EXERGY ANALYSIS OF SOLAR THERMAL SYSTEMS: A NECESSARY COMPLEMENT TO CONVENTIONAL ENERGY ANALYSIS?

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1. Introduction

Current analysis and optimization methods of energy use in buildings are based on the assessment of primary energy flows, where all energy conversion steps from the extraction of energy sources (e.g. fuels) to the final demands to be supplied are assessed. The primary energy approach aims at limiting the use of fossil fuels for providing a given demand, leading to reduce energy demands and maximize the use of renewable energy sources. It is based, thus, on a distinction between renewable and fossil energy sources, being renewable energy flows often disregarded in the final balance. Thereby, an assessment of the efficiency of renewable energy use cannot be obtained from such analyses.

Exergy is a thermodynamic magnitude defined as the maximum theoretical work obtainable from the interaction of a system with its environment as the equilibrium state is reached between both (Moran and Saphiro, 1998). Exergy analysis allows for the detection and quantification of the improving potential of complex energy systems (Szargut, 2005) and has been widely used for the optimization of thermodynamic systems since the middle of the last century (Rant, 1964). Exergy analysis shows the true thermodynamic efficiency of an energy system. All energy flows, renewable or not, are regarded in the exergy balances, thereby allowing the assessment of the efficiency of renewable energy use in a given energy system.

Low temperature energy demands in buildings such as space heating and cooling have low quality, i.e. low exergy content. Low temperature renewable energy systems (e.g. solar thermal systems) are able to lower significantly the quality of the supplied energy in buildings, thereby increasing the exergy efficiency of energy supply.

In the present paper results from exergy analysis of a solar thermal unit for supplying part of the domestic hot water and space heating demands of a multi-family dwelling are presented and compared to conventional primary and final energy assessments. Differences and added value of exergy analysis as compared to conventional primary energy assessment for solar thermal systems is investigated by comparing the conclusions and insight gained from both methods.

The quality of solar thermal heat varies greatly depending on outdoor conditions and on the dynamic behavior of the solar thermal unit, i.e. on inlet and outlet collector temperatures (as it is shown in section 2.2). Therefore, dynamic energy and exergy simulations are required for an accurate and meaningful comparison of such analyses. Furthermore, different configurations and operation modes for the solar thermal system are investigated, allowing to achieve deeper understanding about the differences and information provided by each of the two analyses methods investigated.

2. Method and models

2.1. Models for dynamic energy analysis

For dynamic energy simulations building and solar system models in TRNSYS simulation environment are used with a time-step of 3 minutes. Climatic data for Würzburg are considered to be representative for German climatic conditions (DIN 18599, 2007). In all simulations presented here weather data for Würzburg generated with METEONORM (Meteotest, 2006) are considered.

The multi-family dwelling (MFH-07) consists on a three floor building with a net living area of 927.2 m^2 holding 12 apartments. The overall transmission heat coefficient of the building (H'_T) amounts 0.469 $WK^{-1}m^{-2}$. Each floor is modeled in TRNSYS as a separate thermal zone.

Hourly profiles for internal gains have been defined with different profiles for weekends and weekdays.

Daily loads, including appliances and occupants, amount 97.4 and 100.8 Whm^{-2} d for weekdays and weekends respectively. A ventilation rate of 0.71 h^{-1} is defined, including air exchange due to the use and occupancy of the building and infiltration air rates.

3-minute DHW draw-off profiles are generated using the program DHWcalc (Jordan and Vajen, 2005) , assuming a 40 liters draw-off per person and per day at 45°C and a total occupancy of the building of 29 people. The seasonal variation of the cold water temperature is defined in accordance with DIN EN 12976-2 (2006), assuming average yearly cold water temperature of 10◦°C, an average amplitude for seasonal variation of 3°C and the time-shift parameter as 137 days for Würzburg. With the assumptions mentioned here DHW demands from dynamic energy simulations with TRNSYS amount 16.74 kWh/m2 a, showing good agreement with values from the Standard DIN 18599-10 (2007) .

DHW supply occurs by means of a centralized instantaneous heat exchanger, i.e. no individual DHW tanks are regarded in each apartment. A recirculation loop in the DHW supply circuit operated as stated in (DVGW, 2004) is considered in order to ensure hygienic conditions in the water supplied.

For calculating the fractional energy savings achieved by different configurations of a solar system a reference case is required. The reference case is taken as the multi-family dwelling with standard building shell (MFH-07) and with radiators. A storage tank of 1500 liters for centralized domestic hot water (DHW) supply is foreseen and no storage unit is used for space heating (SH) supply.

The base solar thermal system in this thesis consists of a collector area of 100 m^2 and a storage tank of 8.5 m^3, composed of a specific solar storage volume of 75 lm$^{-2}{}_{\text{colls}}$ and an additional auxiliary volume of 1 m^3. Stratified inlets are assumed for the solar loop as well as the DHW and SH demands. In turn, the outlets for providing both demands are considered at a given fixed position in the tank: the outlet to DHW supply is located approximately at the top of the tank, at a relative height of 0.99; the outlet for SH supply is located at 0.05 relative height above the outlet to the boiler. Both outlets are, therefore, located within the auxiliary volume, which is always kept at temperatures between 65 and 70°C by the boiler in order ensure energy supply even if no solar radiation is available .

2.2. Models for dynamic exergy analysis

Exergy analysis on a system level are performed following the input-output approach found in many building energy regulations (EnEV, 2007; DIN 18599, 2007), where the supply chain is divided into several subsystems directly related with each other. Examples of these energy subsystems are primary energy transformation, generation, storage, distribution or heat emission systems.

The energy supply systems for the multi-family dwelling studied here are divided accordingly in the subsystems mentioned before. For each subsystem equations characterizing its exergy input and output are defined and implemented in a TRNSYS-calculator. In this way, dynamic analysis of the exergy flows in each subsystem are performed.

The display of all equations defined for exergy analysis of the subsystems involved in the models is too extensive to be shown in this paper. Therefore, here only the more relevant equations for characterizing the overall exergy performance of solar systems studied are introduced. Equations 1 to 7 show the expression for calculating relevant exergy flows in each time-step (t_k) stated in kWh.

Equations 1 and 2 show the exergy demands for space heating and DHW supply respectively. In equation 3 the expression for the total exergy demand is shown.

$$Ex_{dem(SH)}(t_k) = Q_h(t_k) . \left(1 - \frac{T_0(t_k)}{T_{op}(t_k)}\right) \quad \text{(eq. 1),}$$

where Q_h the thermal heat demand being supplied by the emission system to the building, T_{op} is absolute value of the operative temperature in the building and T_0 is the reference temperature for exergy analysis which in this study is taken as the absolute value of the outdoor air temperature in each time step.

$$Ex_{dem(DHW)}(t_k)=m_{DHW}(t_k).c_{p,cw}.\left|(T_{supply,DHW}(t_k)-T_{cw}(t_k))-T_0(t_k).\ln(\frac{T_{supply,DHW}(t_k)}{T})\right|$$

(eq. 2)

where m_{DHW} is the mass flow for DHW supply, $c_{p,cw}$ is the specific heat capacity of water, $T_{supply,DHW}$ is the absolute supply temperature for DHW and T_{cw} is the cold water temperature in K.

$$Ex_{dem(SH+DHW)}(t_k)=Ex_{dem(SH)}(t_k)+Ex_{dem(DHW)}(t_k) \quad \text{(eq. 3)}$$

Equation 4 shows the primary exergy flow which needs to be supplied to the building systems in each time-step.

$$Ex_{prim}(t_k)=Ex_{input-g}(t_k).f_p \quad \text{(eq. 4),}$$

where $Ex_{input-g}$ is the exergy input into the generation subsystems (i.e. solar thermal system or boiler unit), and fp is the primary energy factor for the given energy flow.

$$Ex_{input-g}(t_k)=Ex_{input-g,boiler}(t_k)+Ex_{input,colls}(t_k) \quad \text{(eq. 5)}$$

$$Ex_{input-g,boiler}(t_k)=En_{input,boiler}(t_k).F_{Q,fuel} \quad \text{(eq. 6),}$$

where $En_{input,boiler}$ is the energy input into the condensing boiler foreseen as back up system to the solar unit obtained from dynamic simulations in TRNSYS and $F_{Q,fuel}$ is the quality factor for the fuel used to supply the boiler. In this paper values of 0.95 for natural gas in the condensing boiler are assumed (Ptasinski, Prins and Pierik 2005).

$$Ex_{input,colls}(t_k)=m_{colls}(t_k).c_{p,w}.\left[(T_{o,colls}(t_k)-T_{i,colls}(t_k))-T_0(t_k).\ln(\frac{T_{o,colls}(t_k)}{T_{i,colls}(t_k)})\right] \quad \text{(eq.7),}$$

where m_{colls} is the mass flow through the collector field, and $T_{i,colls}$ and $T_{o,colls}$ are the absolute value of the inlet and outlet temperature in the collectors, respectively.

2.3 Parameters for energy and exergy performance

The energy performance of the different solar thermal systems analyzed here is stated in terms of the thermal and extended fractional energy savings, $f_{sav,therm}$ and $f_{sav,ext,}$ as defined in (Weiss, 2003). Equations 8 and 9 show the general expression for both parameters.

$$f_{sav,therm}=1-\frac{\frac{Q_{boil,out,sol}}{\eta_{aux,sol}}+P_{el,coll}\cdot f_{p,el}}{\frac{Q_{boil,ref,out}}{\eta_{aux,ref}}} \quad \text{(eq. 8),}$$

where $Q_{boil,out,sol}$ is the energy output from the boiler acting as back up for the solar system, $\eta_{aux,sol}$ is the efficiency of this boiler, $P_{el,coll}$ is the electrical energy required by the pumps in the solar system, $f_{p,el}$ is the primary energy factor for electricity, $Q_{boil,ref,out}$ is the energy output from the boiler in the reference system (i.e. without solar thermal unit) and $\eta_{aux,ref}$ is the efficiency for the boiler in the reference system.

$$f_{sav,ext}=1-\frac{\frac{Q_{boil,out,sol}}{\eta_{aux,sol}}+(P_{el,coll}+P_{el,boil,sol}+P_{el,SH}+P_{el,DHW})\cdot f_{p,el}}{\frac{Q_{boil,ref}}{\eta_{aux,ref,out}}+(P_{el,boil,ref}+P_{el,SH}+P_{el,DHW}).f_{p,el}} \quad \text{(eq. 9),}$$

where $P_{el, boil,sol}$, $P_{el, SH,}$ $P_{el, DHW}$ and $P_{el, boil,ref}$ are the electricity for pumping in the boiler of the solar system, in the space heating system, DHW supply circuit and the boiler in the reference case (without solar collectors), respectively.

Primary and final exergy efficiencies are used for characterizing the exergy performance of the systems. Equaions 10 and 11 show the expression of the primary and final exergy efficiencies respectively. Both are overall exergy efficiencies since the performance of the complete energy system into analysis (in the final exergy efficiency) or the whole supply chain (in the primary exergy efficiency) are analyzed.

$$\psi_{prim}=\frac{Ex_{dem(SH+DHW)}}{Ex_{prim}} \quad \text{(eq. 10)}$$

$$\psi_{fin}=\frac{Ex_{dem(SH+DHW)}}{Ex_{input-g}} \quad \text{(eq. 11)}$$

Additionally, the exergy expenditure figure as defined by (Schmidt et al., 2007) is calculated. The exergy expenditure figure is defined as the ratio of the exergy input required to supply a given energy demand (effort) and the provided energy demand (use). This parameter needs to be compared to the exergy to energy ratio of the energy demand to be provided, i.e. to the quality factor of the energy demand. Values close to the exergy to energy ratio of the energy demand indicate a good matching between quality levels (i.e.exergy) of the energy supplied and demanded. In turn, values diverging from the exergy to energy ratio of the demand indicate bad matching and, in consequence, lead to conclude that other energy sources shall be used for providing that specific use and/or energy losses need to be reduced.

For the particular application of space heating and cooling of buildings, quality factors of the energy demanded are very low (around 0.07). Subsequently, in space heating and cooling applications, lower exergy expenditure figures indicate more optimized energy supply systems. Exergy expenditure figures can be derived for any subsystem in the energy supply chain within a building. However, the chosen generation system influences more strongly than any other component the overall exergy performance of energy supply. Thus, here for the building cases analyzed in this thesis only exergy expenditure figures for the generation subsystem, ε_g (eq. 12), are presented.

$$\varepsilon_g=\frac{Ex_{input-g}}{En_{output-g}} \quad \text{(eq. 12)}$$

3. Results

In the following sections the behaviour of the regarded energy and exergy based parameters are shown for different configurations of the building systems.

3.1. Different space heating emission systems

The emission system used for space heating also influences the energy performance of solar thermal systems (Zaß et al., 2008). It is expected that space heating systems requiring lower supply and return temperatures lead to an increase in the fractional energy savings obtained from the solar unit. Following, the exergy performance of the solar system is also expected to increase. Additionally, the use of emission systems with low supply and return temperatures is expected to decrease the temperature of the provided solar heat, i.e. its exergy content. Thereby, greater increase in the exergy performance is also awaited.

In this section the influence of using emission systems with lower supply and return temperatures on the energy and exergy performance of the solar thermal system studied is investigated. For this purpose, a space heating supply with radiators (with design inlet and return temperatures of 55 and 45°C, respectively is compared to a supply by means of a floor heating system (with design inlet and return temperatures of 32.5 and 27.5°C, respectively.

To ensure the comparability of both emission systems, it is required that both provide the same level of thermal comfort inside the building. In Table 1 it is shown that the degree-hours under comfort range II as defined in (DIN EN 15251, 2007) for is similar for both emission systems.

Tab. 1:Degree-hours under comfort range II (DIN EN 15251, 2007) for the three thermal zones in the building model MFH-07 with both emission systems

	Degree-hour [°Ch]		
	Ground floor	**First floor**	**Top floor**
MFH-07, radiators	216	117.4	171.5
MFH-07, floor heating	157.9	52.5	187.6

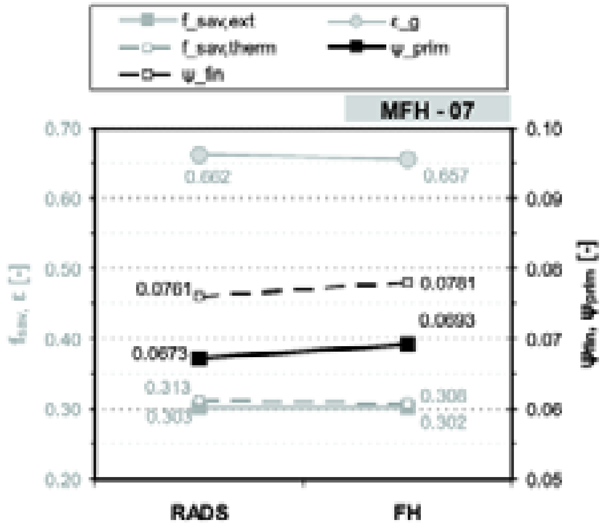


Fig. 1:Thermal and extended fractional energy savings, exergy expenditure figure for the generation subsystem as well as primary and final exergy efficiencies for the solar thermal system with radiators (RADS) and floor heating (FH) systems.

Figure 1 shows the main parameters describing the energy and exergy performance of the solar unit with both emission systems. Thermal and extended fractional energy savings are very similar in both cases. Due to the lower return temperatures from the floor heating system, lower temperatures can be found in the lower part of the solar storage volume. This leads to an increase of 3% in the solar thermal energy output from the collector field, as compared to the system with radiators. However, due to thermal energy losses in the floor heating system, the energy that needs to be supplied to the floor heating is also 2% higher than in the case of radiators. This results in a similar energy performance of both systems: extended fractional energy savings are just 0.1% higher for the system with radiators.

As expected, the quality factor of solar thermal energy output is 3% lower, i.e. has lower exergy content due to its lower temperature level, if the floor heating system is used. The energy from the solar collectors represents around 35% of the total energy input in the systems.

However, due to its low exergy content, the solar thermal output represents only around 8% of the exergy supplied in both cases. Thus, the differences in the quality level of the supplied solar heat become irrelevant and are not able to influence visibly the exergy performance.

Figure 2 shows the energy and exergy input required from the boiler and solar thermal system extrapolated for different extended fractional energy savings. Only with extended fractional energy savings higher than 0.9 the exergy input from the solar thermal unit starts dominating the total exergy input into the system (representing 60% of the total exergy input for $f_{sav,ext} = 0.9$), and the quality of the delivered solar heat might become relevant for exergy analysis. Otherwise, for conventional solar fractions the exergy performance, as the energy performance, is strongly influenced by the high-quality energy required, i.e. the fossil fuel input in the system.

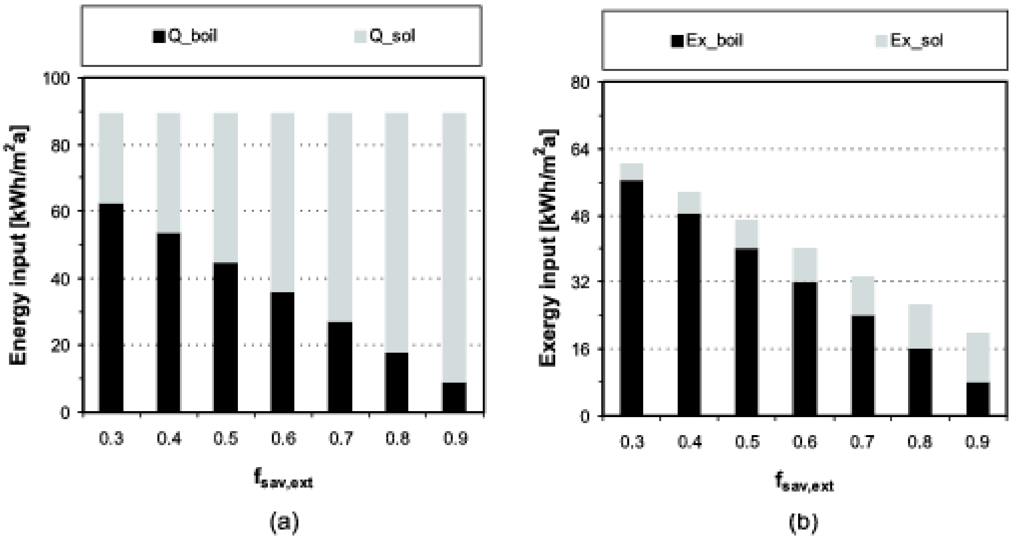


Fig. 2: Energy (a) and exergy (b) input from the boiler and solar thermal unit for different extended fractional energy savings fsav,ext .

For all stated above, exergy expenditure figures for the generation system (i.e. boiler and solar collectors) in both cases are very similar. However, on the contrary to the fractional energy savings, this parameter shows a favourable trend for the floor heating system. This is due to the higher share of solar heat supplied if the floor heating system is used .

Exergy efficiencies show the same trend as exergy expenditure figures, being favorable for the floor heating system. The 0.2% increase in the primary and final exergy efficiencies for the case with floor heating is due to a 4% increase in the exergy demand of the building.

The exergy efficiency is the only investigated parameter directly influenced by the exergy demand of the building: variations in the exergy demand might significantly change its value. In consequence, it represents a suitable parameter for comparing the performance of systems with different emission units, since the energy output from each emission system is thereby also taken into account.

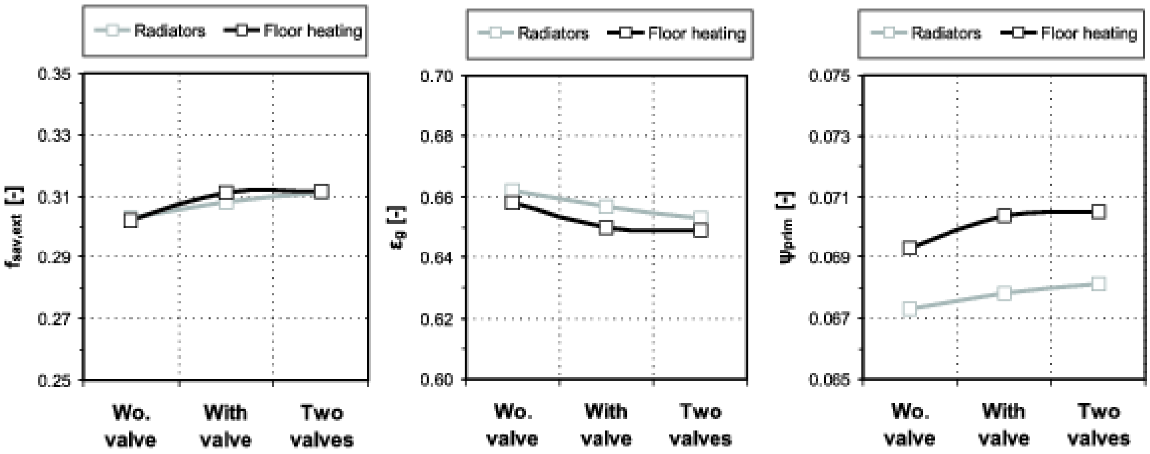
3.2. Three way valves for space heating discharge of the storage tank

In this section the influence of using one and two three-way valves for enabling the outlet for SH supply from the solar volume on the energy and exergy performance of the systems is studied. The three way valves are located at a relative storage height of 0.7 and 0.5, respectively. Whenever the temperature at one of these heights in the solar volume is 5°C higher than the required setpoint for SH supply, water is taken from that layer of the tank. Otherwise, water is withdrawn conventionally from the lower part of the auxiliary volume.

Figure 3 shows the behaviour of the extended fractional energy savings (a), exergy expenditure figure (b) and primary exergy efficiency (c) for the systems with one and two valves as compared to without any additional valve for SH supply.

The use of a single three-way valve for SH supply yields a 0.9% increase in the extended fractional energy savings for the system with floor heating.

If, instead, radiators are used a lower increase can be found (0.5%). The use of two three way- valves for space heating supply does not show any relevant increase in the fractional energy savings for the system with floor heating (0.1%), but causes a further 0.3% increase if radiators are used. These trends are due to the higher temperatures that can be found in the solar tank if radiators are used (due to the higher return temperatures from space heating supply), making the second valve more often usable than if the floor heating system is considered.



(a) (b) (c)

Fig. 3: Extended fractional energy savings (a), exergy expenditure figures for the generation system (b) and primary exergy efficiency (c) for systems without, with one and two three-way valves for SH supply. Results are shown for the systems with radiators and floor heating.

As stated in the previous section for such low solar fractions, results from exergy analysis are completely dominated by the high exergy input represented by the auxiliary boiler. In consequence, the behaviour shown by the parameters characterizing the exergy performance of the systems with and without valves and the conclusions obtained from them, are similar to those from conventional energy analysis.

Differences in the energy and exergy performance with each of both emission systems are coherent with those presented in the previous section: with the use of a floor heating system a more (exergy) efficient energy supply can be achieved, despite slightly higher input of fossil fuels is required.

4. Conclusions

Fractional energy savings indicate the share of saved fossil fuel for a given solar thermal system as compared to the fossil fuel demand of a conventional system without solar unit (i.e. with a condensing boiler as supply system). Thus, they are sensitive to variations in the fossil fuel input from the boiler. In turn, they do not give any information on the behaviour of the energy demands of the building (see section 3.1).

In turn, exergy-based parameters presented give insight on the share of solar energy in the total supply, thereby giving insight on how efficiently a given load is being provided. These parameters are influenced by small changes in the energy demands of the building (e.g. raising from using different emission systems). Following, they are suitable parameters for comparing the performance of solar thermal systems coupled with different emission systems.

The behaviour of the exergy-based parameters is strongly dominated by the high-exergy input from fossil fuels required by the auxiliary boiler (which represents between 80 and 90% of the total exergy input in all cases investigated). In consequence, conclusions from exergy analysis are similar to those obtained from conventional energy analysis . Only in the comparison between the performance with different emission systems conclusions from energy and exergy analysis differ from each other .

The exergy method is a scientifically correct approach for analyzing solar thermal units. However, since exergy analysis is strongly dominated by the high-quality fossil fuel input, similarly as energy analysis, conclusions from exergy analysis are always very similarly to those which can be gained from conventional energy analysis of the systems. Therefore, for conventional fractional energy savings of around 20-30% it can be concluded that exergy analysis and exergy-based parameters do not supply relevant further information for the analysis of solar thermal systems as compared to conventional energy analysis. Only for systems providing much higher fractional energy savings of around 90% differences in the energy and exergy analysis of the different components in the energy systems might arise. Conclusions from a system perspective, i.e. referred to the overall performance of the system, are however expected to be always similar for both analysis.

5. Acknowledgement

The authors warmly thank the German Federal Foundation for Environment (DBU) and the German Federal Ministry of Economy and Technology for their financial support.

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