A review: Thermoelectric generators in renewable energy

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Abstract- In this paper, the role of thermoelectric generators (TEGs) in conversion of geothermal energy into electrical energy has been presented. In addition, the structures of the TEGs used in the electrical energy production have been reported. The TEGs directly convert the thermal energy into the electrical energy. The thermoelectric (TE) technology is used in both the air–conditioning and the electrical energy generation. Also, the TE technology is eco–friendly as it has no greenhouse gas emissions, durable due to the absence of moving parts and is silent. However, the conversion efficiency of the thermoelectric modules (TEMs) used commercially is less than about 10%.

Keywords Renewable energy, energy efficiency, energy production, thermoelectric module, thermoelectric generator.

1. Introduction

Thermoelectric (TE) technology is used both the electricity generation and the air-conditioning. TE power generators convert the thermal energy into the electrical energy directly. Moreover, the TE technology is environmentally friendly. It has no moving parts and is long-lived. Although their efficiency is about 5–10%, considering reuse of waste energy gain, their efficiency cannot be ignored.

The TE is defined as the science and technology related to the electricity generation and the cooling with the TE method. The technology uses the Seebeck and Peltier effects. Basic science of it is referenced to the theory of thermoelement (thermocouple). The basic structure of a thermoelectric module (TEM) using in the electricity generation has a thermoelement. The thermoelement forms from *p*– and *n*–type semiconductors connecting in series as electrical. Then, a large number of the thermoelements are electrically connected in series to increase the operating voltage and are thermally connected in parallel to increase the thermal conductivity. In the end, a TEM is occurred [1-5].

Devices containing the TEM are classified in two groups as depending on the effects in the TEMs; (1) the thermoelectric generators (TEGs) and (2) the thermoelectric coolers (TECs). The TEGs using Seebeck effect convert the thermal energy between two surfaces of the TEM into the electrical energy. TECs using Peltier effect convert the electrical energy applied from the ends of the TEM into the temperature difference [6-11].

TEGs are environmentally friendly in the electricity production for using waste heat as the input source, and they allow the efficient use of energy [12,13]. Despite the low productivity of the TEGs being renewable of energy input source increases the economic viability of the systems. Many studies related to increased efficiency and economic feasibility have been conducted [1,14]. There is no a moving part of a TEG. It is fully scalable, highly reliable and silent [12,15]. In recent years, studies on TEGs such as industrial plants, geothermal areas, automobile engines, computers and the human body on the production electrical energy with the TEGs have focused on the recycling of waste heat [2-3].

When a TEG is compared to other renewable energy resources, the most significant disadvantage is the low semiconductor figure-of-merit used (Z) in the TEGs and quality factor (figure–of–merit, Z) [16-17]. Until recently, the TE applications limited due to the ZT (< 1) values. Since the early 1990s, the ZT of TEMs has been increased from 1 to 2. So, the TEG applications have rapidly increased [3].

2. Basic Theory of TEGs

2.1. Structure of the TEG

TEGs are semiconductor devices [18]. It is tried to establish a connection between thermocouples and TEGs. However, there are big differences between them. Exception of Seebeck effect, thermocouples and TEGs does not show a similarity. Thermocouples are made of two different metals. It is given a T-type thermocouple is made of copper and constantan, in Figure 1. When the junction point of thermocouple is kept in the cold or heat and compared to the ambient temperature, it produces a small voltage 40 µV/°C in per one degree temperature change by Seebeck effect. For this reason, thermocouples are usually preferred as the temperature sensor in coolers, heaters and air conditioners where measurement of the temperature is needed [1].

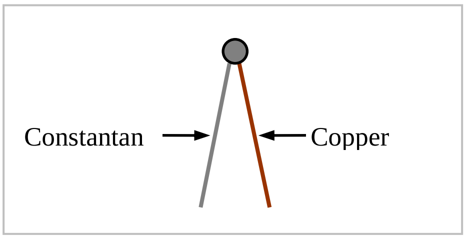

Fig. 1. A T–type thermocouple

On the other hand, TEGs are formed by connecting electrically in series and thermally in parallel. In the produced voltage, thermoelements is higher than thermocouples as depending on the temperature difference. For example, Seebeck coefficient of a thermoelement fabricating from Bi_2Te_3 semiconductor is 560–640 µV/°C and its structure is very different than a thermocouple [19,20]. The structure of a thermoelement is given in Figure 2. The thermoelement forms from connection of an end of *p*–and *n*–type semiconductors. When a temperature difference between surfaces is created, a voltage *V* is produced between its open ends. The value of the voltage depends on the temperature difference between two surfaces and Seebeck constant. The voltage value is given following equation by:

$$V = \alpha(T_H - T_C), \tag{1}$$

where V is the voltage of the thermoelement, T_H is the hot side temperature of thermoelement, T_C is the cold side temperature of the thermoelement and the α is the Seebeck coefficient of the thermoelement [3].

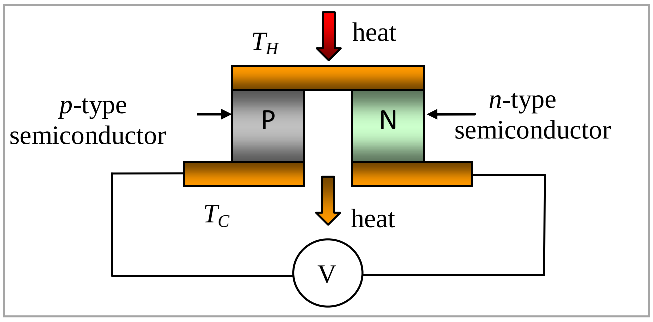

Fig. 2. The structure of a thermoelement

A TEM consists of a large number of thermoelements [21–22]. The structure of a TEM in the generator mode is given, in Figure 3.

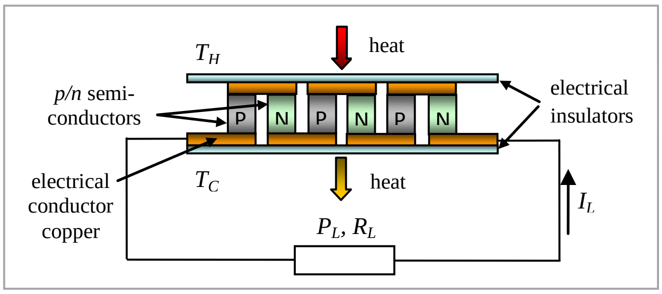

Fig. 3. A TEM in the generator mode

Otherwise, a TEG system consists of three parts; a heater block, a colder block, and a TEM [16,23]. When the high temperature is applied to one side of the TEG, the other side is kept at the lower temperature. As a result of the difference in the temperature between the two sides, the end of the TEG generates an electrical voltage *V*. When the end of the TEG is connected to an external load R_L, a current *I* flows through the load. The electrical power *P* and the current obtained from the TEG depend on the temperature difference Δ*T*, the properties of the semiconductor materials and the values of the external load resistance R_L [24].

2.2. TEG Efficiency

The efficiency of a thermoelectric generator is given by following equation [3]:

$$\eta = \frac{Energy\,Supplied\,to\,the\,Load}{Heat\,Energy\,Absorbed\,at\,Hot\,Junction}, \tag{2}$$

where *the energy supplied to the load* is the output power of the TEG and *the heat energy absorbed at the hot junction* is the input power of the TEG.

A semiconductor power measurement used in a TEG is given as the figure of merit (*ZT*). The semiconductor power measurement of the figure of merit *ZT* is given by:

$$ZT = \frac{\alpha^2}{KR}T, \tag{3}$$

where *T* is the temperature (Kelvin), α ($\alpha = \alpha_{pn} = |\alpha_p| + |\alpha_n|$) is the Seebeck coefficient (*V/°C*), *K* is the thermal conductivity (*W/mK*) and *R* is the electrical resistance (*Ω*) [19]. In addition, the efficiency is given as a function of the *ZT* and the temperature difference between the surfaces ΔT ($T_H - T_C$) in the TEG. In recent years, *ZT* of the produced TEGs is higher. Therefore, it has been a significant increase in efficiency [25,26].

The TEG efficiency is also expressed in terms of Carnot efficiency. Carnot efficiency is given by following equation:

$$\eta_{\max} = \frac{(T_H - T_C)}{T_H}\frac{\sqrt{1+ZT_M}-1}{\sqrt{1+ZT_M}+\frac{T_C}{T_H}}, \tag{4}$$

where T_M is the average TEG temperature $(T_H + T_C) / 2$, T_H is the TEG hot side temperature and T_C is the TEG cold side temperature [25,27,28].

Further, the efficiency is a function of the TEG hot side temperature T_H, the TEG cold side temperature T_C, the temperature difference between hot and cold surfaces ΔT, the quality factor of materials (Z), and the ratio of resistance R_{in} of the TEG with added the load resistance R_L at the same time. It is given by:

$$\eta = {mZ\Delta T}\Big/{\{(1+m)^2 + Z[(m+0.5)T_H + 0.5T_C]\}}, \tag{5}$$

where, m is the resistance ratio between the load R_L and the internal resistance R_{in} ($m = R_L / R_{in}$) [15].

The highest value of the voltage produced by the TEG is when the TEGs ends open. The open circuit voltage V_{OC} is expressed as following equation:

$$V_{OC} = N(\alpha_p - \alpha_n)(T_H - T_C). \tag{6}$$

The TEG open circuit voltage V_{OC} *is* proportional directly with the number of thermoelements N, the temperature difference (T_H - T_C) between hot side temperature and cold side temperature of the TEG, p-type (α_p) and n-type (α_n) material Seebeck coefficients [25].

2.3. TEG Output Characteristics

The produced power P_L on the load R_L connected to a single thermoelement is given by:

$$P_L = I_L V_L = I_L(\alpha\Delta T - I_L R_{in}) = \alpha^2 \Delta T^2 \frac{R_L}{(R_{in} + R_L)}, \tag{7}$$

where P_L is the output power produced on the load of the TEG, I_L is the electric current flowing through the load, V_L is the generated voltage on the load by the TEG, α ($\alpha = \alpha_{pn}$) is the Seebeck coefficient difference between α_p and α_n ($\alpha = \alpha_{pn} = |\alpha_p|+|\alpha_n|$), ΔT is the temperature difference between T_H and T_C ($\Delta T = T_H - T_C$), R_{in} is the TEG electrical resistance, R_L is the TEG load resistance. When the load resistor R_L is equal to the TEG internal resistor R_{in}, the TEG is on matched load condition generating the maximum output power given by [29,30]:

$$P_{L\max} = \frac{\alpha^2 \Delta T^2}{4R_{in}}. \tag{8}$$

The voltage-current and calculated power characteristics of an Altec-GM-1 TEG simulated in the Matlab/Simulink are given as depending on the temperature differences between the surfaces of TEG at the temperature difference ΔT = 100 °C, in Figure 4. The experimental measured values of voltage, current, power are given in Figure 5 for the Altec-GM-1 TEG at the different temperature ranges. In Figure 5, the dashed line shows maximum power points located at the half of the open circuit voltage V_{OC}. The TEG internal resistance R_{in} is equal to the TEG load resistor R_L, in these points. When the TEG ends are open circuit, maximum voltage V_{OC} is obtained. When its ends are short circuit, maximum current I_{SC} is obtained from the TEG. The power P obtained from the TEG varies as depending on the connected to the load value. Also, when the TEG internal resistor R_{in} and the load resistor R_L is equal, maximum power is obtained. The TEG current, voltage and power changes are given together at different temperature ranges, in Figure 6 [6,31–33].

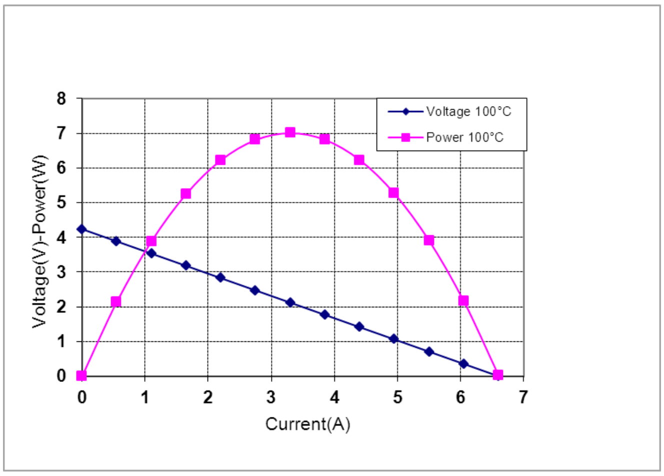

Fig. 4. The voltage-current and calculated power characteristics of an Altec-GM-1 TEG simulated in the Matlab/Simulink at the temperature difference ΔT = 100 °C

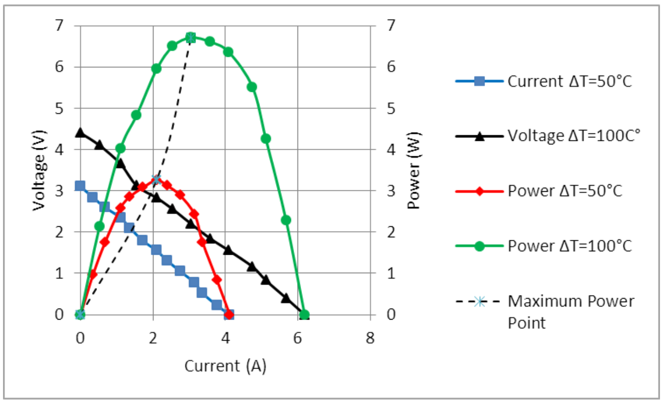

Fig. 5. The experimental measured values of voltage, current, power for Altec-GM-1 TEG at the different temperature ranges

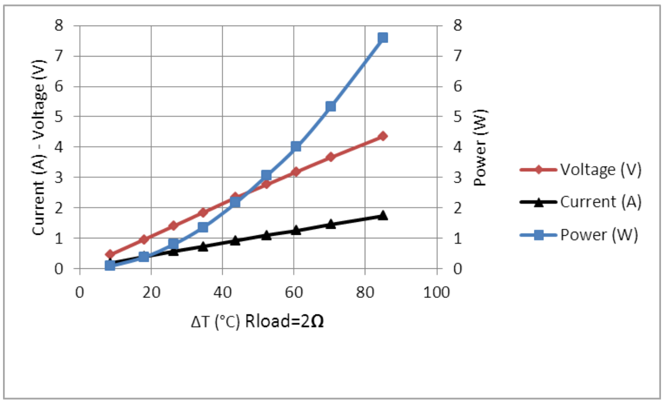

Fig. 6. Current, voltage, and power curves for Altec-GM-1 TEG at the various temperature differences

A TEG can be modeled the open circuit voltage source V_{OC} and the internal resistor R_{in} obtained from dividing (V_{OC}/I_{SC}) the short circuit current I_{SC} of the open circuit voltage V_{OC}. In here, the open circuit voltage V_{OC} is proportional to the Seebeck constant and the temperature difference ($V_{OC} = \alpha\Delta T$). The TEG short circuit current I_{SC} is the current when the TEG ends are the short circuit at the certain temperature difference ΔT. The equivalent electrical circuit associated with using as the TEG of a TEM is given in Figure 7. The power value obtained from the TEG changes as depending on the load resistor value [34–36].

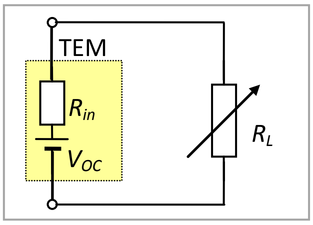

Fig. 7. The equivalent electrical circuit for the measurement voltage and the output power of the TEM

3. TEG Types and Application Areas

3.1. TEG Types

The TE power generation technology aims to convert thermal energy into electrical energy. In the production of electrical energy, the types of TEGs are (1) large-bulk TEM that are preferred for high-power applications and (2) the thin film TEG (micro TEG - µTEG) that are preferred for low-power applications. The µTEGs require less thickness than the 50 μm thickness TE elements. Thickness of commercially available and widely used the bulks TEGs usually are over 500 μm. When it is below of this value, the production efficiency decreases considerably [13,37,38].

The µTEGs is smaller and thinner than the bulk TEGs. Therefore, they take up less space. They are seen that µTEGs can directly integration industry-standard production methods as promising. The thin films in the µTEG are the segment layer materials thickness from one *nm* to a few *nm*. The thin film TE materials can be enlarged with different ways [39,40]. The µTEGs mainly consists of several kinds of structure such as swiss roll, film and thermopile. On the other hand, thermopile has relatively higher power density and therefore is more valuable for researching [41]. The bulk integrated TEG produces the highest output power and voltage. It easily produces sufficient power at a high enough voltage to power a variety of low power sensors even when harvesting energy from the temperature differences as low as 5 °C. Also, the µTEGs are more efficient for applications used acquisition of electrical energy at the high temperature difference [25,42].

For the performances of the µTEG and the bulk TEG, three factors turn out to be crucial: (1) the increase of the thermal resistance of the generator, (2) the decrease of the thermal resistance and (3) finally minimizing the electrical resistance [37,43].

TE materials used in the TEMs shows a large variety. These are TEM materials including different material systems from semiconductors to ceramic, different crystal shapes from mono crystal, polycrystalline to nano-composites, and different sizes from bulk, film and wire to cluster [44,45]. Improving of the figure of merit *ZT* of the TE materials is quite difficult due to the basic properties of the materials. In recent years, some studies on improving of the figure of merit *ZT* of the TEM materials is moving towards the use of nanostructured materials [46]. The nanostructured materials such as quantum wells (QW) [47], superlattices [48], nanowires [49,50], and nano grains [51] are generally used as nano structured materials in the production of new TEGs. The TE conductivity can be quite reduced owing to the nanostructured materials [52].

The new nano materials called QW are made up of 10 nm thick silicon and SiGe films. These have contributed to improving of the TE figure of merit *ZT*. Thermoelements with the figure of merit *ZT* greater than 3 have been obtained with the materials at room temperature [48]. This value is a significant improvement compared to the bulk TEGs with the figure of merit *ZT* less than 1 [53]. Conversion efficiency of TEGs made of the QW materials is approaching up to 20% [54].

In recent years, development efforts on the nano structured TE materials from nanocrystals to nanowires show great advantages, compared to the performance of the bulk crystal with the same chemical composition on account of dramatically reduced thermal conductivity. However, the critical gaps still remain. Therefore, this restricts practical manufacture, scalable, and wide deployment of the nano TE devices [55,56].

Energy conversion technology require several conditions such as (1) the simplicity of the process and scalability of materials, (2) the economical sustainment in the manufacture and recycling, (3) the compatibility and integrality with existing manufacture infrastructure, and (4) performance improvability. These requirements determine the direction of future research for the nanostructured TE [55].

3.2. TEG Application Areas

As societies evolve, energy requirements are increasing. Environment pollution due to the used fossil energy sources has increased people's susceptibility to environmental protection. Also, technological advances raised demand for energy. As a result of this, the importance of the energy efficiency has increased. In addition, the developments caused the international energy crisis have been one of the hot research topics to use new and clean energy resources [57,58]. One of the renewable energy sources is the geothermal. This was a source of renewable geothermal energy. One of the devices converting geothermal energy into electrical energy is TEG. In generation of electrical energy, they do not use greenhouse gas, therefore they are environmentally friendly. For this reason, TEGs have been increasingly attracting attention because of largely meeting on the needs of the people as green and flexible electrical power source [59–62]. During temperature difference in the environment of TEG, they produce electrical energy every time. Because of this feature, they are not like solar panels (PV), day-night, rain-sunny days do not prevent to the production of electricity [63].

The energy acquisition from the TEGs has been an important part for self-powered or a low-power integrated systems. For example, Topal et al. [64], in a conducted study, vibration based a μTEG was been developed at Middle East Technical University Micro ElectroMechanical Systems Laboratories (METU MEMS). As a result of researches, they concluded that TE production is conveniently a potential energy source in the conversion of waste heat into electricity.

Some examples including studies in areas of use TEGs can be given as follows; for the self-powered wireless sensors, it can replace the battery in the areas where no electricity is [65–67], the conversion of solar energy directly into electricity and grid on/off systems [68,69], the biomedical systems using the difference between human body temperature and the ambient temperature [70–72], telemetry systems that require less energy needs [64,73,74], waste heat recovery in the internal combustion engines [75–77], electrical energy generation from overheated roads in the areas where no electric lines are, and use of warning systems [78], self-powered sensors [79,80], the acquisition of grid off energy [81,82], in aerospace [83], and geothermal waste heat recovery [20]. TEGs are also used extensively instead of batteries to provide power in the small electronic circuits powerful applications [84].

Torfs et al. [70], in a conducted study, a wearable, wireless 2–channel electroencephalography (EEG) system had been realized which functions fully autonomously, without any batteries. It was fully powered by human body heat using a TEG which can produce over 2 mW at 23 °C. At the same time, the solar panel energy strengthen had been added as the hybrid system.

Leonov et al. [58,85] combined the TEGs with the PV cells. The main purpose of the work was in the devices that can be worn PV cells and the TEGs, especially when used on clothes. In their study, an optimized TEG generated more power than PV cell in the each unit field of human body They produced a hybrid energy recovery, as a primary objective, to avoid coldness caused by TEGs in the cold weathers in 2008. The fulfilled hybrid system brought about two parallel electrical circuits; a TEG and a PV cell.

Ekuakille et al.[71], in their study, a special recovery circuit designed and applied for biomedical hearing aid. Their target was that a TEG taking the energy from warm body tissue produces in order to provide a resource for biomedical hearing for people with difficulty hearing. Their study was shown the demonstration of a TEG able to extract warmth from body tissue to supply a hearing aid. It was not convenient to feed directly the hearing aids. However was necessary to pass through a conditioning circuit, as regulator, by adding batteries for backup.

Kari et al. [76] were carried out the exhaust energy cycle by a TEG for two-state study. They presented predictions of generated power and fuel saving by TEG placed in the exhaust outlet of a sport vehicle. They obtained for generators using either commercially available Bismuth Telluride (Bi_2Te_3) or QW thermoelectric material. The increase in power between the QW and Bi_2Te_3 based TEGs was about three times for the sports utility vehicle and seven times for the compressed-natural-gas fueled engine generator setting generator under the same simulation conditions.

Ahiska et al. [17] designed a microcontroller controlled TEG which transforms geothermal energy, one of the renewable energy sources, to directly electrical energy, and then they tested the system and its performance analysis was examined. In their system, energy transformation was provided via the Seebeck effect in the thermoelectric modules. Since changeable DC voltage depending on temperature difference was obtained by the thermoelectric modules. Their studies were given in Figure 8 and 9.

Fig. 8. Microcontroller controlled geothermal TEG

Fig. 9. A portable geothermal TEG of 100W

3.3. DC-DC Converters for TEGs

When the temperature difference between the surfaces of TEG is changed, the output voltage of the TEG varies accordingly. It is required that standard voltage give to the loads or the electronic circuits connected to the ends of TEG. In order to provide this standard voltage, TEGs need to the DC-DC converters.

TEGs are connected into the serial and parallel to achieve sufficient power [86,87]. In a DC-DC converter, a power management circuit extracts power as many as possible from the TEG system connected into the serial and parallel and it generates the voltage needed by the electronic circuit. The open-circuit output voltage V_{OC} of the TEG varies depending on the temperature difference ΔT between the surfaces of TEG. The voltage V_i, which is at the entrance of DC-DC converter, affects the internal impedance R_{in} of TEG. In order to transfer a maximum power to the output, the impedance matching is needed. In this case, the input voltage V_i of the DC-DC converter is only half of V_{OC}. V_i is determined by the output voltage V_O and the conversion factor. Since the output of DC-DC converter is connected to a battery. V_O is constant within a short time interval. Therefore, the conversion factor of a DC-DC converter can be adapted to reach matching for the TEG.

Maximum Power Point Tracking (MPPT) algorithms have been developed to achieve this goal [83]. In addition, the controller using in the DC-DC converters requires two operation modes; (1) the MPPT, (2) the power comparator [88–90].

4. Conclusion

TEGs are the devices converting to the geothermal energy into the electrical energy. The electrical energy generation from the TEGs is based on Seebeck effect. As long as to be the temperature difference between the surfaces of the TEG, the TEG generates the electrical energy. Moreover, TEGs are environmentally friendly and have no moving parts. In addition, they are long-lived and work silently, scalable, and no greenhouse gas emissions. On the other hand, their biggest disadvantage is the low conversion efficiency < 10%. However, the low conversion efficiency can be underestimated because of using at the recovery of energy of TEGs. The output voltage of TEGs needs the regulation because it varies continuously with the temperature difference. As long as the energy demand increases continuously in the world, the environmental concerns in connection with today used energy sources continue, the need for renewable energy sources will be continuous and the TEGs continue to be one of the hot research topics.

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