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Control strategies for modulating heat pumps in a plus energy building

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Abstract

Since the feed-in tariff of photovoltaics (PV) decreases [1], PV self-consumption becomes more profitable. Especially heat pumps, which are able to modulate the compressor speed, open up more flexibility for consuming fluctuating PV power. For exploiting the full potential of PV self-consumption smart control strategies for modulating heat pumps (MHPs) are needed. In this research, the development and the real application of optimized control strategies for MHPs in plus energy terraced houses, built in 2017, are realized. Two control strategies, a PV rule based (PVC) and a model predictive control (MPC) are tested and compared in simulation. Results for the MPC of a 12 months simulation show potential for a moderate increasing PV self-consumption up to 2.1 % and significant reducing operating costs up to 36.1 %. In real application in the terraced houses, the PVC offers an increase of PV self-consumption by 4.1 % for a monitored week, compared to a heat controlled operation.

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1. Introduction

Since the feed-in tariff decreased and the electricity price of energy supply companies is increasing in Germany, PV self-consumption is becoming economically interesting for building owners. Smart control strategies in combination with thermal storage tanks have the potential to reduce operating costs by converting the PV surplus into thermal power. Battaglia, M. et al. [2] show, how control strategies can reduce costs for electricity by overheating thermal storage tanks. Psimopoulos et al. [3] investigate control algorithms and their contribution to final energy, solar fraction, self-consumption and seasonal performance factor in the simulation software TRNSYS. Results show an increase of PV self-consumption to 50.5 % by using control strategies in combination with thermal and electrical storage units.

High potential for reducing energy costs is expected by MPC as it uses numerical optimization algorithms and price or weather prediction. Fischer, D. et al. [4] shows in his research work that in a multi-family house MPC increases annual PV self-consumption from 56 % - 58 % up to 64 % - 71 % and decreases energy costs by 6 % - 16 % in the case of variable electricity prices. In his research work, Pichler, M. et al. [5] investigates the direct consumption of PV energy by controlling a heat pump with a MPC in an annual simulation. The MPC increased the direct consumption of PV energy from 20 % to 50 % in a single-family house.

In a previous simulation study, a control strategy, the Demand Side Management System (DMS), for the energy system of eight terraced houses was developed in TRNSYS [6] and is described by Dentel, A. et al. [7]. The DMS was changed during the implementation due to different configuration input parameters from the manufacturers. PV optimized control (PVC) was developed and is implemented in the building automation of the terraced houses since October 2018. The PVC includes the controlling of heat pumps and a battery in the energy system. The energy concept of the terraced houses consists of two shared MHPs, connected to a two storage cascade, eight decentralized domestic hot water heat pumps (DHW-HPs) with a 200 liter storage each and a shared battery of 40 kWh capacity. The first buffer storage has a size of 800 liters and is charged during

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grid and PV consumption. The second surplus storage in the storage cascade has a volume of 2000 liters and is charged only during PV production. The terraced houses represent a total energy system that includes thermal energy for heating and DHW as well as household electricity. Another control strategy, the Model Predictive Control (MPC), is developed in MATLAB [8] and will be implemented in the energy system as well.

In this research, two advanced control strategies, PVC and MPC, are compared to heat controlled strategies in a simulation environment in order to evaluate the potential for increasing PV self-consumption and reducing operating costs. All models and control strategies are developed and tested in MATLAB [8]. Furthermore, the PVC, realized in the terraced houses in October 2018, is compared to a heat controlled strategy by analyzing measurement data from the monitored terraced houses.

2. Method

2.1. PV optimized control (PVC)

The PVC is a rule-based control strategy and aims to increase the PV self-consumption by operating the heat pumps during PV production. As real application and simulation offer different implementation and parameter options, the PVC differs in the real application and simulation. A detailed description of the PVC and the implementation is published by Betzold, C. et al. [9].

In real application four different modes for the heat pump operation are defined:

1. Grid Mode: This mode is active, when PV production is off or already fully consumed by household electricity. The 800 liter buffer storage is charged to maximal 35 °C by the MHPs. The DHW storage tanks are charged up to 50 °C.
2. PV Mode: This mode is active, when there is PV production and a PV surplus is left after fulfilling the energy needs of the household electricity. The 800 liter buffer storage and the 2000 liter surplus storage are charged to 35 °C by the MHPs. The DHW storage tanks are charged up to 60 °C.
3. Load Management: The Load Management aims to avoid electrical load peaks of the terraced houses. The PVC switches all heat pumps off for 15 minutes, if a load peak of 16 kW is reached.
4. Priority Mode: This mode ensures that the thermal comfort in the terraced houses is fulfilled at all times. The Priority Mode starts, when the temperature falls under 27 °C in the 800 liter buffer storage, and ends, when the temperature reaches 32 °C. The DHW storage tanks are charged from 40 °C to 45 °C.

In simulation the energy system is simplified to a model that bases on energy flows coupled in an energy node. The energy node for the MHP system is shown in Equa. 1, where Q_{MHP} is the thermal energy of the MHP, $Q_{st, cap}$ is the thermal storage capacity, $Q_{st, loss}$ is the constant loss of the thermal storage and Q_{th} is the thermal load of the building. In Equa. 2 the DHW-HP system ($i = 1-8$) is shown, where $Q_{DHW-HP, i}$ is the thermal energy of each DHW_HP, $Q_{DHW-st, cap, i}$ is the thermal storage capacity of each DHW storage, $Q_{st, loss}$ is the constant loss of the DWH storage and $Q_{th-DHW, i}$ is the DWH load of each terraced house. Equa. 3 describes the battery system where P_{PV} is the PV surplus, $C_{bat, cap}$ is the electrical storage capacity, P_{MHP} is the electrical energy of the MHP and P_{DHW-HP} is the electrical energy of the DHW-HP. The investigated control strategies use the same models to ensure comparability.

$$Q_{MHP1} + Q_{MHP2} + Q_{st, cap} = Q_{st, loss} + Q_{th} \quad (1)$$

$$Q_{DHW-HP, i} + Q_{DHW-st, cap, i} = Q_{DHW-st, loss} + Q_{th-DHW, i} \quad (2)$$

$$P_{PV} * n_{loss} + C_{bat, cap} = P_{MHP1} + P_{MHP2} + \sum_{n=1}^8 P_{DHW-HP, n} \quad (3)$$

Mode 3, the Load Management and Mode 4, the Priority Mode are not integrated for this investigation of different control strategies. Thus, there are two modes in the PVC simulation:

1. Grid Mode: The MHPs only deliver as much thermal energy as necessary to cover the thermal load. If the DHW storage reaches the minimal storage capacity, the DHW-HP starts to charge the DHW storage with a constant thermal energy until the maximal storage capacity is reached.
2. PV Mode: The MHPs adapt to the available PV surplus power and deliver as much thermal energy as corresponds to the compressor speed. If the thermal load can not be covered during PV adaption, then the MHPs adapt the thermal energy to the thermal load as in the grid mode. The storage is charged to

its maximal capacity for 2800 liters. As soon as there is PV power left after the MHPs, the DHW-HPs start in row to charge the DHW storages tanks with a constant thermal energy until the maximal storage capacity is reached.

2.2. Model predictive control (MPC)

The MPC bases on the same simplified energy models of the heat pumps and storage tanks as shown in Equa. 1 - 3. In this research, a mixed-integer linear programming (MILP) optimization algorithm is used. The MPC is realized in MATLAB [8] with the additional software GUROBI [10], for using the Special Ordered Set (SOS) option. The SOS option enables an interpolation between defined operation points of the MHP in order to describe the MHP polynomial at every modulation step for B5 °C/W35 °C. Thus, the thermal power of the MHPs can be between 4.8 kW and 18.1 kW and the electrical power can be between 1.0 kW and 4.7 kW. The DHW-HPs have a thermal power of 2.2 kW and an electrical power of 0.5 kW. Each storage tank is modeled as an energy node that balances in- and output energy flows. Operating limits are defined by the minimal and maximal storage capacities and by the complete cover of the thermal and electrical load. The cost function bases on operating costs (c) for the household electricity (P_{el,household}), the MHPs (P_{el,MHP,n}) and the DHW-HPs (P_{el,DHW-HP,n}) depending on the consumption of grid, PV or battery as well as a bonus for grid feed-in (see Equa. 4 and Equa. 5).

$$min J = \sum_{t=1}^{t_{end}} P_{el,PV,t} * c_{PV} + \sum_{t=1}^{t_{end}} P_{el,Bat,t} * c_{Bat} + \dots$$

$$\sum_{t=1}^{t_{end}} P_{el,Grid,t} * c_{Grid} - \sum_{t=1}^{t_{end}} P_{el,Feedin,t} * c_{Feedin} \tag{4}$$

$$P_{el} = P_{el,household} + \sum_{n=1}^2 P_{el,MHP,n} + \sum_{n=1}^8 P_{el,DHW-HP,n} \tag{5}$$

In this research work, the MPC has a 15 minute timestep and a 48 hours optimization horizon. After 24 hours the MPC is restarted with the boundary conditions at the end of the previous optimization at time 24 hours. The PV, thermal and electrical load prediction is ideal.

3. Simulation and comparison of PVC and MPC

For analyzing the potential of the MPC, regarding PV self-consumption (see Equa. 6) and operating costs, the MPC is compared to PVC and a heat controlled strategy (HC) for heat pumps for a 12 months period. The HC bases on the grid mode of the PVC and the two heat pumps are on/off heat pumps (no modulation). The PVC enables to adapt the MHPs to the thermal load or the available PV power. As first results have shown that the HC has higher energy consumption due to low COP at on/off HP operation (up to 11.8 %), a second HC variant with modulation option is introduced. The heat controlled modulation strategy (HCmod) operates like the grid mode of the PVC with the ability to adapt to the thermal load. Table 1 shows the four control strategies with the different heat pump models and the operation modes.

Table 1: Heat pump model and operation modes according to the control strategies

Control strategy	On/off HP	MHP	Grid Mode	PV Mode	Free Mode
HC	x		x		
HCmod		x	x		
PVC		x	x	x	
MPC		x			x

Real monitored measurement data of the energy system of the terraced houses is used for the comparison. For offering an overview of the potential a whole period of 12 months from October 2018 until September 2019 is chosen. The measured PV power as well as measured thermal and electrical load are used as ideal prediction for the MPC. For the HC, HCmod and PVC simulation the measurements serve as actual PV production and loads. The operation and comparison are implemented in MATLAB [8]. Boundary and start conditions are the same in the four cases. The energy consumption and production for the period of 12 months are shown in Table 2.

Table 2: Boundary conditions for the 12 month period from October 2018 until September 2019

Energy consumption	
Thermal load in MWh	39.60
DHW load in MWh	25.60
Electrical load in MWh	28.90
PV production in MWh	85.85

This research work is focused on the operation of the control strategies and its contribution to PV self-consumption and operating costs for the 12 months period. Economic efficiency and price increases are not observed in this analysis. Thus, the electricity prices for PV and battery do not include repayments of investments. The price for the PV self-consumption contains fees and taxes. The feed-in tariff depends on the year of commissioning and the PV plant size and is introduced for the terraced houses in 2017. Especially in MPC operation the usage of the battery is avoided due to battery prices that can not compete with grid electricity price and feed-in tariff. In this price scenario, the battery price has to be below 0.147 €/kWh (including battery losses of 30 %) to be cheaper than using the grid as an electricity storage, that costs 0.21 €/kWh. The prices for electricity are shown in Table 3.

Table 3: Energy prices for electricity consumption and PV feed-in

Energy prices	
Grid electricity	0.32 €/kWh
PV electricity	0.12 €/kWh
Battery electricity	0.14 €/kWh
PV feed-in electricity	0.11 €/kWh

The results of the simulation for the 12 months period from October 2018 until September 2019 are shown in Fig. 1 and Fig. 2. The end capacities of the storage tanks are taken into account for the cost calculation. Higher or lower end capacity is added as a bonus or subtracted as an extra fee and is calculated by the average price of 0.19 €/kWh. The electricity consumption is calculated by a COP of 4.8 for the buffer storage and by a COP of 4.3 for the DHW storage tanks.

The results of the PV self-consumption and the self-sufficiency of the comparison are shown in Fig. 1. The definition of PV self-consumption and the self-sufficiency are explained in Equa. 6 and Equa. 7. In general, the results do not vary significantly between the different control strategies. Regarding the PV self-consumption the maximal variation for direct PV is up to 2.1 % and for grid feed-in is 6.0 %. Regarding the self-sufficiency, there is an increase of direct PV up to 9.5 % and a decrease of grid consumption up to 8.7 %.

$$PV \text{ self} - \text{consumption} = \frac{\sum \text{Direct PV}}{\sum \text{PV production}} \quad (6)$$

$$\text{Self} - \text{sufficiency} = \frac{\sum \text{Direct PV}}{\sum \text{Total energy consumption}} \quad (7)$$

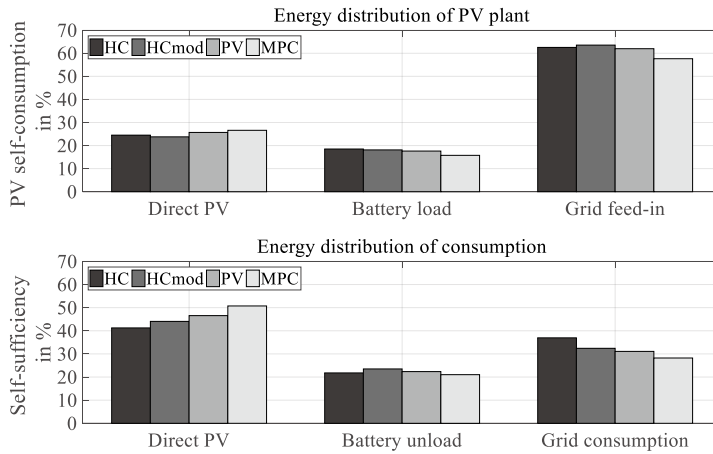


Fig. 1: Energy distribution regarding PV self-consumption and self-sufficiency

The results in Fig. 2 give an overview of operating costs and total energy consumption. Regarding the operating costs, the HC variant is the most expensive and the MPC is the cheapest strategy. However, comparing the HC and the HCmod, both operating in grid mode only, significant cost savings occur in the HCmod, which includes the ability of modulation. The HC also has the highest total energy consumption, which results from the on/off heat pump operation with lower COP. HCmod and MPC have quite similar total energy consumption, while PVC has a higher result for adapting the MHPs to the available PV power and thus, operating in lower COP.

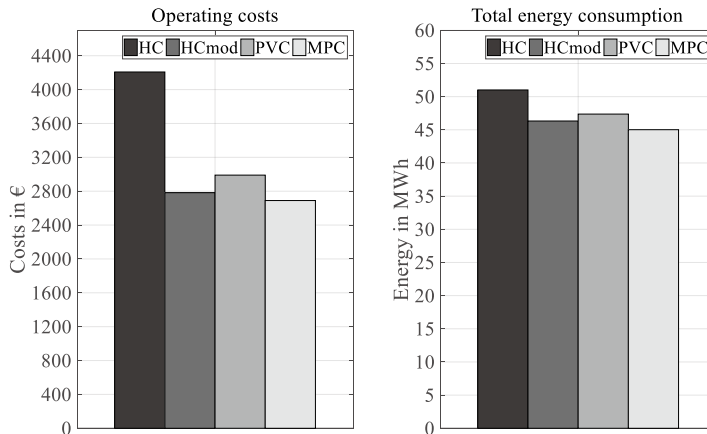


Fig. 2: Operating costs and total energy consumption of 12 months period

4. Comparison of measured operation of HCmod and PVC

The PVC is implemented in the energy system of the eight terraced houses since October 2018. For analyzing the influence of the PVC on the PV self-consumption two time periods are compared. The first time period is a week in December 2018 with low PV production, in which the MHPs operated only in grid mode (HCmod). The second time period is a week in February 2019 with higher PV production, in which the MHPs operated every day in PV mode. Both selected weeks start on Monday and end on Sunday.

For comparing the influence of the PVC on the PV self-consumption and the operating costs, the low PV production of the December week is replaced by the high PV production of the February week. The operation of the MHPs, DHW-HPs and the total energy consumption stays the same. As the operation of the battery is different due to higher load and unload, the battery is modelled as an energy node (see Equa. 3) with battery losses of 25 % from the February week. In contrast to the analysis of the HCmod in December and the PVC in February whose results are only measured, the HCmod with PV from February (HCmodPV) is a combined measured and simulated variant.

Fig. 3 shows the course of the PV production and the total energy consumption in the February week as well as the total energy consumption in the December week. The total energy consumption includes household electricity, MHPs and DHW-HPs electricity. In general, the course of the total energy consumption is quite similar in the two compared weeks, but in February there are higher load peaks. Table 4 gives an overview of the compared variants with the sum of measured energy consumption for both weeks.

Table 4: Overview of variants with measured energy consumption in one week in December 2018 and February 2019

Description	HCmod	PVC	HCmodPV
Time period	Week in December	Week in February	mixed
Control strategy	HCmod	PVC	HCmod
Thermal load in kWh	1.502	1.462	1.502
DHW load in kWh	543	675	543
Electrical load in kWh	480	483	480
PV production in kWh	255	1.191	1.191

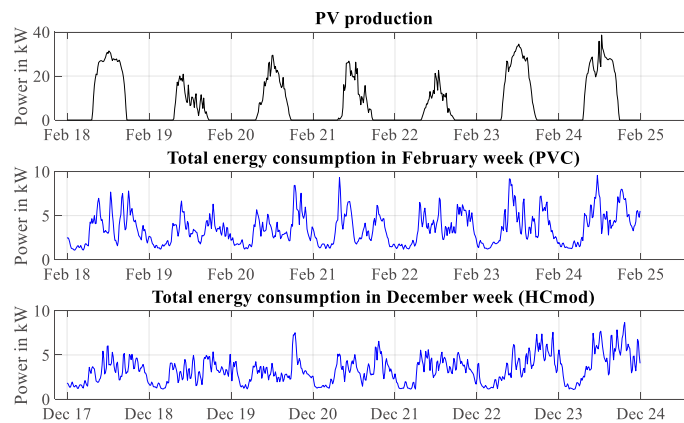


Fig. 3: Course of PV production in February week, total energy consumption of February and December week

The results of the comparison are shown in Fig. 4 and Fig. 5. In general, the total energy consumption of the PVC in February is higher (see Fig. 5 right) and a clear comparison of the variants, regarding operating costs, is not possible. Comparing the PV self-consumption of the variants PVC and HCmodPV, the PVC can increase the PV self-consumption up to moderate 4.1 %. On the other hand a higher grid feed-in of 6.7 % is visible in variant HCmodPV. The results for direct PV, battery load and unload and grid consumption do not vary a lot between the two variants.

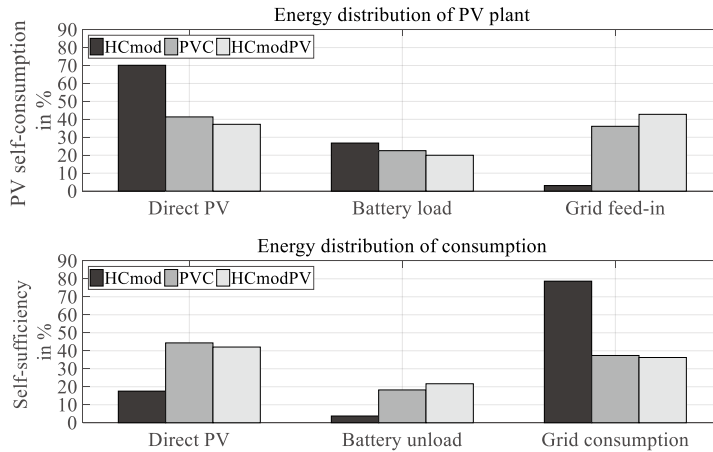


Fig. 4: Energy distribution regarding PV self-consumption and self-sufficiency, measured in variant HCmod and PVC and as well as combined measured and simulated in variant HCmodPV

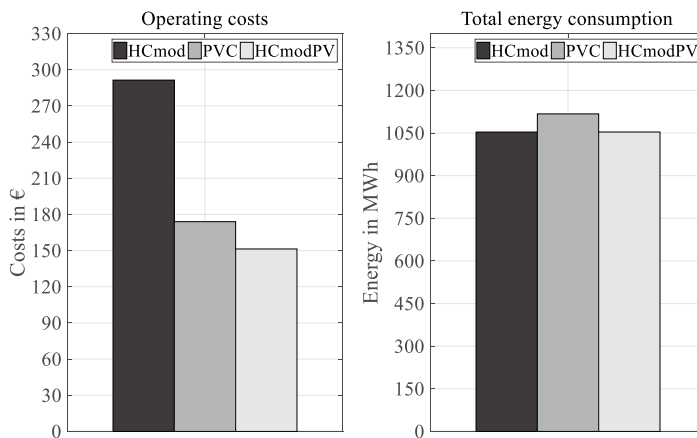


Fig. 5: Operating costs and total energy consumption, measured in variant HCmod and PVC and as well as combined measured and simulated in variant HCmodPV

Conclusion

In this research, two advanced control strategies, a PV rule based (PVC) and a model predictive control (MPC) are developed and compared in simulation with two different heat controlled strategies. Furthermore, the PVC was implemented in real application in eight terraced houses and was compared to a heat controlled operation.

In the simulation study, the control strategies of PVC and MPC increase PV self-consumption with low effect up to 2.1 % and reduce operating costs up to 36.1 % compared to a heat controlled strategy (HC) with on/off heat pumps. However the cost savings mainly result from less energy consumption of a more efficient operation of modulating HPs in part load. Table 5 shows the relative reduction of total energy consumption and cost savings and the relative increase of PV self-consumption and of the Seasonal Performance Factor (SPF) compared to the HC. A heat controlled strategy with the ability to modulate the HPs (HCmod) can easily compete with the advanced control strategies, and even gets partly better results as the PVC.

The influence of the advanced control strategies, PVC and MPC, on PV self-consumption and operating costs is limited. The actual PV and battery prices can not compete to reduce the energy costs significantly because the electricity price for grid and the feed-in tariff offer the economically attractive option to use the public grid as an electricity storage. An energy efficient operation in part load operation of the MHP, as shown in the HCmod, has higher influence than advanced control strategies, increasing PV self-consumption. In further research work, electricity prices are investigated to give an economically attractive solution for PVC and MPC.

Table 5: Relative energy reduction of total energy consumption and cost savings as well as relative increase of PV self-consumption and SPF compared to HC

	Energy reduction	Cost savings	PV self-consumption (without battery)	SPF
HCmod	-9.2 %	-33.9 %	-0.7 %	26.9 %
PVC	-7.1 %	-29.0 %	1.2 %	19.7 %
MPC	-11.8 %	-36.1 %	2.1 %	37.2 %

For comparing the operation of HCmod and PVC regarding PV self-consumption and operating costs in real operation, two periods are analyzed in the monitored terraced houses. The first time period is a week in December 2018 with low PV production, in which the MHPs operated only in grid mode (HCmod). The second time period is a week in February 2019 with higher PV production, in which the MHPs operated every day in PV mode (PVC). To compare the influence of the PVC on the PV self-consumption and the operating costs, the PV production of the December week is replaced by the PV production of the February week (HCmodPV). In general, this method represents a possibility to approximately compare HCmod and PVC mainly with measurements without using detailed simulation tools. The results of PVC show an increase of PV self-consumption of moderate 4.1 % compared to the HCmodPV. As well, the relative parts of battery load and unload and grid consumption do not vary a lot between PVC and HCmodPV. The influence of the PVC is also limited as the course of the total energy consumption in the December and February week are quite similar. In both weeks higher energy consumption occurs during the day and fits to periods of PV production.

In general, the total energy consumption of the variant PVC in February is higher and a clear comparison of the variants, regarding operating costs, is not possible. However under unfavorable assumption, that the additional consumption of the PVC was consumed by grid electricity and thus the highest price is taken into account, the operating costs of the PVC are still 1.5 % higher than the operating costs of the HCmodPV.

As shown in the simulation study and in the comparison of real operation, advanced control strategies increase PV self-consumption in a moderate amount. Furthermore, regarding the operating costs with the assumed electricity prices, it becomes clear, that an energy efficient operation of (modulating) heat pumps has higher influence on operating costs than the increase of PV self-consumption. Under these conditions PV or MPC driven control strategies are not able to compensate an inefficient operation during PV production by cost savings due to higher PV self-consumption.

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