Applied Energy Symposium 2021: Low carbon cities and urban energy systems
September 4-8, 2021, Matsue, Japan
Paper ID: 16

HEAT RECOVERY POTENTIAL FROM PV MODULES: A SIMULATION CASE STUDY FOR A SWEDISH RESIDENTIAL BUILDING CLUSTER

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ABSTRACT

Photovoltaic thermal collectors (PVT) can generate electricity and heat from one module. In a typical aerothermal PVT system, the air flow behind the PV modules is created using air channels, and the heated air is ducted to the point of usage. The central aim of this paper is to simulate a system where the recovered heat from a PV installation is utilized in the energy system of a multifamily building cluster in Sweden. The paper tends to establish if the additional cost of "heat recovery system" components justify the savings obtained due to recovered heat from PV. To achieve this, a simulation model is built in TRNSYS for a multi-family building cluster in Sweden. Specifically, two energy system configurations are simulated.

1) Recovered heat from PV collectors is used for pre-heating of domestic hot water.

2) Heat from PV collectors is used at the evaporator of an air source heat pump to increase its performance. The heat pump is further used to generate domestic hot water.

Results show that the advantage of PVT integration is more pronounced when recovered heat is used directly for pre-heating of DHW. The savings are lower when PVT is coupled with heat pump.

Keywords: PVT, heat recovery, DHW, heat pump

NOMENCLATURE

Abbreviations	
PVT	Photovoltaic Thermal
DHW	Domestic Hot water
ASHP	Air Source Heat pump
DH	District Heating
SH	Space heating
SCOP	Seasonal Coefficient of Performance
HX	Heat Exchanger

1. INTRODUCTION

Photovoltaic thermal collectors (PVT) can generate heat, and electricity using a single collector thus resulting in higher area specific yields. From an urban energy systems context, PVT can potentially play an important role in combination with other technologies, such as heat pump (HP), to decarbonize the heating, cooling and electricity production. PVT has passed its nascent stage of development, reaching a technology readiness level of 8 for most commercial solutions [1]. Continuous research efforts are made to develop various system concepts with PVT, for applications in residential, and industrial settings. The International Energy Agency has concluded Task 60 in year 2020, creating a significant knowledge bank with regards to technology and its associated systems. Recent trends in the PVT market have also shown positive trends, with average global growth rate of 9 % from Year 2018 to 2020, reaching a total thermal installed capacity of 710 MW and electrical peak capacity of 230 MW [2].

Typically, PVT collectors utilize either water or air as a working fluid. PVT water collectors (glazed or unglazed) have dominated the market for its usage in single, or multifamily houses, hotels, hospitals, and industries [3]. However, in past few years, PVT air-based system (also referred as aerothermal) have recorded a significant growth, dominated by the market in France, for air preheating applications in buildings and industries [2]. In a typical aerothermal configuration, the air flow behind PV modules is created using air channels, and the heated air is ducted to the point of usage. The use of air as working media is technically simplistic with a potential for lower cost of overall system in comparison to water-based systems [4]. One interesting aspect of aerothermal is the possibility of converting existing PV installations into PVT collectors, by recovering the heat behind PV modules. There are few suppliers worldwide who provide full PVT air systems or instead can provide standard kits to retrofit the existing PV installation for heat recovery [5]. Such systems have good potential, as it allows users to increase the value of their PV installation by additional savings due to the recovered heat.

The utilization potential of recovered heat from PV depends on several variables such as type of HVAC system, load profile, and meteorological conditions etc. Classically, PVT air systems are widely used for pre-heating of fresh air entering the building, and thus reducing the space heating (SH) demand. Such systems are most cost effective when the building has a central fresh air supply network, and does not have any ventilation heat recovery system in place [6]. However, in presence of ventilation heat recovery (with or without exhaust air heat pump), the system output is lower and thus limiting the potential usage of recovered heat from a PV system, especially in Nordic climates with lower irradiation. Therefore, it is important to understand the energetic gains of PV recovered air in various HVAC configurations.

The central aim of this paper is to simulate a system where the recovered heat from a PV installation is utilized in an energy system of a multifamily building cluster in Sweden. The paper tends to establish if the additional cost of "heat recovery system" components justify the savings obtained due to recovered heat from PV. To achieve this, a simulation model is built in TRNSYS, based on the load, and meteorological conditions of a building cluster located in Sunnansjö, Sweden [7]. Specifically, two energy system configurations are simulated.

1) Recovered heat from PV collectors is used for pre-heating of domestic hot water (DHW).

2) Heat from PV collectors is used at the evaporator of an air source heat pump (ASHP) to increase its performance. The ASHP is further used to generate DHW.

The research results are expected to provide useful techno-economic information for PVT's involvement in future urban building energy systems.

2. METHODOLGY

2. 1 *Reference system*

Initially, a reference system model is modelled, where only district heating (DH) is used for DHW preparation. In the next step, two system configurations are modelled where the effect of recovered heat from PV is quantified

2.1.1 Building and loads

A group of three multifamily houses is considered for DHW load modelling. The buildings are located in the central Swedish town of Sunnansjö in the municipality of Ludvika with geographical coordinates of 60.2 ^{o}N and 14.9 ^{o}E. The building has in total 48 apartments, with 62 inhabitants. The total DHW load is a combination of heat required for fresh water heating (111 MWh/year), and recirculation losses (15 MWh/year). Therefore, total measured DHW load is 126 MWh/year, and specific load of 2625 MWh/apartment/year. The daily variation in DHW flow rate is shown in Figure 1.

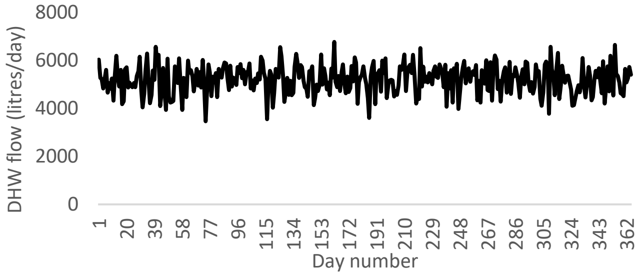


Figure 1 Daily variation in the DHW flow rate for the analyzed building cluster

2.1.2 Reference system: model description

District heating is used as source for DHW preparation. The HVAC system for space heating is out of scope for this paper, and therefore only the DHW part is modelled. The DHW designed temperature is set to 55 °C. The DHW is circulated in the various building zones with a total pipe length of 200 m with a design temperature drop of 5 °C to account for the heat losses through the pipe walls (Type 31). A sinusoidal function representing the cold-water temperature is used for simulations. A counter flow plate heat exchanger (Type 91) is used to supply heat from DH stream to DHW stream. The designed DH inlet temperature is set to 78 °C, and increased by 1 °C for each degree decrease in ambient temperature below 0 °C. An iterative feedback controller (Type 22) is used to vary the pump (Type 110) flow rate in DH circuit to reach set point temperature.

2.1.3 Meteorological inputs

Borlänge is the closest available location for ground measured weather data, located 50 km from Sunnansjö, and data for the year 2014 is used for the analysis. The annual global horizontal irradiation for the analyzed location is 971 kWh/m^{2}. The annual average wind speed for the location is 3.3 m/s and shows slight variations throughout the year. On the contrary, the ambient temperature is characterized by significant monthly variation and reaches sub-zero temperatures for five months per year. The annual average ambient temperature of the location is 4 °C. All the simulations are done for 1 year period, using a time step of 1 minute.

2.2 PVT for DHW pre-heating

2.2.1 System description

In this configuration, a ventilated PV installation is assumed on the roof top of the buildings, and the recovered heat from PV is used to pre-heat the cold makeup water entering in the DHW circuit. A simplistic system concept is shown in Figure 2. The flow behind the PV modules is obtained using a fan and run through the air channel created between backside of PV module, and the roof material. Ambient air enters at a designed flow rate behind the PVT collectors, exchanging heat from back sheet of PV, and the heated air is ducted to the inlet of an air-water heat exchanger (HX). The outlet air from the HX is expelled to the atmosphere, so the PVT collectors works in an open loop. A water storage tank is used to maximize the utilization of recovered heat from PV. The cold make-up water enters on the secondary side of HX, and finally enters the storage tank. Water from this storage tank is pumped to the DHW loop, where DH is used as a main heat source for DHW preparation. With each draw-off, the cold water enters the circuit, and is pre-heated using heated air from the PV collectors. The electricity produced by the PV modules is fed to the grid. No provision of self-consumption is considered for simplicity.

2.2.2 System model

The PVT collectors are simulated using TRNSYS type 568, which is a ventilated PV type with airflow behind the PV surface. The schematic of the PVT collector is shown in Figure 3.

TRNSYS type 568 was validated over a 10 days testing period for Italian climate [8]. In this study, a good match was found between measured and simulation results, with coefficient of variation of 0.14 °C. In another validation study, the performance of a PVT module of 1.26 m^2 area was monitored for a location in Shanghai, China [9]. The PVT outlet temperature, and electrical performance were measured, and results were compared with a simulation study conducted in TRNSYS, concluding a good match between measured and simulated data.

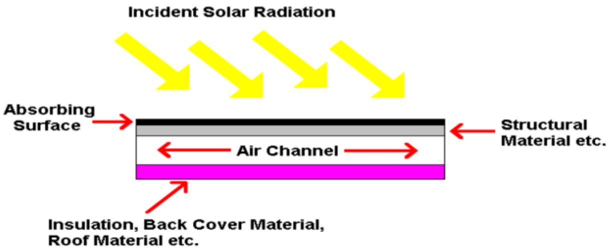


Figure 3 Layout of ventilated PV type used for simulations [7]

The optical and thermal properties of various layers forming the PV module (glass, EVA, PV cell, and back sheet) are used as inputs in a model to derive the thermal resistance as shown in Table 1. The PV is assumed to use multi-crystalline cells, with rated electrical efficiency of 16 %, and temperature coefficient of power at -0.45 %/°C. The inverter is assumed to have a constant efficiency of 95 %.

Table 1 Input parameters for simulated PVT component [10]

			Optical coefficients		
Material	Thickness (mm)	Thermal conductivity (W/mK)	Reflection (ρ)	transmission (τ)	absorption (α)
Glass	4	1.8	0.1	0.88	0.02
EVA	0.4	0.35	-	0.97	0.03
Silicon PV cell	0.4	150	-	-	1
PV back sheet	0.3	0.3	-	-	1

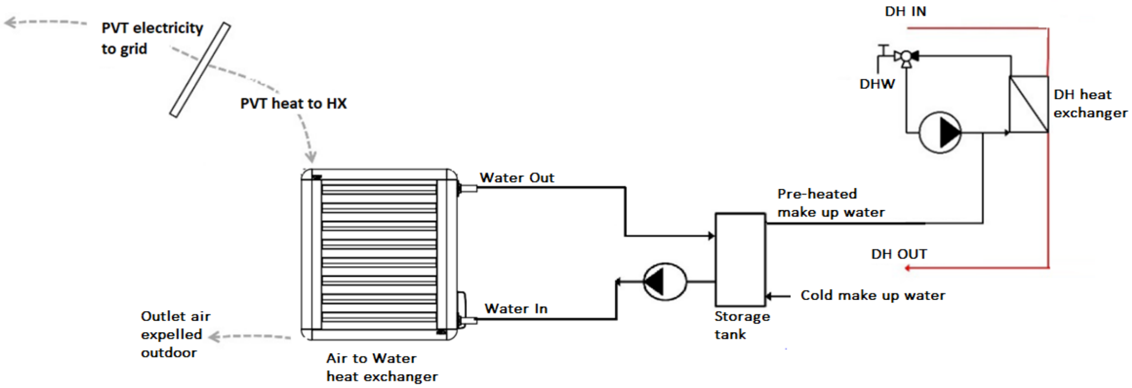


Figure 2: System arrangement where recovered heat from PV is used to pre-heat the cold make up water in DHW circuit

The air channel height is set to 5 cm after component optimization in TRNSYS. A fan with specific power consumption of 0.10 W/(kg·h) is used to obtained the designed flow rate behind PV modules. The air to water HX is a cross flow type, and is using reference from a commercial product to derive temperature and flow dependent UA values [11]. The vertical storage tank (Type 158) is simulated using 10 temperature nodes, without any internal heat exchanger. A differential controller (type 165) is used to control the fan and pumps to avoid reverse heat flow in the HX.

2.3 PVT for air source heat pump evaporator

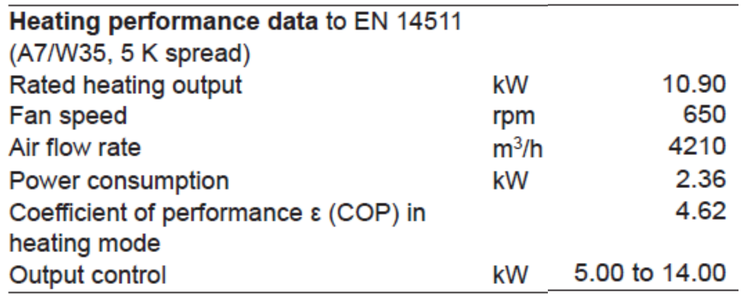
2.3.1 System description

In this case, a series arrangement of PVT collector and ASHP is used for DHW preparation in conjunction with reference system as shown in Figure 4. ASHP uses ambient air as a source for evaporator, and can generate hot water up to 60 °C on condenser side. However, the seasonal coefficient of performance (SCOP) is negatively affected by the decrease in ambient temperatures [12]. Therefore, recovered heat from PV can be used to raise the inlet air temperature to the ASHP, and possibly the SCOP.

In this system arrangement, hot air from PVT is ducted to the outdoor unit of ASHP. On the condenser side, ASHP in conjunction with a storage tank is used for DHW preparation. The hot water from tank enters the DH HX. DH is used for a) back up heating when ASHP capacity is not adequate to reach DHW set point temperature b) to compensate for DHW recirculation losses.

2.3.2 System model

A commercial heat pump model's performance map is used for simulations (Type 941) [13]. The HP capacity is chosen based on average DHW load. The specification of simulated HP is shown in Table 2. An optimization of collector area is done so that the existing fan from in outdoor unit of the ASHP can be used to achieve designed flow rate in the collectors. A damper is provided so that PVT collectors can be bypassed in lack of useful heat. The ASHP is controlled based on the storage tank charging level, and a cut off limit of 60 °C is set to cease the ASHP operation.



Heating performance data to EN 14511 (A7/W35, 5 K spread)		
Rated heating output	kW	10.90
Fan speed	rpm	650
Air flow rate	m^3/h	4210
Power consumption	kW	2.36
Coefficient of performance ε (COP) in heating mode		4.62
Output control	kW	5.00 to 14.00

Table 2 Specifications of ASHP simulated using a performance map

3 RESULTS

3.1 DHW Pre-heating using PVT

Initially, an optimization is performed to conclude that thermal output of collectors has non-linear trend with air flow rate behind PVT collectors, with optimal value of 60 kg/h for 1 m^2 of collector area. This optimal value of flow rate is then used to simulate the system with the rest of components. The system performance results are shown in Table 3. Three collector areas are chosen for analysis (100 m^2, 260 m^2, and 500 m^2), depending on the roof area limitation of buildings.

Table 3 Thermal output of system at various collector areas, evaluated at specific tank volume of 60 l/m^2

Collector area (m^2)	Heat delivered from PVT system to DHW (MWh/year)	Percentage of DHW load met by solar collectors
100	17	13.5 %
260	24	19.5 %
500	28	22.5 %

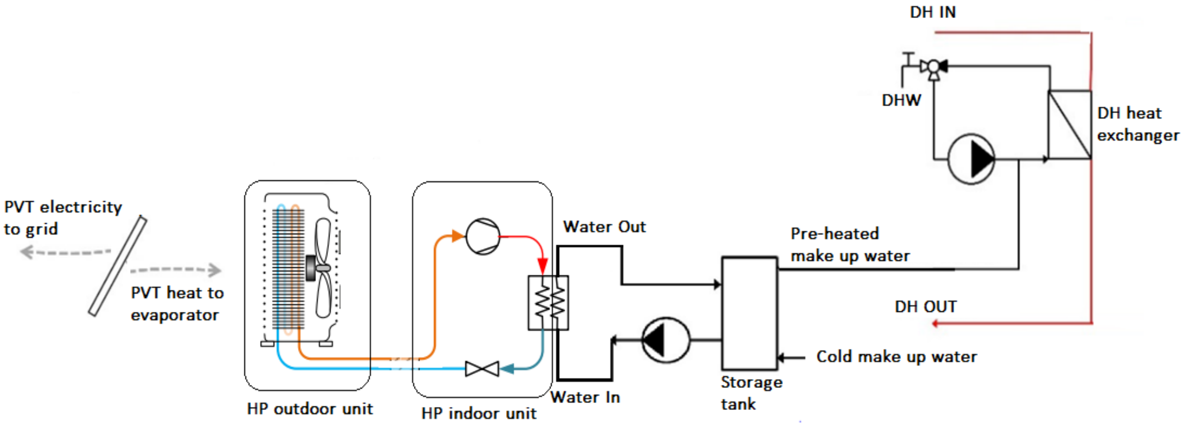


Figure 4 System arrangement where recovered heat from PV is fed to evaporator of ASHP

It can be seen that for fixed DHW load (126 MWh/year), recovery of heat from larger collector areas results in higher thermal output, and thus a larger portion of DHW demand is met by collectors. For a collector field of 260 m^2, the recovered heat from PVT can be used to meet 20 % of total DHW load, and remaining 80 % are provided by DH. It can also be noted that the thermal output increase with collector area is non-linear. This is because increase in collector area results in an increase in tank temperature, which limits the exergy gains from PVT collectors, and decrease the heat recovery potential in air-water HX. The variation of area specific system output at various collector areas is shown in Figure 5.

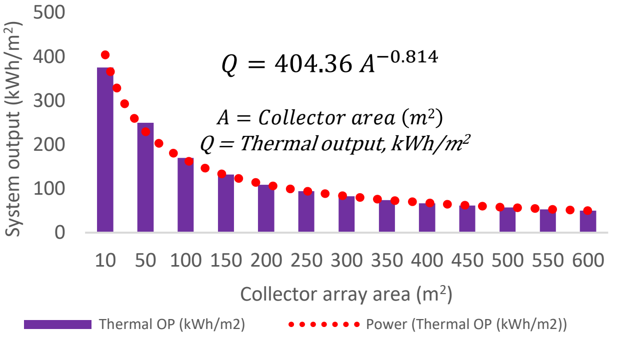


Figure 5 Variation of area specific thermal output with collector area, evaluated for a 45° South facing array, with specific tank volume of 60 l/m^2.

The hourly variation in heated water temperature at outlet of heat exchanger is shown in Figure 6. The maximum temperature is obtained in summer, with highest irradiation and vice versa.

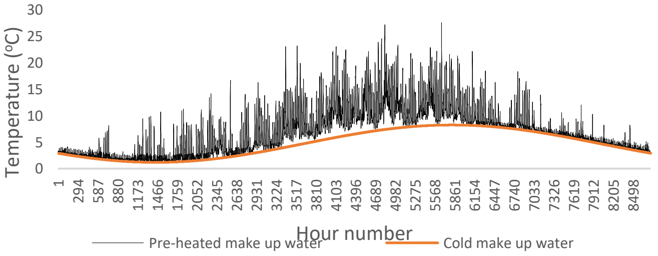


Figure 6 Hourly variation in temperature of make up water heated by recovered heat from PV.

During summer, the ambient air usually has a higher temperature than makeup water temperature, and thus providing advantage of "free-heating" by exchanging heat from ambient air to makeup water. The air flow behind PV modules results in lower modules temperatures, and thus expected increase in electrical output. For PV modules (without any air flow), the electrical output is 972 kWh/kW peak. For PVT, air flow results in a small increase in the electrical output by nearly 1 %, stands at 9.7 kWh/kW peak. But the electricity consumption of the fan is quantified at 21 kWh/kW peak, thus higher than the savings.

3.2 PVT for ASHP

To quantify the effect of increased COP of the ASHP, initially a system is defined where HP, and DH are used as sources for DHW preparation. In this reference case, no utilization of PVT collector is assumed, and thus ASHP evaporators takes in ambient air as heat source. For the selected HP capacity, a sensitivity analysis is performed to reach an optimal tank volume capacity of 3 m^3. The simulation results show that the ASHP can provide 83.5 MWh of heat which is equivalent to 66 % of the annual DHW load, rest 34 % is provided by DH. The SCOP for this reference case is 3.11.

The next step is to utilize the heated air from PV for the evaporator of the ASHP. Based on the fan flow rate capacity of the outdoor unit, the maximum analyzed collector area is limited to 125 m^2. The results of PVT integration to the reference system are shown in Figure 7 for various collector areas.

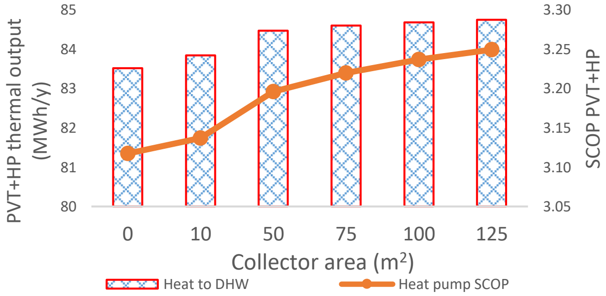


Figure 7 Effect of various PVT collector areas on the thermal output of PVT+HP system, and on ASHP SCOP.

In comparison to the reference case, the Integration of PVT collectors improves the SCOP. Therefore, for the same thermal output, the ASHP consumes less electricity, and similarly for the same power consumption, the ASHP produces more heat. For a ASHP thermal capacity of 10.9 kW, a PVT collector field of 100 m^2 is integrated, and a 3.8 % increase in ASHP SCOP is observed which increases from 3.11 for reference case to 3.23 for PVT+HP case. The increase in SCOP is reflected in the annual electricity savings of 1038 kWh for a PVT field of 100 m^2, thus resulting in area specific electricity savings of 10.3 kWh/m^2/year.

Two simulation variants of above system arrangement are studied. In the first variant, the ASHP was operated only when there is any heat available from PVT collectors, therefore the operation was restricted to daytime only. Results suggest that the SCOP of HP increases by 49 % compared to reference case, as ASHP operates at higher inlet air temperatures. However, due to limited number of operational hours, the share of DHW load met by PVT+ASHP is limited to only 30 %, and rest 70 % is met by DH. The savings due to PVT integration on electricity consumption remains unchanged at value of 10.3 kWh/m^2/year.

In the second variant, the ASHP capacity, and tank volume were increased to maximize the heat output of PVT+ASHP system. The results suggest a ASHP heating capacity of 15 kW, tank volume of 16 m^3, and a PVT array of 100 m^2, this system can generate 115 MWh/year, and thus fulfilling 90 % of the total DHW load. The piping recirculation heat losses (representing 10 % of DHW load) are still compensated by DH. The electricity savings due to PVT integration are evaluated at 15 kWh/m^2/year.

4 DISCUSSION AND CONCLUSIONS

The energetic benefits of recovered heat from PV collector are analyzed. Results shows that the advantage of PVT integration is more pronounced when recovered heat is used directly for pre-heating of DHW. For the system with DHW pre-heating, a solar field of 260 m^2 results in 24 000 kWh thermal output which is 20 % of the annual energy needed for DHW. Assuming DH cost of 0.70 EUR/kWh, the value of this free heat is around 17 00 EUR/year. Based on cost of adding “PVT features” and a water tank, the system will most likely have a positive cash flow. However, for ASHP case, the increase in COP results in electricity savings only in the range of 10 to 15 kWh/m^2. Assuming an electricity price of 0.2 EUR/kWh, the annual savings from an array of 100 m^2 would be 200 to 300 EUR, which is around 6 times lower than DHW savings, and is unlikely to have a positive net present value.

However, the system utilizing ASHP can be used to increase the self-consumption of the PV system, and thus can avoid feeding electricity into the grid at lower revenue. These additional savings can increase economic feasibility, and thus need further evaluation.

The study has some limitations. The collector model does not consider the effect of array arrangement (series/parallel) and therefore temperature gradients within the collector array is ignored. Furthermore, the effect of air leakage is not considered. In any real installation, it is difficult to obtain a fully leak-proof system, and thus there is always some loss of air volume, which results is spillage of recovered heat. For future studies, a few more system alternatives could be interesting where the recovered heat from PV can be utilized effectively, such as integration with 5th generation DH network. One such arrangement could also be use of recovered heat for space heating applications in residential buildings with mechanical ventilation.

ACKNOWLEDGEMENT

The research work in this paper was conducted with financial support from the EST project: Efficient Solar Roof Tops - Case Studies and In-depth Analysis for Optimized Roof Renovation with Solar Cells, Project number (Swedish Energy Agency) 46867-1.

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