubble sizes), in all meteorological seasons. The diagonal line indicates net self-sufficiency on a seasonal basis.
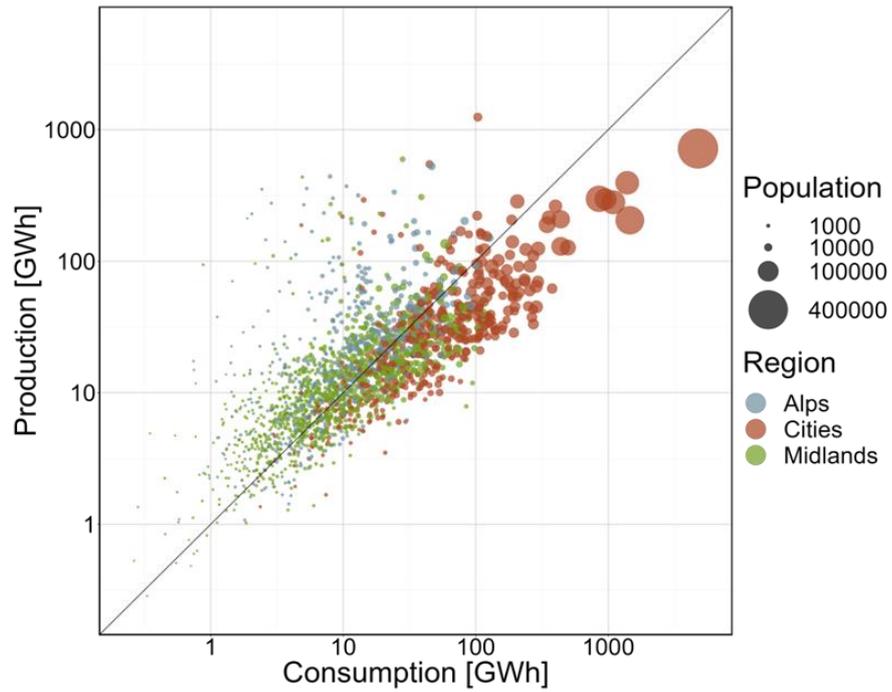
Figure 56. Monthly decentralized electricity production vs. consumption for all Swiss municipalities, grouped into EDGE-regions (colors), scaled by population (bubble sizes). The diagonal line indicates net self-sufficiency on a monthly basis.
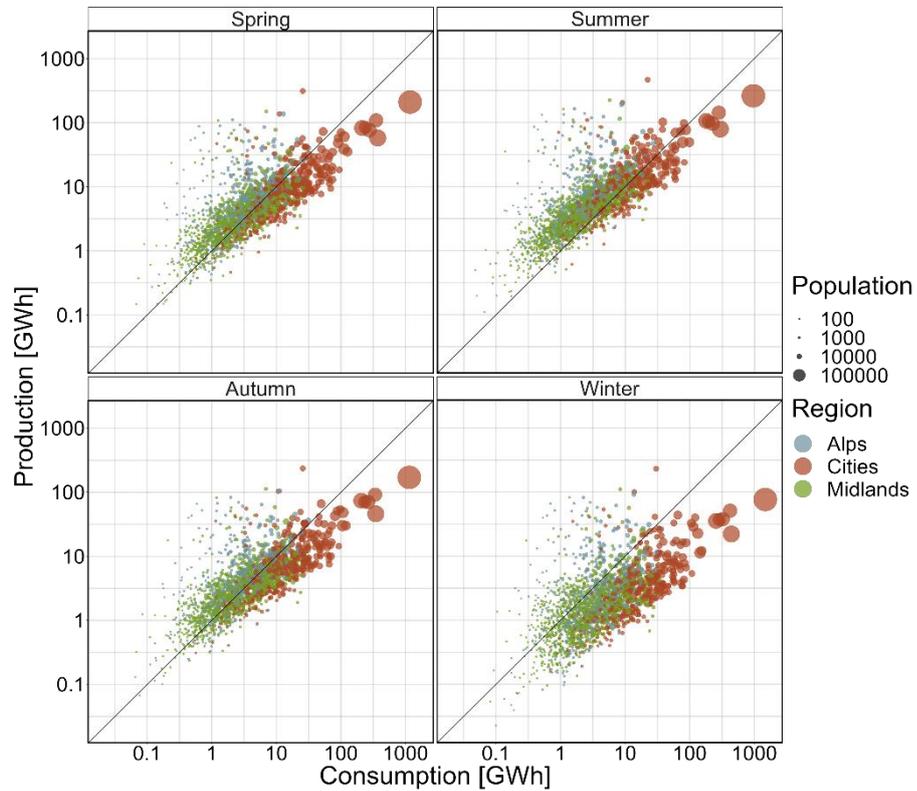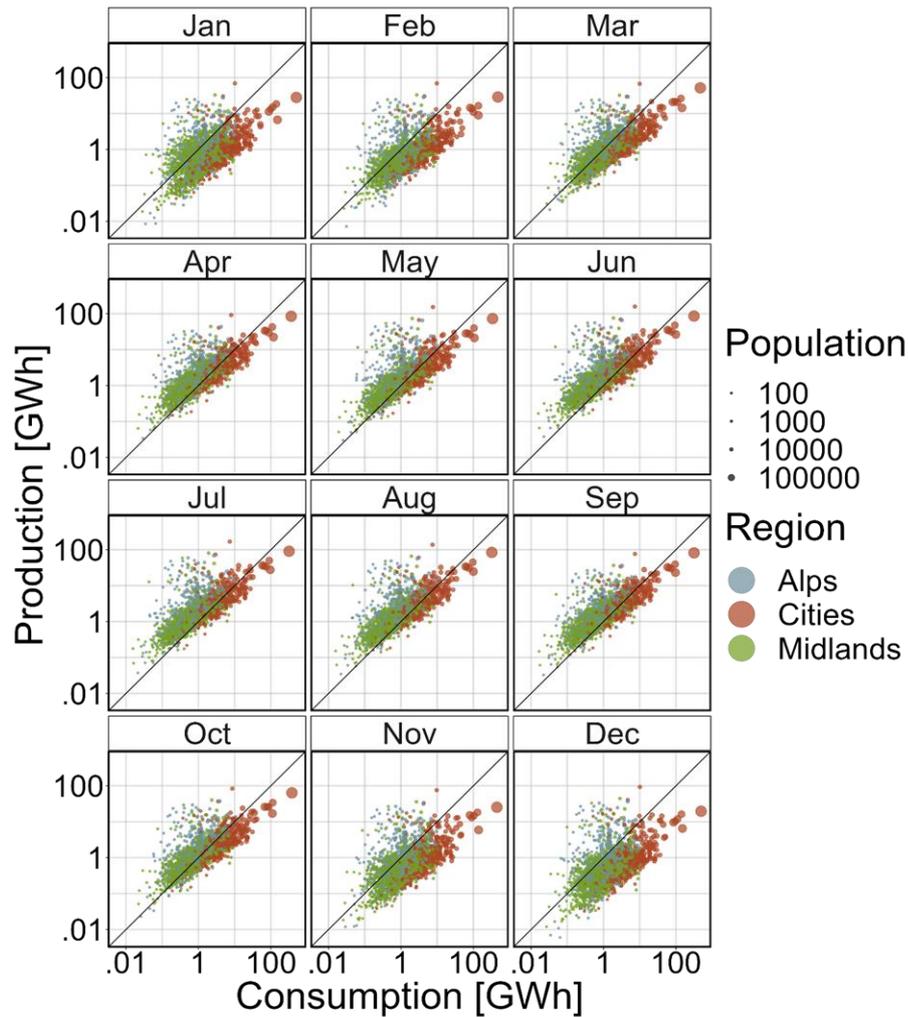
Over a given time period, self-sufficiency can be defined as the ratio between cumulative decentralized production and consumption, with a ratio of 1 being net self-sufficient given energy could be shifted within the time period in question. Obviously, a net self-sufficiency of 1 over a certain period does not exclude the possibility of situations with excess consumption within that timeframe. Figure 57 shows the net self-sufficiency on an annual basis for all Swiss municipalities. Note that values above 2 are not shown for illustrative purposes – with some alpine municipalities reaching values of 100 and higher. A clear trend is visible where alpine municipalities tend to have a significantly higher net self-sufficiency, in general. This can also be observed when comparing annual net self-sufficiency with population density, which is shown in Figure 58. Figure 59 shows the net self-sufficiency of all municipalities for all meteorological seasons. Figure 60 shows the monthly net self-sufficiency for all municipalities.

Figure 61 shows the absolute excess and deficit of decentralized production for the nine regions shown in Figure 49, as the summation of all excess/deficit situations within summer/winter. This data was generated using the native 15-minute intervals used throughout this study. While downsampling to 1-hour intervals yielded no significant change in results, using a 1-day interval clearly decreases both excess and deficits in each region, as intra-day fluctuations are smoothed out considerably. Note that similarly large values of excess and deficit indicate a net self-sufficiency, with fluctuations roughly proportional to excess/deficit values.
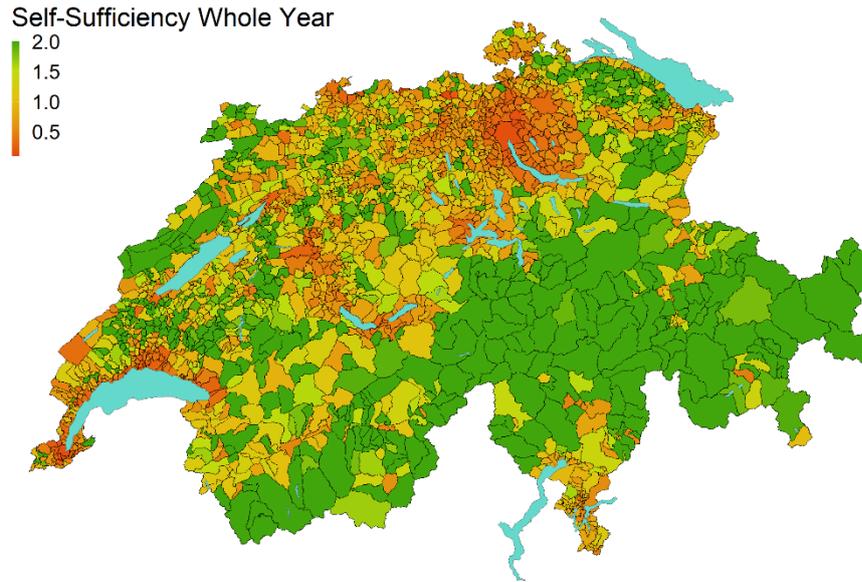
Figure 57. Net self-sufficiency on an annual basis for all Swiss municipalities as the ratio of annual production to annual consumption. Note that values above 2 are not shown – with some alpine municipalities reaching values of 100 and more.
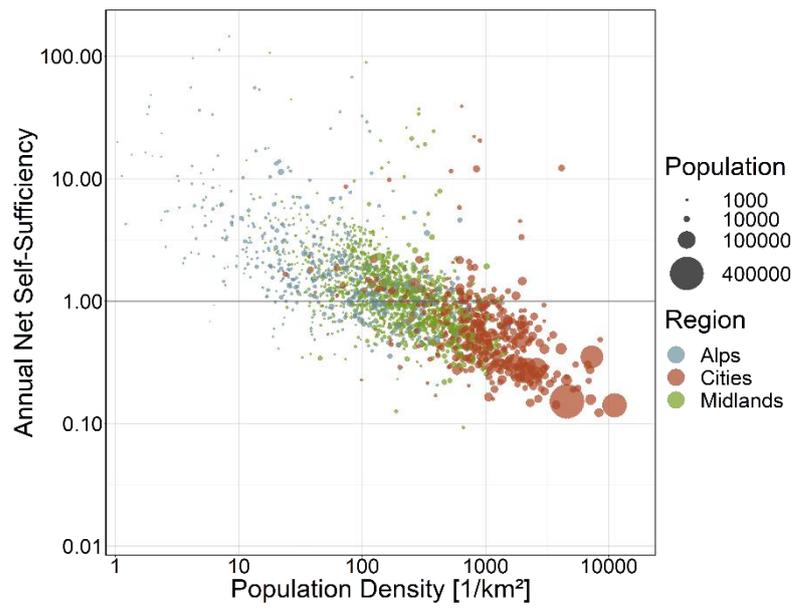
Figure 58. Annual net self-sufficiency versus population density for all Swiss Municipalities, grouped by EDGE region, scaled by population (bubble size).
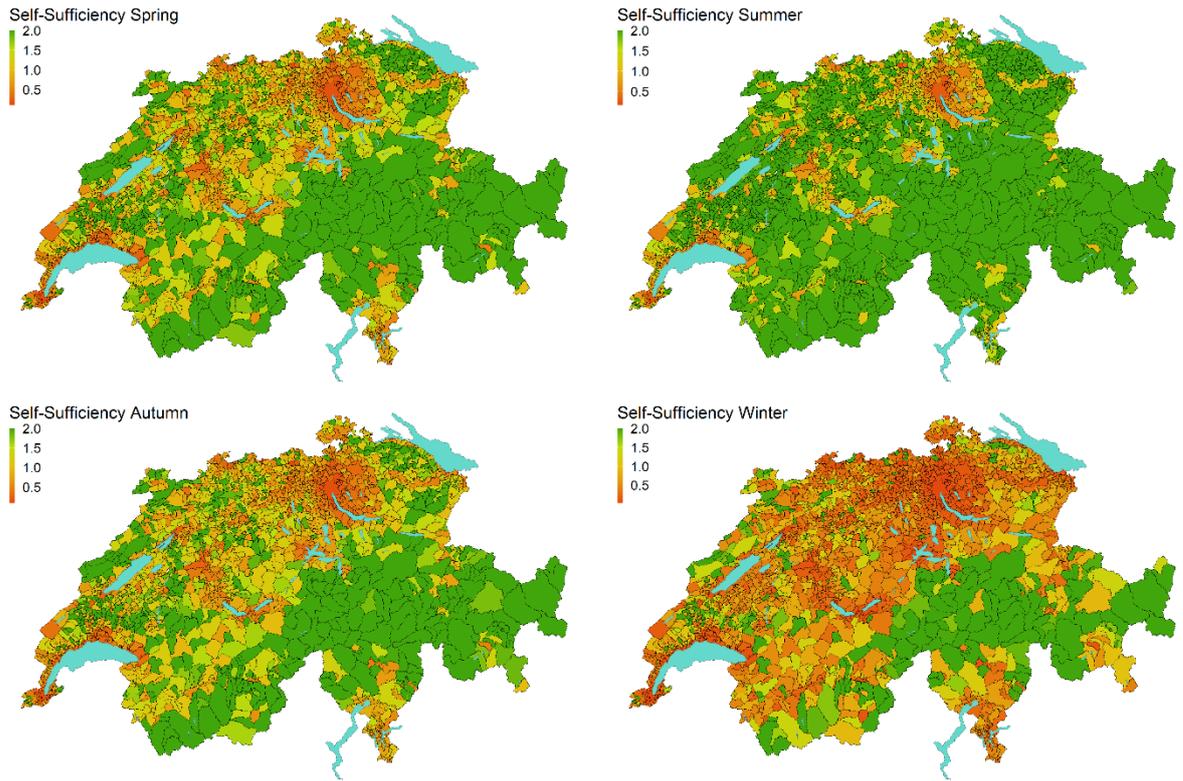
Figure 59. Self-sufficiency of each municipality (defined as ratio between production and consumption) in each meteorological Season. Note that values larger than two are not displayed as such.
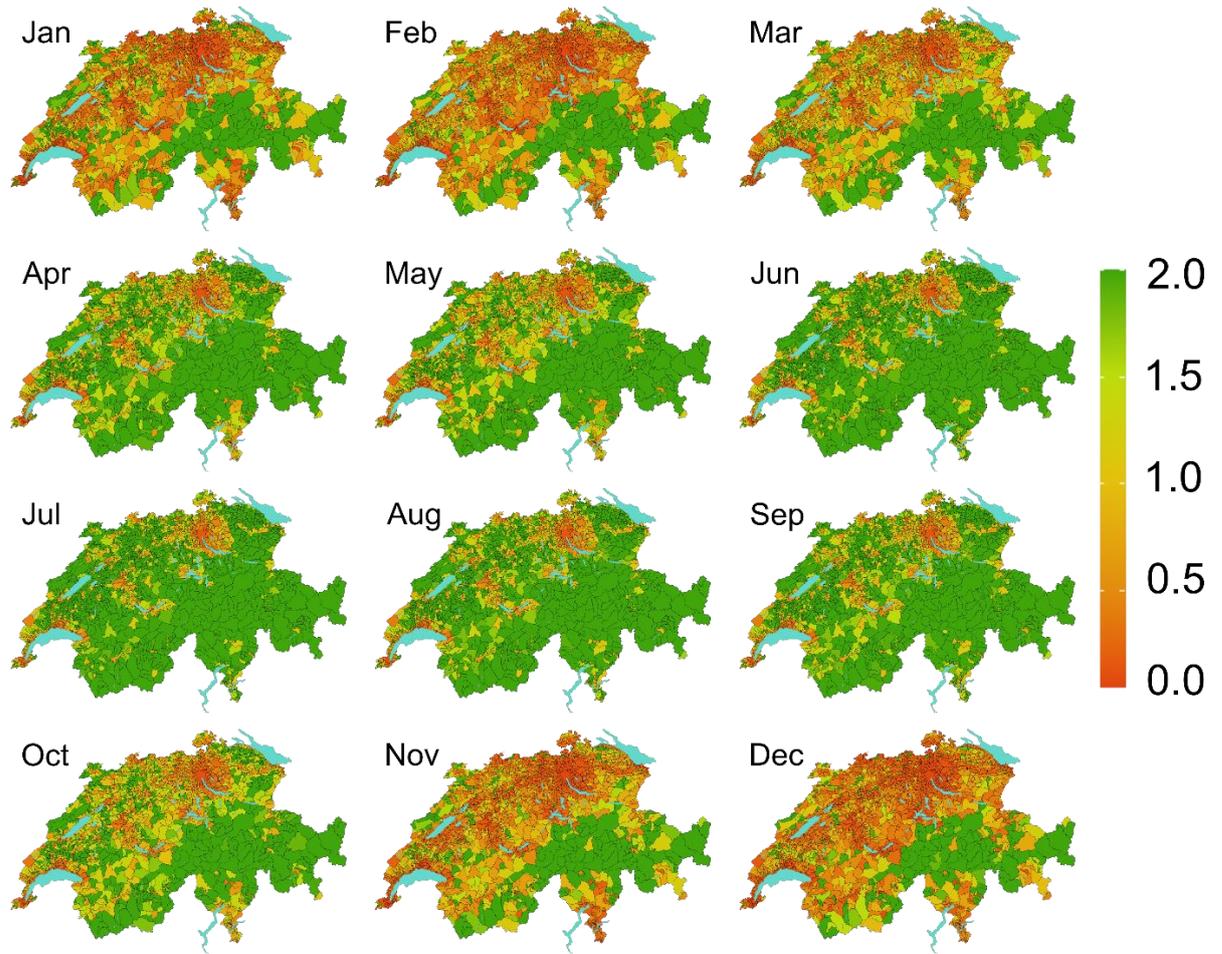
Figure 60. Self-sufficiency of each municipality (defined as ratio between production and consumption) for each month. Note that values larger than two are not displayed as such.
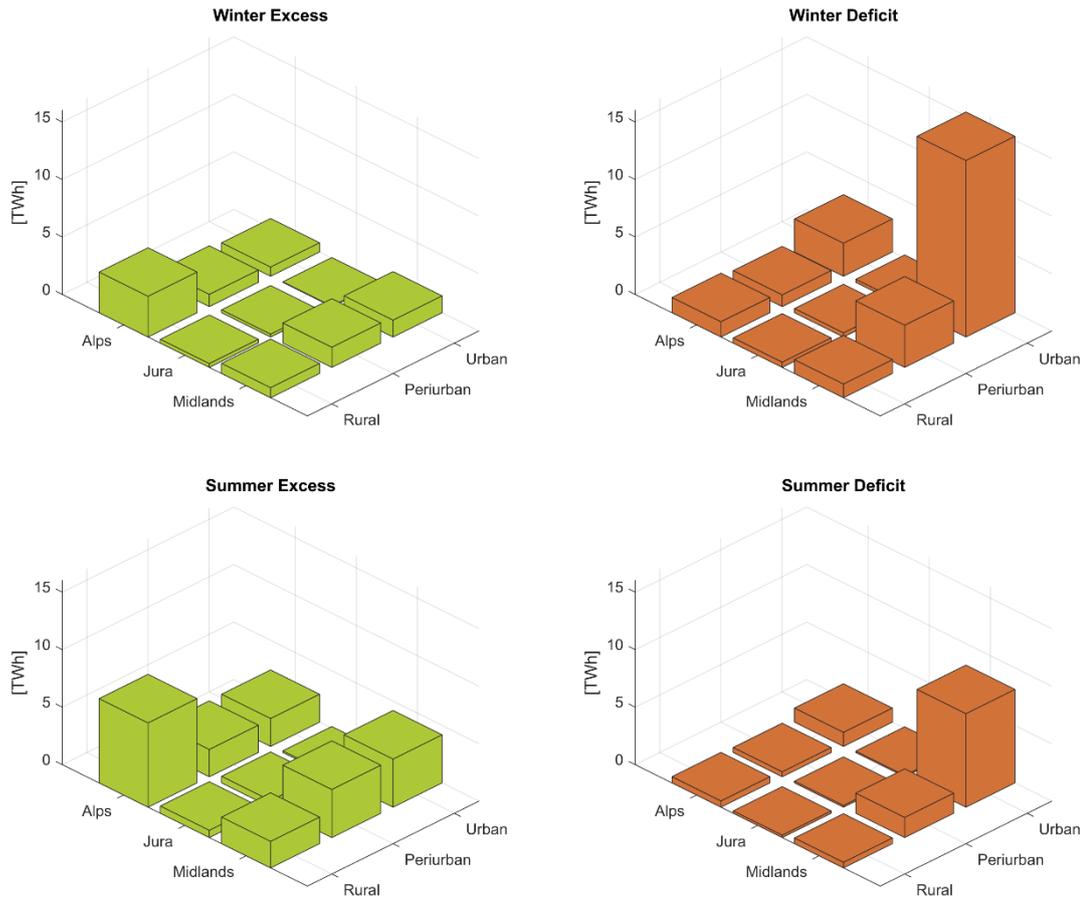
Figure 61. Total absolute excess and deficit in decentralized electricity production relative to consumption in winter and summer half years. Data obtained as summation of timeseries with 15-minute time steps. Region definitions are according to Table 3.

3.3   Limitations and Future Improvements

Data acquisition and processing relies on the availability of data with high quality and fidelity. There are instances in which the best-available datasets are clearly incomplete or out of date. Further, some assumptions of varying severity were made while processing said data. It is therefore important to address and discuss the existing limitations, with possible future improvements, where possible. The following is an unsorted list of such limitations.

Whenever spatial disaggregation included the partial fullfilling of a distributed potential, equal shares of realized potential were assumed. This does not consider possibly differing profitability of various disjointed potentials, where one could assume a realization of the most profitable potentials before others.

The target value for infrastructure PV (7'196 GWh) calculated by weighing the total PV target in EP2050+ (33'611 GWh) with the values found in the study by Meteotest and Swissolar [2] can be deemed very optimistic. A recent study focusing on infrastructure PV solely finds a realistic potential of 1.5-3.0 GW installed capacity, resulting in 1.5-3.0 TWh annual production under normal circumstances [18]. In addition to ongoing work in the area of infrastructure PV potentials in our research group, the findings of a promising meta-study[31] will be considered in future iterations of the model.

---

[31] C. Bucher, M. Hügi, N. Wyrsch, C. Ballif, «*Report PV-Potential CH*», unpublished.

For calculation of the production timeseries of façade PV, a custom, time-dependent (implicitly sun position-dependent) correction function was used to account for the differences in angles of incidence, which was subsequently used with the values found by Bucher & Schwarz [9] for rooftop PV. However, the provided dataset includes, in addition to the here utilized profiles aggregated on a municipal-level, timeseries specific for façade PV and different tilts and orientations of rooftop PV. These specific profiles will be used in the next iteration.

Better accuracy will be achieved for PV production timeseries by the usage of more detailed existing data and by potentially considering more measurement data that is made available. In this report, the profiles for rooftop PV include a certain share of façade systems, while the basis for the profiles for façade systems consist to a large degree of rooftop profiles, which are adjusted for tilt angles. Data on the municipality level with a clear distinction between rooftop and façade PV systems are available and will be employed for the next part of this study [9].

The potential disaggregation of alpine PV is based on a study which was conducted when the laws for (previously illegal) alpine PV installations were not yet finalized. The preliminary state of parliamentary discussions on subsidy schemes and legal requirements for alpine PV therefore had to be used for the study [11]. At the present day, these laws and the detailed regulations are not finalized but it is likely that certain rules will only be applied to a fast-track subsidy scheme. Namely the lower threshold of 10 GWh/a per system applied for the fast-track subsidy scheme might be reduced for long-term regulations. Such changes have an impact on the spatial distribution of the long-term potential of alpine PV.

Modelling of the general (spatial) load distribution used the available annual consumption of 504 out of the 2148 Swiss municipalities. Unfortunately, electricity consumption data is only available in some cantons. The available data clearly shows that electricity demand is often significantly influenced by a single, large consumer. The use of FTE's of the service and industrial sector as a regressor in modelling was able to partly capture this effect, but the very nature of the heterogeneous distribution of these consumers means that it is very difficult to predict the annual electricity consumption of a municipality. Adding to this, while households and the service industry yield a predictable load curve in large numbers, industrial consumers can exhibit very distinct consumption patterns. The assumption of cantonal load curves imparts a correlation of electricity consumption in associated municipalities, even if such a correlation doesn't necessarily exist. The cantonal load curves can also be augmented in a next step by isolating and subtracting existing (partially known) loads of EV's, heat pumps, and pumped hydro.

The relative heating demand of a municipality was modelled as being proportional to the total building area, for lack of better information. The future distribution of heating systems was assumed to reflect the ratios given in EP2050+ for residential buildings. While existing infrastructure (such as district heating networks) was taken into account, the distribution of additional renewable heating systems is assumed to be proportional to the share of fossil heating systems within each municipality. This does obviously not account for existing infrastructure and any other regional differences.

Modelling of the heat demand is limited to space heating, i.e. all demands for hot water are neglected. Obviously, this simplification increases the modelled relative demand in colder periods. Further, modelling the heating demand proportional to instantaneous heating degrees (difference of outside air temperature to desired room temperature) is a strong simplification that does not take into account any thermal inertia and neglects any other non-linear effects.

For this analysis, only decentralized producers and consumers were considered. The distinction between centralized and decentralized entities is not always unambiguous. Clear examples of this problem are the inclusion of waste-to-energy plants, running hydro plants of any size, wind, and alpine PV. In a future improvement, consumers and producers are categorized as to their power grid level connection, with any infrastructure connected to levels 1-3 (national – transregional) being omitted. A

dataset describing the Swiss transmission network (>36kV) is scheduled to be released by June 2023[32], which could provide a clearer distinction.

There are multiple categories of production and consumption that are dependent on weather in some form – from all PV generation curves, wind power generation, to the heating demand, to running hydro production (to some extent). While the datasets used to generate municipal curves are consistent and correlated within each category (i.e. neighbouring municipalities experience correlated weather), they are not correlated amongst categories. The impact of this issue is hard to quantify, but should clearly lessen with longer timeframes, as seasonal variations are correlated amongst all datasets. The current model includes data of one year and for most categories with the weather from the reference year of 2018. It would be a potential future improvement to consider several years with different weather.

In several categories more detailed calculations of the overall Swiss potential and its spatial distribution are currently under developments. This is namely the case for official targets, overall potentials, and their spatial distribution of wind power. The disaggregation dataset used for this report is most likely going to be replaced with more up-to-date data for the next report.

The temporal disaggregation assumes CH-wide uniform production or consumption within several categories, such as running hydro. Although this is not necessarily realistic, the impact of this assumption on the findings of the future analysis are not clear. Within this context, a sensitivity analysis should be conducted across several input variables.

For all categories, verification checks are in place to ensure the consistency of the results, e.g. comparison of the sum of all municipal timeseries with the absolute target value. However, validation of results is a much more open question, inherently being an issue when modelling future developments. A clear path is cross-validation with other models, especially within the EDGE project.

---

[32] Personal conversation with Nico Rohrbach (Geoinformation, BfE)

4   Conclusion

To characterize the need for energy shifting (and/or mitigation/adaption), a production and consumption timeseries of all decentralized sources and sinks of electricity has been produced for each Swiss municipality with a top-down model, considering the portfolio values given in the Energieperspektiven 2050+, scenario ZERO Basis. Starting from both a spatial distribution of annual production/consumption and a relative timeseries per municipality, a 15-minute interval timeseries of relative values was generated for each considered category. This allows a simple scaling with scenario values to find an absolute value timeseries per category and per municipality. Subtracting local consumption from the local production yields a delta timeseries with times of excess and deficit power that can be further analyzed. A detailed analysis of each delta timeseries by municipality to determine suitable energy shifting technologies is going to be conducted in the context of two subsequent reports on the subject. As preliminary results, it can be observed that cities have a deficit in decentralized electricity, alpine municipalities have an excess thereof, and midlands municipalities are inbetween those, with a trend towards deficits. This observation is very much dependent on the timeframe being chosen. Looking only at net self-sufficiency rates in January, our analysis suggests that most municipalities in Switzerland are not self-sufficient on a local level – with the notable exception of mostly alpine municipalities. A similar analysis in July shows that most municipalities are net self-sufficient (on a monthly basis), the exception being a sizeable fraction of the cities. While the demand side of the equation can be assumed to be given subject to DSM, the assumption that all potentials for decentralized production are realized equally is at least questionable. It is certainly realistic that (either through direct planning or incentivization) decentralized producers will be rolled out in such a way as to match local demand as closely as possible – and that regional differences will be pronounced, owed to the federalistic nature of Switzerland.

The temporal and spatial resolution of the presented analysis posesses a high degree of detail, particularly when considering their combined application across the entirety of Switzerland. This is important for two reasons: Firstly, the presented study focuses on decentralized renewable energy systems, which necessitates a detailed spatial resolution. The municipal boundaries have been selected as the defining units for decentralization, given that they generally outline the limits of local electricity distribution networks. Secondly, energy storage, PtX, curtailment, and DSM as energy shifting strategies primarily influence the temporal profile of electricity generation and load. To properly analyze the role of these technologies, it is essential to understand the requirements for energy shifting based on an analysis with sufficiently high temporal resolution. A 15-minute timestep was chosen, as this resolution allows for a meaningful analysis of intraday processes, with data availability being given on that resolution. The present report documents how the necessary model basis to analyze energy shifting approaches in a decentralized manner was created. The two subsequent reports on the role of storage, PtX, curtailment, and DSM in the context of the EDGE-project will be based on this data basis for further analysis. From the combinations of localized power values and the quantity of energy to be shifted, as well as the time duration of the energy shift, suitable technologies for energy shifting will be deduced.

In addition to focusing on decentralized and renewable energy systems, a central aspect of EDGE's research approach involves applying the methodologies with respect to the varied regional characteristics of Switzerland, namely three regions defined within EDGE representing the Alps, Cities, and Midlands. Each of these regions presents unique conditions, which significantly influence both the potential for energy production and the nature of energy consumption. The regional specificity extends to a range of factors, including geographical, climatic, infrastructure and socio-economic conditions, each of which can impact the generation potential of renewable resources and the composition of energy consumption in diverse ways. Regional affiliations of municipalities were therefore considered for aggregated analyses. Recognizing and understanding these individual regional conditions is imperative for a comprehensive and nuanced analysis of the role of storage, PtX, curtailment, and DSM in Switzerland's energy landscape within the scope of EDGE's work.

5 References

[1] "Energieperspektiven 2050+ - Technischer Bericht," Swiss Federal Office of Energy, Technical Report, December 2021.

[2] J. Remund, S. Albrecht, and D. Stickelberger, "Das Schweizer PV-Potenzial basierend auf jedem Gebäude".

[3] M. Jäger *et al.*, "Machbarkeitsstudie Agri-Photovoltaik in der Schweizer Landwirtschaft," ZHAW, Sep. 2022.

[4] D. Heiz, "Erstellung und Auswertung repräsentativer Mobilitäts- und Ladeprofile für Elektrofahrzeuge in Deutschland," Karlsruher Institut für Technologie, Working Paper, October 2018.

[5] "Electric and Hydrogen Mobility Scenarios Switzerland 2022," EBP, May 2022.

[6] S. Rosser, L. Lanz, and P. de Haan, "Verständnis Ladeinfrastruktur 2050 - Wie lädt die Schweiz in Zukunft?," Swiss Federal Office of Energy, May 2023.

[7] A. Vossebein, S. Muster, U. Betschart, and B. Kölliker, "Potential Demand Side Managemente in der Schweiz," Swiss Federal Office of Energy, October 2019.

[8] D. Anderegg, S. Strebel, and J. Rohrer, "Photovoltaik Potenzial auf Dachflächen in der Schweiz - Synthese aus Sonnendach.ch und einer repräsentativen Stichprobe an Dachbelegungen.," ZHAW Zürcher Hochschule für Angewandte Wissenschaften, IUNR Institut für Umwelt und Natürliche Ressourcen, July 2022. doi: 11475/25310

[9] C. Bucher and R. Schwarz, "Studie Winterstrom Schweiz - Was kann die heimische Photovoltaik beitragen?," EnergieSchweiz, Swiss Federal Office of Energy, January 2021.

[10] D. Anderegg, B. Putzi, S. Strebel, and J. Rohrer, "(Winter) Photovoltaik-Potenzial im Kanton Glarus," April 2021, doi: 10.21256/zhaw-22412.

[11] D. De Ferrars, "The role of solar photovoltaics in the Alps for the Swiss electricity system." ETH Zurich, April 2023. Accessed: May 30, 2023. doi: 20.500.11850/610172

[12] D. Anderegg, S. Strebel, and J. Rohrer, "Messergebnisse Juni 2018 bis Mai 2019 Versuchsanlage Totalp." Forschungsgruppe Erneuerbare Energien, IUNR Institut für Umwelt und Natürliche Ressourcen, ZHAW, Wädenswil, November 2019.

[13] O. Thees, V. Burg, M. Erni, G. Bowman, and R. Lemm, "Biomassenpotenziale der Schweiz für die energetische Nutzung" Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft WSL, Birmensdorf, 2017.

[14] "Energie aus Biomasse - Weil in organischen Abfällen und Holz viel drin steckt," EnergieSchweiz, Swiss Federal Office of Energy, September 2017.

[15] A. Siegrist, G. Bowman, and V. Burg, "Energy generation potentials from agricultural residues: The influence of techno-spatial restrictions on biomethane, electricity, and heat production," *Appl. Energy*, vol. 327, p. 120075, 2022, doi: 10.1016/j.apenergy.2022.120075.

[16] G. Bowman, J. Schweier, V. Burg, H. Madi, and T. Schildhauer, "Report with the results on small-scale biogas systems and on combined biomass and solar energy," Swiss Federal Office of Energy, November 2022.

[17] M. Lehning *et al.*, "Annual Report 2022 - SWEET Call 1-2020 – SWEET EDGE," Annual Project Report, Jun. 2022. Accessed: May 30, 2023. [Online]. Available: https://www.aramis.admin.ch/Default?DocumentID=69649

[18] L. Grüter, S. Probst, and L. Konersmann, "Solarstrom auf Infrastrukturanlagen und Konversionsflächen," Energie Zukunft Schweiz, July 2021.