A Feasibility Study of Solar Thermal Power Generation as the Pumping Power Source for Pumped Storage in Indonesia*

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Abstract

A pumped storage hydroelectric generation (PSHG) has been studied as alternative peak power source of the oil-fired power generation in Indonesia. However, because there is no surplus base load electricity even in the night, the economic advantage can not be found. The possibility of solar thermal power generation (STPG) is investigated to restrain the increase of fuel consumption by the existing peak power source. The optimum system simulation and the analysis of economy and environmental impact by a multiobjective optimization method provide the following results. The optimum aperture area and thermal storage capacity of STPG are found by the simulation based on the climate and the solar condition in West Java. PSHG with STPG as the power source of storage pump shows lower generation cost and CO₂ emission than PSHG with existing oil fired peak power sources. Even if the fuel switch from oil to gas is supposed in future, PSHG with STPG will achieve the lower generation cost and CO₂ emission than PSHG with the oil/gas fired combined cycle by sharing the peak electricity supply with the oil/gas fired combined cycle in an appropriate ratio. Furthermore, if the crude oil price hike in future is considered, PSHG with STPG may be the optimal solution for the peak electricity supply of Java-Bari grid.

Key words: Solar Thermal Power Generation, Pumped Storage Hydroelectric, Generation Cost, CO₂ Emission, Multiobjective Optimization

1. Introduction

The solar thermal power generation (STPG) is suitable for dry large land with strong solar radiation. It has been mainly introduced into U.S., Australia and Spain. However, since there are not so many lands with such a good condition on the earth, it is necessary to study various introduction conditions. As Indonesia is located on the equator, solar altitude is high and solar radiation is strong but the annual rainfall is not so small because the rainy season continues for about half a year. A feasibility study was carried out whether STPG could be introduced into such an area.

In Indonesia, the fuel switch from oil to coal or natural gas is proceeded in the field of power generation. Fig. 1 is the typical daily load pattern and fuel constitution of Java-Bari grid in 2007. The load up to about 9,000MW is covered by coal, natural gas, geothermal and hydroelectric, but more than 9,000MW load is mainly provided by oil. Indonesia promotes the construction of coal-fired thermal power plant, but the fuel switch for the peak load is not proceeded. As shown in Fig. 1, the conventional hydroelectric power generation has already covered a part of the peak load, but it cannot increase the water consumption

easily because the reservoir water is responsible for irrigation, life water and industrial water as well as power generation. Since the reservoir water is scarce in the dry season, the water allocation is very important ⁽¹⁾.

The pumped storage hydroelectric generation (PSHG) has been studied as alternative peak power source of the oil-fired power generation. Irrespective of water allocation, it can control the hydroelectric power output. However, because there is no surplus base load electricity in Indonesia even in the night, the electricity for storage pump will be supplied by existing middle or peak power source. It causes the increase of fuel consumption in middle and peak power source, and makes the economy and environment of the grid worse. On the other hand, if the electricity for storage pump will be supplied by the renewable energy, PSHG may become the economical peak power source as well as the environmental friendly peak power source.

The wind power generation cost is said the lowest among the renewable energy power generation cost, and the study to use this electricity as the power source for storage pump of PSHG is already started in U.S ⁽²⁾. However, it is necessary to stabilize electricity of the wind power generation to use for storage pump by installing the large-scale battery or connecting to grid. The large-scale battery still has a problem in the cost and technology. The connection of the large-scale instability power source will not suitable for Indonesian grid because the fluctuation of frequency and voltage is big even at the present condition.

The STPG converts solar energy into thermal energy once, and converts into electricity by a steam turbine. Therefore, it can generate stable electricity easily with thermal storage technology. In addition, in comparison with the other renewable energy power generation, it is easy to make it large-scale power generation. Actually, the construction of several hundred MW class STPG is started in U.S. and Spain. However, it is difficult to generate electricity without solar radiation for a long time even if the thermal storage equipment is installed. Therefore, unreliability of STPG caused by the fluctuation of the generated energy due to the weather should be considered for use as the peak power source and STPG alone does not become an alternative of oil-fired thermal power generation.

This paper presents a feasibility study of optimum system and operation of STPG as the power source of the storage pump for the PSHG planned in Indonesian Java-Bari grid. By the analysis of economy and environmental impact, the possibility of STPG is investigated.

Fig. 1 A typical daily load pattern and fuel constitution of Java-Bari grid in 2007

2. Basic Equation

2.1 Solar Energy

Figure 2 shows the relations of the solar radiation at the top of the atmosphere I_0 (kW/m^2), the direct normal radiation I_n (kW/m^2), the diffuse radiation I_d (kW/m^2), and the solar altitude angle α . From these relations, the amount of solar radiation on a horizontal surface on the earth I_h is calculated in Eq. (1) ⁽³⁾.

$$I_h = I_n \sin \alpha + I_d \quad (1)$$

The daily amount of solar radiation is found by integrating 'I' given in Eq. (1) from sunrise to sunset.

$$H = \int_{\text{sunrise}}^{\text{sunset}} I dt \quad (2)$$

The fraction of daily amount of solar radiation at the top of the atmosphere which reaches the surface of the earth is defined as the daily clearness index K calculated in Eq. (3).

$$K = \frac{H_h}{H_0} \quad (3)$$

Where,

H_h : the daily amount of solar radiation on a horizontal surface on the earth ($\text{kWh/m}^2/\text{day}$)

H_0 : the daily amount of solar radiation at the top of the atmosphere ($\text{kWh/m}^2/\text{day}$)

Between the daily hours of bright sunshine N and H_h , the following equation is known ⁽⁴⁾.

$$\frac{H_h}{H_0} = K = a + b \frac{N}{N_0} \quad (4)$$

Where :

N_0 : maximum possible daily hours of bright sunshine

a, b : empirical constants

The following correlation is also known between the daily direct normal radiation H_n and K .

$$\frac{H_n}{H_0} = c + dK + eK^2 \quad (5)$$

Where, c, d and e are empirical constants. Applying Eq. (4) to Eq. (5). H_n is calculated for a function of N . Fig.3 shows the relations between the surface with any angle and the sun. A is the solar azimuth, ϕ is the surface azimuth, δ is the surface tilt angle, θ is the angle between the sun beam and the surface normal (perpendicular), called the angle of incidence and is calculated in Eq. (6).

$$\cos \theta = \cos \delta \sin \alpha + \sin \delta \cos \alpha (\cos A - \phi) \quad (6)$$

Since the solar radiation collected by the concentrating collector is only the direct normal radiation, the daily solar radiation collected by the concentrating collector H_c is expressed in the following equation.

$$H_c = H_n \cos \theta \quad (7)$$

Figure 4 shows the sun path and altitude in West Java. Since the sunrise point is always between ± 30 degree from East and the attitude at solar noon is always over 60 degree, the angle of incidence to the collector, having an axis in the north and south direction and tracking the sun, can keep small angle through the year. Fig.5 shows the relation between the sun and the collector. From Fig.4 and Fig.5, in case of the collector having an axis in the

north and south direction and tracking the sun, $\delta = 90 - \alpha$ and $\phi = 90$ or 270 is applied. Consequently, Eq. (6) becomes Eq. (8).

$$\cos \theta = \sin^2 \alpha + \cos^2 \alpha \cos A \quad (8)$$

Applying Eq. (4) and Eq. (5), Eq. (7) becomes Eq. (9).

$$H_c = \left[c + d \left(a + b \frac{N}{N_0} \right) + e \left(a + b \frac{N}{N_0} \right)^2 \right] H_0 \cos \theta \quad (9)$$

Fig. 2 The definition of the solar radiation

Fig.3 The solar radiation to the surface with any angle

Fig. 4 The sun path and altitude in West Java

Fig. 5 The relation between the sun and the collector

2.2 Solar Thermal Power Generation (STPG)

Figure 6 shows a typical parabolic trough type STPG system. In parabolic trough type, solar radiation collected by the concentrating collector heats the heat transfer fluid (HTF), typically oil, flowing in the absorber installed in front of the collector. The HTF heated to 400 degC at the collector in the solar field is led to heat exchangers in the power block. At the heat exchanger, the feed water from the condenser is heated to become the superheated steam which drives the steam turbine and generator. To stabilize the generator output, the thermal storage equipment and/or the HTF heater is sometimes applied in the solar field.

The energy output from the absorber Q_a (kW) is expressed in the following equation.

$$Q_a = \eta_{\text{opt}} I_c A_c - Q_L \quad (10)$$

Where, η_{opt} is the optical efficiency of collector, I_c is the solar radiation collected by the concentrating collector (kW/m^2), A_a is the aperture area of the collector (m^2) and Q_L is the heat loss from the absorber (kW). The gross output power of steam turbine generator P_{stg} (kW) is calculated in Eq. 11 with the efficiency of steam turbine generator η_{stg} , the energy output from the solar field Q_s (kW).

$$P_{stg} = \eta_{stg} Q_s \quad (11)$$

Q_s is controlled by the set value Q_{set} to keep P_{stg} in a target value. In case Q_a is greater than Q_{set} , the surplus energy ($Q_a - Q_{set}$) is charged to the thermal storage equipment. In case Q_a is smaller than Q_{set} , the thermal storage equipment compensates the deficit energy ($Q_{set} - Q_a$), if there is enough energy in it.

Fig. 6 A typical parabolic trough type STPG system

2.3 Pumped Storage Hydroelectric Generation (PSHG)

The electricity from STPG is dispatched to the PSHG in the distant place through the grid and is consumed with the same time, the same amount by the storage pump. Hence the storage pump energy P_{pump} is equal to the net output power of STPG which is the gross output power P_{stg} minus the auxiliary power of STPG, and is calculated in Eq. (12) with the pump efficiency η_{pump} .

$$P_{pump} = P_{stg} - P_{aux} = \frac{\gamma H F_p}{102 \eta_{pump}} \quad (12)$$

Where,

P_{aux} : auxiliary power of STPG (kW)

γ : specific gravity of water (kg/m^3)

H : available head (m)

F_p : flow rate of pump discharge (m^3/s)

The PSHG output power P_{htg} is expressed in the following equation with the hydro turbine efficiency η_{htg} .

$$P_{htg} = \frac{\eta_{htg} \gamma H F_t}{102} \quad (13)$$

Where,

F_t : flow rate of turbine discharge (m^3/s)

To perform the firm operation everyday in peak time, the holding water volume of upper reservoir V always must be more than the minimum volume V_{min} as expressed in Eq. (14).

$$V = (V_p - V_t) + V_i \geq V_{\min} \quad (14)$$

Where,

V_p : total amount of storage pump water (m^3)

V_t : total amount of consumed water by hydro turbine (m^3)

V_i : initial volume (m^3)

2.4 Power Generation Cost and CO₂ Emission Factor

The average lifetime levelised electricity generation cost E_{GC} is calculated in the following equation based on OECD formula ⁽⁵⁾.

$$E_{GC} = \frac{\sum_{t=1}^n [(I_t + M_t + F_t)(1+r)^{-t}]}{\sum_{t=1}^n [E_t(1+r)^{-t}]} \quad (15)$$

Where,

I_t : capital cost in the year t (US\$)

M_t : operation and maintenance cost in the year t (US\$)

F_t : fuel cost in the year t (US\$)

E_t : electricity generation in the year t (kWh)

r : discount rate

n : practical lifetime (year)

The capital cost consists of the depreciation and the interest payment. The operation and maintenance cost does not include the labor cost in this study.

The CO₂ emission factor G_{HG} (ton-CO₂/MWh) is calculated in the following equation.

$$G_{HG} = \frac{\sum_{t=1}^n (44/12 C_{EF} m_t)}{\sum_{t=1}^n [E_t(1+r)^{-t} 10^{-3}]} \quad (16)$$

Where,

m_t : fuel consumption in the year t (TJ)

C_{EF} : default carbon content (ton/TJ) ⁽⁶⁾

3. Optimum System Simulation

In Indonesia West Java, 250MW x 4 units PSHG plant is planned. A simulation is performed to study an optimum STPG system for the storage pump power source of PSHG. Table 1 shows (1) the monthly average of daily direct normal radiation ($kW/m^2/day$), (2) daily diffuse radiation, daily total amount of solar radiation ($kW/m^2/day$), (3) clearness index on a horizontal surface, and (4) the daily solar radiation at the top of the atmosphere calculated from (1) to (3) data ($kW/m^2/day$) ⁽⁷⁾.

Campbell-Stokes Sunshine Recorder recorded the direct normal radiation more than $120 W/m^2$ as the bright sunshine for 8 hours from 8:00 to 16:00 in Jakarta, 2007. Fig.7 shows the monthly total of daily bright sunshine hours and the accumulated daily bright sunshine hours through the year. The annual bright sunshine hours are 1,736 hours and about 64% of sunshine hours are provided in the dry season between May and Oct. From the data in Table 1 and the daily bright sunshine hours, constants a , b , c , d , e in Eq. (4) and Eq. (5) are calculated by the correlation analysis. As the result, $a=0.3306$, $b=2563$, $c=0.5797$, $d=-2.786$, $e=4.9853$ are provided. Hence H_c in Eq. (9) is calculated as the angle of incidence θ which is obtained by the solar position in West Java. To estimate the instantaneous solar radiation I_c from the daily data H_c , generalized charts are applied ⁽⁸⁾. The

charts show the ratio of hourly and daily total radiation and the ratio of hourly and daily diffuse radiation as a function of hours from sunrise to sunset. Hence I_c is calculated by the interpolation data of these charts.

Table 1 The monthly average of solar radiations

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
(1)	2.72	2.67	3.47	4.04	4.60	4.74	5.11	5.12	4.98	4.25	3.58	3.44
(2)	2.31	2.37	2.32	2.07	1.79	1.66	1.65	1.83	2.07	2.31	2.32	2.29
(3)	0.39	0.39	0.45	0.49	0.52	0.53	0.55	0.55	0.54	0.5	0.45	0.43
(4)	10.7	10.9	10.6	9.84	9.12	8.64	8.84	9.53	10.3	10.6	10.7	10.8

Fig. 7 The bright sunshine hours in West Java

Table 2 and Table 3 shows technical and economic parameters applied to the simulation respectively ⁽⁹⁾⁽¹⁰⁾. By the simulation, the operation hours of STPG, the input and output energy of the thermal storage equipment, fuel consumption of the HTF heater are calculated. Since the operation hours of storage pump are equal to that of STPG and the operation hours of hydro turbine are four hours per day from 18:00 to 22:00 in the peak time, the total amount of storage pump flow and hydro turbine flow are calculated. Hence the variation of holding water volume of PSHG upper reservoir is obtained. Consequently, the aperture area of concentrator, the thermal storage capacity and HTF heater fuel consumption are determined so that the reservoir holding water volume is maintained more than minimum volume V_{min} in Eq. (13) through the year.

Table 2 Technical parameters

Item		Value
STPG	Collector optical efficiency η_{opt}	80%
	Heat loss from solar field Q_L	10% of total heat
	Thermal storage efficiency η_{sto}	90%
	HTF heater thermal efficiency η_{HTF}	90%
	Steam turbine generator thermal efficiency η_{stg}	37%
	Steam turbine gross power P_{stg}	275MW
	Auxiliary consumption P_{aux}	25MW
PSHG	Available head H	214.5m
	Storage pump flow F_p	87 m ³ /s
	Storage pump electricity consumption P_{pump}	250MW
	Hydro turbine flow F_t	138.2 m ³ /s
	Hydro turbine gross power P_{htg}	250MW

Table 3 Economic parameters

Item		STPG	PSHG
Equipment Cost (US\$/kW)	Solar Field (US\$/m ²)	450	1,000
	Thermal Storage (US\$/MW _{th})	50	
	HTF Heater System (US\$/kW _{th})	516	
	Power Block, BOP etc. (US\$/kW)	1,455	
	Project Contingency	7% of above cost	
Maintenance fixed (US\$/kW)		-	13.14
Maintenance Variable (US\$/kWh)		0.011	0.0033
Practical lifetime (year)		40	40
Discount rate		3%	

Figure 8 shows a typical performance curve of STPG on a clear day calculated by the simulation. The energy from absorber is bigger than the target energy to power block in most of the sunshine hours. This surplus energy is stored in thermal storage equipment once, and when the energy from absorber becomes smaller than the target energy to power block, it is extracted from the thermal storage equipment. Hence the STPG generates net 250MW electricity for 11 hours, which consists of 7.8 hours generation by the energy from absorber directly and 3.2 hours generation by the energy from thermal storage.

Fig.8 A typical performance curve of STPG on a clear day

Table 4 shows a result of the optimum STPG system used for the power source of storage pump of PSHG (PSHG with STPG). The aperture area is the necessity minimum area for the peak electricity supply through the year based on the above operation. The thermal storage capacity is calculated so that the fuel consumption of HTF heater becomes zero. From the above results, the averaged generation cost of STPG shows 0.0946 US\$/kWh and if including the generation cost of PSHG, PSHG with STPG is found to be 0.2121 US\$/kWh.

Table 4 Comparison of three types of STPG system

Parameters	PSHG with STPG
Aperture area (m ²)	1,768,448
Thermal storage capacity (GWh)	2.71
HTF heater fuel consumption (GWh)	0
STPG generation cost (US\$/kWh)	0.0946
PSHG with STPG generation cost (US\$/kWh)	0.2121

Figure 9 shows the variation of the annual holding water volume of the upper reservoir. The holding water volume of the upper reservoir becomes the minimum in the beginning of July, and becomes the maximum 70Mm³ in the middle Oct. The aperture area and the thermal storage capacity are optimized so that the minimum holding water volume maintains more than V_{min} which is defined zero as temporary in the figure. The figure shows STPG in table 4 satisfies the condition of the upper reservoir.

Fig. 9 The variation of annual holding water volume of upper reservoir

Figure 10 shows the result of parametric analysis of STPG system with gas fired HTF heater and thermal storage. The thermal storage capacity and the HTF fuel consumption and the generation cost are calculated against the variation of aperture area. The fuel consumption is calculated based on the practical lifetime of STPG. Aperture area 100% shows 1,768,448m². Regardless of the aperture area, the generation cost of STPG with the combination of HTF heater and thermal storage is higher than that of STPG with thermal storage only shown in Table 4. This is because the high cost of HTF heater equipment. As the aperture area becomes large, the thermal storage capacity increases. If the aperture area is more than 80%, the increasing rate of the thermal storage capacity becomes higher. This is because the peak value of the energy output from the absorber Q_a becomes higher than the target value of energy to power block Q_{set} and the energy to thermal storage increases rapidly. Hence the generation cost of the system shows the relatively minimum around 70% aperture area.

Fig. 10 A parametric analysis of STPG system with HTF heater and thermal storage

4. Economy and Environmental Impact Analysis

In this section, 1,000MW(250MW x 4 units) electricity supply during peak time is considered to compare PSHG with STPG system with other peak power sources about economy and environmental impact. As shown in Fig.1, the conventional hydroelectric, the oil fired gas turbine, the oil fired combined cycle and the oil fired thermal power generation are used for the load adjustment as peak power sources. The gas fired combined cycle whose generation cost is lower than the above peak power sources is almost operated in full load. In case the PSHG is introduced, the electricity for the storage pump will be supplied by the above-mentioned power sources. Since the construction of the coal fired power generation does not reach the annual demand increase at present, the gas fired combined cycle cannot afford to supply electricity to the storage pump. The existing conventional hydroelectric generation also cannot increase the output easily because of the limitation of water consumption of the reservoir as mentioned in section 1.

Table 5 shows the generation cost and the CO₂ emission of the PSHG with above mentioned power generations in (1) to (4), and the existing peak power sources in (5) to (7). The existing peak power sources may shift to the gas fired combined cycle in future if the construction of coal fired thermal power generation will be promoted rapidly and the excessive capacity of the gas fired combined cycle will arise. In table 5, the shift from oil fired combined cycle to gas fired combined cycle after 10 years is considered in (8) and (9). As for these fossil fuel fired power sources, only fuel cost and variable maintenance cost are considered as the generation cost because these power sources will not be built newly for PSHG. In the table, PSHG with STPG shows 0.2121US\$/kWh generation cost which is higher than that of the other systems except PSHG with oil fired gas turbine, but the environmental impact is the lowest. By combining these power sources, a Pareto optimal solution of peak power source showing the trade-off of the minimum generation cost and the minimum CO₂ emission is found.

A multiobjective optimization method using the genetic algorithm is applied to find the solution. Objective functions are shown in Eq. (17) and Eq. (18), and constraint conditions are shown from Eq. (19) to Eq. (20).

Objective :

$$F_1 = \frac{\sum X_i H_i E_{Gci}}{\sum X_i H_i} \rightarrow \text{minimize} \quad (17)$$

$$F_2 = \frac{\sum X_i H_i G_{HGi}}{\sum X_i H_i} \rightarrow \text{minimize} \quad (18)$$

Subject to :

$$\sum X_i = 100,000 \quad (19)$$

$$\sum H_i = 4 \times 365 \quad (20)$$

Where,

X_i : Output power of peak power source i (kW)

H_i : Operation hour of peak power source i (Hour)

Since the above objective function is the linear function, Pareto optimal solution is expected to be the straight line to bind the minimum generation cost point and the minimum CO₂ emission point.

Figure 11 shows Pareto optimal solution for 3 conditions. The black Pareto solution is calculated by the assumption that the crude oil price is US\$60/bbl and the shift to gas fired power generation does not progress. The blue Pareto solution is calculated by the assumption that the crude oil price is US\$60/bbl and the shift to gas fired power generation will progress after 10 years. The red Pareto solution is calculated by the assumption that the

crude oil price is US\$100/bbl and the shift to gas fired power generation will progress after 10 years. The Pareto solution in black is combinations of PSHG with STPG and oil fired combined cycle, but the Pareto solution in blue and red are combinations of PSHG with STPG and oil/gas fired combined cycle. The almost black Pareto solution shows lower generation cost and CO₂ emission than PSHG with oil fired combined cycle. That means the electricity supply to the storage pump by STPG is better for economy and environmental impact than the electricity supply by existing peak power sources. On the other hand, according to blue Pareto solution, if the shift from oil fired combined cycle to gas fired combined cycle will progress in the peak power source, the combination of less than 557MW PSHG with STPG and more than 443MW oil/gas fired combined cycle shows the lower generation cost and CO₂ emission than 1,000MW PSHG with oil/gas fired combined cycle. That means it is better for economy and environmental impact to introduce 250MW x 2 units PSHG and the corresponding STPG than to introduce 1,000MW PSHG only. However if crude oil price is assumed to US\$100/bbl, 1,000MW PSHG and the corresponding STPG becomes the optimal solution as shown in red Pareto solution.

Table 5 the generation cost and the CO₂ emission

	Generation cost (US\$/kWh)	Generation cost (US\$/kWh)	CO ₂ emission
	US\$60/bbl (Crude oil)	US\$100/bbl (Crude oil)	(ton/MWh)
(1)	0.2121	0.2121	0
(2)	0.2073	0.3160	0.878
(3)	0.2530	0.3927	0.918
(4)	0.3007	0.4719	1.412
(5)	0.1011	0.1695	0.553
(6)	0.1298	0.2177	0.560
(7)	0.1598	0.2676	0.844
(8)	0.1479	0.2127	0.744
(9)	0.0637	0.1045	0.468

(1) PSHG with STPG (2) PSHG with oil fired combined cycle (3) PSHG with oil fired thermal power generation (4) PSHG with oil fired gas turbine (5) Oil fired combined cycle (6) Oil fired thermal power generation (7) Oil fired gas turbine (8) PSHG with oil/gas fired combined cycle (9) Oil/gas fired combined cycle

Fig.11 Pareto optimal solution of peak power source

Genetic algorithm
Population: 9
Generation: 1,000
Crossover: 0.4
Mutation: 0.02

5. Conclusion

The possibility of STPG in Indonesia is investigated in this study. The optimum system simulation and the analysis of economy and environmental impact by a multiobjective optimization method using the genetic algorithm provide the following results.

- A) The optimum aperture area and thermal storage capacity of STPG are found by the simulation based on the climate and the solar condition in West Java.
- B) PSHG with STPG as the power source of storage pump shows lower generation cost and CO₂ emission than PSHG with existing peak power sources when the crude oil price is 60 US\$/bbl.
- C) Even if the fuel switch from oil to gas is supposed, PSHG with STPG will achieve the lower generation cost and CO₂ emission than PSHG with the oil/gas fired combined cycle by sharing the peak electricity supply with the oil/gas fired combined cycle in an appropriate ratio. Furthermore, if the crude oil price hike in future is considered, PSHG with STPG may be the optimal solution for Java-Bari grid peak electricity supply.

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