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INTEGRATED OPERATION ANALYSIS OF A GEOTHERMAL-SOLAR HYBRID SYSTEM FOR SUSTAINABLE THERMAL ENERGY SUPPLY: A CASE STUDY IN THE POLITEHNICA BUCHAREST CAMPUS

Constantin IONESCU[1], Roxana PĂTRAȘCU[2], Mihai Rareș SANDU[3]

The main objective of this paper is to define and analyze the operating regimes of a hybrid geothermal-solar system for production and supply of thermal energy. The analyzed system was designed and is being implemented within the framework of the European project Horizon 2020 (no. 857801) "Smart and local reneWable Energy DISTRICT heating and cooling solutions for sustainable living" - WEDISTRICT, into a demonstrator located in the POLITEHNICA Bucharest campus. The aim of the hybrid system is to maintain thermal comfort conditions in a designated target building while maximizing the delivery capacity of thermal energy produced from renewable sources, into the local district heating network of the university. Through simulating the system's overall operation, the coordination between thermal energy production and consumption, as well as electricity production and consumption, will be effectively aligned. This process will identify the primary categories and types of factors influencing these operational regimes.

Keywords: renewable energy, heat pumps, hybrid system, district heating, numerical simulation, working regimes.

1. Introduction

Centralized thermal energy supply systems represent a flexible solution with a high applicability both for different types of consumers, and dimensions of consumption. This allows cities to continuously develop their existing centralized system as new alternative local energy sources are identified, as well as new technologies and funding opportunities become available.

In general, centralized heating systems combine the efficiency of cogeneration with their flexibility to integrate new, renewable, or non-renewable energy sources without disabling the system or disrupting consumers, being much more efficient than changing individual heating systems. Transport networks

[1] Assoc. Prof., Dept. of Energy Generation and Use, UNST POLITEHNICA Bucharest, Romania, e-mail: ionescu.constantin@upb.ro, corresponding author
[2] Prof., Dept. of Energy Generation and Use, UNST POLITEHNICA Bucharest, Romania, e-mail: op3003@yahoo.com
[3] PhD Student, Dept. of Energy Generation and Use, UNST POLITEHNICA Bucharest, Romania, e-mail: mihai_rares.sandu@upb.ro

generally have a long lifespan and can be easily adapted to new heat generation technologies that inject into the system, providing a secure framework for the introduction of new energy sources available in the future [1].

In the context of the evolution of such systems, from “early development” (stage 1G) to the present development, stage 4G and in perspective towards stage 5G there was a diversification of the types of primary energy sources for thermal energy production, type of thermal energy provided to consumers (heat and cold), and the evolution of the transport parameters of the thermal agent within the network [2-4]. The evolution from 1G to 4G has been accompanied by a continuous increase in energy efficiency, resulting from:

- technological evolution.
- optimal interaction of energy production, transport, and consumption.
- diversification of alternative energy resource types.
- imperative necessity to preserve non-renewable primary energy resources.

New district heating projects which have as objective the integration of renewable energy sources in existing systems, have as main advantages: increasing the supply availability, scalability and reduction of CO2 emissions [5].

The urban areas are characterized by a high demand for thermal energy. These areas are suitable for the integration of locally available renewable energy flows, as well as other alternative sources such as industrial waste heat and energy from local non-industrial waste. These solutions lead to significant reductions in the consumption of primary energy based on conventional sources, while also reducing greenhouse gas emissions. This diminishes the urban area’s reliance on energy imported from other regions and/or countries, all while ensuring the comfort and safety standards in supplying thermal energy to the residents [6-8].

The objective of this paper is to define and analyze the integrated operating regimes of a hybrid thermal power supply system based on renewable energy sources, developed within the European project Horizon 2020, no. 857801 - “Smart and local reneWable Energy DISTRICT heating and cooling solutions for sustainable living”, acronym WEDISTRICT. A new thermal energy supply system for a building is being developed in the above-mentioned project’s framework and is implemented in a demonstrator within the National University of Science and Technology POLITEHNICA Bucharest campus. The target building is the Renewable Energy Sources Laboratory from the Faculty of Energy Engineering, POLITEHNICA Bucharest. The proposed system relies on renewable energy sources for heat production, providing heating, hot water, and air conditioning for the mentioned building. The electricity required to operate the heating system is generated using a photovoltaic panel system. Both the excess heat and the excess electricity are injected into POLITEHNICA Bucharest local networks [9].

The simulations conducted to optimize the system's operation were performed for the heating regime only, as this was the main purpose of implementing the demonstrator. Additionally, the duration of the demonstrator's operation in heating mode is significantly longer compared to the cooling period. This is due to both the climatic conditions of the location and the specific activities carried out in the building.

2. Description of the hybrid system

The main objective considered in establishing and optimizing the operating regimes of the entire "thermal subsystem-electrical subsystem" set was to ensure thermal comfort conditions in the building and to deliver in these conditions a maximum amount of heat produced from renewable sources, in the local heat supply system of the university.

To achieve the main objective, it is necessary to fulfil the following specific objectives [10]:

- optimal operation of the thermal subsystem.
- align and synchronize the electricity generated by the installed PV system with the electricity demand of the thermal subsystem.
- optimal use of electricity storage capacities (batteries, local electricity system).

By using numerical simulations of the whole system, the following regimes were achieved:

- correlation of thermal energy production, storage, and consumption regimes.
- correlation of electricity production-consumption regimes.

The sizing of the system was done considering the necessary heat for heating the building, hot water preparation, in the pre-existing conditions: the location of the building at the end of a branch of the secondary network, and the thermal and hydraulic regime do not allow a proper heat supply of the building to ensure the thermal comfort conditions. The climatic conditions in the geographical area (the building is in Bucharest), as well as the type of activity (educational and research) presuppose a much longer duration of the heating period than the period in which the air conditioning of the building is needed.

The thermal energy generation and distribution hybrid system is modular structured in two interconnected subsystems, as shown in Fig. 1 [9,10]:

- thermal subsystem: heat pumps (HPs), borehole heat exchangers (BHE), hot water/cold water storage tank (HW/CW Storage Tank), domestic hot water tank (DHW tank), photovoltaic thermal hybrid solar panels (PV/T), heat exchangers for cooling and injection of heat (HXC, HXI) and fan coil units.

- electrical subsystem: photovoltaic panels (PV), battery, AC and DC micro-grid, energy management system.
- Energy Management System (EMS) for both subsystems.

Overall, the hybrid geothermal-PV system (thermal subsystem and electric subsystem) consists of two ground source heat pumps which provide the necessary thermal energy of the target building and the excess heat is injected into the local district heating network of the university. The electricity consumption of the heat pumps system is covered by a PV system and a storage batteries system. The necessary hot water consumption is provided, during the summer, by a system of hybrid thermal photovoltaic panels (PVTs) and during the cold season by the heat pumps. The distribution of thermal energy in the target building, both heat and cold, is ensured by means of fan coil units. Main equipment used for the thermal subsystem are:

- Master heat pump: heating 42.3 kW / cooling 33.6 kW
- Slave heat pump: heating 20.5 kW / cooling 16.2 kW
- 12 borehole heat exchangers of 100 m depth each
- 2,000 l thermal energy storage tank
- 750 l DHW tank
- 15 fan coil units
- 2 hybrid photovoltaic thermal panels

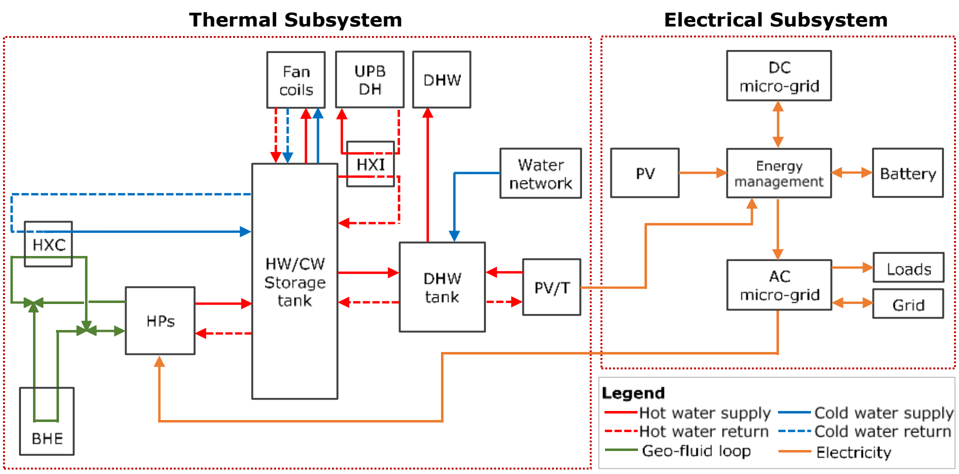

Fig. 1. Conceptual design of the hybrid system

3. Simulation of working regimes

Establishing the working regimes for the hybrid system was performed, bearing in mind the main goal of the project: the injection of heat into the local district heating system while maintaining the thermal comfort of the target building. In order to determine the working regimes, simulations of different scenarios were performed. An important aspect of the working regimes analysis was the integration of the thermal and electrical subsystems. The core of the simulation analysis was the harmonization of the new hybrid system with the requirements of the end user, meaning that it was essential to determine the operating parameters for both.

The geothermal solar hybrid system developed by POLITEHNICA Bucharest within the framework of the WEDISTRICT project can produce both heat and cold, while only heat is injected into the district heating network. Therefore, it was required to consider two different case analysis: one for heating period and one for cooling period. The heating period was defined according to national regulation as being from 15th October to 15th March while the cooling period is defined from 15th May to 15th September. The cooling period was not analyzed since POLITEHNICA Bucharest does not have a district cooling network, therefore throughout the cooling period only the target building will be conditioned.

For both cases, the following working regimes and hypothesis were considered [11]:

- Typical days – based on target building's activity.
- T1 – defined as working days from Monday to Friday with an average working schedule of target building's employees from 9 AM to 6 PM.
- T2 – defined as non-working days in which there is no activity within target building.
- Domestic hot water demand is less than 1% of heating demand therefore it was not considered within the analysis. It is assumed that the DHW demand can be assured during summer by the PVT panels and during winter by the heat pump.
- For electrical energy production, the installed peak power of 66 kW was considered, along with multiple scale factors to compensate for different losses. Considering these hypotheses, a total annual electrical energy production of around 64 MWh was assumed.

The methodology of the simulation of working regimes is presented below:

- Input data:
  - Target building characteristics, heat demand and climatic conditions of Bucharest.
  - Nominal heating power of heat pumps: 62 kW (42 kW produced by Master HP and 20 kW by Slave HP) with a COP (Coefficient of Performance) of 3.
  - On-site outdoor temperature measurements.
  - The outdoor design temperature is -15°C.
  - The value of outdoor temperature from which the heating season is assumed to start is 10°C.
- Simulation of typical days T1 and T2 along with the injection of heat into POLITEHNICA Bucharest district heating system.

- Determination of heating duration curve.

The peak heating/cooling design values were determined by using national standard and simulation software (Design Builder and TRNSYS) [12,13]. The peak values obtained through the numerical simulations were close to the values obtained through the national standards. Since the Target Building has few metering devices installed on site and there are no records of previous data, the numerical models were used to assess the energy baseline. The results are presented in Table 1.

Table 1

Design energy values

	Thermal energy demand – yearly [kWh]	Peak demand [kW]	Average demand [kW]	Operating hours [h]
Heating	127,705	58.9	29.1	4392
Cooling	13,285	43	34.4	254
DHW	625	0.87	0.7	720

4. Results and discussions

The calculations performed have used the measured values of the outdoor temperature from the 5th of December 2020 [11]. The evolution of the outdoor temperature is presented in Fig. 2.

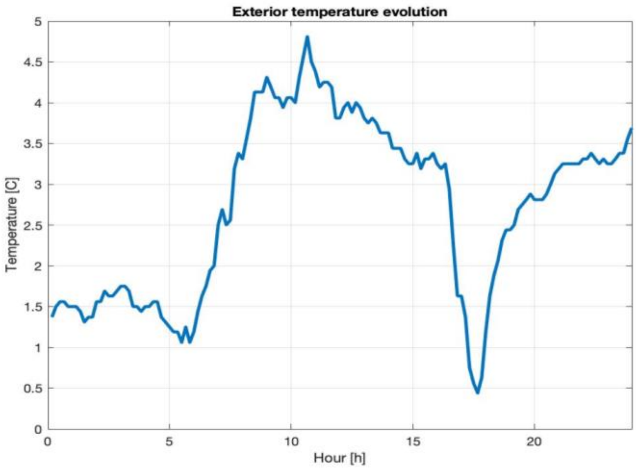

Fig. 2. Evolution of outdoor temperature

The presented variation of outdoor temperature is considered as a typical winter day for Bucharest therefore it was considered as reference for both T1 and T2. With these data, the daily heat demand variation curves were determined, for both typical days T1 and T2, and it was considered that the entire heat demand is covered by the heat produced by the heat pump system. The results are presented in Fig. 3 and Fig. 4.

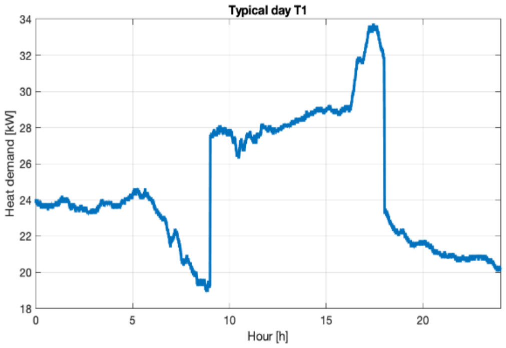

Fig. 3. T1 typical days heat demand of target building

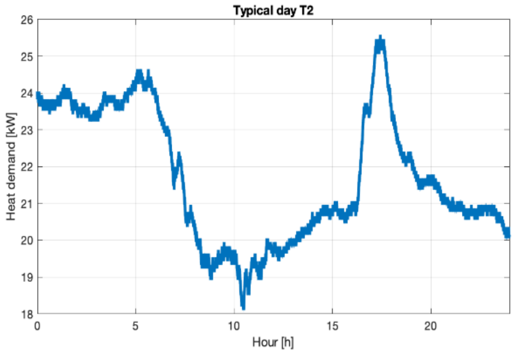

Fig. 4. T2 typical days heat demand of target building

The difference between the production of the heat pumps and the heat demand of the target building is considered to be injected into the university's heating network. The results are presented in Fig. 5 and Fig. 6.

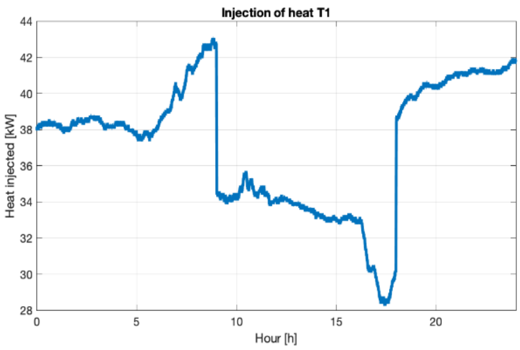

Fig. 5. Injection of heat during T1 typical days

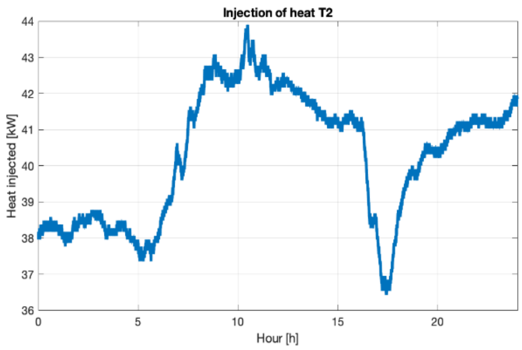

Fig. 6. Injection of heat during T2 typical days

The duration curve of the heating period for the target building was determined considering:

- national standards.
- heat demand of target building.
- a total number of 4,392 hours of the heating period with continuous supply of heat.

The duration curve is determined using the following equation [14]:

$$q(\tau) = q_M \cdot \left[1 - \left(1 - \frac{q_m}{q_M}\right) \cdot \left(\frac{\tau}{\tau_{year}}\right)^{\beta}\right] \quad (1)$$

where: q_M and q_m represent the maximum and the minimum design heat demand values.

τ is the timestep considered in the analysis (24h).

τ_{year} represents the duration of the heating period (4,392 h)

β is a power factor chosen based on the minimum design heat demand value and duration of heating period. For this analysis $\beta = 0.9$.

Based on the duration curve (Fig. 7), the annual thermal energy demand was calculated by approximating the integral throughout the heating period with a timestep of 24 hours. From a graphical point of view, this represents the area below the duration curve. The value obtained is 165.5 MWh/year. Since it is required that the heat pumps to cover the entire heat demand of the building, and considering the imposed COP of 3, it was possible to determine the electrical energy consumed by the heat pumps in order to cover the entire heat demand of the target building. The value obtained is 55.2 MWh/year. Therefore, this value must be covered by the PV panels during an operating year.

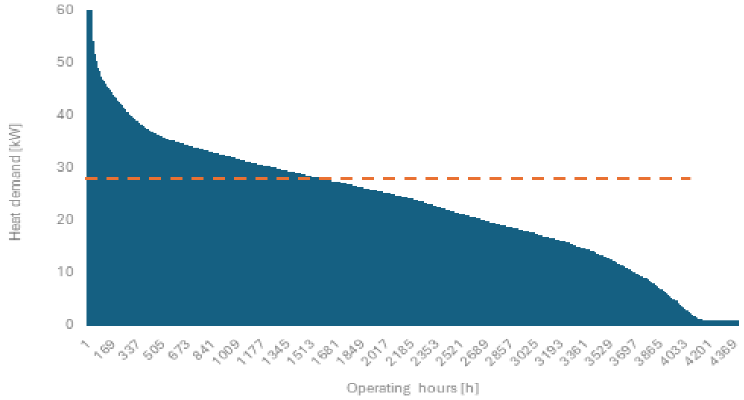

Fig. 7. Duration curve for target building, heating period [15]

The second way of determining the annual heat demand of the target building can be achieved by summing the area below the graph of each daily variation heat demand. Considering that each day consists of 8 working hours and 16 non-working hours, the results obtained through this second method are presented in Table 2.

Table 2

Annual heat demand by type of hours

Type	Number of hours [h]	Annual heat demand [MWh/year]
Working hours	1170	33.9
Non-working hours	3222	69.9
Total	4392	103.8

In Table 2 can be seen that through this method a total annual heat demand of 103.8 MWh was obtained, which represents only 63% of the theoretical value obtained based on the duration curve. This is caused by the fact that for the second method a working schedule was imposed according to the T1 and T2 typical days definition. Another cause of the difference in results is that for the second method the real measured outdoor temperature values were used (only one day of outside temperature variation was used in the analysis for all the calculations, considering that it is the most representative day for winter season in Bucharest). Therefore, the potential amount of heat that can be injected is higher than the estimated one.

The following notations where considered: Q_{HP}^{N} is the nominal heat production of the heat pumps in MWh/year; Q_{TB}^{N} represents the nominal value of annual heat demand obtained using the duration curve for target building expressed in MWh/year; Q_{TB} represents the real heat demand of target building determined using the second method, in MWh/year [16,17].

The minimum amount of heat that can be injected into the local DH is calculated with:

$$Q_{inj}^{\min} = Q_{HP}^{N} - Q_{TB}^{N} \left[\frac{MWh}{year}\right] \tag{2}$$

while the real heat injection value is calculated with:

$$Q_{inj} = Q_{HP}^{N} - Q_{TB} \left[\frac{MWh}{year}\right] \tag{3}$$

In Fig. 8, a comparison of thermal energy consumed by the target building (Q) and heat injected into the DH (Q_{inj}) for T1 and T2 typical days is presented.

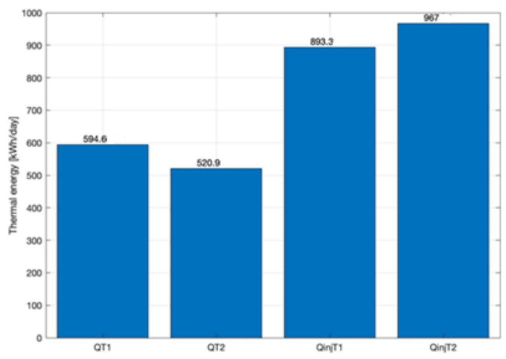

Fig. 8. Thermal energy comparison between T1 and T2

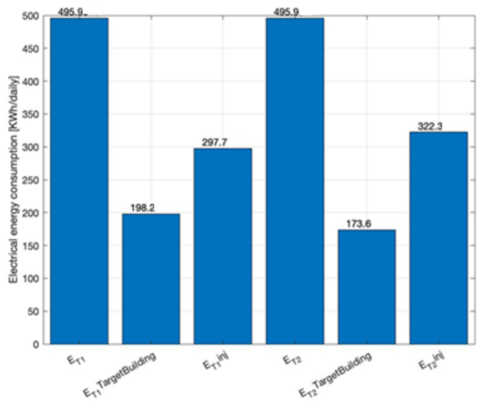

Fig. 9. Typical days electrical energy consumption of heat pumps

Fig. 8 shows that for a reduction of 12% of heat demand of the building, between T2 and T1 typical days, the heat injected into district heating system can be increased with up to 8% maintaining the same working conditions for the heat pumps.

The electrical energy consumption required by the heat pumps (with above considered COP) in order to ensure the heat demand for typical days T1 and T2, is presented in Fig. 9.

The total electrical energy consumption for both typical days T1 and T2 are equal. This is correct based on the assumption of continuous operation of the heat pumps. Overall, the required electrical energy to satisfy the target building's heat demand, in either cases T1 or T2, is between 170 and 200 kWh daily. Considering the installed power of PV panels and the climatic conditions in Bucharest, the required electrical energy for heating the target building, estimated at 35 MWh/year, can be covered by the PV system only on a yearly basis.

5. Conclusions

The results presented in this paper show the opportunity to implement a hybrid geothermal-PV system to produce thermal energy and its integration with existing centralized district heating networks and power grids.

The analysis of the operating regimes had as starting points the thermal energy demand of the target building, particularities of the activities within the building, weather conditions, structure of the hybrid system, the specifications of the main equipment, as well as the structural characteristics of the building and the thermophysical properties of the building envelope materials. Through the numerical simulation of the hybrid system, the following results were obtained: correlation between thermal energy production and consumption; correlation of electrical energy production with the electrical consumption of the thermal subsystem.

The total heat produced annually by the heat pumps, in the considered conditions, is 272 MWh/year. This analysis leads to the conclusion that the hybrid system can assure the heat demand for another similar building through injection into district heating. Moreover, the electrical energy required to supply with heat another similar building can be covered by the PV panels of the hybrid system. In this way, thermal energy is produced 100% based on renewable energy.

The daily variation curves of heat production highlight their correlation between ensuring thermal comfort in the building and the injection of heat into the centralized system of the university campus. The flexibility of the system's operation, as well as its architecture (including storage capacity), allows for maximizing the injection of heat (produced based on renewable energy) into the centralized system. It is also correlated with outdoor temperature, work schedule, and maintaining of indoor thermal comfort based on the type of activities conducted in the building. This fact is evident both from the daily variation curves and from the annual heat quantity delivered by the heat pumps in the building and injected into the centralized system.

The average values of the external temperature measured in Bucharest, used in the analysis, were approximately 15 degrees higher than the calculated value used in the simulations according to the climatic zone. This led to a heat injection into the system that was about 63% higher than the simulated value, as the building absorbed 103.8 MWh compared to the calculated requirement of 127.7 MWh (simulated value), for a heat production of 165.5 MWh and under the same operating scenarios. The impact was reflected in the increase of the estimated energy and ecological KPI values at the system level.

The operation of the system in cooling mode, even though it was not the primary purpose of implementation, enhances the energy, ecological, and economic benefits of system implementation. The cooling demand of approximately 13 MWh is primarily covered by the system’s passive operation, with zero energy consumption from fossil fuels.

The monitoring and data collection is performed for both heating and cooling regime using an autonomous SCADA system. The evaluation of KPIs, for both individual technology and overall demo site, is performed at the end of each working regime in order to have a representative collection of data.

The hybrid system developed, which is implemented withing Bucharest demonstrator, allows the completion of the premises for the transformation of the existing centralized heat supply system of POLITEHNICA Bucharest into “intelligent thermal network” functionally integrated with “intelligent electrical networks”. Both concepts focus on the efficient integration of renewable energy sources, generation of distributed or centralized energy and the involvement of the interaction between a new type of consumers – prosumers, both on thermal and electrical part [18].

This approach allows the use of any available heat sources, the main advantage of smart grids being the operation flexibility, their ability to adapt to any change in supply and the demand for heat in the short, medium, and long period of time.

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