Schweizerische Eidgenossenschaft
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Federal Department of the Environment, Transport, Energy and Communications DETEC

Swiss Federal Office of Energy SFOE
Energy Research and Cleantech

SWEET Call 1-2020: EDGE

Deliverable report

Deliverable n°	2.4
Deliverable name	Techno-economic realization of energy balancing with batteries, power-to-x, and demand-side management
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Delivery date	May 2024

The research published in this report was carried out with the support of the Swiss Federal Office of Energy SFOE as part of the SWEET EDGE project. The authors bear sole responsibility for the conclusions and the results.

sweet swiss energy research for the energy transition

Contents

Summary

This report builds on the learnings and data generated in deliverable report D1.2, “Need for energy balancing by region for renewable energy system scenarios of Switzerland”. The data basis consists of year-long 15-minute-resolution time series for each Swiss municipality in a decarbonised electricity supply scenario, with explicit modelling of each production and consumption category specified in the Energy Perspectives 2050+ published by the Swiss Federal Office of Energy. In this report, the data basis has been updated, extended, and improved. Notably, 148 additional observations of municipal electricity consumption helped to refine the model to determine the electricity consumption of all Swiss municipalities. Further, a new dataset containing all Swiss transmission grid infrastructure became available, which was used to make an informed distinction between centralized and decentralized running hydro power plants. As only decentralized production (and consumption) is to be considered, this alleviates some of the methodological issues presented in the previous report. Other improvements include more precise estimation of PV rooftop and façade generation time series based on the specific distribution of roof and façade orientations in each municipality.

Given this baseline of decentralized production and consumption time series in each Swiss municipality, the necessary increase in grid connection capacity is estimated as a measure of the potential cost associated with this transition. Two counteracting measures are then investigated: First, different levels of PV curtailment are applied to reduce generation peaks. Two different curtailment strategies are discussed, and their energy loss / overbuilding need are assessed. Second, a numerical algorithm was developed to find the mathematically minimal storage size needed to reduce peak power flows over the municipal boundary by a defined amount.

The result of this analysis are necessary storage capacities in all Swiss municipalities, given a certain amount of PV curtailment as well as grid connection capacity increase reductions. This analysis is shown exemplary for one selected scenario. In the presented scenario, most municipalities’ storage needs could be met by batteries. Many municipalities need low-capacity storage, while a few would require significant amounts of storage, highlighting the importance of alternatives like grid expansion, curtailment, and demand-side management.

The results demonstrate how beneficial PV overbuilding and curtailment is for the generation profile in general. They also show how curtailment varies in applicability based on the specific circumstances of individual municipal energy systems. Alpine areas benefit significantly from curtailment due to high excess generation peaks, municipalities in the midlands exhibit a high variance in their situation, while urban areas, with strong grids and high loads, require less curtailment. Urban areas are demand-dominated and should maximize their decentralized generation expansion. They benefit from high consumption, strong grids, and a high density of other potential measures to facilitate the integration of decentralized renewable generation.

To find cost-optimal combinations of curtailment, grid expansion, demand-side management, and storage (or generally energy-shifting measures), costs have to be assigned, which will differ by municipality especially in the case of grid connection. Since this techno-economic analysis is the focus of the third and last report in this series, no aggregated results or comparisons in this regard are shown in this report, such as not to facilitate misguided conclusions.

List of abbreviations

CAES	Compressed Air Energy Storage
DSM	Demand Side Management
EP 2050+	Energy Perspectives 2050+ (“Energieperspektiven 2050+”)
EV	Electric Vehicles
PtX	Power-to-X
PV	Photovoltaics
SFOE	Swiss Federal Office of Energy
SNG	Synthetic Natural Gas
WtE	Waste-to-Energy

1 Introduction and Data Basis Update

This is the second report in a series of three, together detailing the analysis of energy shifting needs in a fully decarbonised Swiss electricity system. While the first report (Deliverable report D1.2 [1]) was concerned with establishing the data basis necessary to address this problem, the present report aims at utilizing the produced municipal-level production and consumption timeseries in order to assess the need and characteristics for energy shifting, in general.

As described in section 3.3 of deliverable report D1.2 [1], there is ample opportunity to improve upon the underlying data. Section 1.2 is comprised of descriptions of updates or expansion of the underlying data basis or improvements in data processing. Wherever the “last report” is mentioned, we refer to this one.

1.1 Objective and Scope

Given yearly electricity consumption and generation timeseries for each municipality of Switzerland in the decarbonized scenario ZERO Basis of the Energy Perspectives 2050+ (EP 2050+) [2], it is the objective of this report to determine the amount and the detailed characteristics of the need for energy shifting on the level of individual municipalities in Switzerland. The amounts of energy to shift and the characteristic of the shifting in terms of necessary power values and storage durations are the basis for conclusions on which technologies and approaches could be used. In contrast to many other analyses of the subject the data basis is of high resolution both on the temporal and on the spatial dimension. Another objective is to identify situational differences of municipalities depending on their urbanization level and location. It is within the scope of this report to identify the technical aspects of the need for energy shifting. Possible approaches to shift and balance energy are storage, power-to-x (PtX), curtailment, and demand side management (DSM), of which demand side management will be more in focus in the third report. Detailed techno-economic analyses are not going to be part of this report but will be the focus of the third report in this series (Deliverable report D3.9, scheduled finalization in May 2025).

1.2 Data Basis Improvements

For a number of generation and consumption categories, the data basis was improved in comparison to the last report. For consistency reasons, all major points noted in section 3.3 of deliverable report D1.2 are adressed here, even if no improvement was achieved – though in most cases, significant developments could be made.

1.2.1 Equal Potential Distribution

The spatial distribution of future generation and consumption based on potentials calculated for each municipality was always distributed equally. This of course does not necessarily reflect reality, as more profitable potentials are more likely to be realized first, and technologies that are not really granular will be more concentrated – e.g. while it is certainly thinkable that all swiss municipalities install PV according to their relative potentials, not every municipality will have a small biogas plant, since aggregation on a regional scale is more economical. Unfortunately, it is practically impossible to ascertain where these potentials will be realized. The impact could best be studied using stochastic methods, but even in that case, assumptions will have to be made with regards to how consolidated certain potentials will be realized.

It is important to note that a large share of generation categories are not or insignificantly affected by this phenomenon. The largest error is accrued in categories with naturally rather large power plants, which are not necessarily being labelled as decentralized, such as waste-to-energy, biogas, alpine PV, and to a lesser degree agri-PV. Referring to the scenario values given in Table 1, these categories do not constitute the majority of power generated, and as such the impact is deemed to be quite limited – which is not to say that there are specific interpretations of results that can be affected.

1.2.2 Target Value Infrastructure PV

The scenario values at the top level of power generation and consumption used in this study are listed in Table 1. As in Deliverable Report 1.2 [1], they are based on the scenario ZERO Basis from EP 2050+ [2] but with updated values to the more granular values for inidividual PV applications. The updates are the result of more up-to-date and in-depth potential assessments becoming available.

Rooftop PV is assumed to be dominant because of favorable techno-economic conditions, close proximity to electricity consumption, few problems in terms of land-use conflicts and visual impact, and considerably underutilized potential (our scenario includes 23 TWh of yearly energy by rooftop PV, as given in Table 1, compared to potential estimations of 54 TWh [3]). PV on façades also features a considerable potential of 17 TWh [4], however, typical rooftop projects are more economic than façade PV.

The assessment of the potential of infrastructure-PV as a category largely depends on what applications of PV are seen as part of it. Nevertheless, it can be stated that studies published within the last two years show that the PV potential of two of its core subcategories, along roads and above car parkings, might be lower than previously estimated and often perform worse economically compared to e.g. rooftops [5] [6]. PV potentials on water bodies are purposely not included in the infrastructure PV category, as such solutions are rather speculative at this point. The utilized target value for infrastructure PV was therefore lowered from 7196 GWh to 2241 GWh (see Table 1).

Alpine PV projects receive state funding based on Art. 71a of the “Energiegesetz” [7]. Special incentives are granted up until a CH-wide production of 2 TWh/a is reached. In addition, there is the legally binding target of 35 TWh of new renewables (without hydropower generation) until the year 2035, which is part of the “Bundesgesetz über eine sichere Stromversorgung mit erneuerbaren Energien” from 2024 [8]. It is to be expected that this ambitious expansion target leads to further incentives that facilitate the realization of alpine PV projects, mainly because each project features substantial electricity generation with a fairly high share thereof being produced in winter, when electricity in Switzerland is a scarce resource.

Table 1. Annual production and consumption scenario values used throughout this study. Used values correspond to scenario ZERO Basis found in the EP 2050+, including a more granular categorisation of photovoltaic generation. The scenario settings are taken from deliverable report D1.2 [1], while subcategories of PV are updated to take into consideration newly published findings on these potentials (values used in the previous report are within brackets).

Production	**Scenario Value [GWh]** (*value in D1.2*)	**Consumption**	**Scenario Value [GWh]**
PV cumulative, of which:	33’611	General Load	41’094
Rooftop PV	23’156 (*16’282*)	Electromobility	13’145
Façade PV	2’241 (*5’731*)	Heatpumps	9’008
Infrastructure PV	2’241 (*7’196*)		
Alpine PV	3’735 (*2’305*)		
Agri-PV	2’241 (*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

Agrivoltaics, also referred to as Agri-PV, features a tremendous technical potential of several hundred Terawatt hours annually in Switzerland [9]. As the main hurdles to realizing this technical potential are political and societal, it is very difficult to predict at this point the actual significance of this technology. Still, the vast potential indicates that realizing an installed rated power on the order of several Gigawatts should be attainable.

1.2.3 Façade and Roof PV Timeseries Improvements

In Deliverable report 1.2 [1] the distinction between the profile of rooftop- and façade-mounted PV timeseries did not originate directly from the underlying data source but was introduced with a heuristic data manipulation. While this approach yielded plausible profiles, there was room for improvements by directly making use of specific façade-PV profiles published in [10][1]. The dataset contains municipality-specific PV profiles for different categories of a combination of roof orientation and tilt. In each municipality, a weighted aggregation was performed considering the potential by roof categories, which were derived from the "Sonnendach" dataset [11]. Of all available reference profiles per municipality, the ones with a tilt angle of 90° were classified as façade-PV in line with the documentation of the dataset. The explicit differentiation in the PV profiles directly at the source especially improved profiles of municipalities with snow coverage of roofs in winter. In contrast to Deliverable report 1.2, snow coverage reduces the yield of rooftop-PV stronger, often down to zero for the whole municipality, while façade-PV does not suffer from a reduction in those circumstances (see the example of "Vals" in Figure 2 and Figure 4 for the distinction). On an aggregated level, this update leads to minor differences as shown in Figure 1 and Figure 3. On the municipality level, however, the difference in case of prolonged periods with snow cover can be substantial.

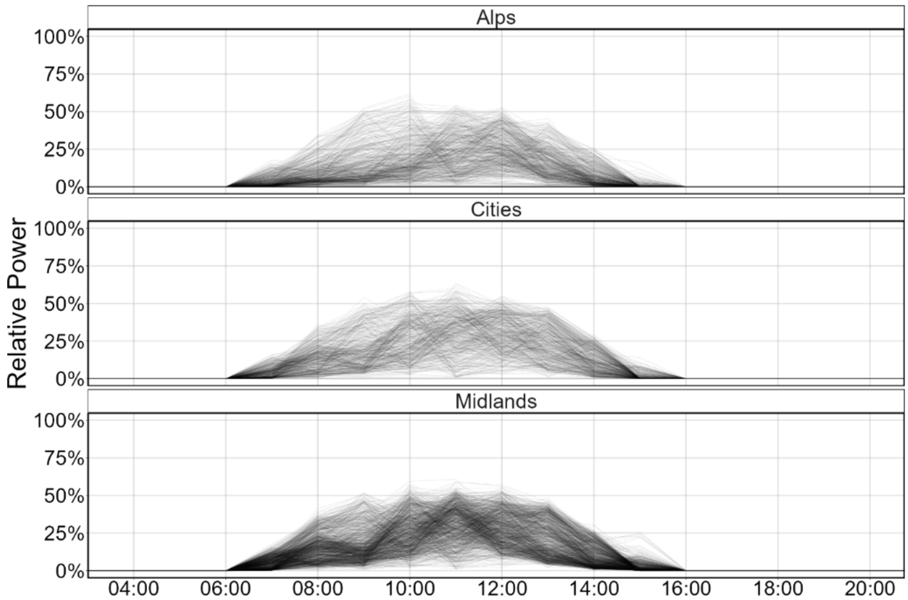

Figure 1. All municipal rooftop PV production profiles on December 1 (exemplary winter day) presented by EDGE-region with updated methodology in creation of profiles. Profiles feature a temporal resolution of 15 minutes and are scaled so that their maximal value over the course of one year equals 1. 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. Profiles are created by a municipality-specific weigthed aggregation based on rooftop categories present. Underlying data are sourced from: [10]

[1] Data source: https://opendata.swiss/de/dataset/studie-winterstrom-aus-photovoltaik-produktionsprofile-aller-schweizer-gemeinden

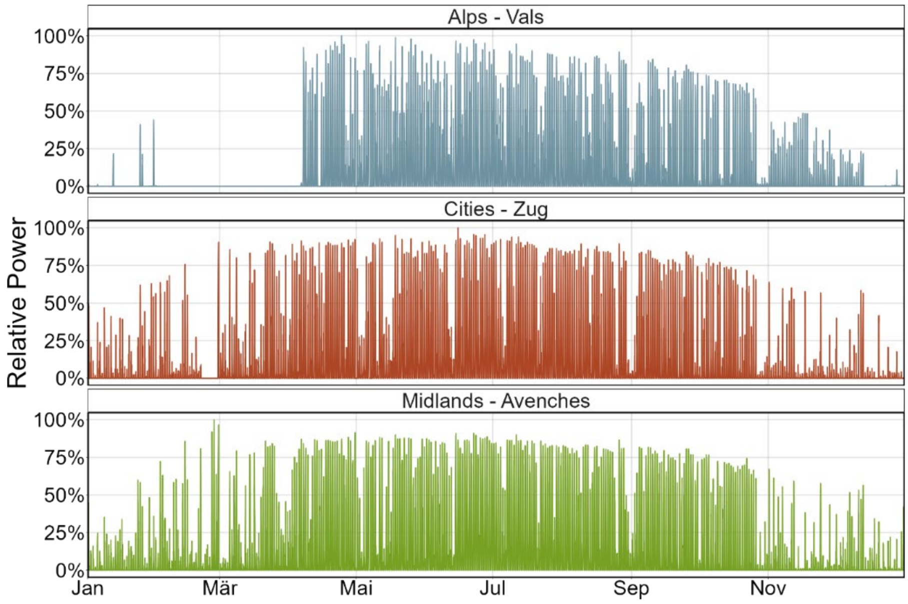

Figure 2. Yearly relative power generation profiles of rooftop PV of one exemplary municipality per EDGE-region with updated methodology. Profiles feature a temporal resolution of 15 minutes and are scaled so that their maximal value over the course of one year equals 1. Profiles are created by a municipality-specific weigthed aggregation based on rooftop categories present. Underlying data are sourced from: [10]

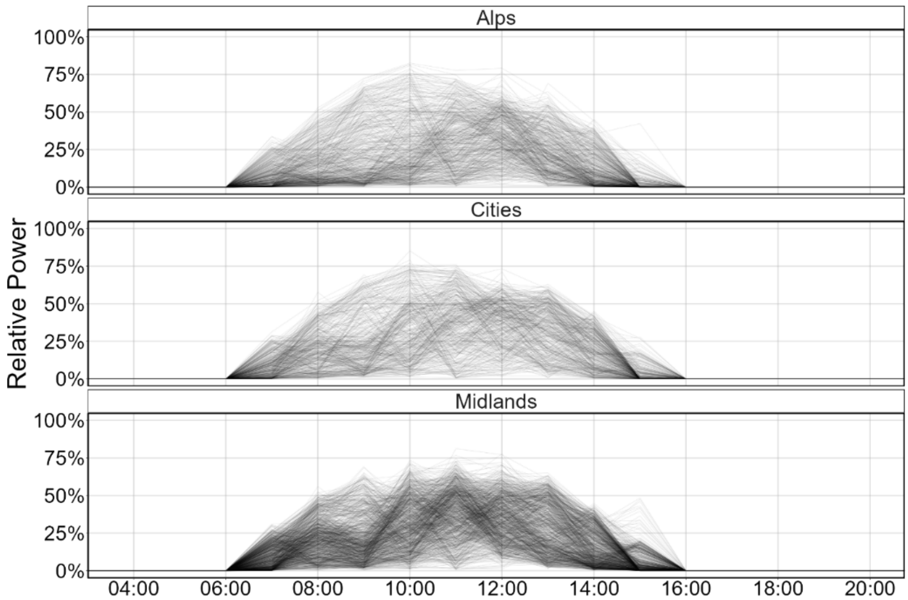

Figure 3. All municipal façade PV production profiles on December 1 (exemplary winter day) presented by EDGE-region with updated methodology in creation of profiles. Profiles feature a temporal resolution of 15 minutes and are scaled so that their maximal value over the course of one year equals 1. Used 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. Profiles are created by a municipality-specific weigthed aggregation based on rooftop categories present. Underlying data are sourced from: [10]

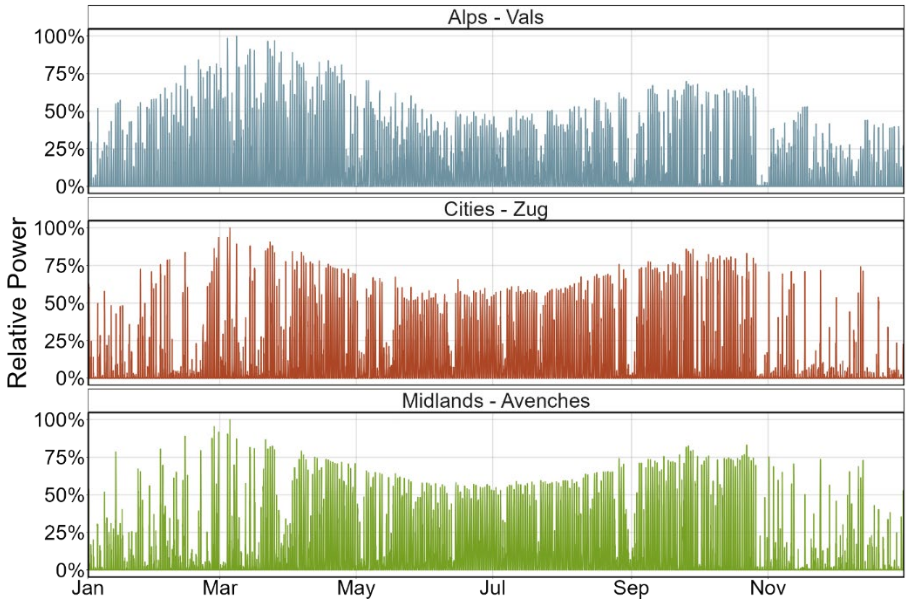

Figure 4. Yearly relative power generation profiles of façade PV of one exemplary municipality per EDGE-region with updated methodology. Profiles feature a temporal resolution of 15 minutes and are scaled so that their maximal value over the course of one year equals 1. Profiles are created by a municipality-specific weigthed aggregation based on façade categories present. Underlying data are sourced from: [10]

1.2.4 Rooftop-PV Potentials Data Update

The "Sonnendach" dataset, which is the underlying source for the spatial distribution of rooftop-PV, was updated to the newest publicated version[2] so that the efficiency of PV modules is homogeneously 20 %. Otherwise, the methodology remained identical. Figure 5 shows the newly calculated rooftop-PV potential for each municipality.

[2] Version published on 11. January 2023

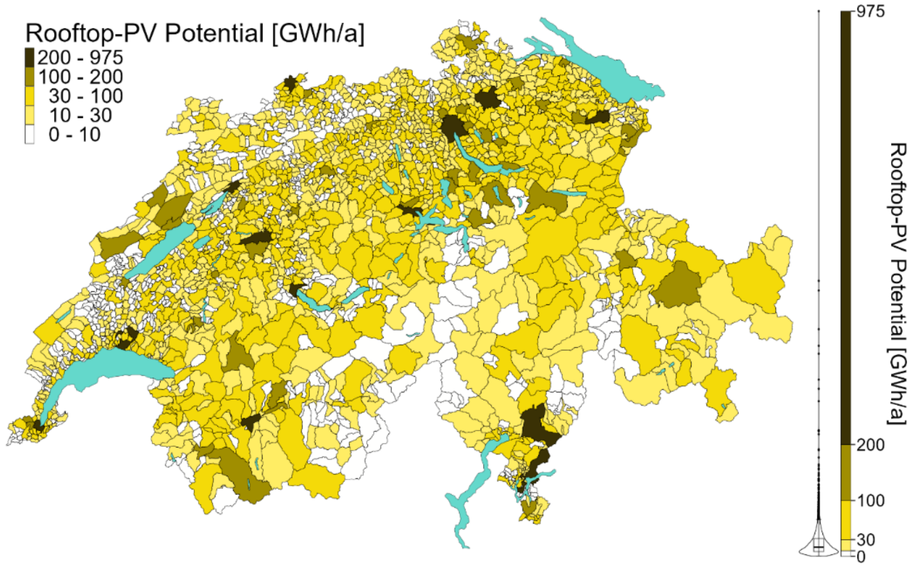

Figure 5. Spatial distribution of annual electric energy production potential by rooftop PV per municipality. Values were calculated applying the reduction factors for roof categories published in [8] to the "Sonnendach" database [11].

1.2.5 Modelling of General Load

A new source for general load data has become available in the form of the "Energie Reporter" by EnergieSchweiz[3]. The general load used throughout the last report was modelled based on known values (i.e. an official statistical value was publicly available). Please refer to section 2.2.1 of deliverable report D1.2 for a detailed description of the utilized methodology. For around 25% of Swiss municipalities, a value could be found, whereas the remaining values were determined by regression modelling utilizing population size and employment data. Given these newly available values, a comparison seems worthwile. Figure 6 shows a log-log comparison of both datasets, with an indication of the data source of the current estimate.

While in general, both datasets are in good agreement, there are examples of very signifiant deviations, not immediately obvious in the plot. Table 2 lists three examples each of municipalities with either significantly lower estimated demands than given in the Energie Reporter dataset, or significantly higher ones. For most municipalities showing large deviations it is fairly easy to identify one or more large industrial consumers that could plausibly explain the difference. Since large consumers (>100MWh/a) can freely buy their electricity on the open market, they are oftentimes not included in municipal statistics (although that is certainly not universal). As an example, the PSI in Villigen has a publicly known consumption of around 126 GWh/a, which corresponds to the value found in the official cantonal statistics provided by the canton of Aargau. Meanwhile, the Energie Reporter dataset lists the demand of Villigen as 15.5 GWh/a, which obviously does not include the consumption of the PSI. A similar situation can be found in Schafisheim, where a large distribution center by Coop is most likely not taken into account. The reverse can be found easily as well, e.g. in the municipality of Düdingen, where the Energie Reporter estimate is around 8 times higher than the one currently used. The large SIKA factory located in Düdingen ist the most probable cause for this difference. With the exception of Péry-La Heutte, all of the examples shown were listed in official, publicly available statistics. However, these statistics exclude large consumers at times, if values from the local electricity provider are being used, as it is not electricity sold by them. To complicate matters further, some of these statistics are published using modelled values too.

[3] https://www.energieschweiz.ch/tools/energiereporter/, data available via https://opendata.swiss/de/dataset/energie-reporter

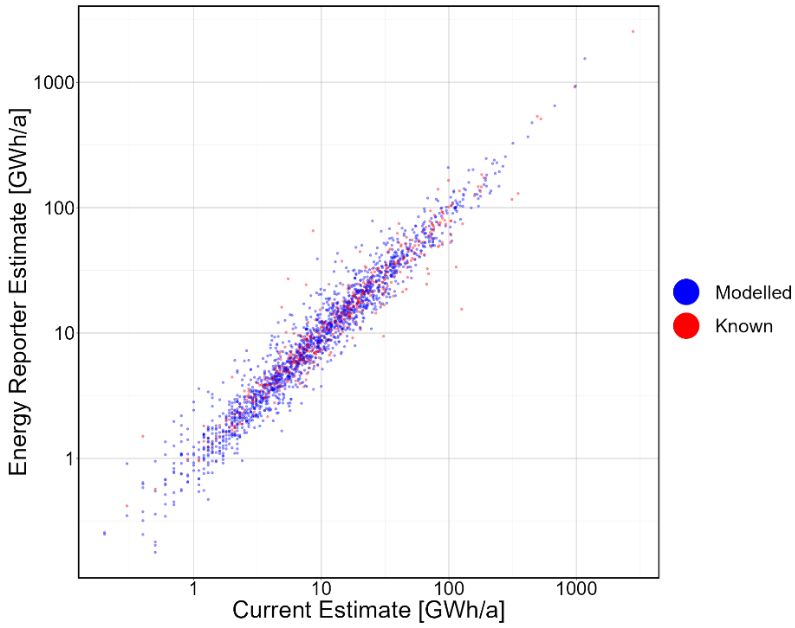

Figure 6. Comparison of currently utilized estimates for general yearly electrical load of Swiss municipalities and corresponding values given by the Energy Reporter (EnergieSchweiz). The Known/Modelled indicator refers to whether or not the estimates are based on official statistics (e.g. from a cantonal energy office) or modelled based on demographic indicators.

This highlights (again) a major difficulty in estimating the electrical load of a municipality: Even with the very granular information given by the STATENT database[4], it is in practice impossible to infer energy intensity reliably based on industrial sectors. It also raises the question whether large decentralized consumers should be considered in the first place within the methodology detailed in the last report. Large industrial consumers will in most cases not follow the load curve that its host municipality follows. The disaggregation methodology utilized here maps all consumers onto a single timeseries, which will be significantly skewed if large consumers are included. Further, large consumers have their own energy concepts, and as such don't necessarily need to be included in this analysis either way.

Table 2. Selection of largest deviations in general electrical load estimates, with deviations in both directions included. Possible causes lists large industrial/other consumers that could explain at least large parts of these differences.

Municipality	Current Estimate [GWh/a]	Energie Reporter Estimate [GWh/a]	Possible Cause
Düdingen	8.6	65.4	SIKA Factory
Wünnewil-Flamatt	5.5	27.1	unknown
Péry-La Heutte	9.3	39.1	Vigier Ciement
Villigen	126.0	15.5	PSI
Sisseln	114.0	33.7	unknown
Schafisheim	69.4	29.7	Coop Distribution Center

[4] Statistik der Unternehmensstruktur: https://www.bfs.admin.ch/bfs/de/home/statistiken/industrie-dienstleistungen/erhebungen/statent.html

Given that the comparison with Energie Reporter revealed errors in both directions, the decision was made to continue with the approach utilized so far. Both datasets have obvious shortcomings, but since there is no publicly available documentation for the Energie Reporter, using the current methodology is more consistent.

The electricity consumption of individual municipalities of Switzerland is only partially available. A linear model was therefore used to generate missing consumption values. The updated spatial distribution of general electric energy consumption per municipality is shown in Figure 7.

The model was calculated using available consumption data. Since publishing deliverable report D1.2 in 2023 [1], additional consumption data was made available to us. The number of municipalities with known electric energy consumption therefore increased to 652, which is equivalent to 30 % of all modelled municipalities. The same log-log model as in Deliverable report D1.2 was used, featuring municipal population and full-time equivalents (FTE) of the industrial and service sectors as regressors[5],

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

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 updated linear regression yields the following results for the intercept and coefficients: β_0 = -3.436, β_1= 0.679, β_2= 0.194. The p-value is below machine accuracy, the adjusted R-squared = 0.925, and the intercept and both predictor terms have p-values $\leq 1.76 \cdot 10^{-6}$.

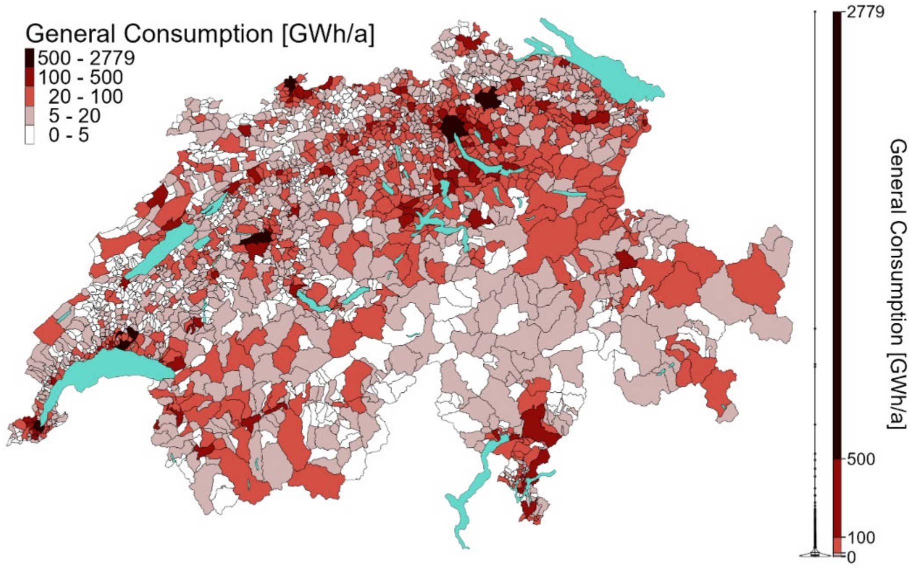

Figure 7. Spatial distribution of general electric energy consumption by municipality per year. 652 municipalities have known general consumption values, which originate from the year 2018 (if 2018 was not available from another year between 2017 to 2022). These measured values were combined with modelled values for the remaining 1496 municipalities (see Equation 1).

1.2.6 Centralized and Decentralized Power Plants

A large part of the presented analysis is dependent on the fact that only decentralized producers are considered to determine the need for decentralized storage, PtX, and DSM. For certain categories of

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

power plants, this distinction is quite obvious, e.g. for nuclear or storage hydro. There is however a whole spectrum of power plant sizes and operating modes where the distinction is not so clear, mainly with running hydro. Here a distinction can be made if the high voltage transmission grid is considered. If a power plant is connected to this grid, then it is considered centralized. Unfortunately at the time of submission of the last report, this grid data was not available – now it is. An analysis was conducted comparing the locations of the power plants and grid infrastructure. Based on heuristic criteria, these power plants were then sorted into "centralized" and "decentralized". Table 3 lists the criteria that were used to generate the categorization shown here. This process was validated as best as possible by comparison to known results (such as the large pumped hydro plants), aerial images clearly showing transmission grid infrastructure, or other publicly available information. Part of the reason for the different criteria for different levels of transmission line voltages stems from the fact that there are a number of small hydro power plants located under or very close to a very high voltage transmission line (naturally co-located in mountainous valleys), but are evidently not connected to it. Figure 8 shows the locations of all Swiss running and storage hydro power plants, as well as the transmission grid infrastructure. The circles represent power plants, with their scale being related to the installed generator capacity. Power plants that are shown in green are considered to be centralized (i.e. directly connected to the transmission grid), whereas decentralized power plants are shown in red. Consequentially, only the power plants determined to be decentralized are considered in this report, consistent with the methodology developed in deliverable report D1.2.

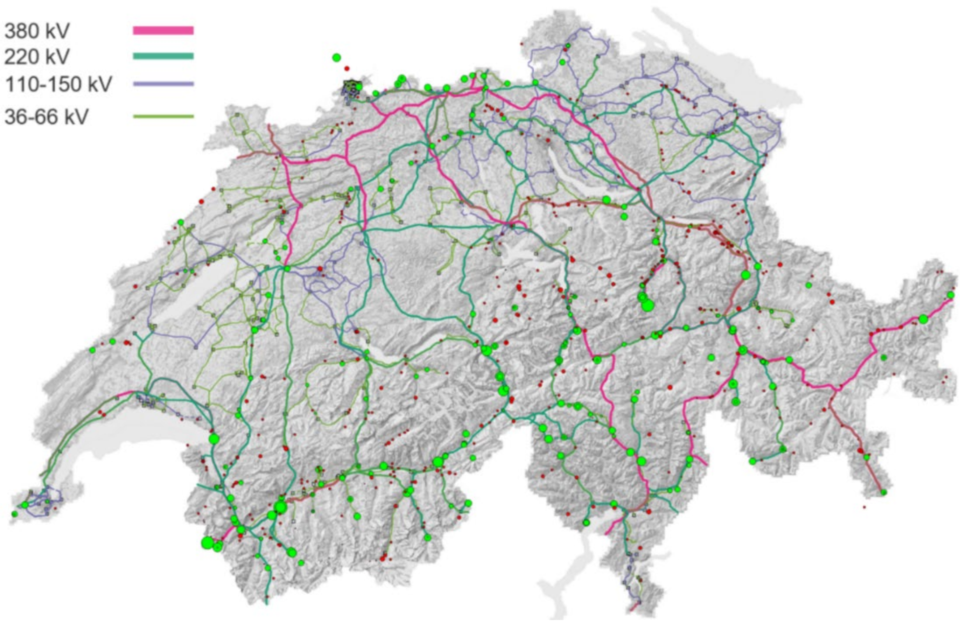

Figure 8. Categorization of hydroelectric (running hydro + storage hydro) into centralized and decentralized production based on proximity to transmission lines. Green circles represent centralized production, red ones decentralized. The circle diameter is proportional to the square root of the installed generator power (i.e. small power plants appear larger than they are in comparison). The color and width of the lines indicates the voltage level of the transmission lines.

Table 3. Heuristic criteria used to determine whether a power plant is deemed to be centralized, i.e. connected to the transmission grid. Example: To be categorized as being connected to a 220 kV transmission line, a specific power plant needs to have an installed generator capacity of at least 5 MW, and be at a maximal distance of 200m to the nearest part of the transmission line.

Transmission line voltage up to:	66 kV	150 kV	220 kV	380 kV
Maximum distance to transmission line:	500 m	300 m	200 m	150 m
Minimum generator power:	1 MW	2 MW	5 MW	10 MW

2 Methodology

2.1 General Remarks

On a technical level, the need to include local storage due to altered production/consumption patterns compared to the *status quo* is motivated by two reasons: Either the local grid connection cannot support the (higher) peak loads/productions, or the overarching grid cannot accommodate the load/production of all municipalities simultaneously. In the second case, this does not necessarily call for localized storage (since it is a non-local issue), however in most cases there is no obvious downside to distributing storage to a certain degree, thereby taking strain off the transmission grid. In the case where the grid connection of a single municipality is not adequate to accommodate the future peak power flow over the municipal boundary, there are three main remedies:

- Increasing the grid connection capability
- Curtailment of PV and other producers
- Local Storage and/or Demand-Side-Management

Within the scope of this analysis, Demand-Side-Management (DSM) is considered as a special case of lossless storage (albeit heavily constrained). These three options can all help to limit peak power flow to match grid capability. It is important to stress however that while increasing the grid capability can fully solve any local problem, curtailment and local storage are not universally able to do so. In the case of curtailment, it is only a fully valid option in the case where local over-production is the limiting factor – which is predominantly not the case in most cities, for example. In the case of storage, the maximum of its ability is to reduce the peak powerflow to the average one (at the cost of an unrealistically enormous, and perfectly efficient storage). This average consumption, depending on the utilized scenario and municipality, can lie outside the current maximum powerflow estimate. Thereby, such a municipality would still require an increase in grid capability, even if an infinitely large storage is employed. While both curtailment and local storage cannot solve the issue on their own, depending on the circumstances, they can still reduce the need for grid expansion. It is however strongly expected that both will show diminishing returns, i.e. that there is a cost-optimal combination of these measures.

Obviously, a fundamentally different solution to this issue is to change the production and consumption patterns in the first place, e.g. by proportionally installing more PV in areas with high consumption, or restricting peak EV charging consumption. The introduction of fully dynamic tariffs could also strongly impact this balance. These measures are however decidedly not the focus of this study. Further, no costs are currently associated with each measure. Especially in the case of grid connection, it is near impossible to find a singular value for a municipality, for reasons of data availability, but also the fact that most municipalities are not connected to the transmission grid with a single line, and will include a wide range of unknown safety factors and futureproofing overbuilding. The cost of a connection upgrade is also very situational. Therefore, the presented analysis focuses on this fundamental question, for every Swiss municipality: *If a certain amount of PV is curtailed, how much (local) storage is necessary to reduce the necessary increase in grid connection capacity by a certain extent?*

The focus on reduction of the necessary increase in grid connection capability is key, as it eliminates a large part of the uncertainties involved at this stage. Further it can point to systematic differences between Swiss regions and municipal characteristics, e.g. if a relatively much larger storage is needed in one municipality vs. another, while achieving the same reduction in necessary grid capability increase. Additionally it is possible to show the interplay between the three discussed measures to some degree.

The three discussed measures are presented here in the order that they are applied to the dataset. In a first step, the production profiles of PV are altered to represent the respective curtailment scenario. This results in a new production timeseries for each municipality, which is then used (together with the existing consumption timeseries) to find the peak mismatch, representing the largest estimated power flow over the municipal boundary. In the last step, the storage size is determined in such a way that the apparent mismatch (municipal mismatch plus storage) does not exceed a predefined limit.

2.2 Curtailment

Curtailment of PV units is an important approach to reduce stress of the energy system to take up power generation peaks. Due to the generation profile of PV, it is typically possible to reduce generation peaks substantially with limited loss in generated energy [12]. Due to our scenario being dominated by an expansion of generation by PV, which is in accordance with the currently known Swiss renewable expansion plans, PV curtailment is most likely going to play an important role in the toolbox to reduce grid strain. Because it is easily implementable and due to its additional benefit for PV integration on the lowest grid levels, a fixed curtailment by a constant factor on the level of single PV units was simulated. The loss of energy due to such a measure for our scenario is shown in Figure 9 and Figure 10. The figures demonstrate that curtailment of PV units could yield strong reductions in generation peaks with limited loss of energy. Three curtailment scenarios were created with the characteristics presented in Table 4. Only the three PV subcategories rooftop, infrastructure, and agri-PV are subject to curtailment.

Table 4. Specific values of PV curtailment scenarios for simulations. Rooftop, infrastructure, and agri-PV were subject to curtailment. Lost energy was calculated with the PV generation profiles of the simulation. Due to our modelling approach in which we set generated electric energy instead of installed rated power, curtailment level was defined as a fraction of the maximum AC power generation of individual PV units. The conventional definition of curtailment can therefore only be estimated. A factor of 80 % as the maximum AC power in relation to the installed DC power was assumed for this purpose. An assumed specific generation of 970 kWh/kWp is used for the estimation of installed PV power.

Curtailment level relative to maximum AC power [%]	Estimated curtailment level relative to rated DC power [%]	Lost energy due to curtailment [%]	Energy generation by curtailed PV* [TWh]	Estimated installed PV power* [GW]
75	60	2.7	27.6	29.2
62.5	50	8.7	27.6	30.9
25	20	48.7	27.6	42.3

*Only the PV subcategories rooftop, infrastructure, and agri-PV are considered for curtailment and the values in this table only refer to those three subcategories. Energy generation and installed power of façade and alpine PV would come on top of values shown here.

It is important to note that the curtailed PV profiles were scaled a posteriori such that their total energy generation stayed constant independent of the strenght of curtailment. This implies that in scenarios with stronger curtailment, the cumulated installed PV power in Switzerland is increased (see Table 4 for specific values). Figure 16 to Figure 23 show the effects caused by how PV curtailment was applied. The stronger the curtailment, the more often the maximum power generation by PV is observed all year round making the technology a firmer power source.

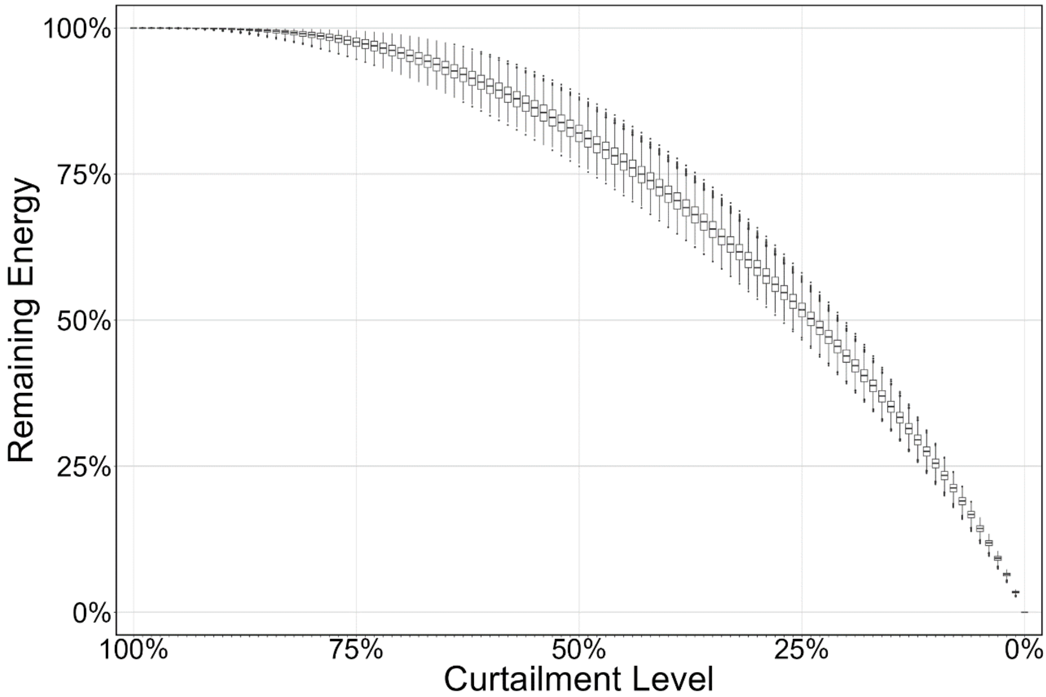

Figure 9. Remaining energy depending on PV curtailment strength. The boxplots depict the distribution of values among the 2148 municipalities in Switzerland. The amount of remaining energy after curtailing all PV units by a fixed factor was calculated for the aggregated PV profiles of subcategories: rooftop, infrastructure, agrivoltaics.

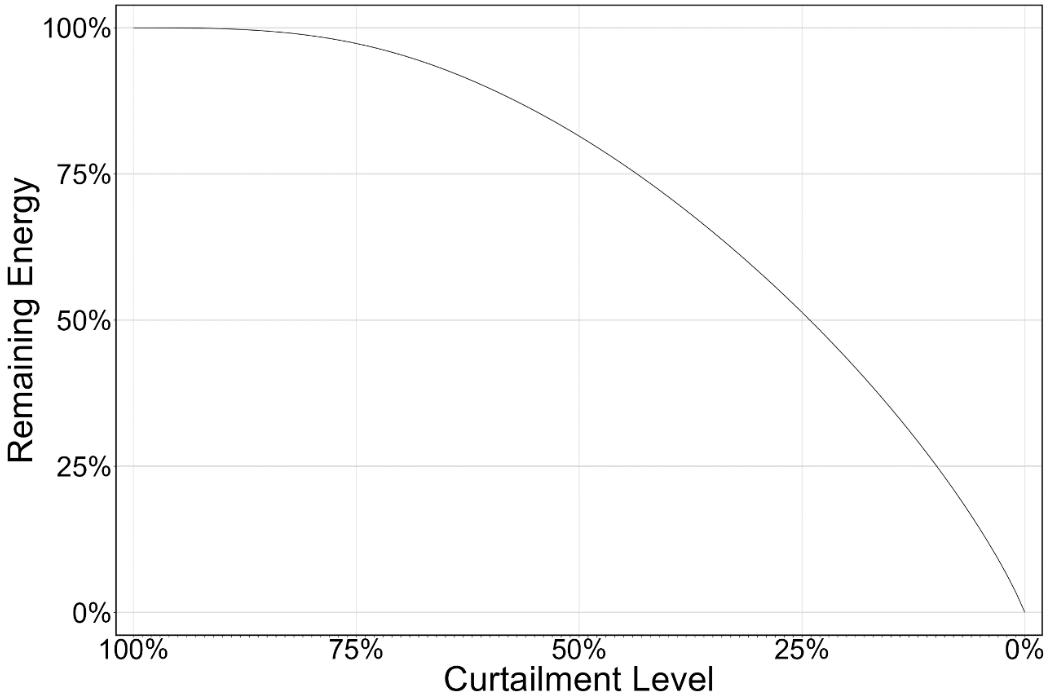

Figure 10. Weighted average of remaining energy depending on PV curtailment strength. Averages were calculated taking into account the PV potential of each municipality as weighting factor. The amount of remaining energy after curtailing all PV units by a fixed factor was calculated for the aggregated PV profiles of subcategories: rooftop, infrastructure, agrivoltaics.

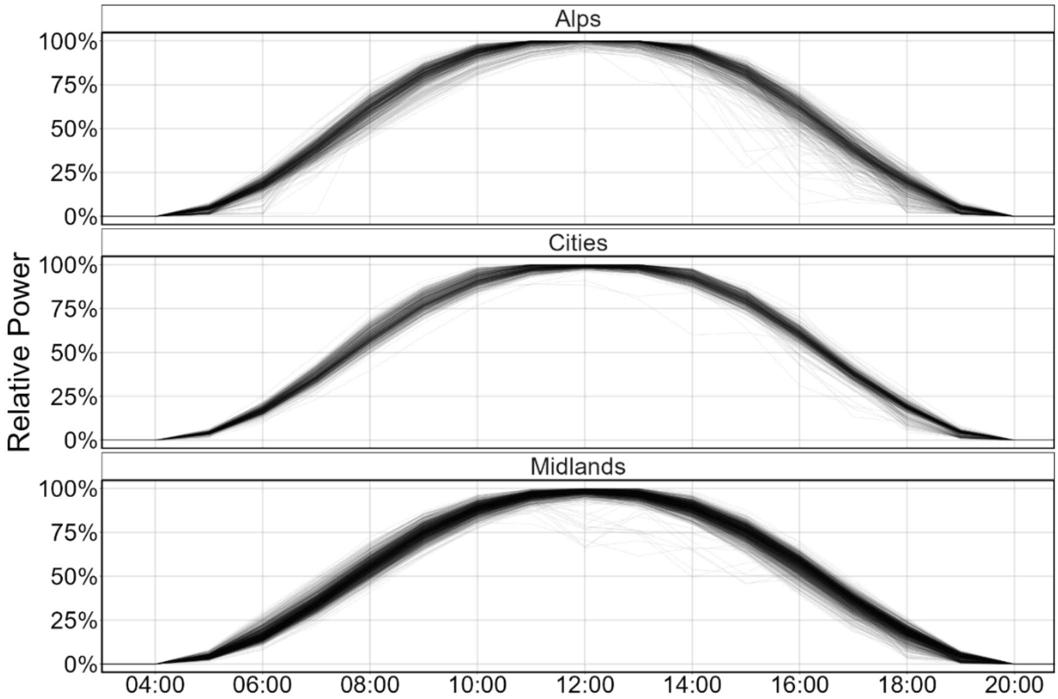

Figure 11. All municipal rooftop PV production profiles on July 1 (exemplary summer day) with a curtailment to 75 %. Profiles feature a temporal resolution of 15 minutes and are scaled so that their maximal value over the course of one year equals 1. Used timezone is Central European Summertime. The data originates from the real weather on July 1st, 2018. Profiles are created by curtailing individual PV units, followed by a municipality-specific weigthed aggregation based on rooftop categories present. Underlying data are sourced from [10].

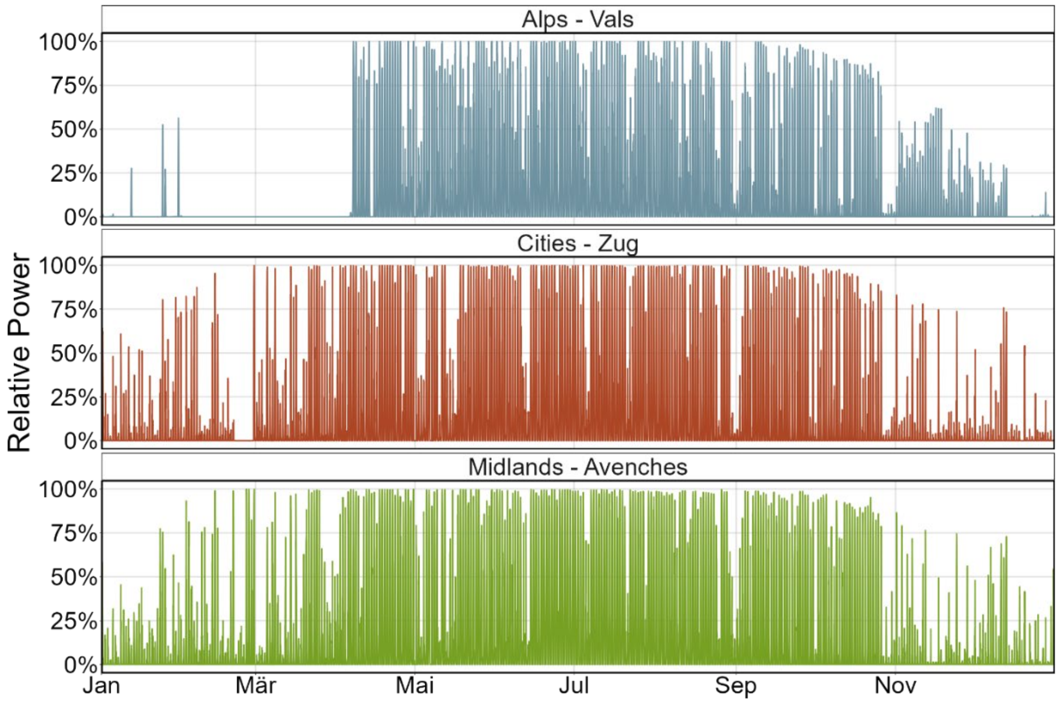

Figure 12. Yearly relative power generation profiles of rooftop PV of one exemplary municipality per EDGE-region with a curtailment to 75 %. Profiles feature a temporal resolution of 15 minutes and are scaled so that their maximal value over the course of one year equals 1. Profiles are created by curtailing individual PV units, followed by a municipality-specific weigthed aggregation based on rooftop categories present. Underlying data are sourced from [10].

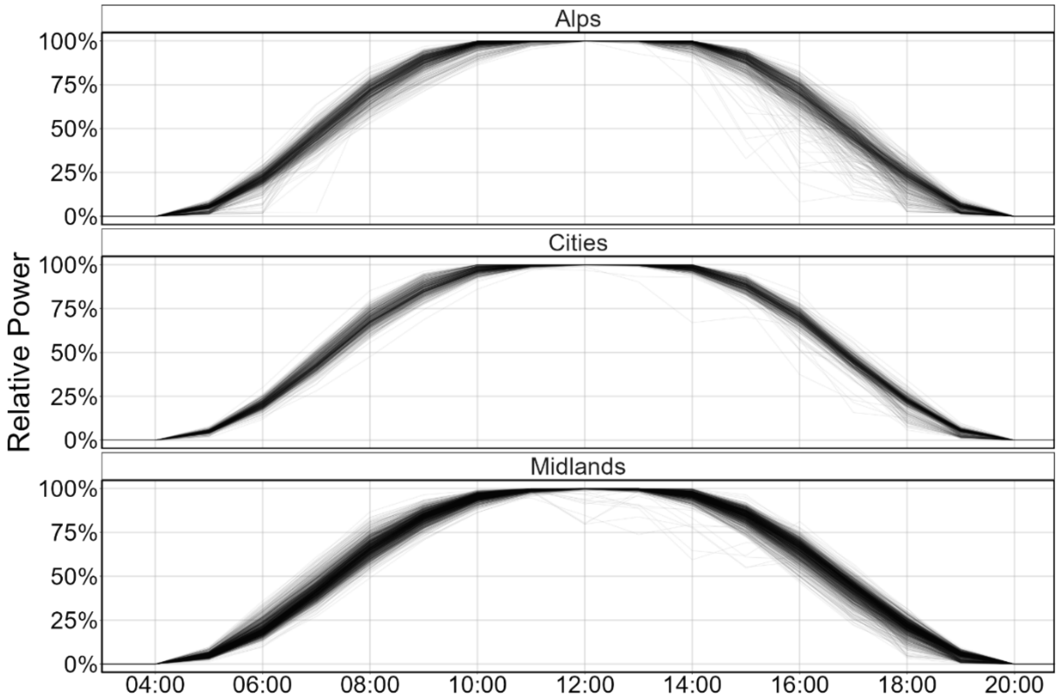

Figure 13. All municipal rooftop PV production profiles on July 1 (exemplary summer day) with a curtailment to 62.5 %. Profiles feature a temporal resolution of 15 minutes and are scaled so that their maximal value over the course of one year equals 1. Used timezone is Central European Summertime. The data originates from the real weather on July 1st, 2018. Profiles are created by curtailing individual PV units, followed by a municipality-specific weigthed aggregation based on rooftop categories present. Underlying data are sourced from [10].

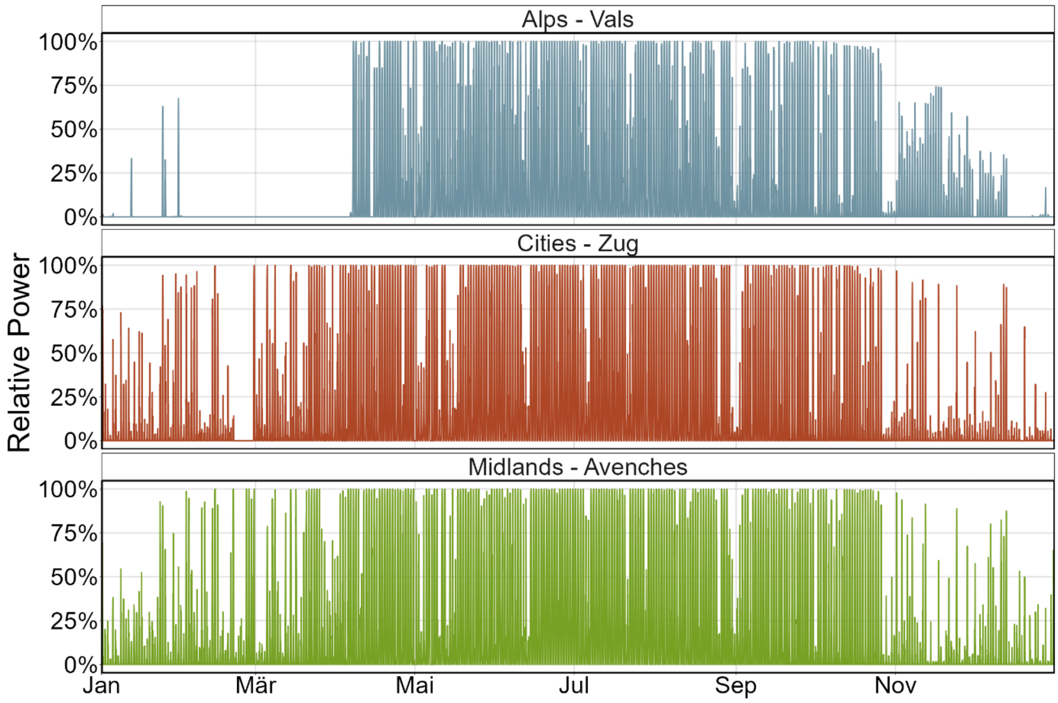

Figure 14. Yearly relative power generation profiles of rooftop PV of one exemplary municipality per EDGE-region with a curtailment to 62.5 %. Profiles feature a temporal resolution of 15 minutes and are scaled so that their maximal value over the course of one year equals 1. Profiles are created by curtailing individual PV units, followed by a municipality-specific weigthed aggregation based on rooftop categories present. Underlying data are sourced from [10].

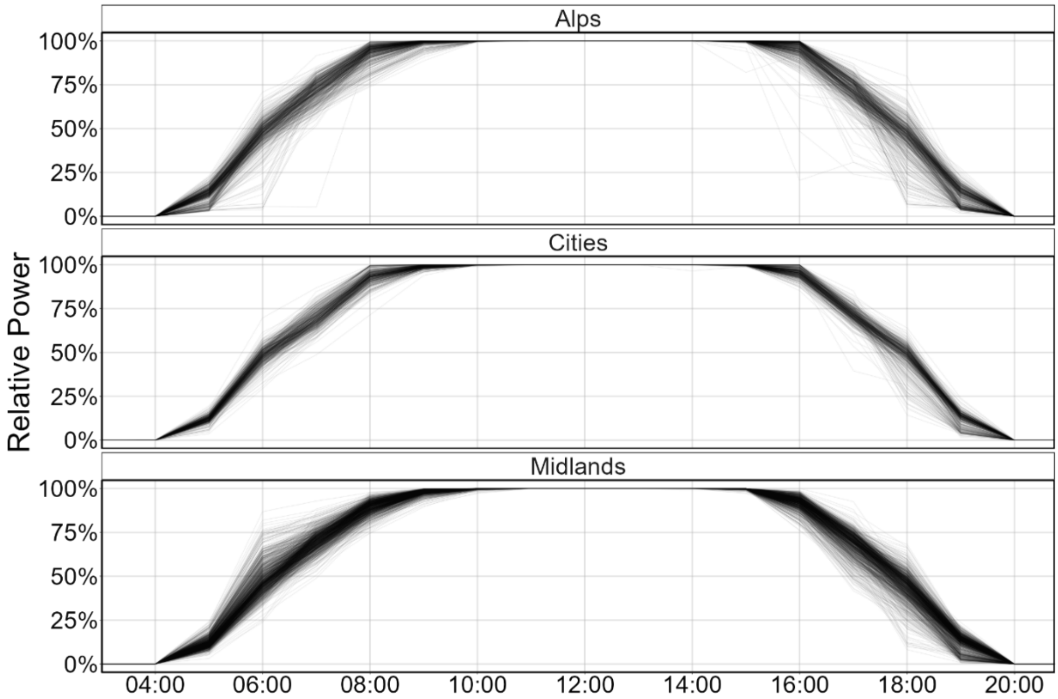

Figure 15. All municipal rooftop PV production profiles on July 1 (exemplary summer day) with a curtailment to 25 %. Profiles feature a temporal resolution of 15 minutes and are scaled so that their maximal value over the course of one year equals 1. Used timezone is Central European Summertime. The data originates from the real weather on July 1st, 2018. Profiles are created by curtailing individual PV units, followed by a municipality-specific weigthed aggregation based on rooftop categories present. Underlying data are sourced from [10].

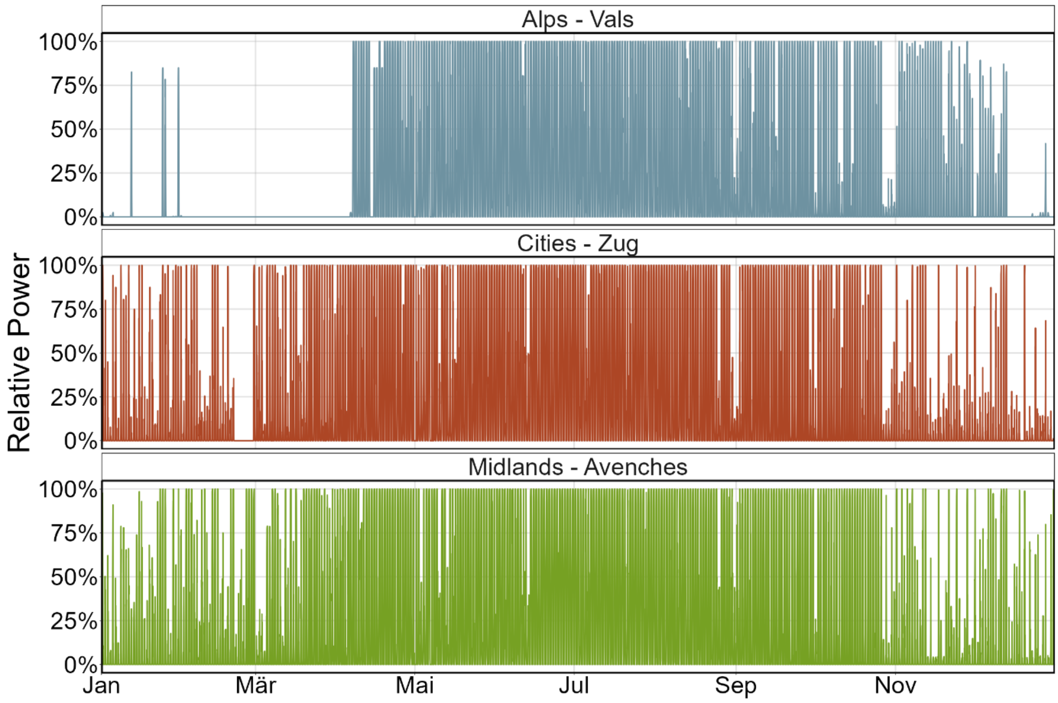

Figure 16. Yearly relative power generation profiles of rooftop PV of one exemplary municipality per EDGE-region with a curtailment to 25 %. Profiles feature a temporal resolution of 15 minutes and are scaled so that their maximal value over the course of one year equals 1. Profiles are created by curtailing individual PV units, followed by a municipality-specific weigthed aggregation based on rooftop categories present. Underlying data are sourced from [10].

2.2.1 Comparison between individually fixed and top-level dynamic curtailment

There are various PV curtailment strategies conceivable. These strategies have different requirements for additional hardware, software, and communication infrastructure in the power system and their effects differ in terms of peak load reduction and energy losses. In this study, a curtailment strategy was modelled where every PV unit is curtailed to a fixed relative value of their maximal potential generation (subsequently called “fixed curtailment”). From a technical perspective, such an approach would be straight-forward to be implemented in the current Swiss power system. In addition, the permanent and universal reduction in generation peaks will decrease the need for capacity expansion on the low grid levels. However, if the goal was to curtail as little energy as possible, while limiting the peak generation to the same value as with such a fixed curtailment, a dynamic, top-level curtailment strategy would be an interesting alternative (subsequently called “dynamic curtailment”). The curtailment would dynamically become active to limit CH-wide aggregated generation to a certain threshold. Such a curtailment approach would only focus on limiting cumulative generation peaks of Swiss PV units.

Figure 17 shows a comparison of how much energy would need to be curtailed resulting in the same aggregated generation peak depending on the curtailment strategy. It is evident that a dynamic, top-level curtailment strategy would lead to significantly less curtailed energy. In the extreme case of a curtailment level of 25 % (meaning that the aggregated generation peak of PV in Switzerland is reduced to 25 % of the level without curtailment) energy curtailed would only amount to 15.8 %. Figure 18 is an illustration of how the curtailment strategies affect the PV profiles used. Both curtailment strategies show higher yields on days with reduced solar irradiance because to achieve the same energy output over the course of a year, the installed capacity would need to be increased (see Table 4 for details on the fixed curtailment strategy).

The comparison demonstrates the complexity of the energy system as even supposedly small differences in approaches come with different cost and technical challenges and lead to vastly different results in the overall system.

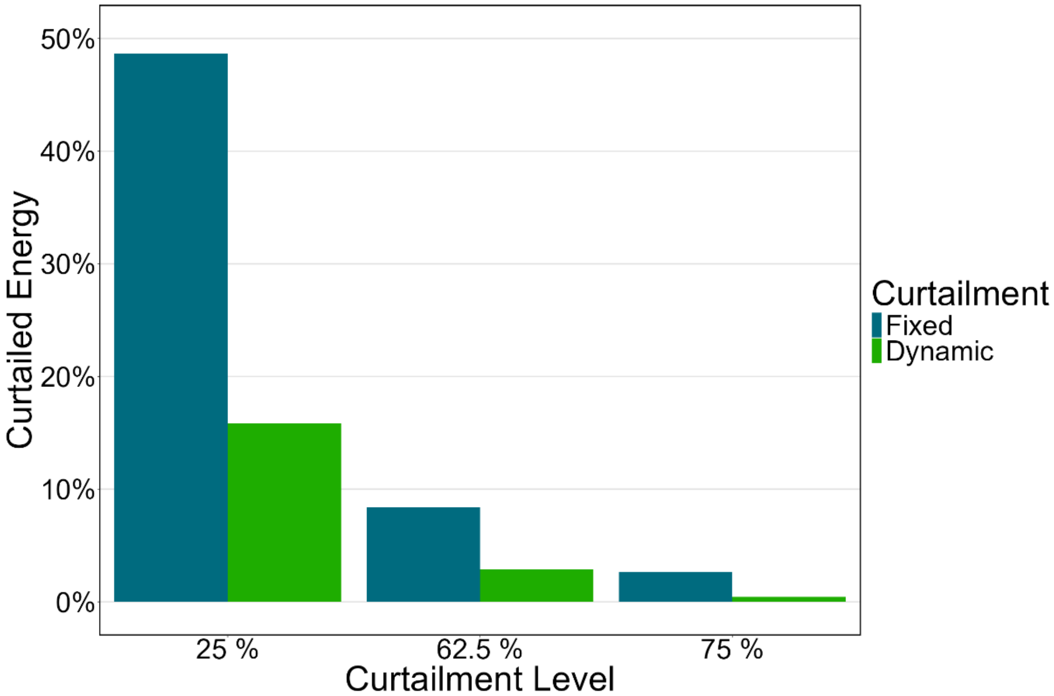

Figure 17. Relative amount of curtailed energy different curtailment strategies. For the three modelled curtailment scenarios, a top-level dynamic aggregation was used to limit the aggregated PV generation to the same yearly maximum observed with the fixed curtailment. The relative number of curtailed energy is calculated as the absolute energy curtailed divided by the total amount of energy that would have been generated without any curtailment.

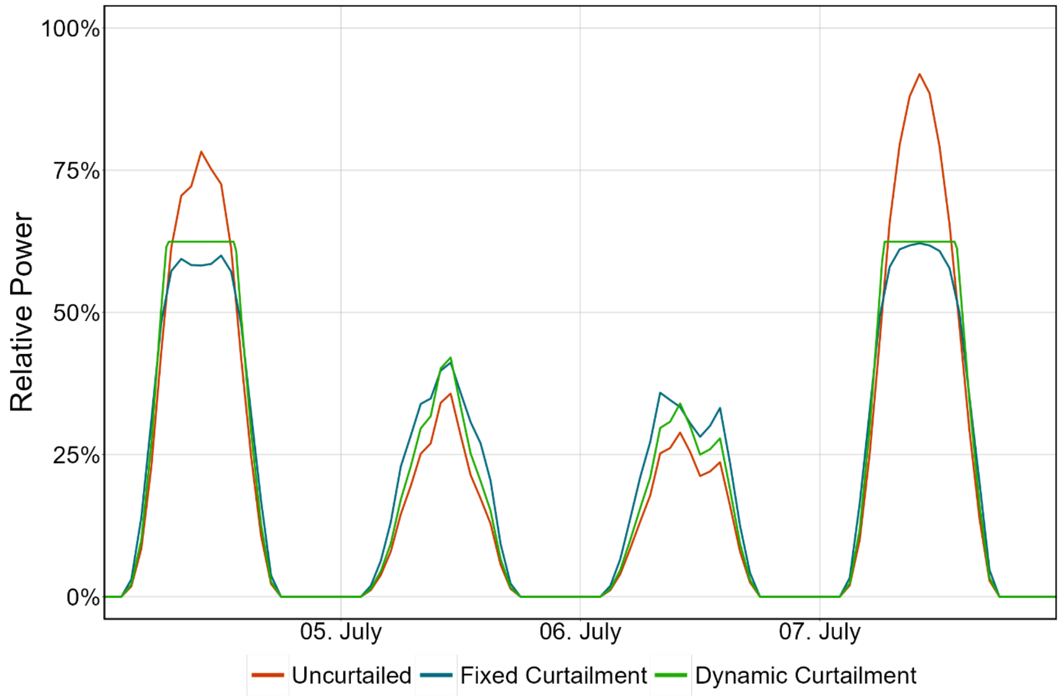

Figure 18. Comparison PV power generation profiles influence of curtailment strategy. Four exemplary summer days are shown of the uncurtailed timeseries, the fixed curtailment, and a dynamic top-down curtailment. Timeseries are aggregated over all municipalities and scaled to the common maximum value. Generated energy over the whole year is identical, which implies that the installed capacity is highest for the fixed curtailment followed by the dynamic curtailment to make up for curtailed energy.

2.3 Estimation of Grid Connection Capability Increase

As discussed in Section 2.1, an estimate of the increase in necessary grid connection capability is made to provide a baseline for all subsequent analysis. This essentially represents the estimated change that needs to be made in order to support the new peak load or production of a municipality under the assumptions made in the previous report [1].

The current peak powerflow is determined using the estimate of general load in each municipality. In the future scenario (corresponding to the CH-wide values given in the EP 2050+, Szeario Zero Basis A), the maximum absolute difference between instantaneous production and consumption values (aggregated for all categories) is used to determine the new peak power flow. It is assumed that the limits are symmetric, so no special consideration is given to whether the peak flow represents a consumption or production peak.

2.4 Calculation of Necessary Storage Size

A detailed description of the the methodology for storage size calculation is given in appendix A. It is important to note at this point that the presented algorithm finds the mathematically minimal storage size that is sufficient to limit powerflow over the municipal boundary to a specified value. It uses perfect foresight and optimal storage control. The resulting absolute values have to be interpreted with this in mind. Furthermore, the resulting storage fill levels and corresponding storage power curves are minimal in such a way that the storage only ever acts if it is actually necessary in order to minimize absolute storage size. Depending on the scenario and municipality, a certain amount of storage might only be necessary for a very limited part of the whole year. Obviously it would make financial sense to utilize a storage for arbitrage at all other times (given that this is more lucrative than any possible storage degradation caused thereby), however this is not reflected in this analysis.

2.5 Exemplary Process

The process of curtailment, grid connection capacity estimation, and subsequent storage size calculation is shown at the example of a single municipality. The municipality of Altstätten (SG) is chosen, as it was used as an exemplary municipality in the previous report. For illustrative purposes, extreme scenarios regarding curtailment and import/export limit restrictions are chosen.

2.5.1 Base Data

The locus of the analysis consists of both timeseries describing the estimates of future local electricity production and consumption. This is a direct result of the previous report, augmented by the alterations described in section 1.2. Figure 19 shows the yearly production timeseries without any curtailment, whereas Figure 20 shows the consumption timeseries. The difference in local production and consumption is shown in Figure 21, whereby positive values correspond to an instantaneous surplus of electricity.

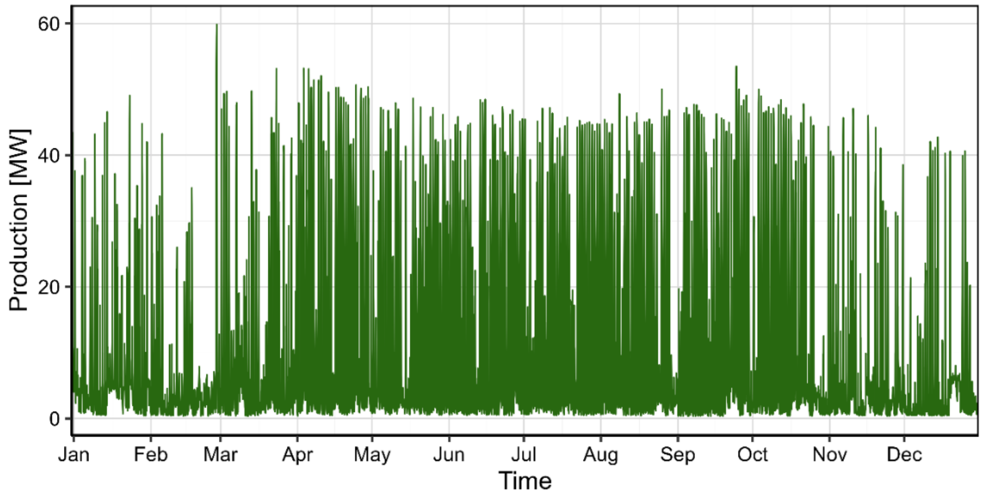

Figure 19. Yearly production timeseries of Altstätten (SG) without any curtailment, utilizing the scenario values described in report D1.2.

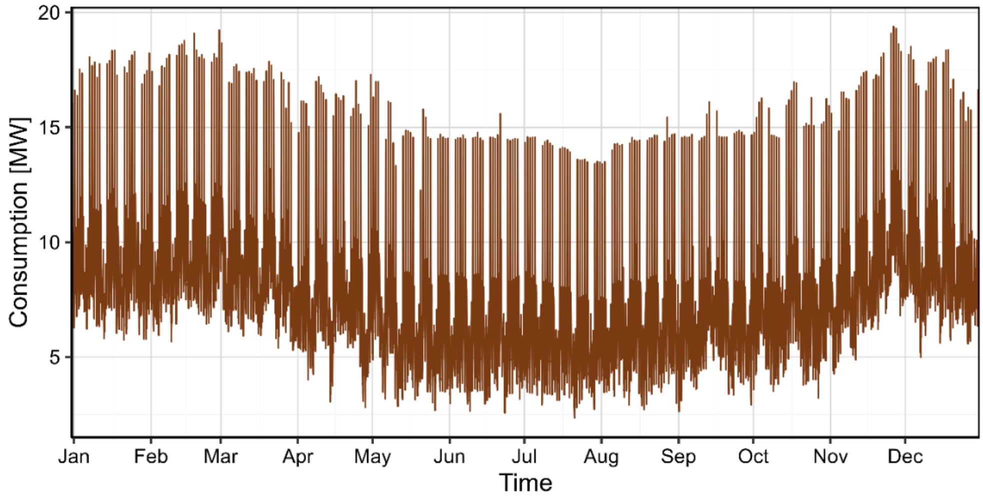

Figure 20. Yearly consumption timeseries of Altstätten (SG), utilizing the scenario values described in report D1.2.

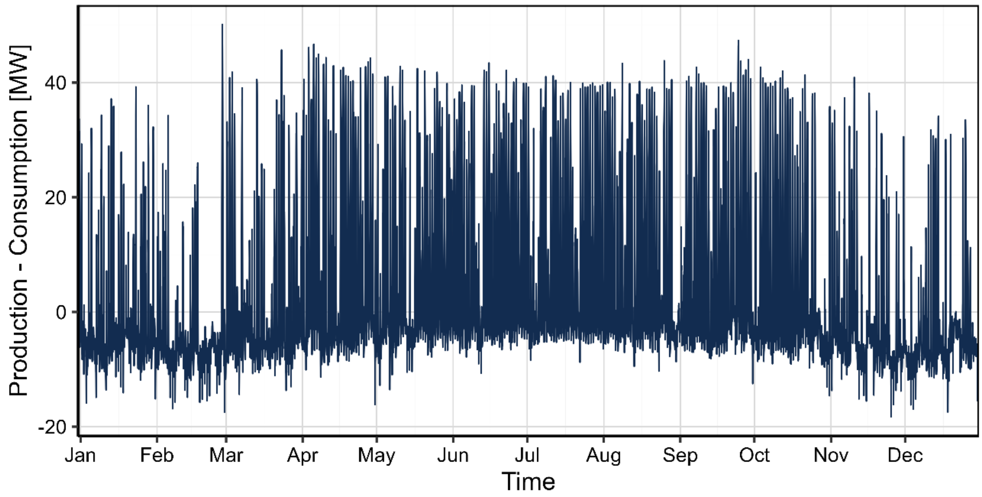

Figure 21. Yearly local production/consumption mismatch of Altstätten (SG), without any curtailment. Positive values correspond to an instantaneous surplus of electricity, negative values correspond to a deficit.

2.5.2 Curtailment Scenarios

The curtailment methodology is detailed in section 2.2. Different levels of curtailment were applied to provide multiple scenarios. Figure 22 shows the production timeseries of Altstätten (SG) under an extreme curtailment scenario of 25%, i.e. the admissible peak production of each PV orientation is reduced to 25%. Note that the total amount of generated PV electricity remains constant. To achieve this, the installed PV capacity is increased (overbuilding and curtailing).

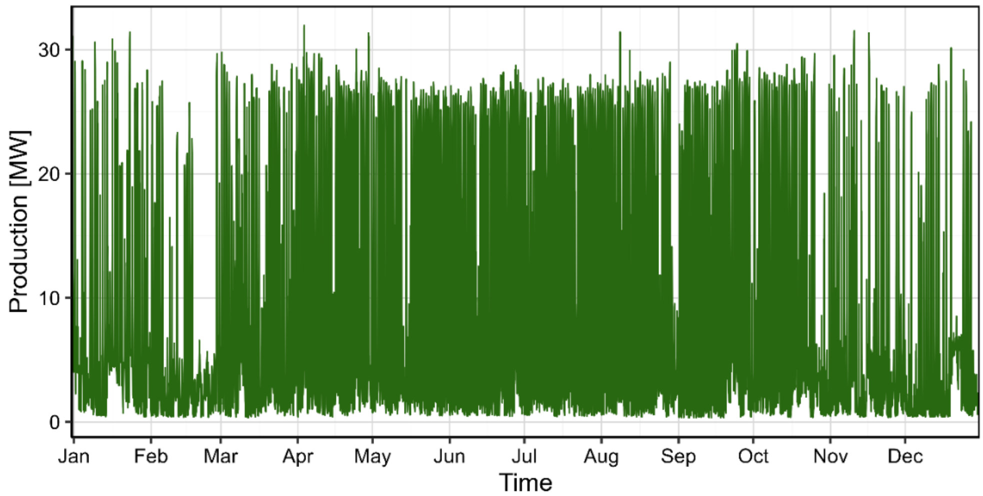

Figure 22. Yearly local electricity production profile of Altstätten (SG) under a 25% curtailment scenario. Note the far more constant production in comparison to the original production profile shown in Figure 19.

Figure 23 shows the resulting yearly local production/consumption mismatch of Altstätten (SG) under an extreme 25% curtailment scenario, with positive values corresponding to an instantaneous surplus of electricity. In comparison to the corresponding original curve (no curtailment) shown in Figure 21, the positive peaks are reduced by roughly 50%. Notably, the negative peaks (corresponding to surplus consumption) are not reduced, as curtailment only has a very limited impact at these times.

Figure 24 shows the cumulative production (all categories) in Altstätten over an exemplary week in July, under different curtailment scenarios. While curtailment reduces the peaks on very sunny days, it conversely mitigates the effects of bad weather. This is due to overbuilding, which is necessary to preserve the total amount of electricity generated by PV. This effect is described in more detail in section 2.2.

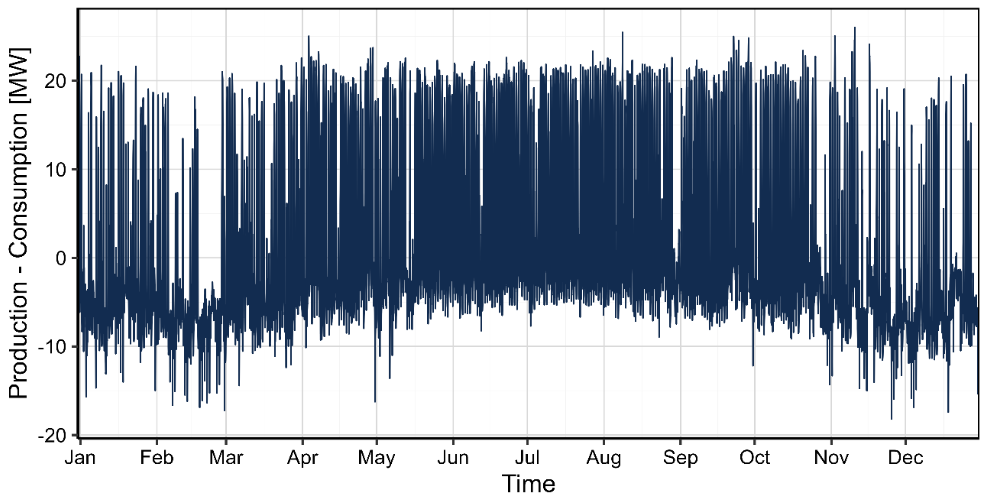

Figure 23. Yearly local production/consumption mismatch of Altstätten (SG) under an extreme 25% curtailment scenario. Positive values correspond to an instantaneous surplus of electricity, negative values correspond to a deficit. Note the pronounced reduction in absolute extreme values in comparison to the scenario without curtailment, shown in Figure 21.

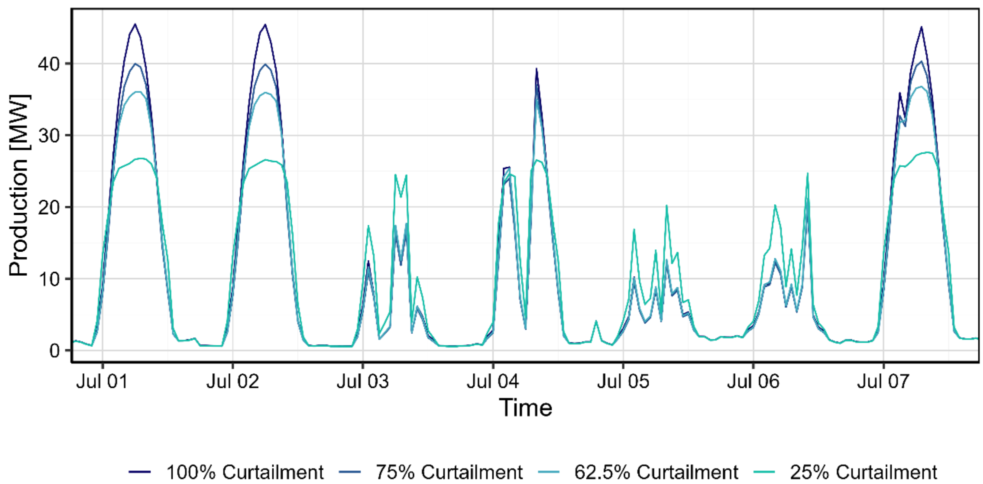

Figure 24. Cumulative production (all production categories, in MW) in Altstätten (SG) for an exemplary week in July. Shown are the original production timeseries as well as the resulting production timeseries under three different PV curtailment scenarios (see section 2.2). Note that while the peaks (days 1,2,7) are reduced under the extreme curtailment scenarios, the influence of bad weather (days, 3 -6) are partially mitigated, leading to a more constant and predictable production.

2.5.3 Estimation of Grid Connection Capacity

The peak power transfer of Altstätten with the overarching transmission grid is estimated using the current total yearly demand (74.9 GWh), in combination with the load variability (itself an estimate from load data of the canton). This results in a peak power consumption of 15.18 MW. The peak power transfer in the future scenario is taken as the absolute maximum local production/consumption mismatch (see Figure 21 and Figure 23 for both shown curtailment scenarios), which amounts to 47.12 MW without curtailment, and 26.01 MW in the extreme 25% curtailment scenario. The difference between those numbers (31.94 MW in the uncurtailed, 10.83 MW in the curtailed scenario) is used as the measure for necessary grid connection capacity increase in a given scenario. As described in section 2.3, it is assumed that safety margins and futureproofing rates remain constant, as well as power factors and reactive power requirements.

As is obvious already from the numbers presented, curtailment can drastically lower the necessary increase in grid connection capacity. Comparing the scenario with 25% curtailment to the one without any curtailment, we can see that roughly 2/3 of the necessary grid connection capacity increase can be avoided, albeit at the obvious cost of increased PV installations.

In the case where the limit for grid connection capacity is set at the peak power consumption (in the given curtailment scenario), no storage is necessary – all power fluctuations can be handled by the grid. Notably, this does not mean that the cumulative fluctuations of all Swiss municipalities (or any other given subset) can be accommodated, which is however not the focus at this stage. If the capacity is to be reduced further (in order to avoid costly investments), local storage or other energy-shifting measures can smooth production and consumption peaks, such that the grid is used in a more constant way. In the scope of this report, three different scenarios were investigated, whereby the increase from current capacity to future capacity under any given curtailment scenario is reduced by 25, 50, and 75%. There is an obvious special case where future maximum load/production is lower than the estimated current one, however this is quite uncommon. In the case of Altstätten, a 50% reduction scenario in the 25% curtailment scenario equates to a grid connection limit of 20.59 MW.

Table 5. Combinations of curtailment scenarios and grid capacity increase reductions for Altstätten (SG), based on a current capacity estimate of 15.18 MW. All unmarked values in MW.

Curtailment Scenario	Future Peak Load/Production	Necessary Increase	Limit 25% Reduction	Limit 50% Reduction	Limit 75% Reduction
100%	47.12	31.94	39.13	31.15	23.17
75%	38.35	23.17	32.55	26.77	20.97
62.5%	34.80	19.62	29.89	24.99	20.08
25%	26.01	10.83	23.30	20.59	17.89

2.5.4 Storage Size Computation

For each curtailment scenario, the resulting production profile (in combination with the constant consumption profile) is used to determine a necessary storage size, for each reduction scenario. For the current analysis, perfectly lossless storage with technically infinite power density is used. While inefficient storage is implemented, it is not used at this stage. Refer to appendix A for an explanation of the methodology.

The plots shown in this section correspond to a curtailment scenario of 75% and a grid capacity increase reduction of 50%. Figure 25 shows the apparent yearly mismatch of production and consumption in Altstätten after employing the determined storage. Note that this curve never exceeds 26.77 MW, which is the specified limit for this combination of scenarios given in Table 5. The corresponding storage fill levels and instantaneous power delivery/consumption are shown in Figure 26 and Figure 27, respectively.

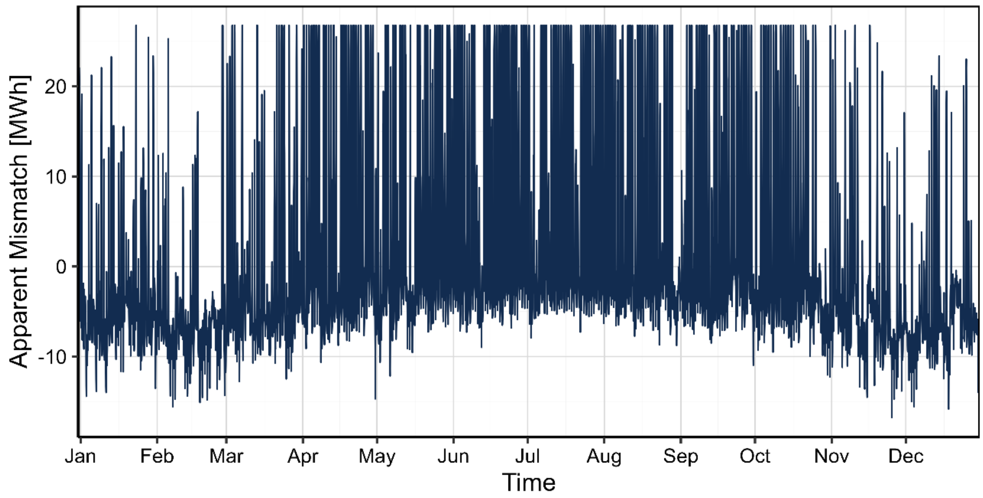

Figure 25. Resulting apparent yearly mismatch of production and consumption in Altstätten after employing storage, under a curtailment scenario of 75% and a grid capacity increase reduction of 50%. Note that this curve never exceeds 26.77 MW (and its negative counterpart), which is the specified limit for this combination of scenarios given in Table 5.

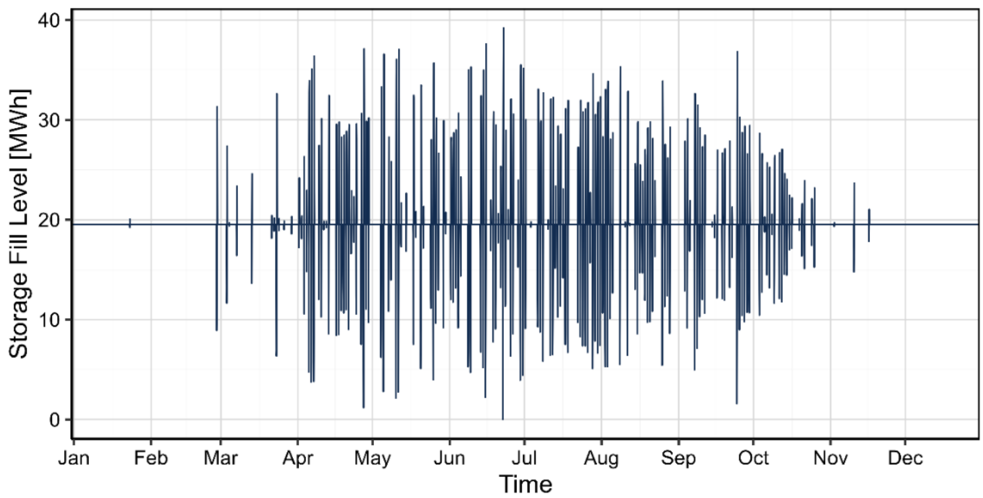

Figure 26. Yearly storage fill level of the mathematically optimal (and perfectly efficient) storage necessary to guarantee flucutations below the limits specified. The graph shows the fill level for Altstätten under a 75% curtailment scenario, with grid capacity increase reduced by 50%. Note that the minimal storage level is 0, and that the storage calculation algorithm always tries to return to a half-full storage. The total necessary storage size in this combination of scenarios is 39.21 MWh.

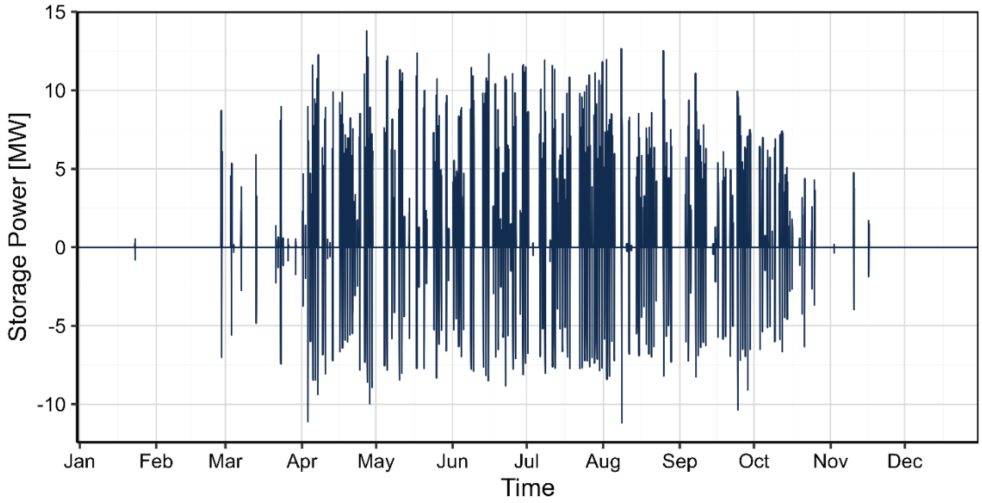

Figure 27. Instantaneous power of the employed storage under 75% curtailment and 50% grid capacity increase reduction in Altstätten. A positive value corresponds to power delivered by the storage to the system. Note that in the case of perfectly efficient storage (as shown here), the storage fill level shown in Figure 26 corresponds to the negative integral over time of the storage power curve shown here. The maximum discharge power is 13.78 MW, whereas the maximum charging power is 11.19 MW.

An excerpt of storage fill level and instantaneous storage power for an exemplary week in October is shown in Figure 28 and Figure 29. Referring to the yearly plot of apparent mismatch shown in Figure 25, it is clearly visible that the limiting factor is surplus generation (for most of the year, but specifically also during this week). On most days, electricity needs to be consumed by the storage locally, in order not to violate the grid limit constraint. To provide the necessary free capacity, the storage is discharged during the early morning hours, by exactly half the amount of electricity that will be stored during the day. As soon as possible, the storage is then discharged again to reach the equilibrium level of half filled storage.

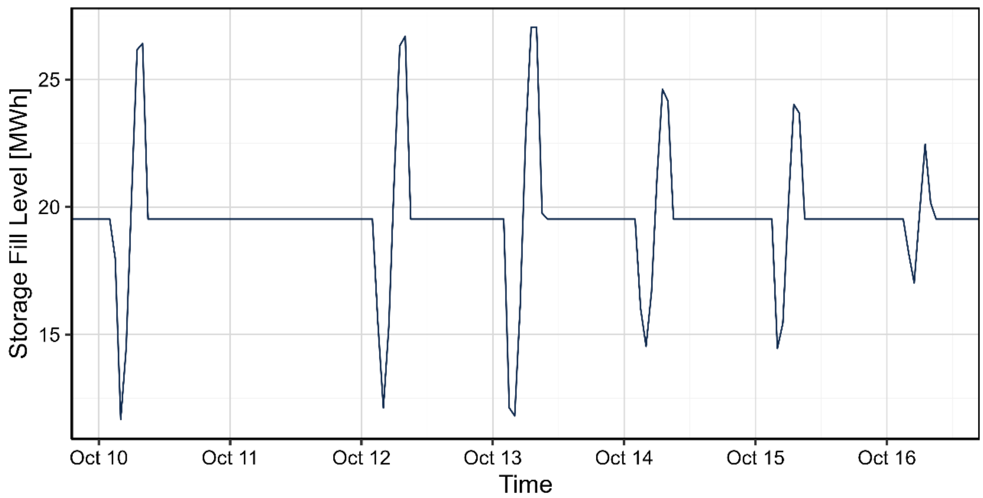

Figure 28. Storage fill level for an exemplary week in October under 75% PV curtailment and 50% grid capacity increase reduction in Altstätten. During this timeframe, the storage operation is dictated by a need to store energy during the day (see also Figure 25). In order to remain close to the equilibrium (roughly 19 MWh in this case), the storage discharges during the night and into the early morning hours to provide the necessary free capacity during the day.

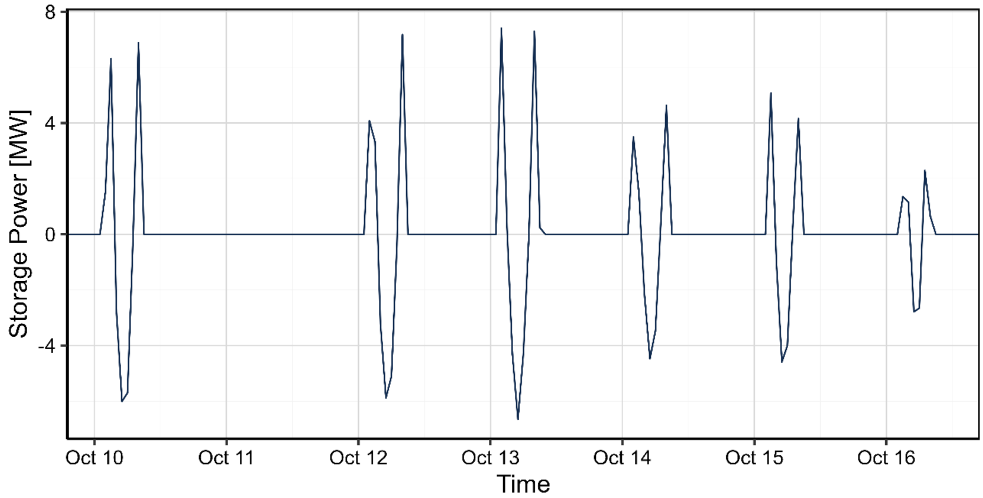

Figure 29. Storage power for an exemplary week in October, under a 75% PV curtailment and 50% grid capacity increase reduction in Altstätten. Note the sign convention where negative values correspond to a consumption of electricity by the storage. The shown values represent the negative derivative of the curve shown in Figure 28. It is very well visible that the storage operation is dictated by the need to store electricity during the day (large negative peaks), the necessary capacity for which is freed up by discharging prior and after the consumption peaks. During large parts of this week, the storage is not needed, as the grid can accommodate all fluctuations.

3 Results and Discussion

3.1 General Remarks

The exemplary process shown in section 2.5 was executed for all Swiss municipalities, selected results of which are presented in this section. In addition to the original production time series, three different curtailment scenarios were implemented, corresponding to limitations of 75, 62.5, and 25 % of peak power output of each individual PV installation. The 62.5% limitation (with respect to actual maximum AC power generation in the original generation timeseries) represents a scenario of roughly 50% curtailment with respect to DC rated power, where roughly 8.7% of energy is curtailed (see section 2.2 for more details). The 75%-curtailment scenario represents a very minimal energy loss, whereas the 25%-curtailment scenario shows the impacts of an extreme curtailment option. In all cases, overbuilding (corresponding to the inverse of the fraction of energy that was curtailed) was applied a posteriori such that the total amount of electricity generated by PV over the whole year remains constant.

For each of those four scenarios, the peak power flow over the municipal boundaries was calculated as a baseline. In addition, the current peak power flow was estimated using the methodology presented in section 2.3. This difference represents the necessary grid connection capacity increase if no local storage (or similar measures, such as PtX and DSM) are employed. Notably, the "cost" associated with this capacity increase does not only stem from the actual local infrastructure need, but also the need of the grid as a whole being able to handle the fluctuations passed into it. To calculate the necessary storage sizes, this capacity increase was gradually reduced by 25, 50, and 75 %, resulting in a total of 12 combinations of scenarios considering the 4 curtailment levels. The case of no reduction by definition leads to no necessary storage capacity, as all local fluctuations are handled by the grid (import and export over municipality perimeter). As described in section 2.1, a cost-optimal solution for a municipality (i.e. combination of curtailment, storage deployment, and grid capacity increase) is assumed in most cases to consist of all three measures to a varying degree. While the results presented in this report do not assign costs to these measures, they show valid combinations for a wide range. Results including economic considerations are intended to be presented in the third report in this series (deliverable report D3.9).

While for most combinations of curtailment and grid capacity increase reduction, there exists a storage with finite capacity that is able to deal with all resulting fluctuations, there are cases where no solution exists because the energy balance cannot be leveled out over the simulation year. In those cases, the average production or consumption of a municipality is larger than the export or import restriction, respectively. In all pertinent plots, those municipalities are shown in gray. It highlights another peculiarity of this analysis, though: Under any given scenario, the obvious impulse is to add all resulting storage sizes in order to give an estimate for the total Swiss need for storage. This can lead to very misleading conclusions however, since the optimal solution for any municipality can differ widely depending on a range of factors. Illustratively, in a rural municipality with a very large share of PV, the positive impact of curtailment is much higher than in an urban municipality with generally much higher consumption.

In the following, the resulting storage sizes necessary to accommodate a certain grid connection capacity increase reduction under various curtailment scenarios is shown. The results are only shown exemplary for a single scenario: 62.5% curtailment, 50% grid connection capacity increase reduction. A comparison of the results (i.e. storage size calculation) under different scenarios is explicitly not made, as it will lead to seriously misguided conclusions. The storage size resulting under a given scenario is only one of three components necessary to achieve a valid solution, the other ones being, as discussed, the amount of PV curtailed as well as an increase in grid connection capacity. A cost-optimal solution is highly dependent on the specifics of each municipality. Therefore, while a certain combination of measures might be optimal for one municipality, it can be very suboptimal for another. There is for example little value in presenting the storage size needed for Zürich in a scenario with high PV curtailment, while local consumption not generation is decisive for the calculation of local storage size. This cost-weighed comparison is the main focus of the next report, which then finally gives a quantitative estimate for the need of storage (or in general energy-shifting measures) under a cost-optimized scenario, for all Swiss municipalities. While the results of only one selected scenario are shown, all described variations are planned on being used to facilitate the described analysis.

3.2 Selected Results

Figure 30 shows the minimum necessary storage capacities in order to accommodate a scenario with 62.5% peak power PV curtailment and local import/export limits of 50% compared to the baseline (see section 2.5.3 for an illustration of this process). Note that the presented numbers with regards to storage capacities correspond to a perfect minimum (i.e. achieved by a perfect control system with absolute knowledge of the future) of a 100% efficient storage. In any real system, the inefficiencies of both the employed technology itself as well as some leeway for inefficiencies in the storage control system as well as a certain safety factor for uncertainties need to be accounted for. While the absolute values give an idea of the scale, the more important result is the distribution of necessary storage sizes.

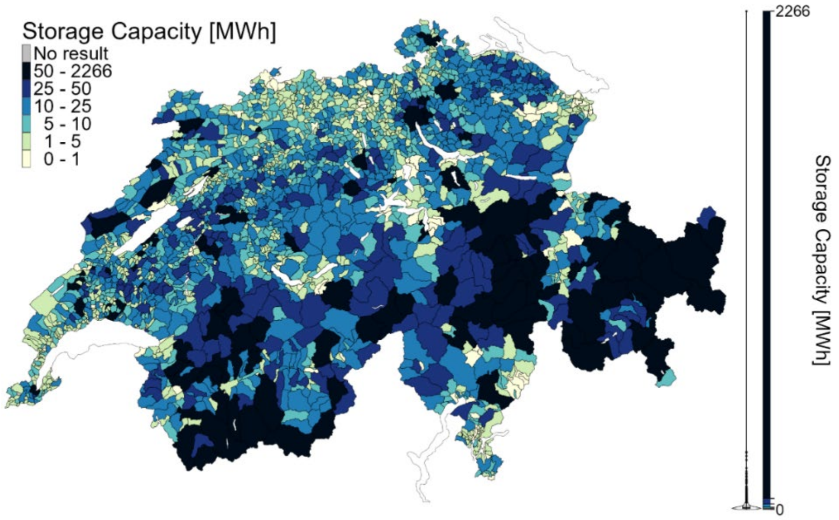

Figure 30. Absolute values of minimum necessary storage capacities under a 62.5% curtailment scenario where import/export capacity is reduced by 50% compared to the baseline. Note that the color scale shows every storage size above 50 MWh as equal.

As can be seen from this example, there are stark regional differences, caused by the differences in production and consumption patterns. It is important to stress the fact that a large value, e.g. >1 GWh necessary storage in a remote grison village merely means that this scenario is highly sub-optimal for this given municipality. The cost-optimal solution in this case will consist of either more curtailment, or more grid capacity. Conversely, a very low value can indicate that either less curtailment is necessary, or more grid capacity increase can be avoided before any additionally necessary storage becomes prohibitly expensive. Even in this quite aggressive scenario, there are multiple municipalities with a storage demand of less than one MWh – roughly the capacity of 20 modern EV's. Figure 31 shows the distribution of necessary storage size under this scenario normalized by relative population. In this form, the correlation with population density is more clearly visible. It also shows that in many municipalities, the necessary storage capacity per inhabitant is in a very attainable region.

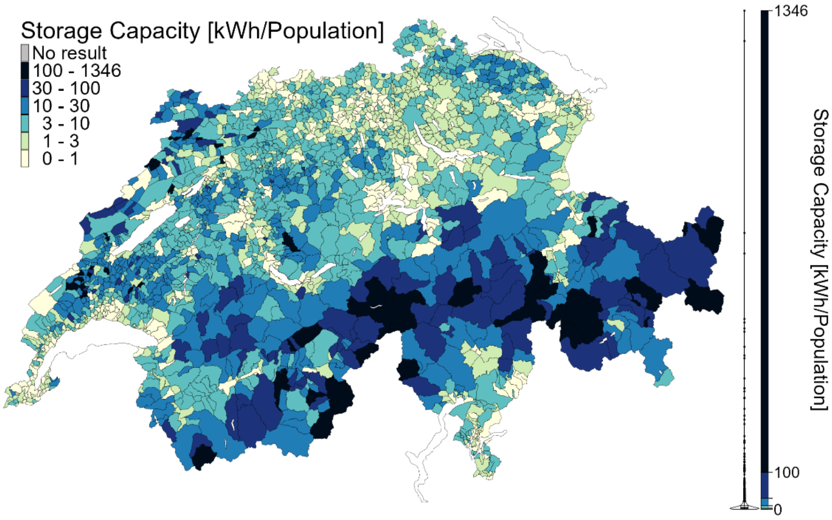

Figure 31. Minimum necessary storage capacities per capita under a 62.5% curtailment scenario where import/export capacity is reduced by 50% compared to the baseline. Note that the color scale shows every storage size above 100 kWh per capita as equal.

Figure 32 shows a spatial analysis of the drivers of storage need in this scenario, i.e. how much of the necessary storage capacity is caused by surplus generation or excessive consumption, in each municipality. In this scenario, there is a clear distinction between urban and rural regions, whereby urban municipalities often are consumption-dominated, while rural muncipalities are dominated by generation. This analysis gives a clear indication over the viability of additional PV curtailment: Wherever the need for storage is dominated by consumption, additional curtailment will not help to reduce this need. Note the similarity of this plot to the distribution of self-sufficiency presented in the previous report.

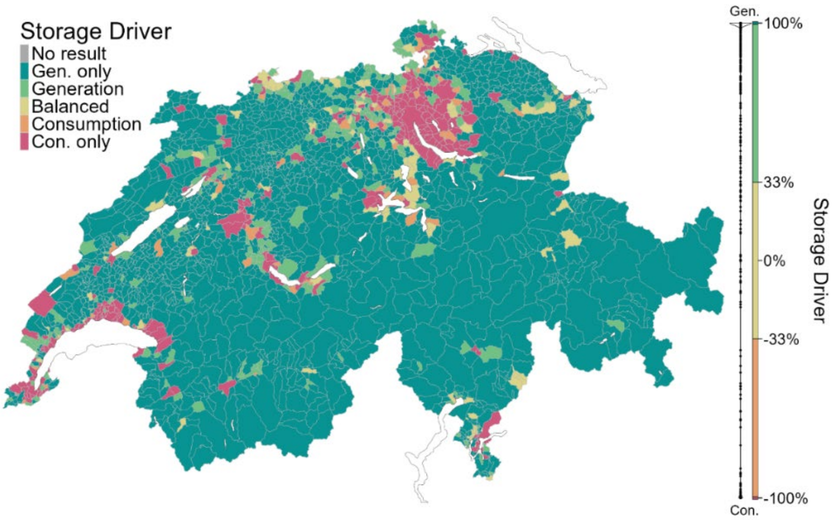

Figure 32. Drivers of storage need in the scenario with 62.5% curtailment and 50% reduction in local import/export limits. The extreme values correspond to municipalities where (under the assumption of symmetric capabilities of the grid) only either generation or consumption are responsible for a need of storage.

An interesting analysis can be made if the minimum discharge time is compared to the necessary storage capacity in each municipality. This discharge time is the inverse of the maximally observed power generation or consumption of the storage, normalized by the storage capacity. A higher value corresponds to higher power density requirements, and at least hints to a storage that operates on shorter timescales (i.e. daily storage vs. seasonal storage). Figure 33 shows the distribution of all Swiss municipalities located by necessary storage capacity and minimum discharge time, with favored technologies indicated in the background (illustration and data adapted from [13]). Figure 34 highlights the region of interest, with all municipalities located within this small excerpt. As the storage size algorithm downsamples the dataset to 1h-Intervals for computational efficiency, the minimum possible necessary charge/discharge time naturally corresponds to this timescale as well. Details regarding the EDGE-Region classification used here can be found in deliverable report D1.2 [1].

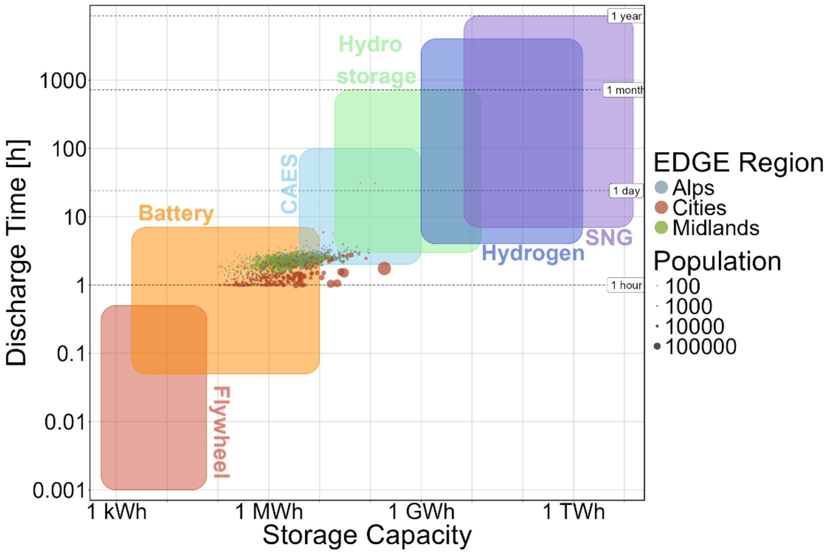

Figure 33. Minimal discharge time vs. necessary storage capacity in a scenario with 62.5% peak power curtailment and a 50% reduction in import/export limits compared to the baseline. Indicated are regions where current technologies are the favored option (CAES: Compressed Air Energy Storage, SNG: Synthetic Natural Gas, illustration adapted from [13]). The color of the datapoints correspond to the EDGE-Region classifications, the bubble size scaling corresponds to the respective population of each municipality. Figure 34 shows a close-up of the region of interest.

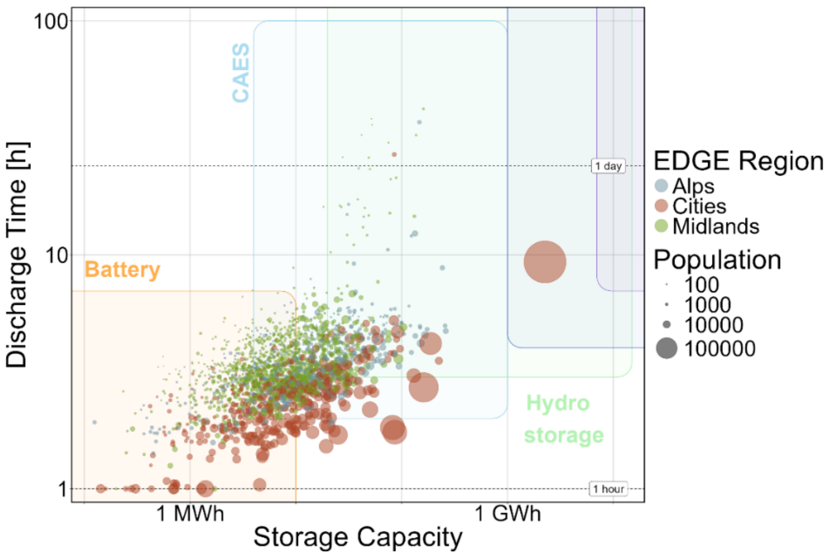

Figure 34. Excerpt of Figure 33, showing in more detail the distribution of municipalities plotted according to necessary storage capacity and minimal discharge time, with currently favored technologies indicated in the background.

Figure 35 shows the number of full charging/discharing cycles plotted against the respective storage sizes as well as the distributions in each dimension according to the EDGE-Regions. Notably, a low number of full cycles can correspond to both seasonal storage as well as storage for only a single, highly volatile day. Figure 36 shows the maximum storage time for each municipality under the presented scenario constraints. While there are some municipalities that show a need for multi-day or even seasonal storage, the vast majority of Swiss municipalities only require intraday storage under these scenario constraints.

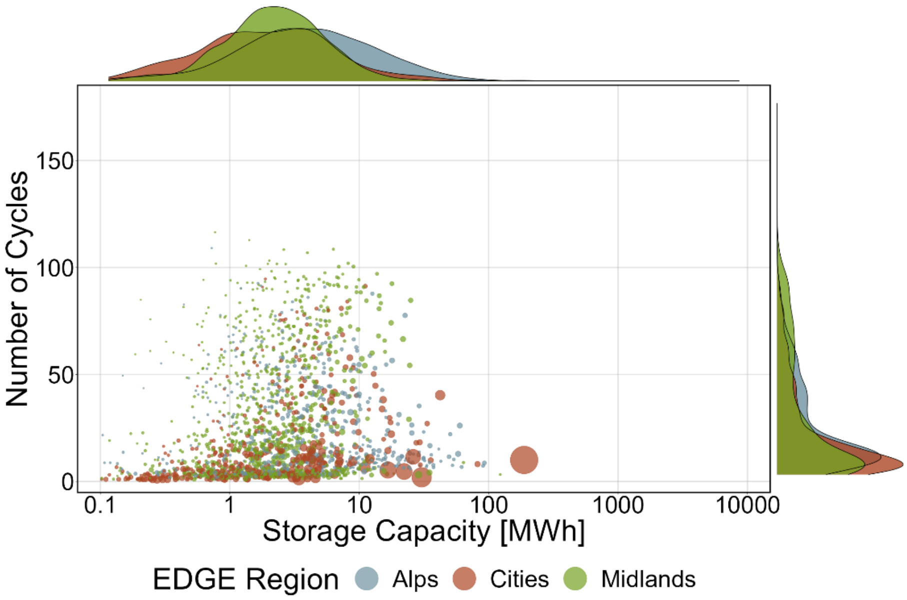

Figure 35. Distribution of necessary storage capacities and number of full charging/discharging cycles (a measure of utilization) over a whole year in the scenario of 62.5% curtailment and a 50% reduction in import/export limits compared to the baseline, with the respective density distributions in each dimension given on the opposing side.

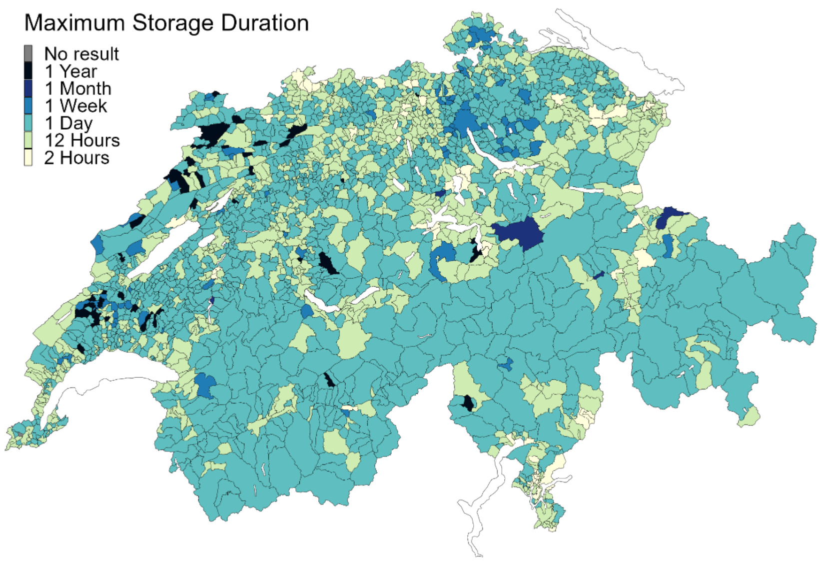

Figure 36. Maximum storage time per municipality in a scenario with 62.5 % peak PV power curtailment and a 50% reduction in grid connection capacity increase, calculated as the maximum time between equilibrium points of the storage fill level. While there are a few municipalities that require multi-day or even seasonal storage to function on a local level given these scenario constraints, the vast majority of Swiss municipalities only requires intraday storage.

The CH-wide aggregated residual power generation under the presented scenario constraints is shown in Figure 37. Note that as discussed before, aggregating all municipalities under the same scenario is far from any cost-optimal solution. The profile shown in Figure 37 is therefore to be understood only as illustratitive of the rough characteristics that are to be expected when implementing curtailment and local storage.

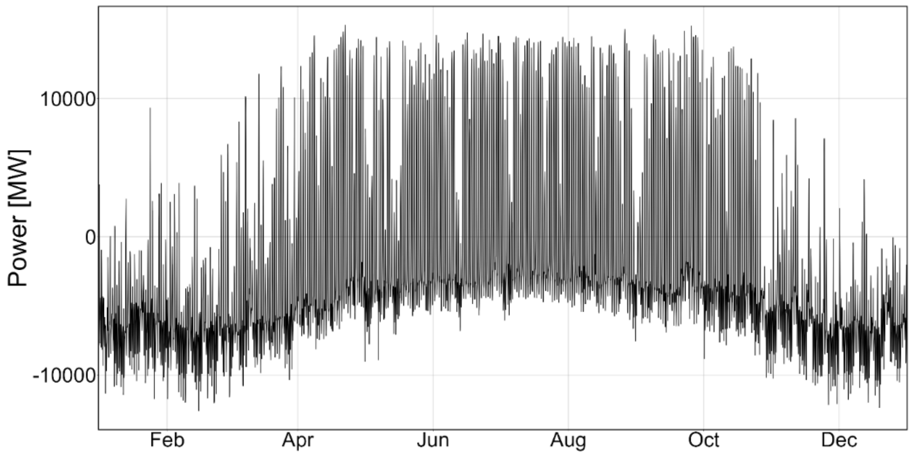

Figure 37. CH-wide aggregated residual power generation (negative numbers correspond to a net load on the grid), under the scenario of 62.5% curtailment and 50% individual grid connection capacity increase reduction.

4 Conclusions

The technical solutions for Switzerland to successfully achieve the energy transition are available today. With much higher shares of intermittent renewables in the power system, energy shifting and power balancing will become more important. The technical analysis of energy shifting methods of this report shows that storage, curtailment, and grid expansion can support the challenges in similar fashion, but each come with their own set of benefits, costs, and specific characteristics.

While increasing grid capability can fully resolve local issues (but problems might arise on higher grid levels), curtailment and local storage have more specific use cases. Curtailment is effective in cases of local overproduction, a problem that is very location specific. Local Storage can reduce peak power flow but not eliminate the need for grid enhancement entirely in every case. The theoretical maximum efficiency of storage aligns peak power flow to average consumption/generation, which may still exceed current grid capabilities. To a large extent, the local characteristics of the electricity system determine which solution is better suitable from a technical perspective. We assume that the technical advantages also translate to economic advantages.

The ultimate choice of which combination of technologies Switzerland will use to achieve its decarbonization goals is a political decision, whereby the technical fit of solutions is going to be one factor among many, with cost and acceptance considerations being two other important aspects. It serves as a basis to go more into certain directions and can unveil general tendencies. The third and final report in this series will include a techno-economic analysis of the need for energy shifting, where costs for different solutions are going to be compared.

In the presented medium scenario (PV curtailment level 62.5 %, grid expansion reduction of 50 %), the required storage characteristics for a majority of municipalities could be served by batteries, while compressed air energy storage or hydro storage could be useful for municipalities with bigger storage requirements. These findings demonstrate that the solutions for the energy transition in Switzerland are available. It is a societal choice, which ones we want to use.

It is also evident that there are vast differences in calculated storage requirements, meaning that a considerable share of municipalities would need storage with low energy capacities to already cover most of their need for energy shifting. Some municipalities on the other hand have such high storage requirements that stronger measures in terms of grid expansion, curtailment, and DSM will most likely be the far better solution from a techno-economic view. Ultimately, a multitude of factors play into finding the best solution, which can and will be different for each Swiss municipality. While minimizing cost is certainly a valid approach, factors such as very long timescales for grid expansion approval processes and limited potential for PV overbuilding (needed for effective curtailment) need to be taken into consideration.

From a technical perspective, PV curtailment comes with many advantages as it is an easily implementable solution that effectively deals with the problem of grid congestion, making PV a firmer source of power. It is especially important in Switzerland because of strong reliance on rooftop PV in the Swiss renewable expansion plan. The less diversity there is in the generation park, the more important curtailment becomes in providing stability. Our analysis shows however, that the role of curtailment should, from a technical point of view, be defined very individually depending on the specific energy system of a municipality. Rural municipalities (often located in the Alps) are projected to feature large excess generation peaks caused mainly by PV. Curtailment is well suited to deal with such situations. Municipalities in the midlands already have more balanced local power systems, where curtailment will most likely play an important but less prominent role. Urban municipalities on the other hand have large loads and strong power grids, thus making them ideally suited to take up additional generation. Curtailment will play a smaller role in such settings.

On top of the location specific suitability of curtailment, the curtailment strategy has a strong influence on its effectivity and location where its effects materialize. When deciding for a strategy, it is therefore important to clearly analyze the problems that need to be solved and set the goals that should be achieved.

The results demonstrate that even in our fully decarbonized setting, many highly urbanized areas are still mostly demand-dominated in terms of need of energy shifting. The additional decentralized generation was allocated to municipalities evenly according to their potential. Highly urbanized areas should therefore realize more of their potential than other parts of the country, relatively speaking. In addition to having a big consumption, urban areas profit from other advantages due to the higher population density namely strong power grids for easier grid integration and a lot of potential for other approaches like DSM or bidirectional car charging.

The energy system's complexity involves various technologies, long investment cycles, policy dependencies, legacy issues, location specific challenges, and a big number of actors. Simulations can highlight broader trends but are limited by the complexity and the necessity to make a plethora of assumptions. The therefore may not serve to give definitive answers to detailed questions. Synergies between municipalities and regions, as well as between different technological solutions, play a crucial role in optimizing the overall energy system. For almost all municipalities there is very likely no silver bullet but an individual composition of several measures like grid expansion, curtailment, storage, and demand side management that proves to be optimal, with diminishing returns for each measure when used in isolation.

This report intentionally contains few quantitative details because it is essentially a presentation of interim results. The use of precise figures at this stage could lead to erroneous conclusions; therefore, quantitative comparisons were only presented to a limited extent. With the third report the analysis will be completed by integrating cost assessments, and only from that point will it be meaningful to make precise quantitative comparisons. This report focused on the quantitative methodology and interactions between optimal storage size determination and PV curtailment. The third and last report[6] in the series will focus on the techno-economic considerations, contain a synthesis of findings to propose the role of energy shifting technologies in Switzerland and analyses of synergies between municipalities or even regions.

[6] Scheduled for May 2025

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Appendix A: Storage Size Calculation Method

A.1 Introduction

Determining the minimum necessary storage size for a given production and consumption timeseries with such that the combination with an instantaneous storage power (i.e. change in storage fill level over time) does not violate imposed export and import limits, is not straigth-forward. Here, a methodology is presented that results in an optimally small storage size for this given problem, assuming perfect knowledge of the future, which is necessary to operate the storage in an efficient way. Obviously this does not result in a realistic number, as any real-world application does not have perfect foresight. This course of action has two major advantages however, being a) that it makes results as comparable as possible between multiple municipalities, and b) that it provides a hard lower limit, that any conceiveable advanced control system could only approach. All quantitative results obtained should be interpreted with this in mind. Further, even thought the extension to inefficient storage is shown in this section, it is not applied at this stage.

A.2 Definitions and Problem Statement

The following timeseries data (in sufficient resolution, 15'-Intervals in this report) are assumed to be given:

- Local Production Timeseries $P(t) > 0$
- Local Consumption Timeseries $C(t) > 0$
- Export and Import Limit Timeseries $L_e(t), L_i(t)$
-

By definition, both production and consumption as well as the export and import limits are all defined as positive values. Figure 38 shows exemplary production and consumption timeseries for illustrative purposes, the values of which are used throughout this document.

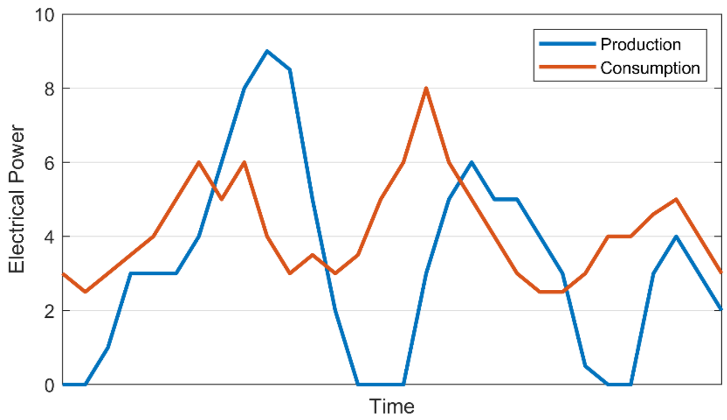

Figure 38. Exemplary evolution of local production and consumption. The curves are unitless for illustrative purposes. All further shown plots are based on these values.

From production and consumption, a local mismatch (delta) is calculated such as

$$\delta(t) = P(t) - C(t) \quad (1)$$

therefore, $\delta(t)$ is positive if power is exported. Importantly, all "continuous" variables shown here are discrete in reality, usually in 15' intervals (but can be longer if downsampled for efficiency). The derivation can be discretized at a later stage. Figure 39 shows the exemplary mismatch timeseries with import and export restrictions. Note that even though both import and export limits in general are time-dependent variables, they are chosen constant for the purposes of illustration in this context.

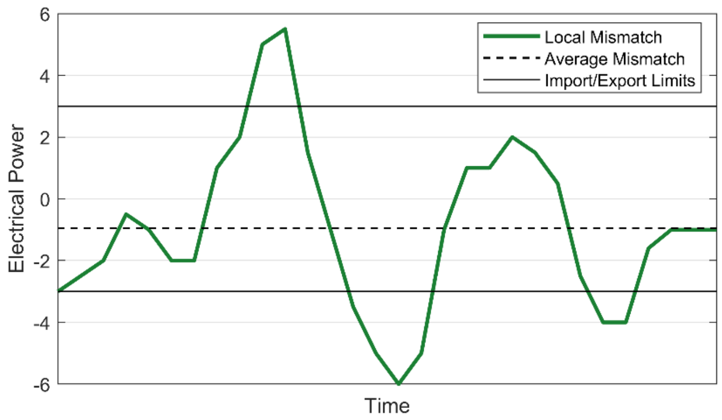

Figure 39. Local mismatch calculated as production (P) minus consumption (C). The dashed line shows the average mismatch, which in this case is negative, i.e. representing a municipality with net consumption. The upper (export) and lower (import) imposed limits are indicated with black lines. While the mismatch curve (apparent production curve of the municipality) mostly stays within the limits, there are three distinct violations (one export and two import limit violations).

The value of $\delta(t)$ can be understood as the apparent production of a municipality if its own consumption is already subtracted, and no other measures are taken. We prescribe that it should be bounded by the export and import limits at all times. In any interesting case, this causes an issue where either of the limits is violated.

We can introduce a measure to remedy this problem, i.e. a battery storage (but more generally any measure that can either consume or produce electricity in some form). The word "storage" will be used throughout to refer to a general measure capable of removing and returning electrical energy from the system. We define $\gamma(t)$ to be the net production of such a measure, from which follows that $\gamma(t) < 0$ if it is consuming electricity locally. The apparent local mismatch then becomes:

$$\delta'(t) = \delta(t) + \gamma(t) \tag{2}$$

The limit through import and export is now applied to this local apparent mismatch, instead of the actual mismatch. Importantly, this now creates two separate regimes: (1) when the local mismatch exceeds import/export limits, the measure $\gamma(t)$ *has* to provide or consume a certain amount of electricity in order to have the apparent local mismatch conforming to the limits, and (2) when the local mismatch is within import/export limits, the measure $\gamma(t)$ *can* produce or consume electricity up to a certain extent.

Further, we have to introduce a constraint with this measure. In its simplest form, a perfectly efficient energy storage, we can prescribe:

$$\int_0^T \gamma(t)\, dt = 0 \tag{3}$$

which forces all electricity production and consumption to equal over a chosen timeperiod T (e.g. a year). We can further define the current storage level as

$$\Gamma(t) = \int_0^t -\gamma(t)\, dt \tag{4}$$

where the negation is a direct consequence of the sign convention introduced in the beginning of this section. The necessary storage size is then found as

$$S = \max(\Gamma(t)) - \min(\Gamma(t)) \quad (5)$$

If one visualizes this measure as e.g. a battery storage, it becomes apparent that the solution for $\gamma(t)$ is not singular, but rather depends on charging/discharging strategies. As a practical example: Assume a very sunny summer day in a municipality with very large PV production and unlimited export capacity – however no import capacity. A storage needs to make up for all unmet consumption during the night. The electricity needed for this needs to be consumed by the storage during the day. This can however be achieved in infinitely many possible ways, as the the equation is only loosely constrained in many regions.

We can define an upper and a lower boundary for storage (or more general, any measure) consumption and production at any time:

$$\begin{aligned} \gamma_{max}(t) &= L_e(t) - \delta(t) \\ \gamma_{min}(t) &= -L_i(t) - \delta(t) \end{aligned} \quad (6)$$

Note the (positive) definition of the import limit. The given equations describe a maximum and minimum net storage production at any time, such that the apparent mismatch is within the prescribed limits.

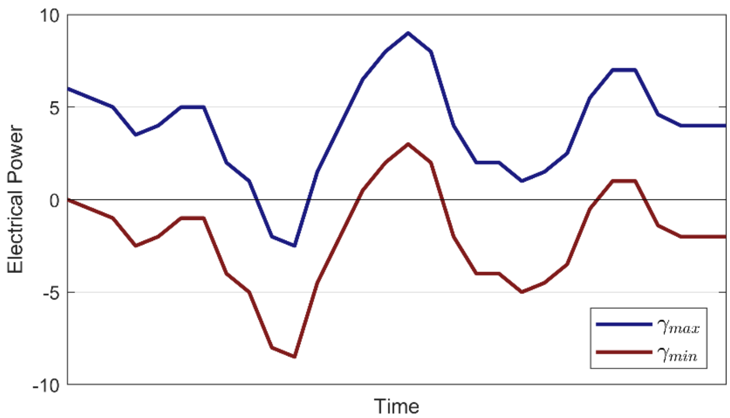

Figure 40. Upper (γ_{max}) and lower (γ_{min}) boundaries for net storage production. The solution to the optimization problem must be contained between those boundaries and satisfy eq. (3).

The question can now be formulated as follows: What is the minimum storage size able to accommodate these constraints?

$$find: \gamma_{min}(t) < \gamma(t) < \gamma_{max}(t) \;\; s.t. \;\; S \; is \; minimal$$

A.3 Iteration Algorithm

A.3.1 Initial Values

In the following, subscripts define (real) time steps, whereas superscripts are used to identify algorithm iterations. We define for each timestep a relative production/consumption rate:

$$\Gamma_{i+1} = \Gamma_i - (t_{i+1} - t_i) \cdot \gamma(t_i) \\ = \Gamma_i - (t_{i+1} - t_i) \cdot \left(a_{i+1} \cdot \gamma_{max}(t_{i+1}) + (1 - a_{i+1}) \cdot \gamma_{min}(t + 1)\right) \quad (7)$$

With $0 < a_i < 1$, the rates are bounded at all times by the prescribed minima/maxima. The algorithm works on altering these values over many iterations. An initial guess is made:

$$a_{i+1}^{(0)} = \min\left(1, \max\left(0, \frac{\gamma_{min,i} + \frac{\Gamma_i^{(0)}}{t_{i+1} - t_i}}{\gamma_{min,i} - \gamma_{max,i}}\right)\right) \quad (8)$$

To put this formula into plain words: For each timestep, it is assumed that the goal is to get the filling level (Γ) as close to zero as possible. This can be limited by 0 and 1, respectively, to yield a curve that conforms with the import and export limits. Although this initial curve is a valid solution, it is not an optimal one. Specifically, it does not minimize the storage size, mainly due to the fact that it only ever reacts, even though perfect knowledge of the future is available. As an example, let's envision a situation where the storage has to provide a certain amount of energy, then sits idle for some time, then needs to consume that same amount. An optimal solution would leave the storage depleted after the first step, since the storage space is needed in the third. The initial solution however would immediately try to reach its base state again, with additional storage capacity then being required.

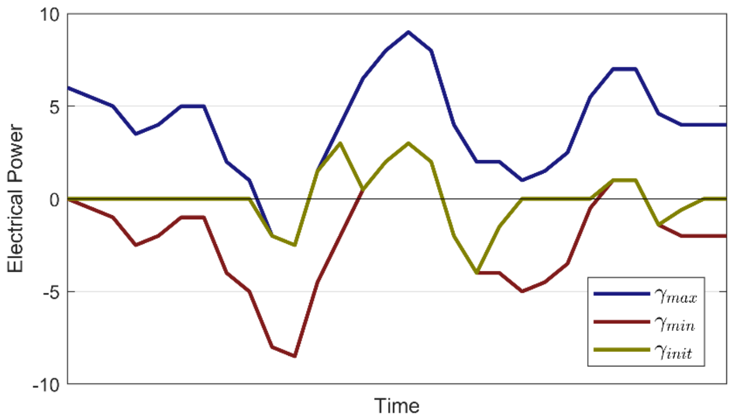

Figure 41. Initial guess for storage net production (γ_{init}) according to eqn. (8).

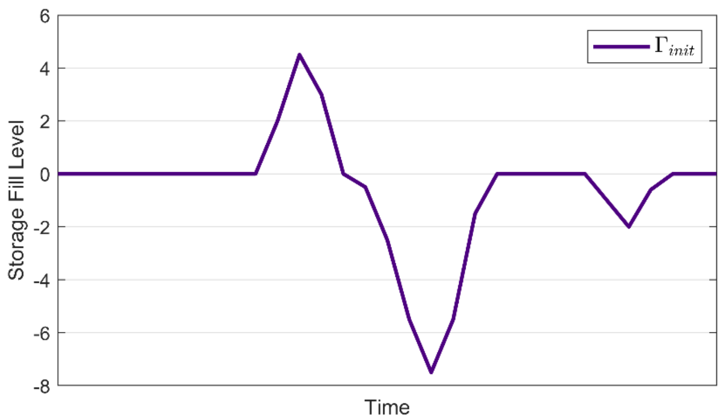

Figure 42. Initial guess for storage fill level (dt = 1) according to eqn. (7). Note the (virtual) negative storage levels.

Figure 41 shows the initial guess for the storage net production according to eqn. (8), while Figure 42 shows the resulting storage fill level (using a unitless timestep dt = 1).

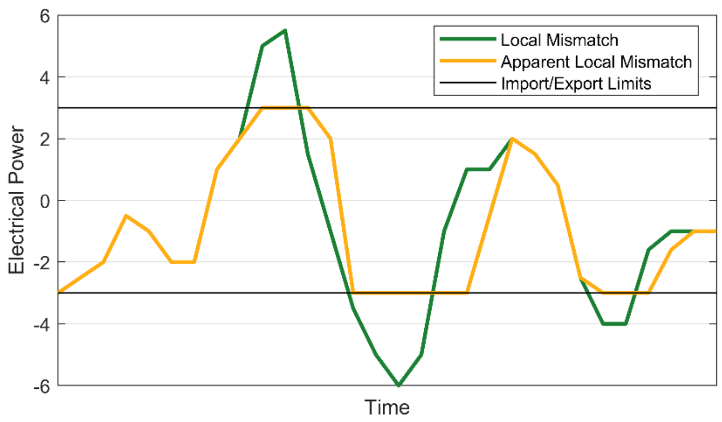

Figure 43. Local mismatch (δ) and apparent local mismatch (δ') according to eqn. (2). Note that the apparent mismatch perfectly conforms to the imposed import and export limits.

An important note here: This algorithm can and should produce negative storage fill levels. In fact, given the methodology shown in the next steps, positive and negative fill levels should be exactly balanced. However, the whole fill level can be shifted to positive values a posteriori, without changing the actual rates – thereby leaving its impact unchanged.

The resulting apparent local mismatch curve according to eqn. (2) can be seen in Figure 43. While this is (by virtue of its construction) a valid solution to both the constraints of eqn. (3) as well as $\gamma_{min}(t) < \gamma < \gamma_{max}$, or more broadly $-L_i(t) < \delta'(t) < L_e(t)$, it is not a solution that necessarily minimizes the absolute storage size S. In fact, there is no indication why that would be the case in the first place. From the example seen in the figures, it clearly is not optimal.

<u>A.3.2 Optimization</u>

The shown initial (educated) guess for the storage fill level is subsequently iteratively modified to be more optimal. To this end, a quasi-physical simulation of nodes affected by gravity and spring forces is employed. Each node Γ_i is affected by two (usually) opposing forces:

- A force counteracting the actual (absolute) storage level, trying to minimize it
- A force affecting two nodes that violate the $a_i \in [0,1]$ condition.

Formally, these are constructed as such:

$$F_{a,i} = -\alpha \cdot |\Gamma_i|^{\nu} \cdot sign(\Gamma_i) \tag{9}$$

$$F_{v,i}^{+} = -\frac{1}{2}\beta \cdot \begin{cases} a_i & if \quad a_i < 0 \\ 0 & if \;\; 0 < a_i < 1 \\ a_i - 1 & if \quad a_i > 1 \end{cases} = -F_{v,i+1}^{-} \tag{10}$$

The condition violation forces F_v are applied symmetrically to the two nodes affected by it, hence $F_{v,i}^{+} = -F_{v,i+1}^{-}$. The cumulative force on a node then becomes

$$F_i = F_{a,i} + F_{v,i}^{+} + F_{v,i}^{-} \tag{11}$$

The evolution of each storage fill level in iteration k is then defined as

$$\Gamma_i^{(k+1)} = \Gamma_i^{(k)} + F_i^{(k)} \quad (12)$$

where a relative strength term is implicitly defined by the choice of α and β. The parameter ν is chosen to be larger than 0, such as to minimize the maximal storage levels. For each virtual timestep, parameters α and β have to be chosen in a numerically stable region. This generally implies $\beta < 1$, with α dependent on ν but generally $\alpha \ll 1$ and $\alpha \ll \beta$. The idea is to gradually reduce absolute storage fill levels, while violations of possible fill level changes (imposed by import/export restrictions) are penalized much more strongly.

Finally, this system will reach equilibrium if $F_i = 0\ \forall i$. This implies either that all storage levels are 0 (which usually is not a satisfactory outcome), or that the aforementioned fill level change restrictions are violated in equilibrium, proportional to $\frac{\alpha}{\beta}$. An applicable solution to this issue is to gradually relax the forces acting on the absolute storage fill level, i.e. decreasing the parameter α. This is achieved by $\alpha^{(k+1)} = (1 - r_\alpha) \cdot \alpha^{(k)}$ where $r_\alpha \ll 1$. In most cases, a decrease parameter of $r_\alpha = 5 \cdot 10^{-6}$ was used. As the absolute storage fill level forces gradually decrease, the relative strength of the fill level change violation penalization increases, thereby leading to a solution with very minimal violations.

The algorithm uses a convergence criterion to determine its endpoint:

$$c^{(k)} = \sqrt{\frac{\sum_{i=1}^{N}\left(\Gamma_i^{(k)} - \Gamma_i^{(k-1)}\right)^2}{N}} \quad (13)$$

i.e., the algorithm stops as soon as the standard deviation of the storage level changes gets below a certain threshold. Generally, a value of $c_{lim} < 10^{-8}$ is used.

By the nature of the force construction, all fill levels tend to zero. This obviously results in a fill level curve with a large number of negative values. However, as technically only fill level changes are analysed, it is trivial to adapt this a posteriori by adding the minimum storage level throughout. However, this means that the storage always tries to return its fill level to half full, which is not necessarily realistic – even though it does not influence the calculation of an optimally small storage size.

A.4 Inefficient Storage

So far, only perfectly efficient storage was considered, i.e. with a 100% round-trip efficiency. Obviously, this presents a strong simplification. No storage is perfectly efficient, and efficiencies can be furthermore tied to storage durations. It is therefore necessary to introduce the parameter of efficiency, $\eta \in [0,1]$. We can further make the distinction between charging and discharging efficiency, η_c and η_d, by defining $\eta = \eta_c \cdot \eta_d$. For simplicity, time-constant efficiencies are assumed at this stage, i.e. losses are incurred during charging/discharging, as opposed to during actual storage. Eq. (4) can thus be extended to

$$\Gamma(t) = -\int_0^t \eta_c \gamma(t) \cdot H\big(\gamma(t)\big) - \frac{\gamma(t)}{\eta_d} H\big(-\gamma(t)\big)\, dt \quad (14)$$

where H denotes a Heaviside unit step function. Note that $\gamma(t)$ is defined as the power going into or being retrieved from the storage, i.e. with a system boundary outside the inefficiencies. Note also that consequentially, a charging efficiency of $\eta_c = 0$ could be used to represent general curtailment within the scope of this analysis. Using this definition ensures the continued validity of eqn. (6).

The difference in the continuous storage fill level equations, eqn. (4) (representing perfectly efficient storage) and eqn. (14) (representing inefficient storage), is now extended to the discretized form (analogous to eqn. (7)):

$$\Gamma_{i+1} = \Gamma_i - (t_{i+1} - t_i) \cdot \left[\eta_c \gamma(t_i) \cdot H\big(\gamma(t_i)\big) - \frac{\gamma(t_i)}{\eta_d} H\big(-\gamma(t_i)\big)\right] \quad (15)$$

where

$$\gamma(t_i) = \big(a_{i+1} \cdot \gamma_{max}(t_{i+1}) + (1 - a_{i+1}) \cdot \gamma_{min}(t+1)\big) \quad (16)$$

The initial guess for the coefficients a_i has to be formulated conditional:

$$a_{i+1}^{(0)} = \begin{cases} \min\left(1, \max\left(0, \dfrac{\frac{1}{\eta_c}\frac{\Gamma_i^{(0)}}{t_{i+1}-t_i} - \gamma_{min,i}}{\gamma_{max,i} - \gamma_{min,i}}\right)\right), & \Gamma_i^{(0)} \leq 0 \\ \max\left(0, \min\left(1, \dfrac{\eta_d \frac{\Gamma_i^{(0)}}{t_{i+1}-t_i} - \gamma_{min,i}}{\gamma_{max,i} - \gamma_{min,i}}\right)\right), & \Gamma_i^{(0)} > 0 \end{cases} \quad (17)$$

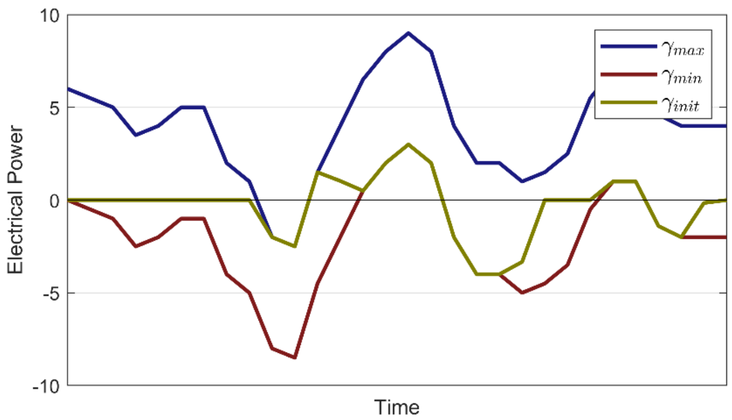

Figure 44. Initial guess for storage net production (γ_{init}) according to eqn. (16), with charging and discharging efficiencies of 75% each. Indicated are the upper and lower bounds for storage net production, which remain unchanged with respect to the perfectly efficient case.

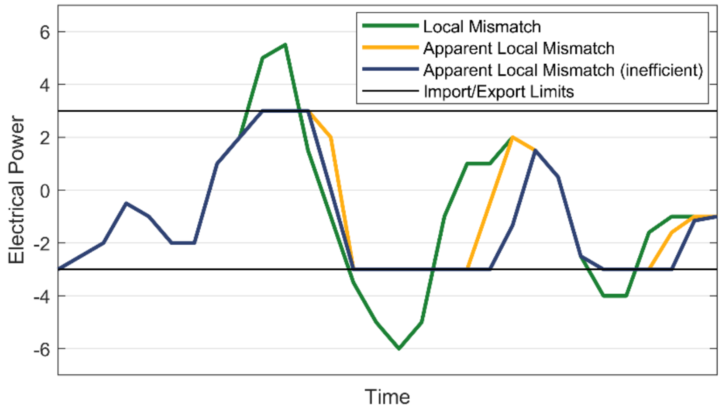

Figure 45. Local mismatch (δ) and apparent local mismatch (δ') according to eqn. (2), for both perfectly efficient as well as inefficient ($\eta_c = 0.75, \eta_d = 0.75$). Note that the apparent mismatch perfectly conforms to the imposed import and export limits, in both cases. Note also that the apparent mismatch is lower throughout in the inefficient case, as electrical energy is continually lost due to inefficiencies.