The Potential of Flexibility Utilisation for Municipalities to Optimally Use the Electricity Grid

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Abstract— **Electrifying the energy system with heat pumps and electric vehicles is a strategy of many countries to reduce CO2 emissions. Large electrification, however, poses several new challenges for the electricity system, particularly in combination with a simultaneous substitution of nuclear power plants by volatile renewables such as photovoltaics. The increasing consumption of electricity and the growing number of installed photovoltaic systems are pushing the existing electrical grid to its limits. Today's grid must be expanded with smart controllers and their components regulated. For this purpose, an understanding of flexible participants such as boilers, heat pumps and electric vehicles, and new production plants such as photovoltaic systems must be built up. The aim of this paper is to present the flexibility potential of the municipality and the proposed energy scheduler for flexible shifting of loads to the optimal location considering defined constraints. The results are used to calculate the new parameters for the locally installed energy management systems, which control appliances according to the scheduler setpoints, to utilise flexibilities for peak shaving optimally.**

Keywords— ***Electric Boilers, Electric Vehicles, Flexibility, Grid Optimization, Heat Pumps, Photovoltaic systems***

I. Introduction

With the net zero target, which the Swiss federal government described in its Energy Perspectives 2050+, the development of the Swiss energy budget is described in detail in three sub-scenarios and in one main scenario, the ZERO Basis scenario. Although overall energy consumption will decrease, electricity consumption will increase. On the one hand, this is due to digitisation and, on the other, to the electrification of different technologies. Electric vehicles (EVs), for example, will experience a multiple increase, and space heating will increasingly be generated by heat pumps (HPs). On average, there will still be CO_2eq emissions. However, direct air capture (DAC) and its storage in the ground, both domestically and in projects abroad, will bring this balance to zero. [1]

Due to the 2050 Energy Strategy, the electricity grid will change significantly. With the strong expansion of renewable energies, such as photovoltaics (PV), wind turbines and hydropower, the foundations of the current grid system are being rattled. Today, electricity no longer flows only from the large power plants, such as nuclear power plants, down to the lower grid levels, but is also increasingly produced locally, consumed, or fed back into the higher grid levels. With electrification comes the high power peaks that push the grids to their technical limits and cause high costs for grid operators. [2]

To manage this expansion of renewables, electrification and digitalisation, the Swiss Federal Office of Energy (SFOE) released a road map to develop smart grids for the Swiss electricity grid. It shows that such smart grids need to be developed in which consumers, prosumers, producers and even grid levels communicate. The basic functionality of a smart grid in Switzerland includes information, control of consumption, storage and production, cyber security, individual system services, market participation of consumers and producers, solutions for influencing consumer behaviour, and easier customer changeover. [3]

A SFOE study states that the estimated theoretical potential of demand side management (DSM) is between 31,030 and 46,556MW. Whereas the potential for use is around 1,077 to 2,613MW. This shows that Switzerland has great potential for DSM and should implement and use this with new smart grid solutions and business models. However, as things stand today, measures are already being taken to shift the burden. On the one hand, through the tariff setting of high and low tariffs and through the ripple control systems, which mainly control boilers and HPs and limit their operating time to date.[4]

A recent result of economic analyses of Consentec, EBP, and Polynomics [5] for Energy Perspectives 2050+ scenarios shows that the real investment required by 2050 is between 45 billion CHF (Business as usual (BAU)) and 84 billion CHF (ZERO A scenario). This additional investment, considering the changed amounts of energy, lead to an increase in low voltage grid usage tariffs between 27 and 70%.

Additionally, current discussions about the failed negotiations of the Framework Agreement between Switzerland and the European Union (EU) show that DSM is becoming increasingly important for Switzerland. As the Association of Swiss Electricity Companies (VSE) and Swissgrid fear, the EU will continuously optimise electricity trade, and Switzerland will be excluded from it without an electricity agreement. This means that import capacities would be cut, and Switzerland would have to deal with more irregularities in the grid. To compensate for these irregularities, the hydroelectric power plants would then be needed, which in turn would be lacking in winter to cover the higher demand. [6]

To counteract this, distribution system operators must prepare and invest in the development and expansion of smart grid systems. To reduce massive investments and

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reinforcement costs of the distribution grid, this work investigates the flexibility utilisation potential for peak shaving purposes, preventing investments into the grid. This is in alignment with the NOVA principle (=Netzoptimierung vor Netzverstärkung vor Netzausbau) demanded by the regulator.

The main sections are explained in the following: Section 1 defines the goals and structure of the paper. The initial situation is intended to show the topic's basis and introduce the reader to the topic. Section 2 introduces the used approach and methodology. Assumptions and considerations are presented in order to develop the energy scheduler and its scenarios for a municipality. The mathematical structure of the algorithm is described in detail. Section 3 explains connections between the federal study and the development in Municipality and summarises the results of the energy scheduler. In section 4, the Discussion and Outlook of results are being interpreted.

II. Approach and Methodology

In the following section the overall controlling concept, the task of the Energy Scheduler (ES) and the program definition, which are used in JupyterLab, for the optimisation task are described. There will be two different program types, the optimal one and the main one. Furthermore, the used data and their preparation as input for the ES and processing of its output are explained.

A. Overall Control Concept

The grid structure dealt with in this work includes not only the different grid levels, but also the communication of the consumers with controllers. Until now, the municipality under investigation has worked with energy management systems (EMSs) as well as smart meters. These communicate and control the corresponding flexibility directly through data from the transformer station. In this way, the load curve is continuously adjusted according to the given situation. However, this procedure does not allow any control by the grid operator (DSO). With the ES, a higher-level calculation of the loads for the municipal grid is to be carried out. An overview is shown in Fig. 1. By considering past load data and weather forecasts, an overall load profile for the next 24 hours is generated by using the Energy Model [7]. This overall profile of the municipality is then given to the ES where its loads are being scheduled, considering shifting limitations and consumer preferences as well as the optimised profile parameterised. These parameters are transmitted to the respective flexibility's local EMSs and control units.

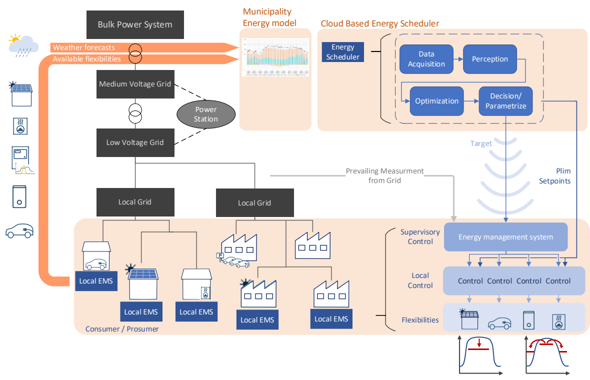

Fig. 1. An overview of the relations between the power grid and communication from the ES to the local flexibilities and their EMSs.

The "Target" is transferred to the EMS, where the EMS follows the scheduled grid loading while considering substation measurements during the day. At the same time, a "Plim" (Power limitation) is passed to the corresponding control units of the flexibility (EV, boiler or HP). A sunny weather forecast translates to a high PV production. Thus, more flexibilities can be shifted to the daytime. In case of bad weather forecasts, the parameters can be adjusted accordingly, and the loads being kept as flat as possible in advance by activating them predominantly during the night.

The EMS calculates an adjusted "Plim" considering the transferred "Target". The control unit now controls the flexibility taking both "Plims" into account. This influence of two "Plims" makes it possible to respond better to the entire municipal grid and thus the local solar power production. But it also makes it possible to respond specifically to each system, as it still allows for autonomy where system-specific influences can be addressed.

B. Data Pre-processing

To optimise the load profile with Gurobi, further steps are needed to prepare the data in such a form that the optimiser can handle it. The main process is shown in Fig. 2. Each block shows a section from the JupyterLab overview and how it is structured. The main process follows the arrows, whereas the dashed lines shows further calculation in a section.

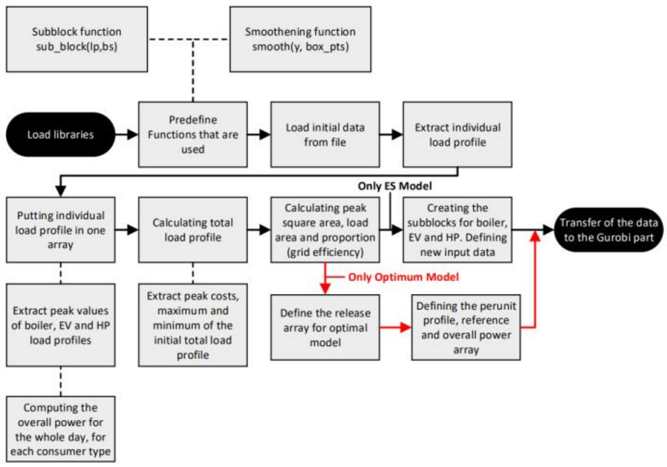

Fig. 2. Process for preparing the input data for the Gurobi program part.

To process the data, there are two different functions needed, which were defined only for this work:

- *sub_block(load profile, block size):* This function is needed to split an aggregated load profile into smaller blocks. It is defined that the user can transfer the load profile and the desired size of the subblocks to the function and they are splitted properly in smaller blocks of the same size and one rest block for each time step. The parameter can be adjusted according to the size of the input load profile.
- *smooth(values, resolution):* This function is needed for smoothing the Plim values. The user transfers the array, which is strongly oscillating and the desired resolution for smoothing it. After the computing, the function returns the smoothed array.

C. Definition of the Pre-parameters

This Section shows the parameters, which are used in the end to compare with the initial situation. It is shown how the costs and the grid efficiency are calculated.

Cost Parameters:
- *peakprice* = 11300 CHF/MW/Mt [9]
- $init_{max}$: Contains the maximum value of the initial profile
- $init_{min}$: Contains the minimum value of the initial profile
- *initalgridcosts* = $\text{init}_{\max} * \text{peakprice}/1000$

Flattening Parameters:
- *peakflattening* = $init_{max} - init_{min}$

Shifting Efficiency Parameters: The shifting efficiency shows, how well the consumers are shifted to obtain the flattest possible profile. If it is 100%, the total load profile will be one straight horizontal line:
- *peak_area* = $init_{max} * 96$ steps
- *totalpower:* Contains the total initial load profile
- *load_area:* sum(totalpower)
- *init_proportion* = *load_area*/*peak_area*

D. Optimisation definition

In the following section, the input parameters, the decision variables, the objective function, and all constraints of each model type are described. There are two different model types considered, the first shows the ideal solution (Optimum model) and the others the realistic scenario (Energy Scheduler Model) with a priority classification.

1) Overall Parameters

The parameters described in this section are used in each model type that is shown below, therefore they are defined here.

t $\in$ *times* = {0, 1, ..., 95}: Set of time steps.
n $\in$ *consumers* = {0, 1, ..., 5}: Set of consumer types.
nconsumer $\in Z^+$*:* Number of consumer types in the load profile. (nconsumer = 6)
ntimestep $\in Z+$*:* Number of time steps in the load profile. (ntimestep = 96)
$\boldsymbol{release_n}$ $\in \{0; 1\}$: Contains whether a consumer can be shifted or not. The value 1 means it is shiftable, and 0 not. In this model it is defined for each individual load profile of each type, which means it contains 6 values.
$\boldsymbol{perunitprofile_{t,n}}$ $\in [0; 1]$: Proportion of each initial load profile to its maximum peak.
$\boldsymbol{overallpower_n}$ $\in R$: Contains information about the sum of the power for each consumer type of the initial load profile.
$\boldsymbol{reference_n}$ $\in R$: The values of each maximum of the initial load profile for each consumer type are saved in the reference.

2) Decision Variables

The following variables are used in each model:
$\boldsymbol{sumtotalload_t}$ $\in R$*:* Total sum of all consumers in the grid.
$\boldsymbol{totalload_t}$ $\in R^+$*:* Absolute values of the sum of all consumers.
minload $\in R^+$*:* Absolute minimum value of the total load profile.
maxload $\in R^+$*:* Absolute maximum value of the total load profile.
peakcost $\in R^+$*:* The main grid costs of the highest peak value of the total load profile.
$\boldsymbol{loadblock_{n;t}}$ $\in [0; 1]$: Variable contains load profile; for Optimum Model variables are continuous, values are between 1 and 0; for Energy Scheduler Model variables are binary, are 1 or 0 according to the $reference_n$ values.

3) Overall Constraints

The following two constraints are used in every model, they are defined to calculate the minimum and maximum for the objective functions 3 and 4.

minconstraint: to determine the minimum value of the shifted total load profile.

$$\text{minload} = \min(\text{sumtotalload}) \tag{1}$$

maxconstraint: to determine the maximum value of the shifted total load profile.

$$\text{maxload} = \max(\text{sumtotalload}) \tag{2}$$

4) Multi-Objective Function

Peakcost to be minimised after optimisation:

$$\text{Min Z} = \text{maxload} * \text{peakprice}/1000\ [\text{CHF}] \tag{3}$$

Flatprofile to minimize the fluctuations between the minimum and maximum peak:

$$\text{Min W} = \text{maxload} - \text{minload} \tag{4}$$

Eq. 1 has the higher priority and has the most impact on reducing the peaks and its costs during a day and months. With Eq. 2, the curve will be more flattened to reduce fluctuations in the overall load profile.

5) Optimum Model Constraints

sumconstraint: This constraint compares the initial area of the power profile with the optimised and defines, that they have to be equal.

$$\sum_{t=1}^{\text{ntimestep}} \text{reference}_n * \text{loadblock}_{t,n} = \text{overallpower}_n \tag{5}$$

shiftconstraint: used to ascertain if the consumer is shiftable or not.

$$\text{loadblock}_{\ t,n} = \mid \text{perunitprofile}_{t,n} \mid \ \text{If} \ \ \text{release}_{\ n} = 0 \tag{6}$$

sumtotal: The absolute value of the total load profile in each time step, needs to be equal as the value in the sumtotalload.

$$\sum_{n=1}^{\text{nconsumer}} \mid \text{reference}_{\ n} * \text{loadblock}_{\ t,n} \mid = \text{sumtotalload}_{\ t} \tag{7}$$

6) Energy Scheduler Model specific parameters

HPsw *= 10:* This value contains the window in time steps how far the HP can be shifted back and forward in time. In this case it is possible to shift it ±2.5h.

EVsw = *12*: This value contains the window in time steps how far the EV can be shifted forward in time. In this case it is possible to shift it about 3h.

nblocks *∈ Z^+:* This parameter contains the amount of all blocks including the subblocks and the not splitted blocks, which were taken from the initial data.

nboiler_blocks *∈ Z^+:* This parameter contains the amount of subblocks that are made to shift the boiler load profile. This value can change according to the amount of boiler energy which is consumed and the size of the chosen subblocks.

nhp_blocks *∈ Z^+:* This parameter contains the amount of subblocks that are made to shift the HP load profile. This value can change according to the amount of HP energy that is consumed and the size of the chosen subblocks.

nev_blocks *∈ Z^+:* This parameter contains the amount of subblocks that are made to shift the EV load profile. This value can change according to the amount of EV energy that is consumed and the size of the chosen subblocks.

nposs *∈ Z^+:* This parameter contains the amount of possible locations to which an EV or a HP can be shifted within the given EVsw or HPsw.

$$nposs\_ev_{ev} = \begin{cases} 96 - \text{start}_c - \text{dutycycle}_c + 1 & ,\text{start}_c + EVsw + \text{dutycycle}_c > 95 \\ \text{EVsw} & , \text{else} \end{cases}$$

$$\forall c \in [\ \text{evpos}, \text{evpos} + 1, \dots, \text{nev\_blocks}\ ]$$

$$\text{nposs\_hp}_{hp} = 1 \begin{cases} \text{start}_c + HPsw - \text{dutycycle}_c + 1, \ \text{start}_c - HPsw < 0 \\ 96 - \text{start}\ c + HPsw - \text{dutycycle}\ c + 1, \text{start} + HPsw > 95 \\ \text{HPsw}\ , \text{else} \end{cases}$$

$$\forall c \in [\ \text{hppos},\ \text{hppos} + 1, \dots, \text{nhp\_blocks}]$$

c ∈ *datarows* = {0, 1, ..., nblocks}: Set of rows in the initial data. **ev** ∈ *evdatarows* = {0, 1, ..., nev_blocks}: Set of rows in the subblock data of the EVs.

hp ∈ *hpdatarows* = {0, 1, ..., nhp_blocks}: Set of rows in the subblock data of the HPs.

i ∈ *possiblelocations* = {0, 1, ..., nposs}: Set of possible locations where the HPs, and the EVs can be shifted.

j ∈ *lengthdutycycle* = {0, 1, ..., dutycycle_c}: Set of steps in length of the dutycycle for each consumer type.

boilerpos = 3 ∗ 96: This parameter contains the position of the first boiler in the input data.

hppos = *boilerpos+nboilerblocks*: This parameter contains the position of the first HP in the input data.

evpos = *hppos* + *nhpblocks*: This parameter contains the position of the first EV in the input data.

$\textbf{power}_c$ ∈ R: Amount of power for each consumer and time step.

$\textbf{dutycycle}_c$ ∈ {0, 1, ..., 95}: This value shows how long the current block is switched on. If only aggregated load profiles are used each of them should be 1. In case it is 0, it will get an error at this place.

$\textbf{start}_c$ ∈ {0, 1, ..., 95}: This value contains information about the time step at which the block is switching on.

$\textbf{end}_c$ ∈ {0, 1, ..., 95}: This parameter contains information at which time step the current block is switched off. The value shows the last step at which it was still switched on. This means, if start = 2 and dutycycle = 3, then it is defined as end = start + dutycycle − 1 = 2 + 3 − 1 = 4.

$\textbf{release}_c$ ∈ {0, 1}: Contains information if a consumer can be shifted or not. Value 1 means it is shiftable and 0 the opposite.

newboilermax ∈ R +: Value for the maximum peak that the optimised boiler load profile may not exceed. This value can be adjusted to each situation. If this value is not chosen high enough, it will get the model infeasible! In order for this to happen this value needs to be increased, so that the amount of the boilers power fits between the defined time window.

newevmax ∈ R +: Value for the maximum peak that the optimised EV load profile may not exceed. This value can be adjusted to each situation.

newhpmax ∈ R +:Value for the maximum peak that the optimised HP load profile may not exceed. This value can be adjusted to each situation.

7) Energy Scheduler Model specific Decision Variables

loadblockc,t ∈ {0, 1}: Contains a binary load profile, 1 shows that the power in each step is > 0 and 0 that the consumer is switched off.

$\textbf{total\_boiler}_t$ ∈ R +: Total consumption of all boiler blocks for each time step.

$\textbf{total\_ev}_t$ ∈ R +: Total consumption of all EV blocks for each time step.

$\textbf{total\_hp}_t$ ∈ R +: Total consumption of all HP blocks for each time step.

$\textbf{heatpump}_{hp,i}$ ∈ {0, 1}: Creating for each block an amount of possibles location within the HP sw, only one of them can be chosen for the final solution. In this case, it is considered that the HP can be shifted forward and back in time steps. Furthermore the boundaries are considered in order for it not to be shifted outside of the time range.

$\textbf{electricvehicle}_{ev,i}$ ∈ {0, 1}: Creating for each block an amount of possibles location within the EV sw, only one of them can be chosen for the final solution. In this case, it is considered that the EV can only be shifted forward. Furthermore the boundaries are considered in order for it not to be shifted outside of the time range.

8) Energy Scheduler Model Constraints

hpsplitconstraint: To shift all HP blocks within the right time window, and consider if the block is longer than one time step, that he may not be splitted and located at two different locations. Furthermore it is considered that they cannot take place in negative time step, in case of shifting backwards.

$$\text{heatpump}_{hp,i} = 1 \begin{cases} \text{If} \displaystyle\sum_{j=1}^{\text{dutycycle}_q} \text{loadblock}_{q,\ 0+j+i} = \text{dutycycle}_q,\ \text{start}_c - \text{HPsw} \\ \text{If} \displaystyle\sum_{j=1}^{\text{dutycycle}_q} \text{loadblock}_{q,l} = \text{dutycycle}_q,\ \text{else} \end{cases}$$

$$\forall l = (\text{start}_q - HPsw + i + j) \wedge q = hp + hppos$$

evsplitconstraint: To shift all EV blocks within the the right time window, and consider if the block is longer than one time step, that he may not be splitted and located at two different locations.

$$\text{electricvehicle}_{ev,i} = 1 \text{ If } \sum_{j=1}^{\text{dutycycle}} \text{loadblock}_{q,l} = \text{dutycycle}_q$$
$$\forall l = (\text{start}_q + i + j) \wedge q = ev + \text{evpos}$$

hpsumconstraint: Constraint, that Gurobi only can take one option for the new HP location.

$$\sum_{i=1}^{\text{nposs}} \text{heatpump } p_{hp,i} = 1$$

evsumconstraint: Constraint, that Gurobi only can take one option for the new EV location.

$$\sum_{i=1}^{nposs} \text{electricvehicle}_{ev,i} = 1$$

boilershift: This defines, that the boilers can be located completely during night time. In this model it is chosen to be between 8 pm and 6 am.

$$\text{loadblock}_{c,t} = 0 \text{ If } t < 59 \forall c \in [\text{boilerpos}, \text{boilerpos} + 1, \dots, \text{nboiler\_blocks}]$$

boiler_totalconstraint: Constraint, where the total load profile only for the boilers is calculated. This restriction is needed as an intermediate step

$$\sum_{c=boilerpos}^{\text{boilerpos + nboiler\_blocks}} |\text{ power}_c * \text{loadblock}_{t,c}\ | = \text{total\_boiler}_t$$

boilershift2: This constraint has a similar definition, such as described in *boilershift*. Only in this case it fixes the total load profile to the location if the time is between 8 pm and 6 am, without it the ES will shift not every block proper in the defined time zone.

$$\text{total\_boiler}_t = 0 \text{ If } t < 59$$

boiler_limit: The new optimized peak of the boiler may not exceed the value that is given with *newboilermax*.

$$\text{total\_boiler}_t \leq \text{newboilermax}$$

boiler_overall: To compare the initial size of the boiler load profile area with the optimised and fix it at the same value, that Gurobi not deletes or adds more power to the profile.

$$\sum_{t=1}^{\text{ntimestep}} \text{total\_boiler}_t = \text{overall\_power}_n \ \forall n = 3$$

hp_totalconstraint: Constraint, where the total load profile only for the HPs is calculated. This restriction is needed as an intermediate step.

$$\sum_{c=hppos}^{\text{hppos + nhp\_blocks}} |\text{ power}_c * \text{loadblock}_{t,c} | = \text{total\_hp}_t$$

hp_limit: To limit the optimised HP load profile to a new peak value that Gurobi not creates artificial peaks in the new profile.

$$\text{total\_hp}_t \leq \text{newhpmax}$$

hp_overall: To compare the initial size of the HP load profile area with the optimised and fix it at the same value, that Gurobi not deletes or adds more power to the profile.

$$\sum_{t=1}^{\text{ntimestep}} \text{total\_hp } p_t = \text{overall\_power}_n \ \forall n = 4$$

ev_totalconstraint: Constraint, where the total load profile only for the EVs is calculated. This restriction is needed as an intermediate step.

$$\sum_{c=\text{evpos}}^{\text{evpos + nev\_blocks}} |\text{ power}_c * \text{loadblock}_{t,c} | = \text{total\_ev}_t$$

ev_limit: To limit the optimised EV load profile to a new peak value that Gurobi not create some artificial peaks in the new profile.

$$\text{total\_ev } v_1 \leq \text{newevmax}$$

ev_overall: To compare the initial size of the EV load profile area with the optimised and fix it at the same value, that Gurobi not deletes or adds more power to the profile.

$$\sum_{t=1}^{n\text{timestep}} \text{total\_ev}_t = \text{overall\_power} \ \forall n = 5$$

sumconstraint: Each amount of ones in each row of the loadblock may not exceed the time, which the block can be switched on.

$$\sum_{t=1}^{\text{ntimestep}} \text{loadblock}_{t,c} = \text{dutycycle}_c$$

shiftconstraint: Is needed to ascertain, if the consumer is shiftable or not.

$$\text{loadblock}_{t,c} = 1 \text{ If release}_n = 0 \wedge \text{start}_c \leq t \wedge end_c \geq t$$

sumtotal: um of all ones in each row of loadblock are summed up and compared with the value of dutycycle for each row and must be equal.

$$\sum_{c=1}^{\text{nblocks}} |\text{ power}_c * \text{loadblock}_{t,c} | = \text{sumtotalload}_t$$

III. Scenarios and Results

A. Scenarios

For a realistic scenario development with a focus on the municipality, the Energy Perspective 2050+ is taken as a basis, considering ZERO Basis, BAU and a so-called potential, or POT (fully exhausted potential) scenarios and shown in Fig. 3

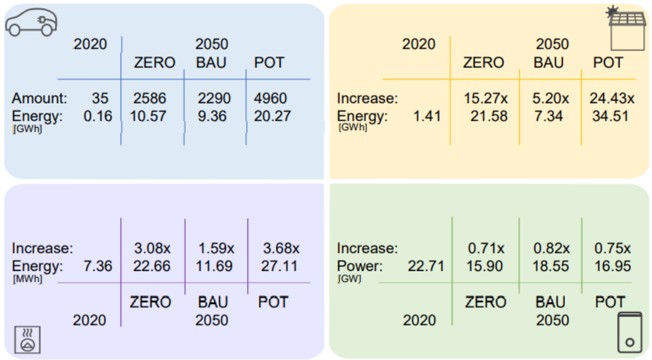

Fig. 3. Three scenarios for the municipality are based on the Energy Perspectives 2050+ [1].

Since the focus is on flexibilities, only these are extrapolated from 2020 to their possible potential in 2050. Households and industry are taken over from ZERO for this scenario. Households will experience an increase from the original 19.1 to 19.3TWh in Switzerland. Industry, on the other hand, will see a reduction from 17.3 to 13.7TWh. For municipality, this means an increase of 1.01 for households, which is from 14.4 to 14.5GWh per year and Industry will decreases from 5.5 to 4.3GWh per year.

In addition to considering future scenarios, alternatives (ALT) were also considered. These are simulations of current loads, but with flexibility scaled up by a factor of 1.2 and 1.5. For each scaling factor, two weather situations are considered, a sunny day and a cloudy day. By scaling individual flexibilities in the total load, both the optimiser is to be checked and the electricity grid analysed. Integrating two weather scenarios is intended to represent a fluctuating electricity production of the PV systems. This leads to a more irregular distribution of the flexibilities during the day. The existing EM was used as the basis for the load profiles [7]. Boiler load profiles are not being adapted and further analysed in these simulations, as the tendency clearly shows, in all scenarios of the energy perspectives, that the consumption will decline over the next years and will therefore decrease its importance of a flexibility.

B. Results

In the following section, the results of this work are shown and described. Only one scenario, in this case the ZERO scenario, is discussed in detail, the others are summarized at the end of the section, the achieved values are compared to show the influence of the different amounts of flexibilities.

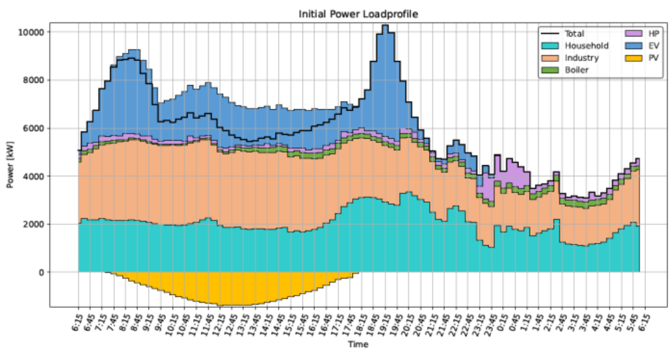

Fig. 4. Initial load profile for the ZERO Winter scenario, before optimization.

1) ZERO Winter

a) Initial Situation

In Fig. 4 is the initial situation for the ZERO Winter scenario shown. The EVs produces two significant peaks. Due to the assumed technology used in the boilers and HPs, their share of the load profile is very small, but most of them run all day. From the PV production it can be seen that these results are from a sunny day without many clouds. This profile is considered as the initial situation and how it could look in the future if no load management were carried out in the grid. This would result in the following peak values and the costs derived from them:

- Peak of 10,290 kW
- Cost of the Peak of CHF 116,279
- Shifting efficiency of 56.6%

b) Optimal scheduling

To show what could be theoretical possible, the extreme model was created and it gives an interesting solution as it can be seen in Fig. 5. Because Gurobi itself decides how many percent it can shift where, the total load profile (black line) in this example is perfectly horizontal. Furthermore, the HPs and boilers are shifted very randomly during the day, in order to fit in an optimised way with EVs and to flatten the total profile. The target in this case would take on a value of 5,823kW. This corresponds to a change in the peak of 43.4%, compared to the initial value. In this case it is possible to decrease the peak related costs to CHF 65,799, this represents a change of CHF 50,479. In this case the shifting efficiency amounts to 100%, with which the consumers are optimally shifted, to get a flat profile and the lowest peak.

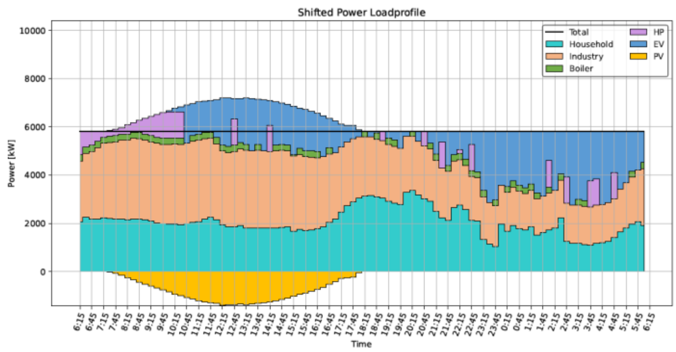

Fig. 5. The theoretical best solution, if many factors are neglected.

c) Energy Scheduler Result

In Fig. 6, the shifted load profile is shown. As it can be seen, the boilers are shifted to nighttime after most of the EVs are finished with charging. The relatively small number of HPs are located during the day, so that no loss of comfort of the end customer takes place. From the picture it can also be seen that the peak has decreased by 3,819 kW to 6,471 kW. This means that costs can be reduced by 37% to CHF 73,124. This means that all the PV power from the EVs can be used throughout the day without having to feed anything into the grid or generate high peaks. The utilisation of the grid also increases to a value of 90% in this scenario due to the control of flexibilities.

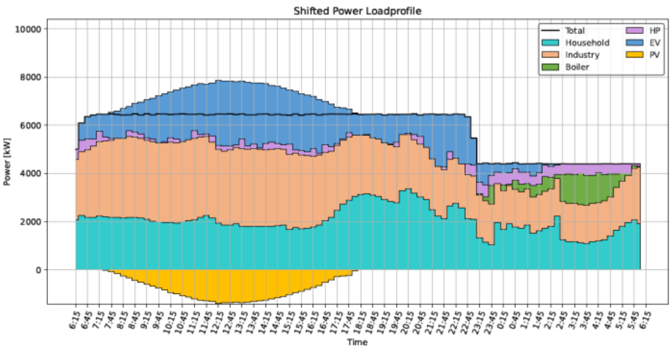

Fig. 6. Winter ZERO constrained load profile.

d) Flexibility Priority

In order to get the flexibility with the highest impact, the algorithm described in Section II was carried, leading to the results shown in Fig. 7 and Fig. 8. In the first case, where only the HPs are not shifted, only small changes are noticeable in the total load profile. Fig. 8 reveals, that the boilers can be used to flatten the oscillating behaviour during the nighttime. According to the results, which are listed in TABLE I. , where Model 1 contains all flexible loads as shiftable, in model 2 only the EVs and boilers can be shifted and in model 3 only the EVs can be shifted., following classification can be made according to priority:

1. EVs, with a cost reduction of CHF 40,538
2. Boiler, with a cost reduction of CHF 1,877
3. HPs, with a cost reduction of CHF 740

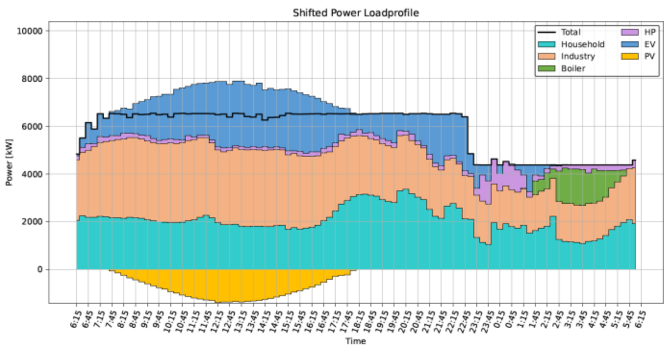

Fig. 7. Optimized load profiles of the priority calculations, where only EV and boilers can be shifted

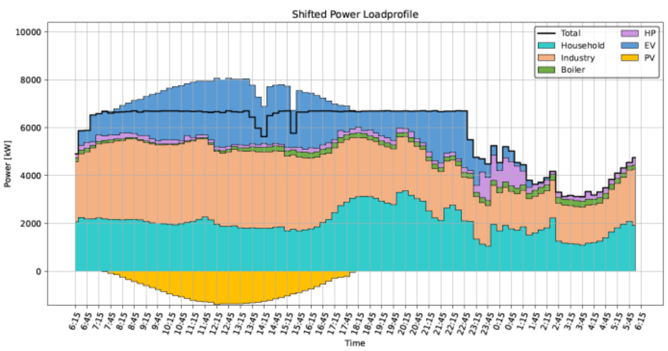

Fig. 8. Optimized load profiles of the priority calculations where only EV can be shifted

TABLE I. COMPARISON OF PARAMETERS FOR THE THREE MODELS OF THE PRIORITY CALCULATIONS FOR THE ZERO WINTER SCENARIO.

	Model 1 EV + boiler + HP	Model 2 EV + boiler	Model 3 EV
Peak Cost [CHF]	73,124	73,864	75,741
Cost change [CHF]	43,155	42,415	40,538
Max Value [kW]	6,471	6,537	6,703
Min Value [kW]	4,395	4,369	3,119
Shifting Efficiency [%]	90	89	87

e) Optimisation specific Results

In addition to the results that directly concern the load profile and management, information about the entire model can also be extracted from Gurobi. These have been summarised for all three priority models and presented in TABLE II.

TABLE II. OVERVIEW OF THE MODEL SPECIFICATION FOR THE PRIORITY CASE FOR THE ZERO WINTER SCENARIO.

	EV + Boiler + HP Model	EV + Boiler Model	EV Model
solving time [s]	387.9	339.54	96.49
Number of Constraints	46448	41020	36591
Total Number of Variables	362938	357332	357236
Number of Non-Zeros	982854	951206	911737
Number of Iterations	755659	477326	276935

In the first line of the table there is the necessary time for each model which is needed to find an optimal solution. During the definition of the models, it was found that this time does not really depend on the number of constraints and variables, as one might think from the listed variables. The second and third rows show the number of variables and constraints that the ES creates from the definitions to solve the model. The so-called simplex iterations are entered in the last column. These show how many of these the ES had to make to achieve the result at the end.

2) ZERO Summer

a) Initial Situation

This profile represents the initial state in the future summer without any load management in the grid. What is striking in Fig. 9 is the high amount of PV that creates the main costs for the peak, because the produced power cannot be consumed at the same time. Furthermore, the rapid change from the negative peak of PV to the new positive peak of EVs in the evening will create issues for the grid stability.

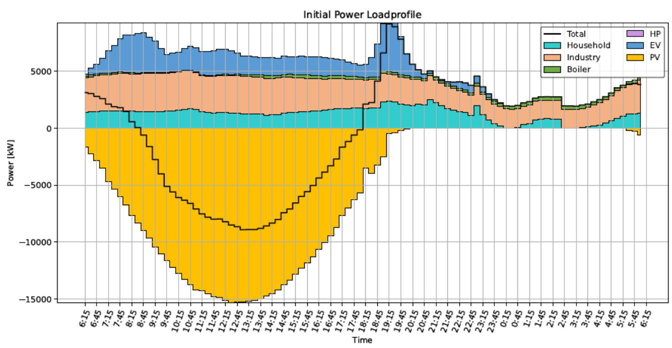

Fig. 9. Initial load profile for the ZERO Summer scenario

This would result in the following peak values and the costs derived from them:

• Peak of 9,140 kW
• Cost of the Peak of CHF 103,284
• Shifting efficiency of 47.2%

b) Optimal scheduling

In this scenario, the ES tries to minimise the negative peak of the PVs, as can be seen in Fig. 10. It could limit the feed in on 5,757 kW, with the most optimal usage of the EVs and the boilers during the PV production. This reduced costs by CHF 38,225 to a total of CHF 65,058. It is theoretically possible to reduce peaks and its cost up to about 37% for this scenario. The optimal shifting efficiency that can be achieved in this case is up to 69.3%, this is a change from the initial profile of 22.1%. Accordingly, it is not possible to place the sliding elements in such a way that a profile can be obtained as with the ZERO Winter, as can be seen in Fig. 5

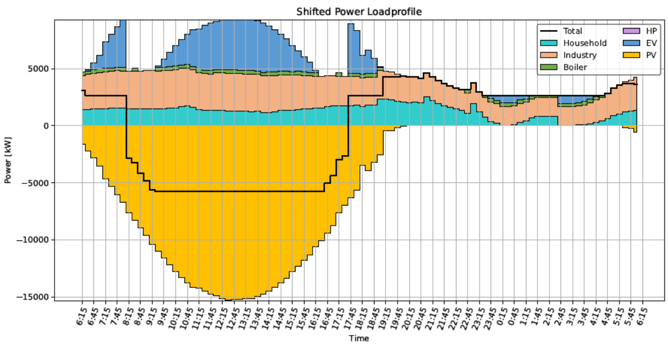

Fig. 10. The theoretical best solution, if many factors are neglected.

c) Energy Scheduler Result

Fig. 11 shows the optimised load profile for the ZERO Summer scenario. It can be seen that the boilers are located during the nighttime, such as it was in the ZERO Winter scenario. The main peak which influences the costs, comes from the PVs, with an amount of 6,814 kW. With the assistance of the control of flexibilities it was possible to decrease the costs to CHF 77,001. In terms of shifting efficiency, just 47.2% was achieved, while in winter 90% could be reached. It shows that the high proportion of PV can strongly influence the result. According to the season the HPs are not used during the summer and are switched off.

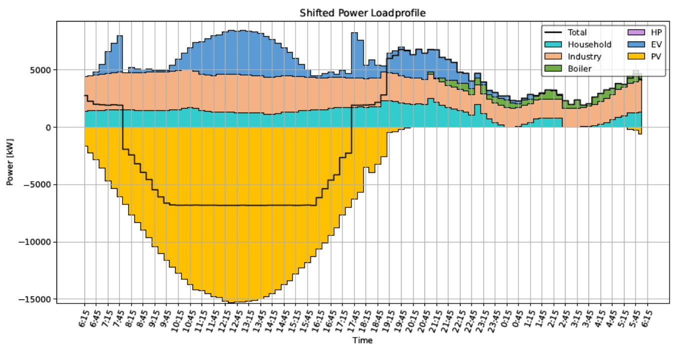

Fig. 11. Summer ZERO constrained load profile.

d) Flexibility Priority

As in the winter scenario, the flexibilities are again listed according to their influence on the costs. The results are shown in TABLE III. , where Model 1 the EVs and boilers can be shifted and in model 2 only the EVs can be shifted. What stands out in Fig. 12 is the difference between the costs of the first and the second model.

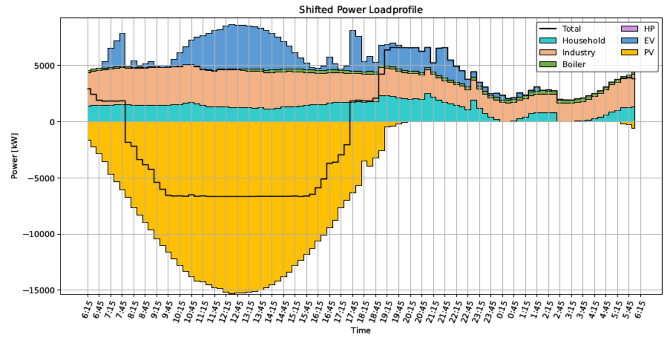

Fig. 12. Shifted load profiles of the priority calculations, where only the EVs are shiftable during the day.

Since it is specified to release the boilers only at night, less costs can be saved because less of the PV production is consumed locally. The priority of the flexibilities is in following way:

1. EVs, with a cost reduction of CHF 28,204
2. Boiler, with a cost reduction of CHF 1,920
3. HPs, because they are switched off.

e) Optimisation specific Results

The ES exceeded the time limit set at the beginning (15 minutes) for the first time in Model 1, as can be seen from the first line of TABLE IV. There is a significant difference between this to models in the solving time, the biggest part of this was solving the second objective function, which was described in section II.

TABLE III. COMPARISON OF PARAMETERS FOR THE TWO MODELS OF THE PRIORITY CALCULATIONS FOR THE ZERO SUMMER SCENARIO

	Model 1 EV + boiler	Model 2 EV
Peak Cost [CHF]	77,001	75,080
Cost change [CHF]	26,284	28,204
Max Value [kW]	6,814	6,644
Min Value [kW]	1,922	1,827
Shifting Efficiency [%]	67	66

TABLE IV. OVERVIEW OF THE MODEL SPECIFICATION FOR THE PRIORITY CASE FOR THE ZERO SUMMER SCENARIO

	EV + Boiler	EV Model
solving time [s]	902.15	392.86
Number of Constraints	46621	36351
Total Number of Variables	348387	346279
Number of Non-Zeros	928697	877052
Number of Iterations	1084609	575980

3) Overview of different Scenarios

To compare the achieved results of the three different scenarios ZERO, BAU, POT the TABLE V. was deriver.

TABLE V. THE THREE FUTURE SCENARIO RESULTS AND ITS SEASONS

	ZERO Winter		ZERO Summer		BAU Winter	
	init	optim	init	optim	init	optim
Peak Cost [CHF]	116,279	73,124	103,284	77,001	112,709	75,435
Cost change [CHF]	-	43,155	-	26,284	-	37,275
Max Value [kW]	10,290	6,471	9,140	6,814	9,974	6,676
Min Value [kW]	3,097	4,395	46	1,922	1,196	2,882
Shifting Efficiency [%]	57	90	47	67	48	72
	BAU Summer		POT Winter		POT Summer	
	init	optim	init	optim	init	optim
Peak Cost [CHF]	104,323	62,207	152,370	82,141	187,696	146,500
Cost change [CHF]	-	42,116	-	70,230	-	41,196
Max Value [kW]	9,232	5,505	13,484	7,269	16,610	12,965
Min Value [kW]	1,700	2,867	422	4,294	83	1,633
Shifting Efficiency [%]	41	68	39	77	41	55

With TABLE V. it gives an overview of the possible changes which could occur until 2050. If the DSO uses the whole potential it can get from PV, it will produce high peaks and high costs. With the possibility to shift the loads to more optimal locations, they can reduce them in each of this case. POT winter achieves a saving of over 70,000 CHF. The governmental based scenarios BAU and ZERO both show similar results, between 26,300 and 43,200 CHF can be saved. Thus, the peak costs can be limited to less than 80,000 CHF. The load shifting efficiency is just over 20% for both in summer and winter. In both scenarios the efficiency in the summer season reaches 67% and 68%. In winter, however, they reach 72% in BAU and even 90% in ZERO. With the latter value being the highest value across all three scenarios.

4) Alternative scenarios

In the following TABLE VI. , the results of the alternatives for the three flexibilities PV, EV and HP are listed.

TABLE VI. THE RESULTS FROM CHANGING THE SCALES OF EACH FLEXIBILITY AND TWO WEATHER SITUATIONS.

	PV							
	20%				50%			
	Sun		Cloud		Sun		Cloud	
	init	optim	init	optim	init	optimi	init	optim
Peak Costs [CHF]	78,509	70,258	78,509	71,280	78,509	72,274	78,509	72,479
Cost Change [CHF]	-	8,251	-	7,229	-	6,235	-	6,029
Maximum Value [kW]	6,948	6,218	6,948	6,443	6,948	6,396	6,948	6,414
Minimum Value [kW]	3,828	4,947	3,828	4,810	3,828	4,814	3,828	4,813
Shifting Efficiency [%]	81	90	82	88	80	87	81	88
	EV							
	20%				50%			
	Sun		Cloud		Sun		Cloud	
	init	optim	init	optim	init	optimi	init	optim
Peak Costs [CHF]	79,336	72,351	79,336	72,790	80,577	72,437	80,577	72,746
Cost Change [CHF]	-	6,985	-	6,547	-	8,140	-	7,831
Maximum Value [kW]	7,021	6,403	7,021	6,442	7,131	6,410	7,131	6,438
Minimum Value [kW]	3,828	4,832	3,828	4,830	3,828	4,857	3,828	4,863
Shifting Efficiency [%]	81	88	81	89	80	89	80	89
	HP							
	20%				50%			
	Sun		Cloud		Sun		Cloud	
	init	optim	init	optim	init	optimi	init	optim
Peak Costs [CHF]	79,281	72,232	79,281	72,893	80,438	73,021	80,438	73,537
Cost Change [CHF]	-	7,048	-	6,387	-	7,417	-	6,901
Maximum Value [kW]	7,016	6,392	7,016	6,451	7,118	6,462	7,118	6,508
Minimum Value [kW]	3,828	4,895	3,828	4,890	3,828	4,989	3,828	5,007
Shifting Efficiency [%]	81	89	82	89	81	90	82	90

With regard to the load shifting efficiency, almost no differences can be seen between the two factors 1.2 and 1.5. The reduced costs with ES vary between just under 6,000 and 8,300 CHF. The minimum load increases by about one MW for all alternatives. The peak power is usually reduced by about 700 kW.

IV. DISCUSSION AND OUTLOOK

A. *Discussion of the Scenarios*

Three future scenarios were simulated with the ES. An improvement in the load shifting efficiency can be seen in all of them, both in summer and in winter. Highest savings can be seen in POT winter. However, as this scenario is not based on studies, fundamental calculations or market data, this result should not be used for statements regarding the grid development in municipality. However, it does show that if the respective potentials of the flexibilities are fully utilized, considerable sums can be saved with the ES. The grounded scenarios ZERO and BAU, which are closer to reality, both show similar results. Comparing the peak costs after optimization with the peak costs of the ALTs shows that the two scenarios ZERO and BAU produce similar values. Thus, the ES makes it possible that the peak costs for the distribution grid operator will not increase in the future. The scenarios used in this paper focus heavily on the federal government's energy perspectives. On one hand, these are based on statistical values and market developments, but on the other hand they are also based on the objective of achieving net zero emissions. For this to be achieved further measures must be implemented. How these will be implemented, and whether other extreme political measures will contradict these energy guidelines, cannot be predicted at this point in time. Also, technologies continue to develop, or new technologies find a firm foothold in the market. However, these scenarios cover a spectrum that strongly suggests an increase in the flexibilities defined here. This also reinforces the increase in load flows and ultimately the application of the ES for distribution grid operators.

B. *Discussion of the Alternatives*

However, the cost reduction and load shifting are not increased in the alternatives in which PV production is increased. These are in the same range as the ALT in terms of HP and EV. This may be due to the fact that relatively few PV systems are installed and EVs are used now in municipality. Also, the HPs do not yet show such extreme consumption as would be expected according to the three possible scenarios. Therefore, there is not yet a large playing field for the ES. This is expressed, among other things, by the change in the minimum loads, which are small compared to the scenarios in TABLE V. It is assumed that these savings are not yet high enough for the ES to be actively implemented in the local grid by the DSOs. This assumption leads to the fact that the algorithm would still need to be refined and adjustments, such as the communication with the local EMS and control systems, are needed to be established.

C. *Discussion of the Model*

The model developed in this work, with Gurobi and Jupyter, was able to handle all scenarios and find an optimized solution to where the flexibilities should be shifted to. However, the model needs to be improved and its behavior tested with field measurements. In each result, the solver shifts the loads in such a way that artificial peaks are created in the optimized profile. On one hand, it could conclude with the given syntax that these nevertheless provide an optimal solution, or on the other hand that some boundary conditions play off each other and thus artificially create these "errors". It could help to adjust the values to the parameters newhpmax, newboilermax and newevmax so that they are not too high.

More clearly defined constraint can even help to decrease the overall solving time, because each constraint cuts the area of overall solutions into smaller parts. Also, a different formulation of the already existing constraints could reduce the time. As can also be seen from the results, the solution time depends on many external factors, such as the shape of the initial load profile, the number of flexible loads, but also the computing power of the computer being used. Therefore, it is hardly possible to estimate the needed time in advance. To improve the shifting, it would be helpful to know how far load can be shifted without any negative consequences for the end customers. The used parameters in this work are only assumptions according to discussions between ZHAW, industry and municipality.

To use the ES in more local grid parts of a municipality, it is crucial to know as much as possible about the grid infrastructure and what is behind it, such as the installed devices, its power, type of technology, consumed energy of the device, grid information (cables, lines, capacities, length, etc.) as well as transformer data and information. To handle such big data, a smart data logistics is necessary to collect the details and arrange them in a way, so they can be found and retrieved rapidly.

D. *Outlook*

The developed ES as a basis, the improvement of the electrical grid and the integration of renewable energy sources can be initiated. This new algorithm needs to be adapted to shift the loads even more locally, to achieve the best results in relieving the grid and the DSO of large peaks and their consequential costs and prevent possible disturbances. It is recommended for the industrial partner to invest time and resources to develop their own MIP solver, which is programmed for their purposes and that the company knows what it is doing behind in detail. Since the costs for Gurobi as a program are rather to be classified as high. Furthermore, data needs to be collected about the grids and its components, in order to understand what is behind the total load profile and to know what consumer types are hidden behind.

V. Conclusion

The results of this study demonstrate, how the Energy Scheduler can handle three possible future scenarios, based on recent data from the SFOE. The data clearly indicate that it is important to handle the increasing consumption of electrical energy with demand-side management and utilize available flexibility. It was possible to shift the loads during the day to achieve a reduction of costs in the future scenarios for winter and summer with sunny weather, between 22% and 46.1%. Furthermore, the alternative scenario, is representing a growth of flexibility in the recent infrastructure of the municipality for two different weather situations, it was possible to decrease the costs between 7.7% and 10.5%.

Acknowledgment

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