EXAMINING THE IMPACT OF DEMAND-SIDE MANAGEMENT THROUGH DYNAMIC SIMULATION: INTEGRATING SMART-GRID-READY CONTROL OF RESIDENTIAL HEAT PUMPS

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Abstract

This paper investigates the suitability of air-to-water heat pumps for smart grids, with a particular focus on load shifting. The research uses dynamic building energy simulations to show that the utilisation of these features effectively addresses the energy consumption challenges of heat pumps while ensuring that heating and domestic hot water demands are met. The implemented control system successfully shifts the morning and evening peaks to the daytime period, resulting in a modest 2% increase in total energy demand.

These results not only demonstrate the balancing of heat pump energy consumption, but also provide insights for the development of objective functions. Such functions can play a key role in supporting the smooth integration of renewables into the wider energy framework.

Keywords

Smart Grid, heat pump, demand-side management, dynamic simulation

1 INTRODUCTION

Climate change is a well-known global challenge of our time, with the average temperature of the planet rising. To reduce the strength of this phenomenon, the use of renewable energy sources and other sustainability efforts are increasingly being promoted. Today, solar photovoltaic systems are an ever more widespread and affordable option for generating electricity. The main drawback is that the production profile does not coincide with the consumption profile. This is a load matching or simultaneity problem, which is unfavourable for the electricity grid as it can lead to overloading of the grid and cause control and distribution difficulties.

This burden can be mitigated by locally using or storing as much generated electricity as possible. Changing the level of storage and consumption is called Demand Side Management (DSM). Most modern heat pumps are already equipped with Smart Grid Ready functionality which allows them to be included in this process, further improving the prospects for DSM. In this research, dynamic building energy simulation will be used to investigate the possibilities and potential offered by consumer-side control using a heat pump system.

2 METHODOLOGY

Energy storage options

One option for household-scale energy storage is the use of batteries, which are advantageous because the stored electrical energy can be used with relatively low losses when it is needed. The disadvantages are that the cells currently available take up a lot of space and most of them are sensitive to ambient temperature. Additionally, the investment cost is very high. Battery manufacturing and trading is considered a simple solution for the world and is therefore also very widespread. For this reason, it has been embraced by the scientific community and several studies have been carried out to determine optimal storage capacity and appropriate control signal [1], [2], [3], [4].

Another energy storage option is the conversion of electricity into thermal energy, and storage in this form, where the conversion is in most cases done by a heat pump. In terms of storage, a distinction can be made between

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storage options: in a buffer tank for heating/cooling or domestic hot water (DHW) storage, building thermal mass temperature control, internal temperature variation, or storage with phase change materials (PCM).

The simplest and most commonly employed solution for thermal energy storage is the use of heating and/or cooling buffer storage and the auxiliary heating of DHW storage. Regulus and the Czech Technical University (CTU) have jointly developed a new storage tank that can be used as both a domestic hot water and a heating storage tank. The design was based on the option of connecting to a common solar collector and heat pump system. The development included fixed pumping circuits in a compact design with individual fittings, a heat trap and common external insulation. The main objective was to improve the heat loss factor per cycle. This metric plays a significant role in the efficiency of the capacity of each storage tank and therefore has an exceptional role to play in heat storage [5]. Lizana et al. combined the control of domestic hot water and heating water temperatures by means of a heat pump and used a PCM heat storage tank. The aim here, as in many cases, was to reduce energy bills. In his model, a smart controller operated the system, monitoring energy prices in the electric grid, forecasting current and future weather conditions and taking into account the consumer's predefined user behaviour. The controller itself determined the best means of energy management based on all parameters. The study was carried out in TRNSYS, and energy savings of 17–25% were achieved by defining several modes [6]. In another study, Steffen Bechtel et al. (also in TRNSYS) determined the energy saving potential of heat pump applications with a simpler design, but still considering the case of DHW and heating. They provided control via an artificial neural network which determined and predicted real consumer behaviour. They highlight the need for this with regard to the heating flow rate, combined with the proper sizing of the heat pump. This is important because if the heat pump is undersized, it will not be able to heat the tank properly and this will be reflected in the heated area, where the desired temperature will not be achieved. Oversizing the heat pump will result in more frequent on/off cycling of the heat pump, which will reduce the lifetime of the unit. Alternatively, it may cause higher buffer tank temperatures, which will result in a reduced COP [7].

Heat pump Smart Grid control

To achieve demand-side control, an information network is needed that can control the network, i.e. it must be flexible. If this is managed together with the electric grid, we have created a smart grid. This makes it possible to monitor and control the production and transmission of electricity.

Connecting to a Smart Grid is not only important from an economic point of view, but also from the sustainability perspective. This is because the transmission losses in the electricity grid increase with the load on the system, and these losses can be measured in terms of CO_2 emissions. According to the International Energy Agency (IEA), the integration of user-side feedback into the Smart Grid system could reduce the constraints of renewable energy diversified electricity grid by 25% by 2030, thereby increasing the energy efficiency of the grid and reducing costs for users [8]. There are now several existing case studies and other papers on this topic which demonstrate the benefits and applicability of the technology in real life [9], [10], [11].

The integration of heat pumps into the smart grid system will completely change the way most appliances are currently used. Over the years, many studies have focused on analysing the different operational options, but overall, the research can be divided into three control strategies. There are control systems that consider the state of the grid, as well as those based on renewable energy generation and those that monitor changing energy prices.

The grid-side approach refers to when a heat pump is operated according to the voltage state of the grid, which thus solves low and overvoltage problems. This is also related to the valley and peak periods mentioned earlier. In the present interpretation, the heat pump operates during the peak periods, which makes the balance of supply and demand more even. This control mode also considers the CO_2 emissions of the network, thus further supporting the system in operation.

The second approach is from the perspective of integrating renewable energies. This could be wind or solar, although the latter is a much more common solution. The main objective is to maximise self-consumption. When the production of the solar panel exceeds the amount consumed by the household, the heat pump is triggered to switch on and then stores the excess electricity as thermal energy using one of the previously mentioned heat storage methods.

The third approach is based on energy prices. This becomes more important in the case of dynamic pricing. Two types of dynamic pricing can be identified. In the first case, a banded system is used, and energy prices remain static to some extent, since prices are defined for specific bands. In the second case, there is also fully dynamic pricing where the price changes at every moment. However, minimising costs does not always result in energy savings, and it is important to consider the comfort requirements of the building when applying a given control system [12].

There are four modes of operation for smart grid ready heat pumps: blocked, normal, recommended start and commanded. Blocked means that the heat pump is not allowed to run for a maximum of two hours, i.e. it must be in a mandatory off-mode during this time period. The normal operating mode means, as the name implies, uninterrupted energy-efficient operation. Encouraged operation means that hot water production or the heating/cooling system requests start-up, but the heat pump can decide whether to start production depending on the control strategy. Commanded operation is when the heat pump must start in any case regardless of any external condition [13]. In this study, we investigate these operating conditions.

Control logic and control signal

For the Smart Grid contact discussed above, it was important to implement a control that could be used to simply transform any input signal.

This required the implementation of the logic shown in Fig. 1., in which the input signal, if 1, encourages the system to reduce generation; if 2, the physical content of the signal is favourable to us; and if 3, the most favourable, then a two-step generation increase is implemented. And if our input signal is 0, then there is no action from the controller. This is the same as when we have no control signal.

The reason why it is useful to build on this logic is that it can be matched to any objective function. It is immaterial whether it is a function of the solar PV production, the CO_2 emission data of the electricity system, or a range of energy prices. The user can even define his own target function.

As shown in Fig. 1, we've defined 4 operating states, the temperature data for which are given in Tab. 1.

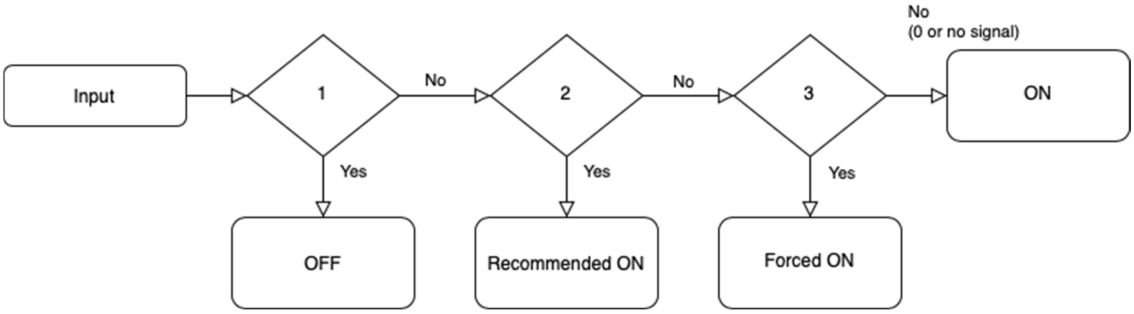

Fig. 1 Control logic.

Tab. 1 Temperature data for operating conditions.

	Normal operation	Off operation	Recommended On operation	Forced On operation
°C	ON	OFF	RON	FON
DHW tank temperature	50	40	55	60
Heating tank temperature	60	60	65	65
Zone temperature	20	20	20	22

In the simulations, we used our own generated input data series, which are daily repeating control signals. This was adjusted to the magnitude of CO_2 emissions expected in the future in the electricity grid in Hungary. This was done by examining the Hungarian emissions data provided by the Electricity Maps website [14], which showed that the peak consumption in the morning and evening hours increases the emissions value, while during the day the value decreases due to the high share of solar PV generation. On this basis, the implemented control signal and the operation modes are presented in Tab. 2.

Tab. 2 Control signal.

Time	Control	Operation
0:00	0	ON
1:00	0	ON
2:00	0	ON
3:00	0	ON
4:00	0	ON
5:00	0	ON
6:00	0	ON
7:00	1	OFF
8:00	1	OFF
9:00	0	ON
10:00	0	ON
11:00	2	RON
12:00	2	RON
13:00	3	FON
14:00	3	FON
15:00	2	RON
16:00	0	ON
17:00	1	OFF
18:00	1	OFF
19:00	0	ON
20:00	0	ON
21:00	0	ON
22:00	0	ON
23:00	0	ON

Application of dynamic building simulation

The study was carried out using the DesignBuilder simulation program. This is a 3D graphical building modelling software application with the EnergyPlus program as the computational engine. There are 11 modules available within the software, making it suitable for a comprehensive analysis of our buildings. These include a 3D modeller (where you can build your model and specify its properties), a visualisation panel (which uses your input data to create a realistic image of your building, taking into account the sun's path and thus shading), and certification and energy simulation options, as well as detailed mechanical and weather settings. It is also suitable for partial budgeting, CFD and multi-criteria optimisation modelling [15].

The simulation engine used by the program, EnergyPlus, allows for whole-building simulation, including energy consumption for heating, cooling, ventilation, lighting and other loads, as well as the use of hot water for building use. The model can handle unheated spaces, various mechanical systems, internal thermal mass and thermal bridges. Simulation results are available in graphical and textual form as well [16].

Although DesignBuilder basically provides a lot of options for the setting and scheduling of different parameters, it is not suitable for controlling a more complex logic. Compared to the basic pre-defined settings, DesignBuilder also offers a scripting option. This allows the simulation to be customised depending on the inputs you want to implement. This can be done using EMS, C#, and Python programming.

The EnergyPlus Energy Management System (EMS) makes available settings and options that are not available in the standard EnergyPlus service. The EMS can be used to write custom control algorithms, modify modelling properties, and output data. C# programming provides the ability to pre- and post-process the model and simulation results at key points in the program execution. This provides the same access to program and model data that DesignBuilder developers have. Python programming provides the same capabilities as C# programming.

In this study we used the EMS platform to implement the programming. This built-in EMS interface contains all the necessary sensors, variables, outputs, and many other parameters that can be easily called. With these and the right programming basics, all the functions of the EMS are simple, understandable, and accessible to everyone. All these features make the EMS ideal for researchers or more experienced modellers investigating the performance of innovative systems that are not predefined in standard EnergyPlus calculations [17].

3 RESULTS

The building under study was designed according to data on Hungarian building typology [18], specifically Type 10, created within the framework of the KEOP-7.9.0/12-2013-0019 project. For this purpose, a heat pump is used as a heat generator and the DHW and heating buffer tanks are used as energy storage. This is achieved by varying their temperatures and by increasing the zone temperatures as a secondary energy storage option, the values of which are presented in Tab. 1.

Fig. 2 illustrates the impact of Smart Grid (SG) control on energy use. A reduction in energy consumption at 7 am (OFF) and an increase at the end of this period can be observed. There is a RON command at 11 am and a FON command at 1 pm, which result in a large energy consumption surplus. These occur as energy consumption peaks, as the storage tanks do not need to input additional energy once the increased temperature is reached. As a result of these extra energy inputs, we see lower demand throughout the afternoon, which only approaches normal usage in the evening hours as the DHW tank heats up.

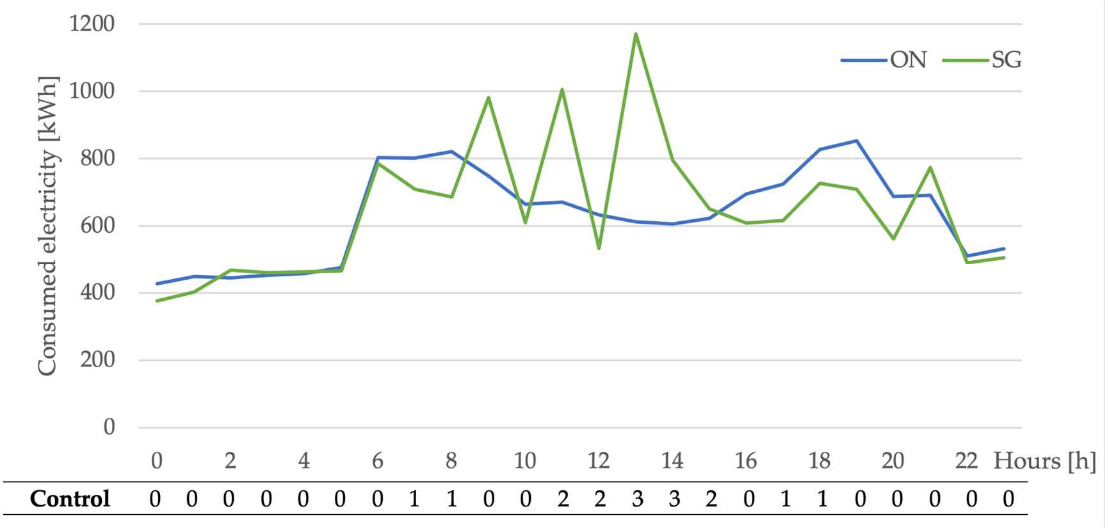

Fig. 2 Hourly energy consumption of the building and the control signal.

The table below shows the controlled annual energy consumption and its difference compared to the normal situation. Overall, our control signal caused a minimal increase in annual energy demand. However, the lesson from the previous figure is that the time course of the energy use has changed greatly under our control system.

Tab. 3 Controlled annual energy demand and its deviation from normal.

kWh	ON	SG
SUM	15204	15546
Divergence	-	2.2%

Yearly energy consumption

The following graphs show the data for the whole year. The ‘heat map’ type of graph is best suited to display such a large data set. Before presenting the graphs, it is important to note some general information that helps in interpreting them.

The horizontal axis shows the days of the year from left to right, and also separates the different months. The vertical axis shows the hours, from top to bottom. For each hour of each day, there is a data point which is the sum of the hours, the magnitude of which is indicated by a certain colour. On the right, we can use a colour scale to show the magnitude of the value associated with a given colour. In each case, black indicates the lowest value and red the highest values.

It is also important to note that for the different schedules, the simulation considers the 1-hour time difference between winter and summer time. This is very noticeable in the heat map, and the break seen in the spring and autumn is caused by this difference.

Earlier, in Fig. 2, it is visible that the control signal was used to induce daily consumption peaks. This is echoed in Fig. 3 and Fig. 4, where the similarity is visible when looking at a full year of data. Seasonal variations can also be observed, as energy consumption is consistently high at night during the winter months, followed by a gradual decrease during the transition periods. At the same time, during daytime hours, the positive effect of solar gains is observed, resulting in lower energy use. In the summer period, as there is no heating, the main demand comes from the production of DHW. The base case (ON) consumption curve for DHW can also be observed during this period.

In the controlled case (SG), on the other hand, the energy usage shows a more uniform schedule. In the summer, when electricity is only used for DHW production, the effect of the controller is highlighted on the diagram. There is no consumption at night and no significant demand between 7 am and 9 am thanks to the OFF command. When this ceases, the ON command is followed by a noticeable increase after 9 am due to the higher tank setpoint. At 11 am, another increase is visible due to the increased temperature caused by the RON command. This is further increased by the FON command at 1 pm, where a further increase in energy consumption is observed. In all cases, heating of the DHW tanks to the higher temperature is achieved within 1 hour, and since there is no significant demand on the taps, the additional heating is not required. Thus, there is no significant energy consumption for the RON and ON commands at 3 and 4 pm, respectively.

A similar trend can be observed in the winter and transition periods, where heating energy demand is also present. It is important to note that in the wintertime all earlier values are shifted by 1 hour. In the case of heating, the demand is more continuous and steady, but the same effect of the commands can be seen due to the DHW production and the increased heating buffer tank temperatures. In addition, in the vertical bluer bands, it can be observed which days had milder weather, which resulted in lower heating energy demand.

In summary, the energy consumption appears as a band, decreasing for off-load conditions and increasing for on-load conditions. This confirms our idea and expectations regarding the shift in electricity demand that arises over time.

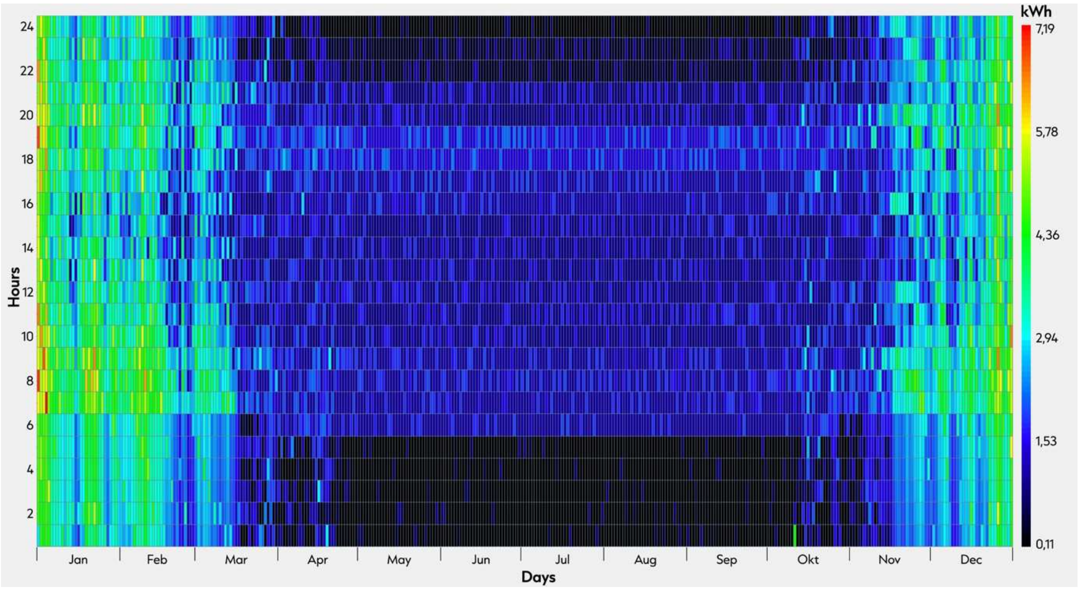

Fig. 3 Consumed electricity – ON operation mode.

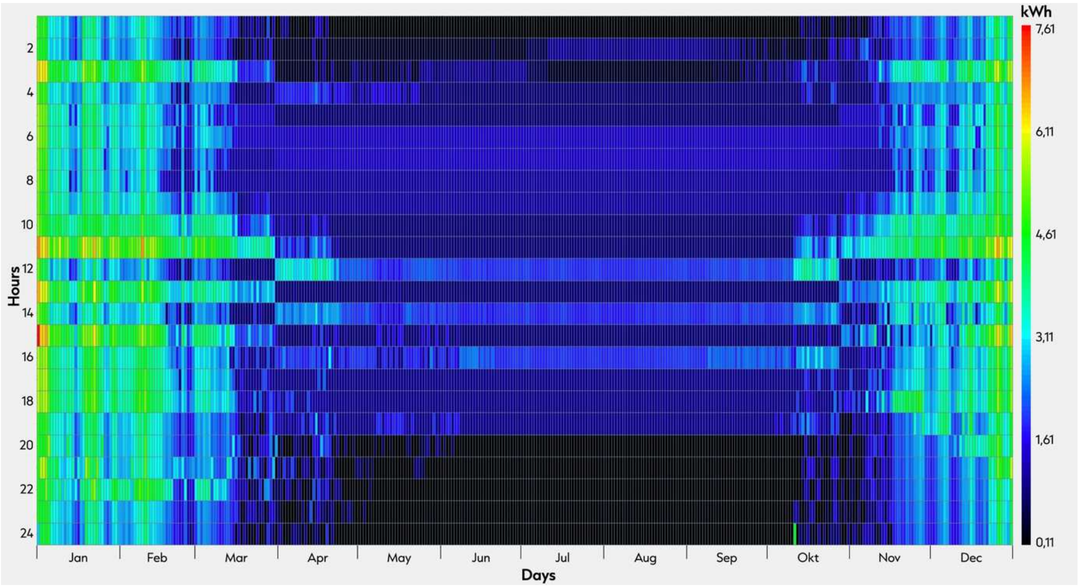

Fig. 4 Consumed electricity – Smart Grid operation.

5 DISCUSSION

The aim of our research was to implement the control of heat pump systems in a dynamic simulation of the Smart Grid. To do this, we tested the operation of the available Smart Grid Ready heat pumps by scripting our control signal in the simulation program. In contrast to previous research, we did not use deep learning or other analytical methods [2] [3] to determine the control but implemented a much simpler logic control. As a result, the control logic we defined offers a wide range of applicability with any input signal.

It clearly visible from Tab. 3 that the control does not significantly increase electricity consumption, which was in line with our expectations. Only the temperature of the hot water tanks was modulated, which have resulted in different heat loss rates. This caused a significant part of the additional energy consumption. The net energy consumption of the building hasn’t changed as a result. Nevertheless, as seen in Fig. 2, the electricity consumption was grouped over time, which shows that significant consumer-side influence is possible.

The current limitation of the research is that it only lays the foundations. There is a need for further investigation into what control signals can and should be used in real-world settings to achieve climate or economic goals. In addition, no research has yet been done on the controlled and uncontrolled cases of real-world energy use to validate our simulation results. Different heat pumps may have different COP values depending on the outdoor temperature, which may affect the energy use differentials due to the effect of control.

6. CONCLUSION

To achieve sustainability and net zero emissions, there are a number of options to choose from. In this paper, we have confirmed that system control can also be of significant importance for energy savings and sustainable usage. In addition, if it is possible, local energy production can also bring us closer to the net zero target.

In the latter two cases, the demand-side regulation that is the subject of this article is of relevance. It can be seen that the impact of control can be demonstrated via dynamic simulation. The effect of the fictive schedule studied in this paper is as expected and can be used as a basis for further investigations.

With the control available through the Smart Grid contact, more conscious and smarter energy use can be achieved. Even though this may mean some additional energy use for the user, it is worthwhile to look into. In this work, only the operation and modelling of the control logic was investigated, but in the future it is proposed that additional control signals be integrated in order to model real states.

This could be the case for a control system based on the production of a building-mounted solar PV system. In this case, the surplus energy produced could be stored, thus increasing the self-consumption of the building. This control signal will be of great importance in the future with the transformation of the net metering system into a gross metering system.

Another possible control principle suggests a larger scale of environmental awareness. Control can be based on the actual CO_2 emissions of the electricity system, which will help to reduce the carbon footprint. However, it can also be beneficial for the whole system if the operation of heat pumps is reduced to a certain extent, rather than starting up the gas power plants. This is a complex issue on a larger scale, which is more relevant from an electricity grid perspective. However, it could also become an important issue at the residential level if a CO_2-related tariff is introduced, which would also provide an incentive to use cleaner energy.

In addition, from a building engineering point of view, further investigations are also possible, for example examining how the system behaves when a cooling system is also utilised. This is also important because cooling demands are becoming increasingly energy intensive. The applicability of other mechanical equipment, such as an air-to-air heat pump or surface heating and cooling, can be investigated, and in conjunction with this, building thermal management should also be mentioned in the context of heat storage.

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