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OPERATING EXPERIENCE AND TECHNICAL DEVELOPMENTS OF AN INNOVATIVE INTEGRATED SOLAR COLLECTOR

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ABSTRACT

Installations using solar energy have negative visual impact and this discourages some potential users. The aesthetic of solar thermal collectors can be an obstacle to their development and limits the growth of the market. The integration of solar collectors in buildings allows to make them invisible from the ground. In France, the law remains rigid and promotes the appearance of the buildings to its energy aspect. Although there is a recent release, the conditions are strict, and tend, at the same time that financial aid at a maximum integration of energy components. Government guidelines are also reaffirming the priority given to the solar technologies integration into the building in order to promote friendly aesthetic solutions landscape and architecture, and position the industrial sector and artisans on a higher value added. In this paper we present a new patented concept of solar collector totally integrated into a gutter. We developed a two- dimensional thermal model using a finite difference method and we modeled the hydraulic loop. The model was implemented and the numerical results were validated from experimental data. We present also the feedback performances of this solar installation in a building located in Corsica during one-year period. Another modeled conception was simulated and performance comparisons were realized. This project is built on the objectives of contributing at the European politic on the «Building Integration of Solar Thermal Systems» (BISTS) through the COST Action «European Cooperation in Science and Technology» - TU1205.

Key words: Solar Energy, Thermal Collectors, building Integration.

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Introduction

Building-sector energy demand is rising fast in many countries. In France, 30 million homes use around 50% of the energy budget and produce 25% of national greenhouse gas emissions. In Europe, the building sector accounts for around 40% of total energy demand, which makes improving building energy performances crucial in order to meet EU energy efficiency targets and combat global climate change—and create a platform towards domestic energy security. In 2002, the EU introduced the Energy Performance of Buildings Directive ('EPBD') giving EU States an integrative methodology-based approach designed to foster efficient energy use across the building sector.

The EC then recognized that there was non-negligible potential for profitable energy savings still going unexploited, which is why in November 2008 it proposed a recast of the EPBD designed to enable energy savings amounting to a further 60 to 80 million tons of oil equivalent per year to 2020, i.e. a further 5–6% reduction in total EU energy consumption, over and above the previous maximum achievable if the recast directive was integrally implemented across the board. Based on these proposals, in April 2009 the European Parliament passed a legislative motion calling for even tougher more ambitious legislation. The EU Council now needs to reach a position on this strand of proposals.

Introducing innovative and environmentally-friendly solutions is a vital task made complicated by the number of bottlenecks involved—some financial, others technical, psychological, and even legislative (building code). The solutions proposed need to be seamlessly building-integratable and minimize eyesore (psychological bottleneck). They also need to be easily installed onto new builds and old housing stock (technical bottleneck), not too expensive (financial bottleneck), and environmentally friendly. Our basic idea, in a nutshell, is to 'activate' passive components of a build.

Outline of the New Solar Collector Concept

The H2OSS flat-plate thermal solar collector concept, as developed and patented [1], was devised as a solution to tackle the above-cited bottlenecks via a strategy based on activating housing components that have traditionally remained passive.

Developed to the fully building-integrated design brief, the H2OSS thermal solar collector is a flat-plate collector designed as a forced-circulation home solar water-heating system. The innovation lies in its long slim geometry enabling it to slot into a pre-profiled aluminum gutter channel used for rainfall evacuation. This aluminum gutter channel profile can be built in place, in one piece (running up to twenty-odd meters long), using the industrial extrusion process. The gutter channel obviously retains its rainfall evacuation role.

The gutter channeling comes in an array of styles and colorways for enhanced building integration. These modules are quick and easy to install, and the installed system is invisible from ground level, as the main circuit inflow and outflow tubing is hidden away inside the rainfall evacuation tubes (see Figure 1).

Figure 1 : Illustration of the H2OSS concept installed in situ

The H2OSS solar module draws on the most tried-and-tested technology for this type of collector, i.e. a semi-transparent glazed cover top sheet, a highly-selective absorber plate, a heat-insulating back sheet, and two copper tubes that recover the heat energy converted by the absorber (see Figure 2). An installation is comprised of a set of modules interconnected in series and/or parallel circuits. Each module measures 1 m long by 0.14 m wide and is connected to the next by a split-point junction making it possible to swap a given module in or out, as necessary.

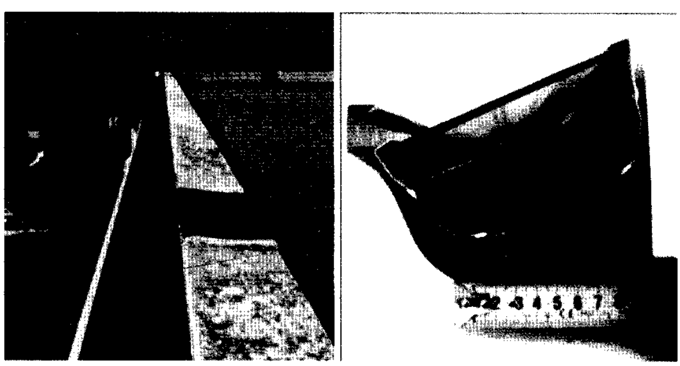

Figure 2 : The system installed at the Vignola Lab (Corsica)—overhead view and cross-section view of the H2OSS solar collector.

The tube located just under the fin is the outflow tube, and the other is the inflow tube containing the coolant that recovers heat from the absorber.

Concept Characterization, Model and Validation

Defining parameters of the solar collector

We previously tested the solar collector's thermal behavior to validate the thermal model [2] and attempt to improve performances [3] by trialing certain parameter adjustments. Briefly, the trials were led on a site at our laboratory in the Gulf of Ajaccio (latitude: 41°55'N; longitude: 8°55'E) at an altitude of 70 m asl and about 200 m from the seafront. This trial setup enabled us to operate closer to European Standard EN 12975-1 [4], with 4 rows of 4 modules (2.24 m^2) connected in series and fixed on a solar tracker for better control of solar intensity and direction. The solar modules are connected to a thermal loop that regulates the input fluid temperature by heating the fluid if it is too cold or cooling it via an air cooler if the fluid is too hot. Measurements were taken on each module at 60-s intervals to record: solar irradiance on the collector plane (using a Kipp & Zonen CM11 pyranometer), ambient temperature, humidity, wind speed and direction, fluid flow rate and input and output fluid temperatures. This experimental trial enabled us to plot the performances of the new solar collector. Performance efficiencies were calculated experimentally for various measured reduced temperatures, and linear regression was applied to determine optical efficiency and thermal losses according to equation (1):

$$\eta = -KT_r + B$$
$$\text{with } T_r = (T_m - T_{amb})/\phi \quad (1)$$

where Φ is solar irradiance, Tm is mean temperature, T_{amb} is ambient temperature, B is optical efficiency (dimensionless) and K represents the thermal losses ($W.m^{-2}.K^{-1}$) [5]. Table 1 reports the optical efficiency and thermal losses.

Table 1 : Optical efficiency and thermal Losses

	H2OSS
Optical Efficiency, B	0.903
Thermal Losses, K ($W.m^{-2}.K^{-1}$)	13.80

While our optical efficiency was high, the coefficient relative to thermal losses was bad. This difference is due to the geometry of the H2OSS® modules, as thermal losses are heavier on the sides of the modules and so performances decrease rapidly when reduced temperature increases. The H2OSS collector performed better with a low reduced temperature and worked better when input water temperature was low, which prompted us to use a water storage tank with thermal stratification making the system work at low flow rate so that the water coming from the tank to the solar collector will be colder.

Thermal model

- H2OSS numerical model

We developed a two-dimensional thermal network model [2] based on nodal discretization method. The solar collector is broken down into 97 finite-element volumes that are assumed to be isothermal, and for each node, we describe the governing thermal equilibrium equation based on an electric circuit analogy in which temperatures, sources of flow and boundary temperatures are assimilated to electric potentials, currents, current generators and voltage generators. The thermo-physical properties of the component collector materials are assumed to be constant within the effective range of working temperatures.

The input parameters used in the model are solar irradiance Φ, ambient temperature T_{amb}, airspeed over the front face of collector V, temperature at ground level T_{ground}, temperature overhead T_{sky}, and temperature of the coolant fluid at the collector in-feed. To illustrate, the equation corresponding to the first node of the glazed flat plate is detailed in equation (2)

$$\rho_{glass} C_{p_{glass}} V_1 \frac{dT_1}{dt} = A_1 \alpha_{glass} \phi - \epsilon_{glass} \sigma A_1 f_{1-sky} \left(T_1^4 - T_{sky}^4\right) + \frac{T_{amb} - T_1}{R_{cond} + R_{conv}} + \frac{T_{amb} - T_1}{R_{cond} + R_{conv}} + \epsilon_{glass} \sigma A_{trans1} f_{1side-sky} \left(T_1^4 - T_{sky}^4\right) + \frac{T_2 - T_1}{R_{cond}} + \frac{T_{12} - T_1}{R_{cond} + R_{esistance\_contact\_1} + R_{cond}} \quad (2)$$

where A is surface, α is attenuation coefficient, Φ is solar irradiance, ε is coefficient of emissivity, f is form factor, T is temperature, and R-value is thermal resistance. All three types of heat transfer are mapped as thermal resistances. Higher R-values mean lower heat flux values. R_{cond} corresponds to a conductive resistance that is dependent on thermal conductivity λ of the material, thickness e to be crossed, and heat transfer area A. R_{conv} corresponds to a convective resistance that is dependent on heat transfer coefficient h. Radiative transfer was expressed using the linearizing Stefan–Boltzmann equation that can translate radiative transfers into thermal resistances. However, for sharper accuracy, we used the non-linear Stefan–Boltzmann equation, which means thermal equilibrium is expressed as stated in equation (2). For the equation governing energy balance of the fluid circulating inside the copper tubes, the temperature at the coolant tube wall was estimated using the NTU method (Eq. 3) that produces an estimate of the temperature profile of a fluid circulating inside a homogeneous tube (T_a) for an internal surface area S_{fc} under steady-state flow [6].

$$T_{fc/s} = T_a + \left(T_{fc/e} - T_a\right) e^{-NTU} \quad (3)$$

where NTU is number of transfer units (Eq. 4)

$$NTU = \frac{h_{fc/a}.S_{fc}}{\dot{m}_{fc} C_{p_{fc}}} \quad (4)$$

Using equations (3) and (4), and knowing the inflow temperature of the fluid and the mean tube temperature, it becomes possible to calculate fluid temperature at the collector outflow. The 97 equations—one for each of the 97 finite-element volumes—were solved numerically. The model thus obtained is resolved using an implicit direct integration method.

- The Hydraulic Loop

During the experimental phase, we noted that one of the key problems with our solar collector is hydraulic resistance due to the collector's linear structure. Consequently, it would be wise to keep this solar system working in low flow-rate conditions. By reducing hydraulic losses, the low rate regime also brings other advantages, as reported in [8]. Thermal stratification: using low-flow operation results in an increased solar collector outlet temperature and consequently induces a higher degree of thermal stratification inside the tank. Moreover, water temperature at the top of the tank will be closer to set point load temperature, which means auxiliary energy consumption will be decreased, thus increasing solar fraction. Furthermore, with highly-stratified heat storage, the return temperature to the solar collector will be lower and the working periods for the solar collector will be longer, which should lead to increased net energy output from the solar collector [8-9].

The thermal loop behavior is simulated using a numerical code based on a nodal approach [7-11]. It is divided in 19 nodes: 7 for fluid circulation, 10 for the storage tank (optimal number of nodes to optimally take into account the thermal stratification [7]), and 2 for the water storage inlet and outlet. The temperature of the water at the outlet of the solar collector and the average temperature of the solar absorber are obtained by modelling the solar collector, keeping in mind that all 97 temperatures in the solar collector need to be computed to determine these two temperatures. The energy balance, in 1-D, is applied and an iterative method is used to solve the first-order differential equations. A reversion-elimination mixing algorithm based on a thermal mix of certain storage tank nodes to obtain a correction factor giving a positive temperature gradient from bottom to top of the tank [12-13] was used to simulate in-tank thermal stratification. The tubes between the tank and the solar collector are 9 meters long, with 3 m inside the building (ambient temperature is thus the temperature inside the building - thermal losses are thus taken into account). The coil heat exchanger is modelled by 5 nodes, and thermal power between the heating fluid and the water into the tank is calculated using the NTU method [14].

<u>Experimental validation</u>

With implementation of the thermal model, we moved on to validate the model based on experimental data collected with the second experiment (including a solar tracker) [2]. A thermal solar module was specially instrumented with 9 thermal sensors (type PT100 class B) measuring surface temperature at different specific points. The solar thermal modules are connected in parallel delivering a water flow rate of 450 $L \cdot h^{-1}$; in these conditions, the increase in water temperature is small but the temperature gradient inside the module is more clearly visible. An experimental verification was carried out on the all-year data. The simulated and experimental temperatures show fairly good fit. We also simulated output water temperature with the thermal module connected in series and delivering a water flow rate of 140 L·h-1. These conditions were chosen to approach real operating conditions. We computed RMSE and RRMSE for output water temperature over four seasons (using about 90 days) and obtained the following values: RMSE = 1.4°C and RRMSE = 5.2%. These errors are fully acceptable. These two validations certify that the model robust enough to be used in future work studying the influence of changes in materials, structure, or other possible modifications.

Process of Evolving This Solar Collector into an Optimized Version

The solar collector was numerically optimized for a conventional installation in single-family housing in the south of France. We previously showed [3] that repositioning the cold water tube into the absorber rather than the insulation layer yields much better performances than with the current prototype. Thermal insulation and air layer thicknesses were then optimized, and the influence of water flow rate proved very high by virtue of the design of this new solar collector. Three configurations were studied (see Figure 3).

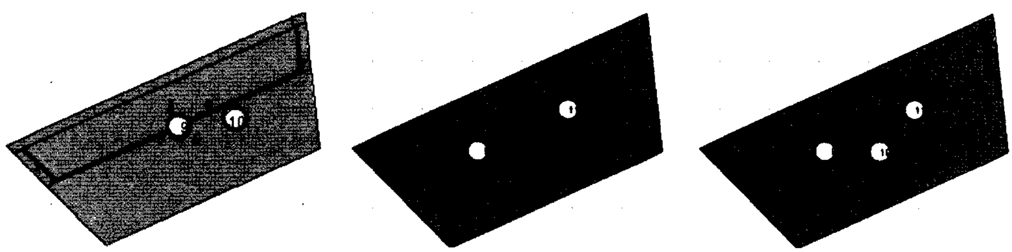

Figure 3 : Different configurations studied.

The configuration that best optimizes performances is configuration 'b' with the two parallel tubes on the same plane. Table 2 gives the new computed optical efficiency and thermal losses of configuration 'b'.

Table 2 : Optical efficiency and thermal losses.

	H2OSS
Optical efficiency, B	0.780
Thermal losses, K ($W.m^{-2}.K^{-1}$)	6.25

This new configuration of the H2OSS concept will be simulated for a single-family house, and performances will be compared against the installed prototype.

Real-world Performances of a Solar Facility Located in Southeastern France

This building-integrated solar thermal system is located in Corsica, at latitude 42°42′10″N, longitude 9°26′59″E, altitude 51 m asl, in a Mediterranean climate zone. We instrumented the thermal solar system in order to benchmark the energy performances of the installation.

The installation set up comprises a 200-L electric–solar hot water storage tank with a 2 kW resistance. It features 20 serially-connected H2OSS solar collectors covering a total working surface of 20 m^2. The main solar circuit comprises 9 linear meters of pipework between first collector and storage tank, including 6 linear meters that are outside the collector system loop. The installation runs at 80 $L\cdot h^{-1}\cdot m^{-2}$. Table 3 lists the recorded mean monthly demand-water temperatures and mean monthly outdoor temperatures.

Table 3 : Mean monthly demand-water temperatures and mean monthly outdoor temperatures.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Demand-water temperatures	8.6	8.2	8.8	10.5	12.6	14.7	15.9	16.6	15.8	14.2	12.0	10.5
Outdoor temperatures	9.2	9.5	11.9	13.5	18.9	22.8	24.9	25.8	20.8	17.6	12.8	10.0

Figure 4 charts the year-averaged over-day demand profile recorded for this detached home housing four occupants (two parents and two children).

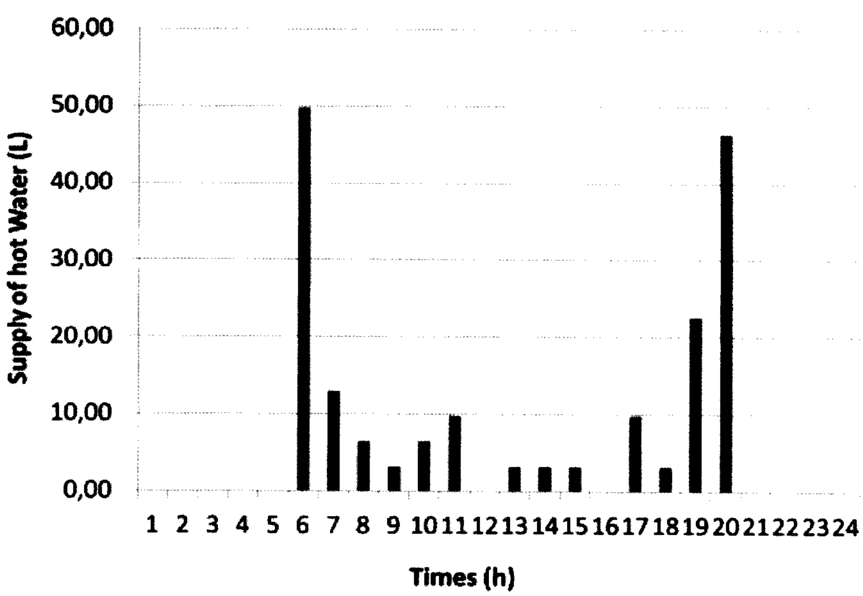

Figure 4 : Average daily profile for domestic hot water supply

Results of the installed running prototype

We measured energy performances over a 12-month year (2013) in operation. This solar power installation delivers a solar fraction of 27%. Over the year 2013, we get a net solar power output of 835 kWh for a domestic hot water demand of 3055 kWh and a solar radiation of 4901 kWh received. Figure 5 charts solar radiation received, domestic hot water demands, effective solar power output and solar fraction month-by-month over 2013.

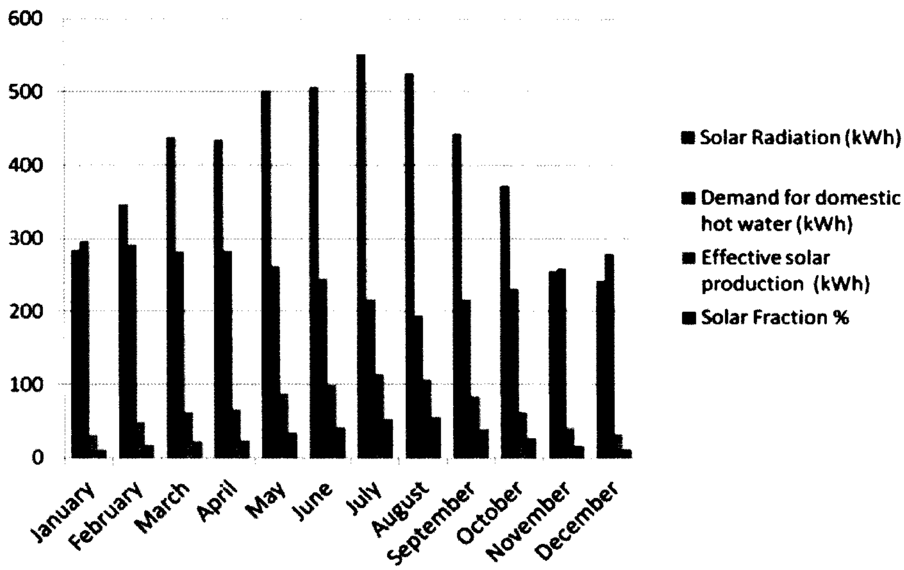

Figure 5 : Energy performance of the existing solar thermal system (K=13.80/B=0.903).

Note that over the trial year 2013, the installation showed energy losses on the main solar circuit (tubing) amounting to 93 kWh and losses via the electric–solar hot water storage tank amounting to 371 kWh. Annual energy consumption of the solar circuit pump amounts to 63 kWh.

Simulated performances computed for a new-version H2OSS

We simulated energy performances over a 12-month year (2013) in operation for the optimized new-version H2OSS solar collector. This solar power installation now delivers a solar fraction of 48%. Over the year 2013, we get a net solar power output of 1408 kWh for a domestic hot water demand of 3055 kWh and a solar radiation of 4901 kWh received.

Figure 6 charts solar radiation received, domestic hot water demands, simulated solar power output and solar fraction month-by-month over the 2013.

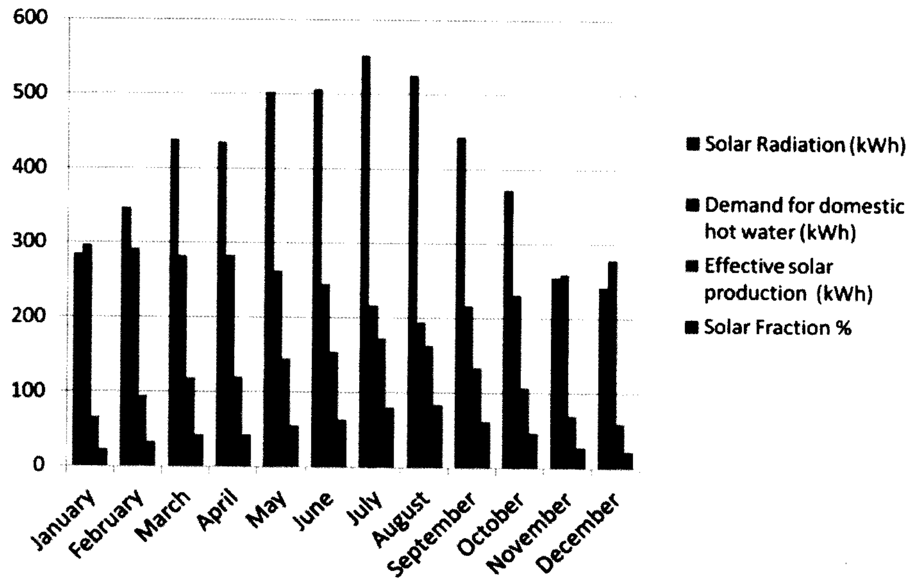

Figure 6 : Energy performance of the simulated solar thermal system (K=6.25/B=0.78).

This new version, as simulated over the trial year 2013, showed energy losses on the main solar circuit (tubing) amounting to 121 kWh and losses via the electric–solar hot water storage tank amounting to 429 kWh. Annual energy consumption of the solar circuit pump amounts to 64 kWh.

Conclusions

Despite extensive deployment of solar power worldwide, the solar economy still faces a number of bottlenecks. One of the take-home messages from an R&D seminar hosted by the ADEME—French Environment and Energy Management Agency at Sophia Antipolis (France) on 27 and 28 April 2004 to address "innovation needs for thermal solar power" was that the thermal solar systems on the market are essentially unintegrated "add-ons" to the building. The problems that emerged—both on the technical front and the aesthetics front— are patent bottlenecks to development. Furthermore, as the solar market has now gained relative maturity, solar product costs have begun to stabilize and are unlikely to show any fresh drop in the near future. The upshot is that short of any economies of scale driven by a boom in the market, only a disruptive technology causing a shift in design–engineering could spark a significant new shift in solar economics. The bottlenecks, in order of importance, are first financial, then technical, legislative, and finally psychological. It is in this context that we propose a new home-integrated solar power concept. This paper outlines the French legislative constraints governing the deployment of thermal solar collectors in France, before going on to introduce the new integrated concept by outlining the modelling process and model validation ready for use in simulations. We report a running prototype installed in Corsica, France, and its energy efficiency performances achieved over the year 2013. This solar power installation delivers a solar fraction of 27% for a net solar power output of 835 kWh. Simulations of a new optimized version of the solar collector prototype run for this same installation yielded improved results, with a solar fraction of 48% for a net solar power output of 1408 kWh—and consequently a net gain approaching 78%. This research addresses EU energy policy challenges tied to integrating thermal solar systems into buildings, and specifically the COST—European Cooperation Science and Technology—framework action TU 1205 "Building Integration of Solar Thermal Systems" (BISTS).

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