Quantifying the potential of smart heat pump control to increase the self consumption of photovoltaic electricity in buildings

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Abstract

Energy management systems that efficiently use self-produced renewable energy are becoming popular. However, quantifying their benefits in terms of self-consumption increase and associated financial benefits, is difficult in real life conditions. In that context, the Prosumer-Lab project was launched. In the latter, a building, grid and photovoltaic installation are emulated and real energy management systems can be connected for evaluation. In this article, we describe various control strategies for energy management systems and benchmark their yearly performance in simulation in order to quantify the potential of the different approaches. This works is the first step towards the identification of possible improvements.

Keywords: Self consumption, energy managements systems, photovoltaic, rule based control

Introduction

In ProsumerLab we aim at testing energy management systems (EMS) in a controlled environment. For that purpose, a test bench was developed by the Berner Fachhochshule (BFH), that is composed of grid and photovoltaic (PV) emulators, real batteries as well as a load emulator to mimic the electric consumption of a building. The latter is simulated using Polysun. The Centre Suisse d'Electronique et de Microtechnique (CSEM), is in charge of evaluating various EMSs and implement novel control strategies. The work presented in this paper focuses on following aspects:

- Impact of various EMS control strategies on self consumption ratio (SCR) improvement and comparison with the maximal theoretical SCR. SCR is defined as the ratio between the locally used PV energy and produced PV energy.
- Impact of SCR increase on the electricity bill.

It will be shown that SCR can be increased by 8% by using rule based control acting on storage tanks or building overall heating (i.e. storage in the building envelope), by up to 37% by adding batteries combined to the rule based controller mentioned before. It is also shown, that the SCR increase obtained by rule based controllers, is far from the theoretical maximum that could be reached by implementing model predictive control (MPC).

For the impact on the electricity bill, it is shown that depending on the electricity tariffs, high SCR might not have the desired results on the electricity bill. Indeed, if electricity buying and selling tariffs are equal (or the difference between these tariffs is small), high SCR penalize the electricity bill and can lead to a yearly increase of 263 chf in the considered scenarios. Whereas if the difference between buying and selling is high, in the same simulation scenario savings of 540 chf can be achieved.

Scenarios and simulation setup

In the frame of this work, the Polysun (Velasolaris, 2018) simulation environment was used. In order to assess the impact of the various EMS control concepts two types of buildings and two type of inhabitants were selected, as summarized in Table 1. These correspond to the *Sx* simulation scenarios, where *x* denotes the simulation scenario number.

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Tab. 1: simulation scenario summary

	House type	Inhabitant type[1]	PV (kWp[2])	Battery (kWh)	Yearly thermal load (kWh)
S1	Well insulated	Family (2 adults, 2 kids)	7.4	7.4	8'170
S2	Well insulated	Working couple (2 adults)	5.5	5.7	7'642
S5	Poorly insulated	Family (2 adults, 2 kids)	11.1	11.7	21'332
S6	Poorly insulated	Working couple (2 adults)	9	9.2	21'141

Further details about the house configuration:

- Surface: 150m^2
- Building u-value[3]: 0.19W/K/m^2 for the well insulated and 0.5W/K/m^2 for the poorly insulated
- Location: Koppigen in the canton of Bern (Switzerland)
- PV: sized according to the “1:1” rule (1kW$_p$ PV for 1MWh of electricity consumption)
- Batteries: the in house battery was sized according to the “1:1” rule (1kWh of battery for 1MWh of electricity consumption). The car battery was set to 100kWh.

For each scenario, different control strategies were tested, as summarized in Table 2. It is worth pointing out that the batteries are always controlled by the Polysun default battery controller. The latter stores excess PV energy in the battery and uses the battery power to minimize the energy drawn from the grid. Regarding the heat pump (HP) control, in the “ref” scenario the HP and 3-way mixing valve is controlled by the standard Polysun controller. The latter aims at maintaining the domestic hot water tank and space heating tank temperatures between desired temperatures. This is done without any considerations regarding PV production. Note that domestic hot water has priority over space heating. Whereas in the *C1,2,5-8* control strategies, the HP as well as the 3-way valve are controlled by the Matlab based controller as illustrated in Figure 1. The latter is described in further details below.

Tab. 2: control strategies summary

Strategy (#)	Description
ref	reference controller (from Polysun)
C1	storage of excess PV energy in water tank
C2	storage of excess PV energy in building envelope
C3	storage of excess PV energy in in-house battery ("small capacity")
C4	storage of excess PV energy in car battery ("large capacity")
C5	C1 and C3 (battery controlled by Polysun)
C6	C1 and C4 (battery controlled by Polysun)
C7	C1, C2 and C3
C8	C1, C2 and C4

[1] The space heating demand is adapted as a function of the number of inhabitants.
[2] kW peak
[3] The space heating demand is computed based on this value, coupled to other parameters such as window area, orientation, floor surface, number of floors etc. these parameters are set equal for the two buildings.

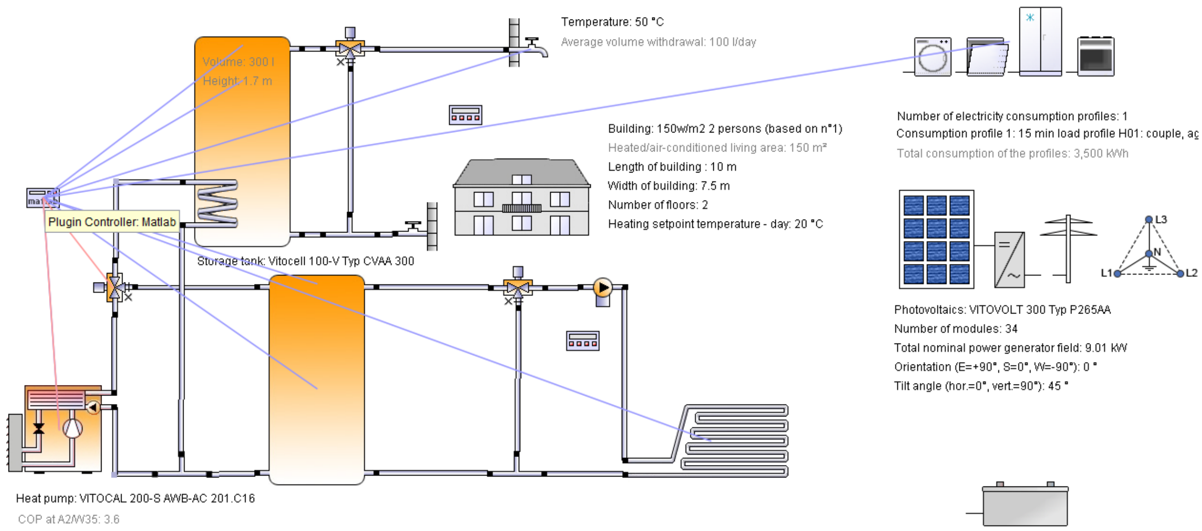

Fig. 1: Simulation layout in Polysun

The Matlab rule based heating controller used in C1 aims at reducing the electric energy injected into the grid, by increasing the domestic hot water (DHW) tank set-point (SP) temperature and/or the space heating (SH) tank set-point temperature. To do that the following steps are followed:

1) Check if there is PV overproduction, if yes, is it bigger than the HP nominal (electric) power?

2) If so, increase the DHW tank SP by 5°C and the SH tank SP by 10°C

3) Let the classical HP controller activate the HP and 2-way valve as needed (with priority to DHW and no SH if the average exterior temperature is above a given threshold)

It is worth noting that commercial EMSs (Smartfox, 2018, Sloarlog, 2918, Solarwatt, 2018) operate in a similar way, regarding PV overproduction.

For the case C2, as there is no direct way in Polysun to dynamically increase the building (indoor) temperature SP, an additional buffer tank, that mimics the storage in the envelop was added. The sizing of the latter was done based on the house surface and assuming a thickness of about 20cm. This tank is coupled to a “virtual” heating circuit. This additional heating circuit controller is configured so as to take energy from the buffer tank and allow over heating of the rooms. Naturally, the main controller has an upper temperature boundary to prevent excessive over heating. The developed Matlab rule based controller for this case is similar to the one of C1 except that if there is still overproduction and both the SH and DHW tanks are already fully heated up, the third water tank temperature is increased.

Theoretical SCR boundaries

In order to fully assess the potential of SCR increase for each scenario, the following key performance indicators (KPI) are computed. This self-consumption could be optimally unlocked by MPC as in (Candanedo and Athienitis, 2011) and/or usage of optimally sized batteries. The two additional KPI are SCR_{max}^{EMS} and $SCR_{max}^{battery}$, which respectively represent the maximum theoretical SCR achieved with the use of an EMS and a battery.

To illustrate how these indexes are computed, the simplified power profiles presented in Figure 2 are used.

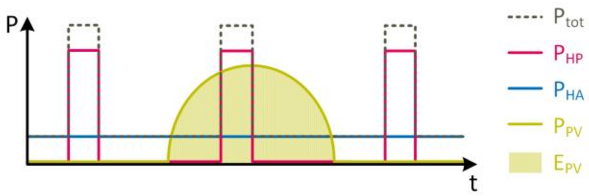

Fig. 2: Basic power profile to illustrate the computation of SRC_{max}^{EMS} and $SRC_{max}^{battery}$

In the simplified case illustrated above one can observe: a constant consumption of the home appliances (P_{HA}), a pulsed consumption of the heat pump (P_{HP}), the total power consumption (P_{tot}) and the photovoltaic production

(P_{PV}). Moreover, the surface below P_{PV} which represent the produced PV energy (E_{PV}) is highlighted. In this example, the HP consumption is considered controllable and the consumption of the home appliances is fixed.

The SCR_{max}^{EMS} is defined as the maximum achievable SCR by shifting and modulating P_{HP} without any constraints. Visually, the maximum self-consumable energy using an EMS (E_{sc}^{EMS}) is represented in Figure 3.

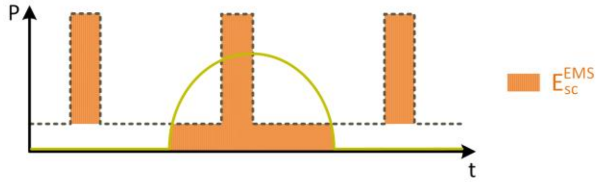

Fig. 3: Illustration of the maximum self-consumable energy using an EMS (E_{sc}^{EMS})

It is the sum of the total HP consumption and the self-consumed home appliances consumption. The SCR_{max}^{EMS} is then defined with the following equation:

$$SCR_{max}^{EMS} = min\left\{\frac{E_{sc}^{EMS}}{E_{PV}}, 100\%\right\}$$

The $SCR_{max}^{battery}$ is defined as the maximum achievable SCR when using a battery big enough to store the total PV production to use it for self-consumption. The maximum self-consumable energy using a suitable battery (E_{sc}^{bat}) is simply the total load consumption, as depicted in Figure 4.

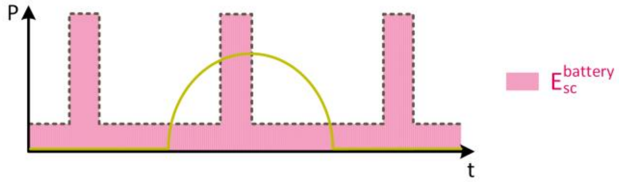

Fig. 4: Illustration of the maximum self-consumable energy using suitable battery (E_{sc}^{bat})

The $SCR_{max}^{battery}$ is then computed with the following equation:

$$SCR_{max}^{battery} = min\left\{\frac{E_{sc}^{battery}}{E_{PV}}, 100\%\right\}$$

Controller evaluation results

Several key performance indicators (KPI) are investigated:

- self consumption (Table 3) and self-sufficiency (Table A.1). Self sufficiency is the ratio of locally used PV production and total electric consumption.
- exchanges with the electric grid (Tables A.2 and A.3). Figure 5 shows for *S1* the interplay between controller, grid exchanges and self-consumption.
- financial aspects (yearly costs are available in Tables A.4 to A.6, the cost difference with respect to the reference controller is provided in Tables 5 to 7). Given the scope of the work, only operational expenses linked to electricity purchasing and selling are considered. The used tariffs are highlighted in Table 4 were obtained through (ElCom, 2018) and (PVtarif, 2018). It is to be noted that these three locations were chosen to illustrate the impact of difference between the electricity buying and selling price.

Tab. 3: self consumption

Case	Ref	C1	C2	C3	C4	C5	C6	C7	C8
S1	25%	28%	35%	47%	62%	49%	63%	55%	66%
S2	24%	29%	34%	47%	63%	50%	63%	55%	66%
S5	22%	23%	27%	43%	51%	44%	52%	47%	54%
S6	21%	22%	24%	39%	51%	39%	51%	42%	53%

Tab. 4: used electricity tariffs

	End user tariff for:		Difference between buying and selling
	Buying (CHF/kWh)	Selling (CHF/kWh)	-
Koppigen	0.155	0.155	Zero
Bern	0.1869	0.1009	Low
Eggiwil	0.2197	0.04	High

Tab. 5: yearly cost difference of Cx with respect to reference (electricty only, negative: gain, positive: losses) for tariffs from Koppigen

Case	C1	C2	C3	C4	C5	C6	C7	C8
S1	10.4	113.9	139.3	173.4	142.4	168.6	211.9	215.9
S2	4.0	84.9	72.7	135.5	71.0	131.0	123.8	165.5
S5	0.9	81.7	136.1	205.1	132.2	198.2	201.5	263.0
S6	0.0	47.3	93.9	168.8	91.3	164.5	130.2	199.8

Tab. 6: yearly cost difference of Cx with respect to reference (electricty only, negative: gain, positive: losses) for tariffs from Bern

Case	C1	C2	C3	C4	C5	C6	C7	C8
S1	-12.6	66.1	-61.0	-139.2	-69.9	-143.6	-25.8	-109.7
S2	-20.7	50.0	-67.1	-108.3	-81.8	-111.2	-46.5	-86.2
S5	-8.4	40.1	-126.2	-164.8	-135.3	-171.9	-90.5	-124.3
S6	-12.7	29.2	-87.1	-135.4	-93.3	-138.3	-67.4	-110.9

Tab. 7: yearly cost difference of Cx with respect to reference (electricty only, negative: gain, positive: losses) for tariffs from Eggiwil

Case	C1	C2	C3	C4	C5	C6	C7	C8
S1	-37.8	12.5	-281.0	-481.9	-303.1	-485.9	-287.5	-467.2
S2	-47.7	10.8	-220.4	-375.7	-249.1	-376.8	-233.6	-362.5
S5	-18.6	-6.2	-413.6	-570.5	-428.4	-577.6	-411.1	-549.6
S6	-26.6	9.0	-285.6	-468.9	-295.6	-470.2	-284.3	-452.0

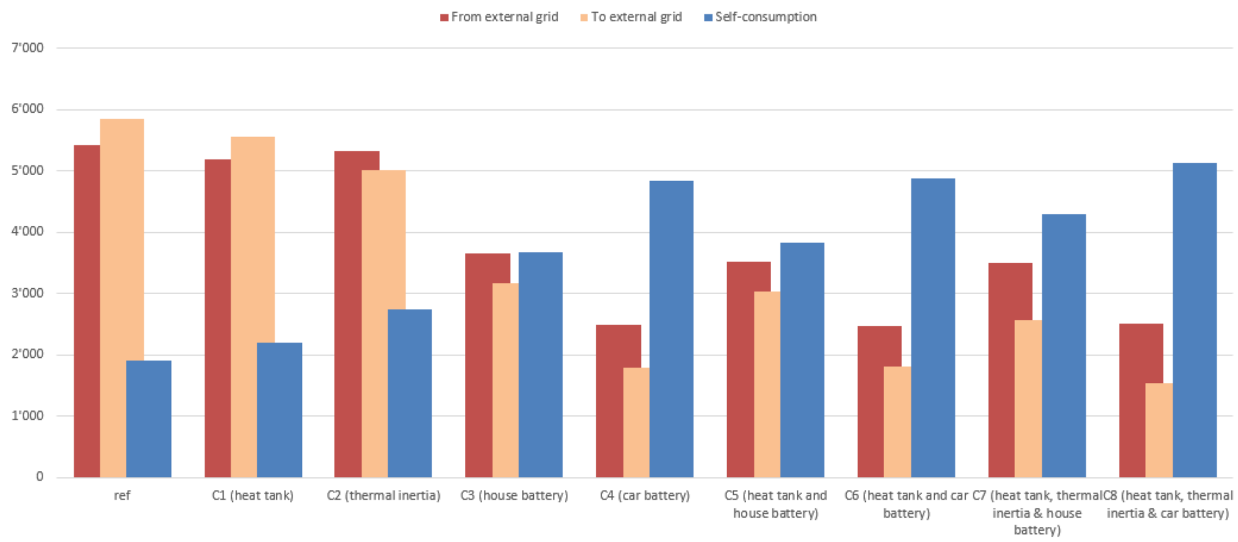

Fig. 5: grid exchanges and self-consumption (kWh over the year) for scenario S1 and different controllers

Analysis

The analysis will first focus on SCR increase as a function of the control strategies. Table 8 summarizes the SCR increase with respect to the reference controller and provides also an average SCR increase by controller. It can be observed that:

- Storage of excess PV production in the storage tanks (C1) or in the building envelope (C2) leads to an SCR increase of 3%, respectively 8%. These results are in line with (Vandhoudt et al., 2014).
- Storing electric energy overproduction in house sized batteries (C3) or in a large car battery (C4) increases the SCR by 21%, respectively 34%.
- By combining tank storage and batteries (C5 = C1 + C3, C6 = C1 + C4) and by adding thermal storage in the building envelope (C7 = C5 + C2, C8 = C6 + C2), the SCRs increase as expected.

Tab. 8: SCR increase with respect to reference case and average SCR increase by control strategy

Case	C1	C2	C3	C4	C5	C6	C7	C8
S1	4%	11%	23%	38%	25%	38%	31%	41%
S2	5%	10%	23%	39%	26%	39%	31%	43%
S5	1%	6%	21%	30%	22%	30%	26%	33%
S6	2%	3%	18%	30%	19%	30%	21%	32%
Average	**3%**	**8%**	**21%**	**34%**	**23%**	**34%**	**27%**	**37%**

In addition, an investigation of the financial benefits is done. As mentioned before, only the costs linked to energy buying and selling are considered. The link with electricity tariffs, SCR and control strategies is highlighted in Figure 6. It can clearly be observed that if the buying and selling tariffs are equal, as it is the case in Koppigen, high SCR lead to higher electricity bills. In other terms, increasing SCR in such cases is not desirable. On the other hand, if the incentive of selling electricity to the grid is low, as in Eggiwil, increasing the SCR to lower the electricity bill is desirable.

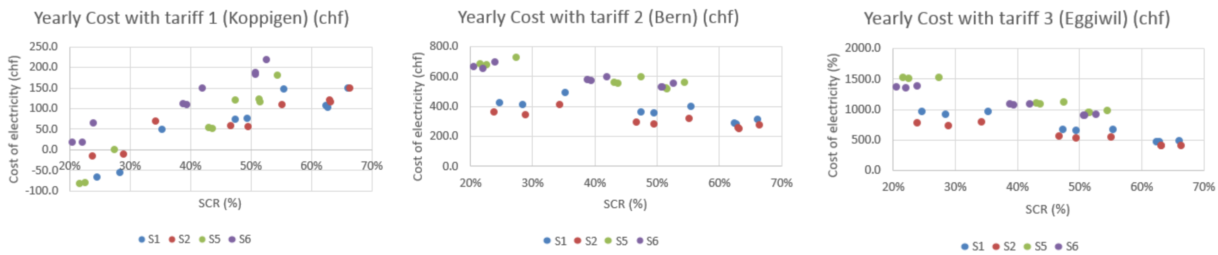

Fig. 6: yearly electricity costs for 3 different electricity tariffs and different control strategies for the four scenarios

In terms of theoretical maximal SCR. The values of these yearly KPIs for the four systems previously defined are gathered in Table 9.

Tab. 9: Current yearly SCR and SCR maximal values (with EMS or batteries)

Case	Current SCR (controller: C1)	SCR EMS max	SCR bat. max
S1 ref	25%	46%	93%
S2 ref	24%	54%	97%
S5 ref	22%	64%	94%
S6 ref	21%	75%	100%

Theoretically, the use of an EMS can more than double the SCR for the studied cases. It can be observed that this theoretical maximum increases for increasing system reference number. Note that in badly isolated systems (5 and 6), the energy consumed by the HP represents a higher share of the total energy consumption than for well isolated ones (1 and 2). The amount of energy which can be shifted to better fit with the PV production is thus higher in such cases.

When implementing a battery in the system, the SCR could theoretically increases up to 100%. This is explained by the fact that the system is designed to have a yearly consumption matching the yearly PV production. In that case, and with a hypothetically big enough battery, all the produced energy can then be stored for a latter local use.

Even though these results are highly promising, it important to emphasize the fact that these are theoretical maximum which do not take into account the constraints of the system, especially the comfort temperature for space heating and domestic hot water and the battery capacity. The purpose of these KPI is only to provide an upper bound to the achievable performances.

Another interesting assessment is the evolution of these KPI over the year. As example, Figure 7 depicts the evolution of the daily SCR over the year for the case S1 ref, in the upper graph. In the lower one, is represented the heat pump daily operating rate (OR_{HP}). It is defined as the percentage of the time during which the HP is in operation during the day. In order to improve the reading, a 7-term moving average trend line is superposed for each parameters.

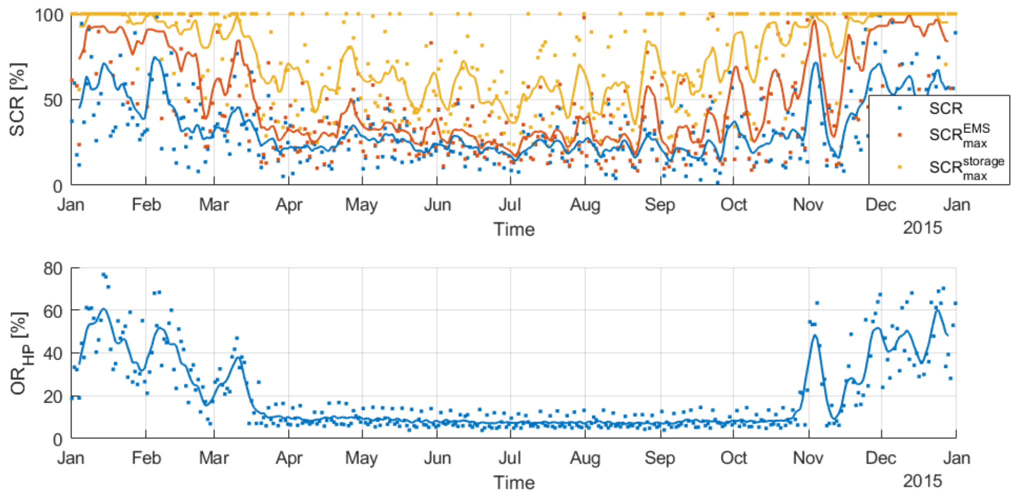

Fig. 7: Yearly evolution of the different SCR and the HP operating rate for case S1 ref

This figure allows to highlight the fact that the theoretical maximum benefit of an EMS is not constant over the year. Indeed, the SCR improvement which can be provided by the use of an EMS is higher in winter than for the rest of the year. This is explained by a higher amount of controllable energy consumed by the HP during this period, as it can be observed in the lower graph.

During this same period, the additional SCR increase with the use of a storage system compared to an EMS is relatively low. Since the PV production is low in winter and the consumption is higher (due to space heating), a high SCR can already be achieved with the use of an EMS only. However, the use of a storage system during the hot seasons is way more beneficial than an EMS.

Conclusion and outlook

In this article 8 control strategies that are aimed at increasing SCR were presented and tested against standard controllers using different scenarios.
The first objective was to find what control strategy or combination of strategies would lead to the highest SCR and assess how far this value is with respect to the theoretical maximal SCR. It was shown that the SCR increase ranges on average from 3% to 37% depending on the used control strategy (or combination of strategy), however, this SCR is far from the maximal SCR. There is room for improvement that can be achieved for instance by employing smarter control, such as MPC or larger batteries.
The second objective, was to investigate the impact of SCR increase on the electricity bill. It was shown that depending on the local electricity tariffs (for buying and selling), SCR increase is not always desirable. Indeed, if both tariffs are equal, increasing SCR leads to higher overall costs. Whereas if the tariff for selling PV energy to the grid is significantly lower than the buying tariff, higher SCR leads to savings. In the considered scenarios the yearly losses can go up to 263 chf and the savings up to 540 chf, when compared to the reference controller.
Future work will be carried out to refine the financial analysis by taking into account capital expenditure and component ageing, development of smarter controllers (typically MPC based) and exploring the potential of optimal component sizing rules.

Acknowledgement

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Appendix

Tab. A.1: self sufficiency

Case	Ref	C1	C2	C3	C4	C5	C6	C7	C8
S1	26%	30%	34%	50%	66%	52%	66%	55%	67%
S2	24%	29%	32%	48%	64%	50%	64%	53%	65%
S5	23%	24%	27%	45%	54%	46%	54%	48%	55%
S6	20%	22%	23%	38%	50%	39%	50%	40%	51%

Tab. A.2: energy to the grid (i.e. sold to the grid)

Case	Ref	C1	C2	C3	C4	C5	C6	C7	C8
S1	5'843	5'551	5'014	3'180	1'793	3'033	1'809	2'572	1'540
S2	4'432	4'135	3'822	2'632	1'273	2'486	1'302	2'155	1'109
S5	9'116	9'005	8'437	5'741	4'324	5'689	4'338	5'239	3'983
S6	7'487	7'339	7'164	5'157	3'546	5'122	3'573	4'878	3'396

Tab. A.3: energy from the grid (i.e. purchased from the grid)

Case	Ref	C1	C2	C3	C4	C5	C6	C7	C8
S1	5'416	5'191	5'322	3'652	2'485	3'525	2'470	3'512	2'506
S2	4'330	4'059	4'268	2'999	2'045	2'842	2'045	2'852	2'075
S5	8'587	8'482	8'435	6'090	5'118	6'013	5'088	6'010	5'151
S6	7'604	7'456	7'586	5'880	4'752	5'828	4'751	5'835	4'802

Tab. A.4: yearly cost (electricity only, negative: gain, positive: losses) for tariffs from Koppigen

Case	Ref	C1	C2	C3	C4	C5	C6	C7	C8
S1	-66.2	-55.8	47.7	73.2	107.3	76.3	102.5	145.7	149.7
S2	-15.8	-11.8	69.1	56.9	119.7	55.2	115.2	108.0	149.7
S5	-82.0	-81.1	-0.3	54.1	123.1	50.2	116.3	119.5	181.0
S6	18.1	18.1	65.4	112.1	186.9	109.4	182.6	148.3	217.9

Tab. A.5: yearly cost (electricity only, negative: gain, positive: losses) for tariffs from Bern

Case	Ref	C1	C2	C3	C4	C5	C6	C7	C8
S1	422.7	410.1	488.8	361.7	283.5	352.8	279.1	396.9	313.0
S2	362.1	341.4	412.0	294.9	253.8	280.3	250.8	315.6	275.9
S5	685.1	676.7	725.2	559.0	520.3	549.8	513.2	594.7	560.8
S6	665.7	653.0	695.0	578.6	530.4	572.4	527.4	598.4	554.8

Tab. A.6: yearly cost (electricity only, negative: gain, positive: losses) for tariffs from Eggiwil

Case	Ref	C1	C2	C3	C4	C5	C6	C7	C8
S1	956.2	918.4	968.7	675.1	474.2	653.1	470.3	668.7	489.0
S2	774.0	726.4	784.8	553.6	398.4	524.9	397.2	540.4	411.5
S5	1521.9	1503.3	1515.7	1108.3	951.5	1093.5	944.3	1110.8	972.4
S6	1371.1	1344.5	1380.1	1085.6	902.2	1075.5	900.9	1086.8	919.2