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Industrial Energy Efficiency Optimisation Through Cogeneration Using Biomass

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***Abstract*—Combined heat and power (CHP) is considered one of the most appropriate and promising technologies for the improvement of industrial energy efficiency. This study is a feasibility analysis of the application of various cogeneration systems using biofuel (rice husk) based on Rankine, Brayton and Combined cycles for a medium-sized paper mill in Pakistan, to assess the potential for energy savings in this sector through improved energy efficiency. Thermodynamic and economic analysis are carried out to suggest the most appropriate option for the studied industrial unit. It was found that cogeneration based on the Brayton cycle is the most feasible option for the studied mill based on technical and economic perspectives, as it has the highest energy utilisation factor (EUF) and lowest annualised life cycle cost compared to the other proposed options. The overall saving of the proposed CHP system based on Brayton cycle is calculated at 2,515,216 USD annually. Keeping in view the energy crises in Pakistan, using energy efficient cogeneration systems and bio-fuel (rice husk) in the industrial sector, a significant amount of energy can be conserved, resulting in the reduction of GHGs and helping to achieve sustainability and a cleaner environment.**

Keywords—Energy efficiency, Cogeneration, Biofuel, Industrial sector

I. INTRODUCTION AND BACKGROUND

Energy security is one of the major issues of many developing countries these days. Pakistan has been facing an acute energy crisis over the last two decades [1]–[3]. Its current energy requirement far exceeds its indigenous supplies, fostering reliance on imported oil and natural gas that place a substantial burden on the economy of the country. The industrial sector, as the most energy-intensive sector of Pakistan, consumes almost 35% of the total energy generated [4].

As a result of the energy crisis in the country, the industrial sector of Pakistan was badly affected in terms of its operational productivity and lost at least 12% of its potential output during the early years of the 21st century [5]. At the same time, Pakistani industries are highly inefficient in energy usage with significant energy losses that in turn reduced its level of overall operational productivity, and there is little recent sign of significant improvement [6], [7]. The electricity is supplied from the grid, where electric transmission and distribution losses are over 30% [8].

Industrial energy efficiency can be improved up to 18–26% through proven technologies, resulting in a reduction of 19–32% of CO_2 emissions [9]. Energy conservation through improved energy systems using alternative fuels can play a key role in reducing fossil fuel use in industries. Research shows that a number of alternative fuels and conversion technologies have been proposed for industries in recent years to tackle this situation. Of these, cogeneration is considered one of the most suitable and promising options for the improvement of energy efficiency[10].

Cogeneration, also known as CHP generation, is any system that generates electricity and thermal energy simultaneously from the same primary energy source (Knopf 2012). It is a highly efficient way of capturing wasted heat during the electricity production process and converting it into useful thermal energy for other applications such as industrial process needs or water heating, or as an energy source for another system component.

To address the requirements of improved energy efficiency and CO_2 mitigation, industrial application of cogeneration is considered to be the most feasible and practical choice. As cogeneration systems are generally located close to end users, power transmission losses are eliminated. A cogeneration system (CHP) operates at about 80% efficiency, in comparison with a standard power plant which operates at about 45% efficiency [13]. This improved efficiency not only reduces cost but also decreases carbon emissions when compared to conventional standalone electricity and heat generating systems.

The concept behind cogeneration is not new, and the technology is well recognised and reliable. It accounts for around 9% of global power generation [14], while the majority of energy-intensive industries such as pulp and paper, chemical, metals, food processing and oil refineries represent more than 80% of total global power CHP capacities [15]. In recent years, the use of CHP in industries has increased for many reasons, including fluctuation in oil prices, worldwide desire for environmental protection and energy security. Implementation of CHP to energy generating systems has significantly reduced CO_2 emissions and 10% CO_2 reduction is expected by 2030 in those countries where electricity generation, transmission and distribution systems are old and inefficient [15].

Cogeneration is mainly used in industries where solid/gas-fuelled or electric boilers can be replaced by CHP units, allowing waste heat and electricity to be used for plants' own requirements. This helps to ensure the security of energy supplies, and, in ideal cases, the excess of electricity is supplied to the main grid. In countries where biogas or biomass is utilised as fuel, cogeneration is considered part of the country's renewable energy activities and as a cheaper energy generation system.

Selecting the appropriate mode of operation is a significant step in the feasibility process of a cogeneration system [16]. Theoretically, the mode of operation is a simple decision to operate the plant when electricity produced is cheaper than purchasing from the main grid. However, practically, a number of factors are involved in deciding the optimised mode of operation, including energy demand, nominal power of prime mover, coefficients of performances (COP) of devices involved and import/export electricity prices [17].

The pulp and paper industry is an energy-intensive sector and a high requirement of both heat, and electrical energy in this sector, which, given the current power shortage in Pakistan, are motivating forces for the study of implementation of cogeneration systems in the existing energy set up. Apart from a few studies regarding implementation of CHP options in Pakistani sugar production sectors (NEPRA 2013), its application in the industrial sector of Pakistan has not developed. Keeping in view the rapid growth and increasing energy demand of the paper industry in Pakistan, application of cogeneration can be considered a feasible option.

II. METHODOLOGY

A. *Case Study*

In this case study, a medium-sized paper mill is examined for a feasibility analysis of various cogeneration options based on Rankine (steam turbine), Brayton (gas turbine) and Combined cycles, to assess the potential for energy conservation in this sector through improved energy efficiency by adopting cogeneration technology. The mill is situated in central Punjab in Pakistan and produces writing and printing paper. The annual requirements for electrical and thermal energy of this paper mill were measured as 21,267 MWh (mean 2,585 kW) and 56,766 MWh (mean 6,904 kW) respectively, with a heat to power ratio of around 3:1. Currently, two fuels i.e., rice husk (biomass) and natural gas are used in the existing plant of the mill in a total of 8,227 hours of operation to meet its annual requirements of process heat in the form of steam. To fulfil its electrical energy requirements, the mill purchases electricity from the grid. Figure 1 shows the configuration of the proposed cogeneration plant based on Bryton cycle.

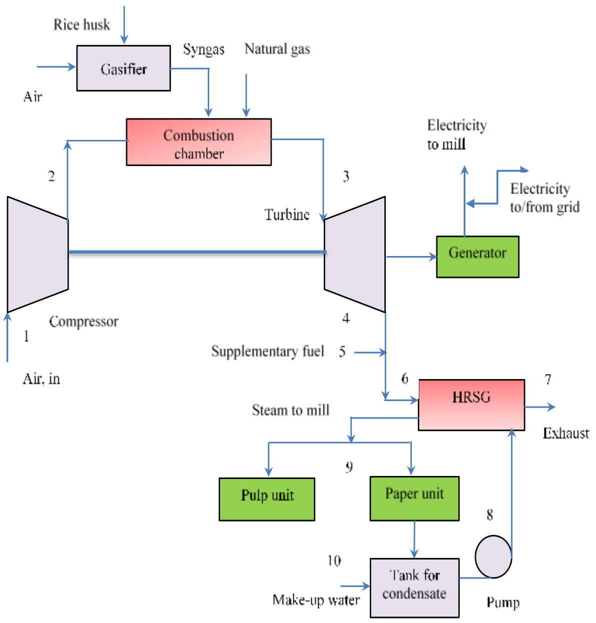

Fig. 1. Proposed CHP plant based on Brayton cycle (gas turbine)

Implementation of different configurations of CHP systems for improvement of the existing energy efficiency of the mill are investigated in detail. Thermodynamic and economic analysis are carried out and compared to suggest the most feasible option for this case study. The data for this study was provided by the paper mill, which requested to remain anonymous to preserve commercial interests. Nevertheless, for the purposes of a case study, the data can be regarded as indicative.

The following criteria are considered and discussed while comparing various cogeneration options during thermo-economic analysis.

- Energy utilisation factor (EUF)
- Capital (investment) cost (C_c)
- Annual operating cost (O_c) = Fuel + labour + maintenance + electricity costs
- Avoided electricity cost (A_c)
- Income by CHP from selling electricity (S_{CHP})
- Pay-back period
- Annualised life cycle cost (annualised LCC)

Annualised LCC = [C_c x C.R.F (Capital recovery factor)] + [O_c] – [S_{CHP} + A_c] *(1)*

Total annual savings = Total cost with CHP – Total cost without CHP (existing system) *(2)*

Total cost with CHP = [Cost of fuel + cost of buying electricity + capital cost + labour cost + maintenance cost] – [income from selling electricity] *(3)*

Cogeneration involves production of two types of energies – heat and electricity. To determine the overall efficiency of a CHP system, common criteria should be established [18]. The criterion used in this study to compare all three proposed cogeneration configurations is based on the first law of thermodynamics, which deals with the quantitative side of energy, described as the EUF.

Optimisation in the design and operation of a cogeneration system is usually carried out in two separate steps – a technical step and an economic one [19]. Thermo-economics combines these steps into a single process, in which both technical and economic factors are taken into account [19].

Thermodynamic analysis is carried out assuming that air and combustion gases behave as ideal gases with constant specific heats. The data shows that 99,755 tonnes per annum of steam is currently utilised in the paper mill, equal to 6.90 MW, and this is assumed as a fixed requirement of the mill during design calculations and analysis of the proposed cogeneration system.

Three configurations of cogeneration systems are chosen to examine the different technological alternatives that could be applied to the selected paper mill for improvement to its existing energy efficiency: namely, Rankine cycle (steam turbine), Brayton cycle (gas turbine) and combined cycle. As explained in the literature review, cogeneration can be electrically or thermally led. For this study, the following selection of basic parameters was made:

- ***Mode of operation***

In this study, the thermal energy requirement is more than twice as high as the electric energy demand. The thermal-lead mode is therefore assumed, and there is no priority of surplus electricity generation.

- ***Plant size***

Determination of plant size and other parameters used are based on actual thermal requirements of the mill.

- ***Fuel ratio***

The exact ratio of fuel (biomass and natural gas) consumed in the studied mill is used for the analysis – based on the existing operation of the mill, of the total 8,227 operating hours, the plant will run for 1,808 hours using rice husk as fuel and 6,419 hours on natural gas. Each cogeneration option contains the following key components:

- Gasifier
- Gas clean-up section
- Turbine (gas or steam cycles)
- Heat exchangers
- Electric generator

It may not be necessary that an energy efficient cogeneration system will be a cost-effective option as well. It is therefore essential to analyse all cogeneration options economically before selecting the best one for the requirement. Most commonly used criteria for such analysis are: internal rate of return, pay-back period, annualised life cycle cost and levelised cost of electricity [19]. The indicator used in this case study to compare the economics of three proposed cogeneration systems is life cycle cost (LCC). Such analysis provides a basic understanding for making a decision to adopt the most cost-effective technology from various available choices [20].

The investment decisions of any large project are usually based on the capital costs (C_c) and the pay-back period. Although exact C_c of equipment for specific models can be obtained from sellers, when there is no available cost data available for the required size or capacity, the following methods for cost estimations and economic evaluation can be used [21]:

i. Equipment cost estimations by capacity ratio exponents
ii. Yearly cost indices
iii. Factored cost estimates
iv. Computer cost estimates
v. Thermo-economic factored cost estimates

All these methods have their own merits and demerits, keeping in mind the available data of paper mill "thermo-economic factored cost estimates", also known as thermo-economics, is used to calculate the C_c of the proposed cogeneration systems in this case study. Thermo-economics is an effective tool to study and optimise any energy system. In this study, the optimal design begins by first selecting the cogeneration configuration that matches the thermal requirements of the mill and then assembling material and energy balances for the selected cogeneration configuration, as explained in section 7.3. These performance equations provide the required flow rates, temperatures and pressures, which are then used to size and calculate the C_c of equipment by thermo-economics.

Many researchers use thermo-economics as a comprehensive way to calculate CC as a function of key parameters [11], [22]–[24]. They have derived various empirical functions and coefficients, which also take into account the cost of installation, electrical equipment, control system, piping and local assembly [25]. While there are limits to the validity of these equations, the authors consider them to be valid within normally expected operating parameters.

III. RESULTS AND DISCUSSION

Thermodynamic and economic analysis is carried out for the cogeneration systems based on the Rankine cycle, Brayton cycle and combined cycle to compare and propose a suitable option for the studied paper mill to increase its existing energy efficiency. As already discussed, the thermal-lead mode is assumed in this study for analysis and calculations, because the mill's thermal energy demand is around three times higher than the electric energy demand. The main priority of the proposed cogeneration system is to meet the thermal demand of the studied mill.

The results in table 1 show that the thermal requirement (6.90 MW processed heat through saturated steam) of the paper mill is 100% satisfied in all the proposed cogeneration options. The electricity generation figures per year in various CHP options are: 6,072 MWh, 22,983 MWh and 31,508 MWh in the cases of the Rankine cycle, Brayton cycle and combined cycle respectively. After fulfilling the mill's own electrical requirements (21,267 MWh/year), 1,716 MWh/year electricity can be transferred to the grid in the case of the Brayton cycle cogeneration option and 10,241/year MWh electricity can be available to sell in the case of the CHP system based on the combined cycle. However, in the case of the Rankine cycle cogeneration system, the electricity generation (6,072 MWh/year) is less than the plant's own requirement and 15,195 MWh electricity is required to be purchased per year from the grid (see table 1). This makes steam turbine an unsuitable option for the studied paper mill.

It is important to note that the power to heat ratio is significantly low in the case of the Rankine cycle cogeneration system and, after satisfying the thermal requirements of the mill, only 6,072 MWh/year electricity can be generated in this case. According to the U.S. Department of Energy (2016), most of the cogeneration systems based on steam turbine (Rankine cycle) are characterised by low power to heat ratios, often below 0.2.

As discussed above, the EUF is a significant thermodynamic criterion to compare and evaluate various cogeneration options for feasibility studies. The EUF of a system or plant can be calculated from total energy output (thermal and electrical) divided by total energy input. Table 1 shows a comparison of EUF (as calculated) of the existing and proposed cogeneration systems. The overall results show an EUF of 78% for Brayton cycle cogeneration, 66% for the Rankine cycle and 77% for the combined cycle cogeneration system. The most effective use of energy can be seen in the case of the Brayton cycle (78%) and combined cycle (77%) cogeneration systems. It can be seen from table 1 that, of all the options, the highest amount of electricity (3.83 MW) is generated in the case of the combined cycle but, meanwhile, it consumes the highest thermal energy (13.81 MW) as well.

Of the three proposed cogeneration systems, even the lowest EUF option (Rankine cycle cogeneration option) has higher EUF (0.66) than the existing system (0.52). Thus, from an energy utilisation point of view, cogeneration is the best alternative for a mill to increase its energy efficiency. As the main target is to match thermal load, cogeneration based on Brayton cycle is the best option for the studied mill under its current fuel ratio.

TABLE I. A COMPARISON OF ENERGY EQUILIBBRIUM AND EUF (AS CALCULATED) OF EXISTING AND PROPOSED SYSTEMS

Parameters	***Existing plant***	**Proposed CHP systems**		
		Rankine-cycle	***Brayton-cycle***	***Combined -cycle***
Thermal energy requirement	6.90 MW 56,766 MWh/year	6.90 MW 56,766 MWh/year	6.90 MW 56,766 MWh/year	6.90 MW 56,766 MWh/year
Electricity demand	2.59 MW 21,267 MWh/year	2.59 MW 21,267 MWh/year	2.59 MW 21,267 MWh/year	2.59 MW 21,267 MWh/year
Electricity production	0	6,072 MWh/year	22,983 MWh/year	31,508 MWh/year
Surplus electricity (MWh/year)	0	0	1,716	10,241
Bought-in electricity (MWh/year)	21,267	15,195	0	0
Energy input (MW)	10.6 Th +2.59 E = 13.19	11.59 Th	12.40 Th	13.81 Th
Energy output (MW)	6.90 (Th)	6.90 Th + 0.74 E = 7.64	6.90 Th +2.79 E = 9.69	6.90 Th +3.83 E = 10.73
Energy utilisation factor	0.52	0.66	0.78	0.77

Table 2 shows the detail of various cost used to calculate the annualised LCC, as discussed above. The results show that annualised LCC is a minimum of 881,233.3 USD for the gas turbine cogeneration option and its value is a maximum of 5,940,700 USD for the steam turbine option.

TABLE II. DETAIL OF ANNUALISED LCC OF PROPOSED CHP OPTIONS

Parameters	**Proposed CHP systems**		
	Rankine-cycle	***Brayton-cycle***	***Combined -cycle***
Total investment of equipment (C_C)	3,447,966	2,306,516	3,810,665
Annual operating cost (O_C)	603,8614	2,659,730	3,125,475
Avoided cost (A_C)	488,221.6	1,933,270	1,933,270
Financial saving by CHP from selling electricity (S_{CHP})	0	128,701.3	768,107.2
Annualised LCC	5,940,700	881,233.3	1,130,911

The above analysis and results provide a comparison of the existing system with three proposed cogeneration systems. The results of two significant indicators – the EUF and the annualised LCC – show that a cogeneration system based on the Brayton cycle is the most feasible option for the studied paper mill (see tables I and II). The EUF is maximum (78.15%) and annualised LCC is minimum (881,233.3 USD) for this proposed cogeneration system (see figure 2).

The overall savings from the proposed Brayton cycle cogeneration system can be calculated using equation (2) above.

The economic analysis shows that the studied mill can save an amount of 2,515,216 USD annually by using the proposed Brayton cycle cogeneration plant, with a pay-back period of 1.92 years. Using the proposed CHP plant, 1716 MWh surplus electricity can be sold annually. As the studied mill is located near Lahore, the average value of the electricity selling price set by the Lahore Electric Supply Company (LESCO) 2016, is taken as 75 US$/MWh. Using the current export price of electricity, 128,700 USD can be saved by selling surplus electricity to the grid.

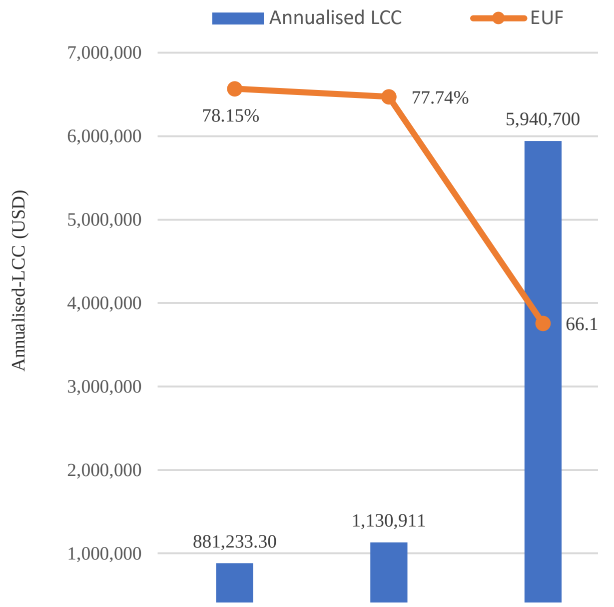

Fig. 2. Annualised LCC and energy utilisation factor (EUF) of proposed CHP options

A. *Impact of the Increased Price of Electricity Export on Annual Savings*

In order to seek the possible impact of an increase in the existing selling price of electricity on overall savings of the proposed cogeneration options, a graph is drawn (see figure 3).

In the case of the Brayton cycle cogeneration system, a gradual increase in annual savings can be noted with the increase in selling price of electricity. However, the graph of annual savings is more sensitive in the case of the combined cycle. This is because 10,241 MWh surplus electricity is available to sell in the case of the combined cycle compared to 1,716 MWh in the case of the Brayton cycle cogeneration system. From the graph in figure 7.8, it is also apparent that, if the selling price of electricity is increased up to 50%, the annual saving of the combined cycle will still be less than the Brayton cycle cogeneration option and the Brayton cycle cogeneration system will remain a more economical option for the current case study.

As no surplus electricity is generated in the case of a steam turbine, there will be no effect of the increased selling price of electricity on its overall savings.

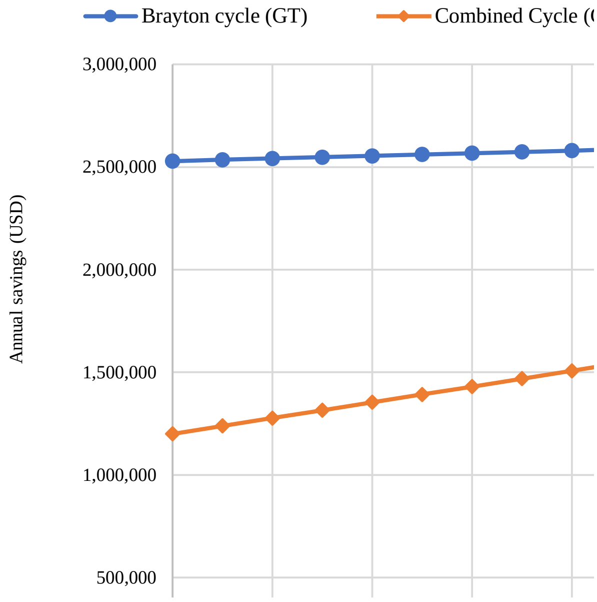

Fig. 3. Impact of increased price of electricity export on annual savings

B. Impact of Varying Electricity Generation (% of Demand Load) on Annual Cost and Overall Savings – Brayton cycle cogeneration

The graph shown in figure 4 represents a relationship between annual costs, annual savings and amount of electricity generation (in %) for the proposed Brayton cycle cogeneration system. Annual costs and savings vary with the amount of electricity generation changes, from 0% to 200% of total demand load of the paper mill. It can be noted that best output (where annual cost is minimum and annual saving is maximum) can be achieved in a case when generated electricity is between 100% and 120% of total electrical energy requirements.

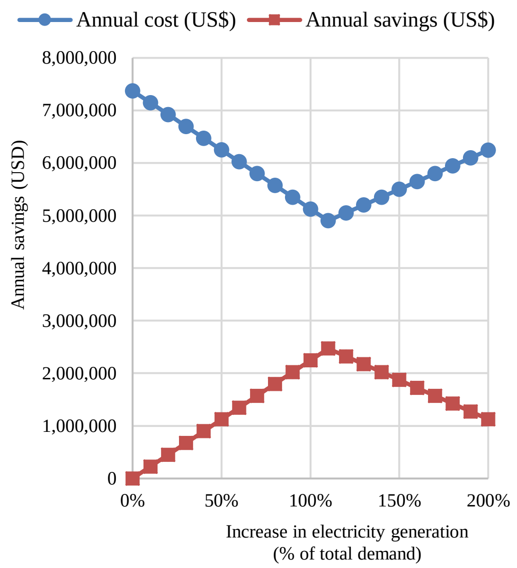

Fig. 4. Impact of varying electricity generation on annual cost and overall savings

It should be noted that these analyses are based on the current case study where the thermal energy requirement of the mill is almost three times higher than its electrical energy requirements and the same fuel ratio (rice husk to natural gas) is assumed as currently used in the mill.

IV. SUMMARY

In this case study of a paper mill, thermodynamic and economic analysis of cogeneration systems based on Rankine cycle (steam turbine), Brayton cycle (gas turbine) and combined cycle are carried out using rice husk and natural gas as a fuel. It was found that cogeneration based on the Brayton cycle (gas turbine) is the most feasible option for the studied mill based on technical and economic perspectives, as it has the highest EUF and lowest annualised LCC compared to the other proposed options. The overall saving of the proposed cogeneration system based on Brayton cycle is calculated at 2,515,216 USD annually.

For any cogeneration system, if the cost of fuel, maintenance and labour, coupled with the overall efficiency of the CHP, is lower than the buying price of electricity, CHP is a good option. Similarly, if the overall cost of generating electricity is less than the selling price, a surplus of electricity will save money. If the cost of generating electricity is higher than the selling price, it will result in a loss by generating surplus electricity. Thus, the results of both indicators – EUF and annualised LCC – of the cogeneration based on the Brayton cycle make it the most feasible option for the studied paper mill.

It was noted that, generation of surplus electricity will not be cost-effective for the studied medium-sized paper mill in the current scenario where electricity export price is not attractive. However, government can encourage the industrial sector by introducing various incentives in selling prices of electricity. Keeping in view the energy crises in Pakistan, implementation of cogeneration systems in the industrial sector of Pakistan will not only benefit in terms of financial savings but also help to avoid the possible risks of power outages.

It can be concluded that, the industrial sector of Pakistan should step forward in the implementation of cogeneration systems to tap the practical benefits of this technology. The result of this study is promising for other industrial sectors in Pakistan, specifically for large enterprises where energy consumption is much higher. Improved energy efficiency through cogeneration systems in this industrial sector will not only be rewarding to them financially but also help the country in the reduction of GHGs and improvement in energy security.

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