1. Introduction

To restrict global warming below 1.5 °C, a 40%-60% reduction of CO_2 is indispensable by 2030. Moreover, the amount of CO_2 should be net zero around 2050. To achieve this goal, the development of a significant amount of variable renewable energy (VRE) generations, chiefly solar and wind, will be an absolute necessity, and the removal of fossil carbon from all energy parts containing heating, cooling and transport is required. Meanwhile, the various methods of generation for power systems should be adapted [1]. Having said that, electricity production from wind and solar power plants has an unstable state due to the alteration in the weather condition [2]. So some of the downsides relevant to intermittent renewable energy sources (IRES), like solar and wind, are making a balance between production and demand (particularly during the peak times), constancy and the times when production amount transcends the demand. Particularly, production and demand balancing seems to cause limitation and inefficiency in production, and possibly can not safeguard the supply [3]. To address the problem, electrical energy storage in the form of chemical one has been proposed as a chief solution. Power-to-gas (P2G) means both hydrogen and methane are generated employing electrical energy, which has been suggested as an option that makes the storage of electrical energy into chemical one possible [1]. As depicted in Figure 1, P2G can be in 2 forms. If the final product is hydrogen, the configuration is called P2H2 or PtH2, and it is called P2SNG or PtSNG on the condition that the final production is synthetic natural gas (SNG). Electrolysis is the first step of P2G technology, in which water is dissociated to hydrogen and oxygen by cheap and excess electricity. In the PtH2 configuration, the hydrogen produced can be used as a direct fuel or an injection to the natural gas pipelines. Yet, There are some issues with this application. For instance, the NG grid's design is not compatible with some features of hydrogen, such as pipelines fragility, higher leakage, lower volumetric energy density and heat value in comparison with NG. Therefore, to satisfy safety aspects, hydrogen level control is a must up to the determined percentage (12% vol. relevant to national standards). This limitation makes the PtSNG configuration desirable for short and mid-term projects. In this configuration, electrolytic hydrogen reacts with carbon dioxide in the exothermic reaction, which is called methanation, producing methane (CH_4), which is known as synthetic natural gas or substitute natural gas. The real plus point of SNG is the storage of renewable energy in the gas and transportation through abundant, available natural gas infrastructures with fewer restrictions related to hydrogen [3-5].

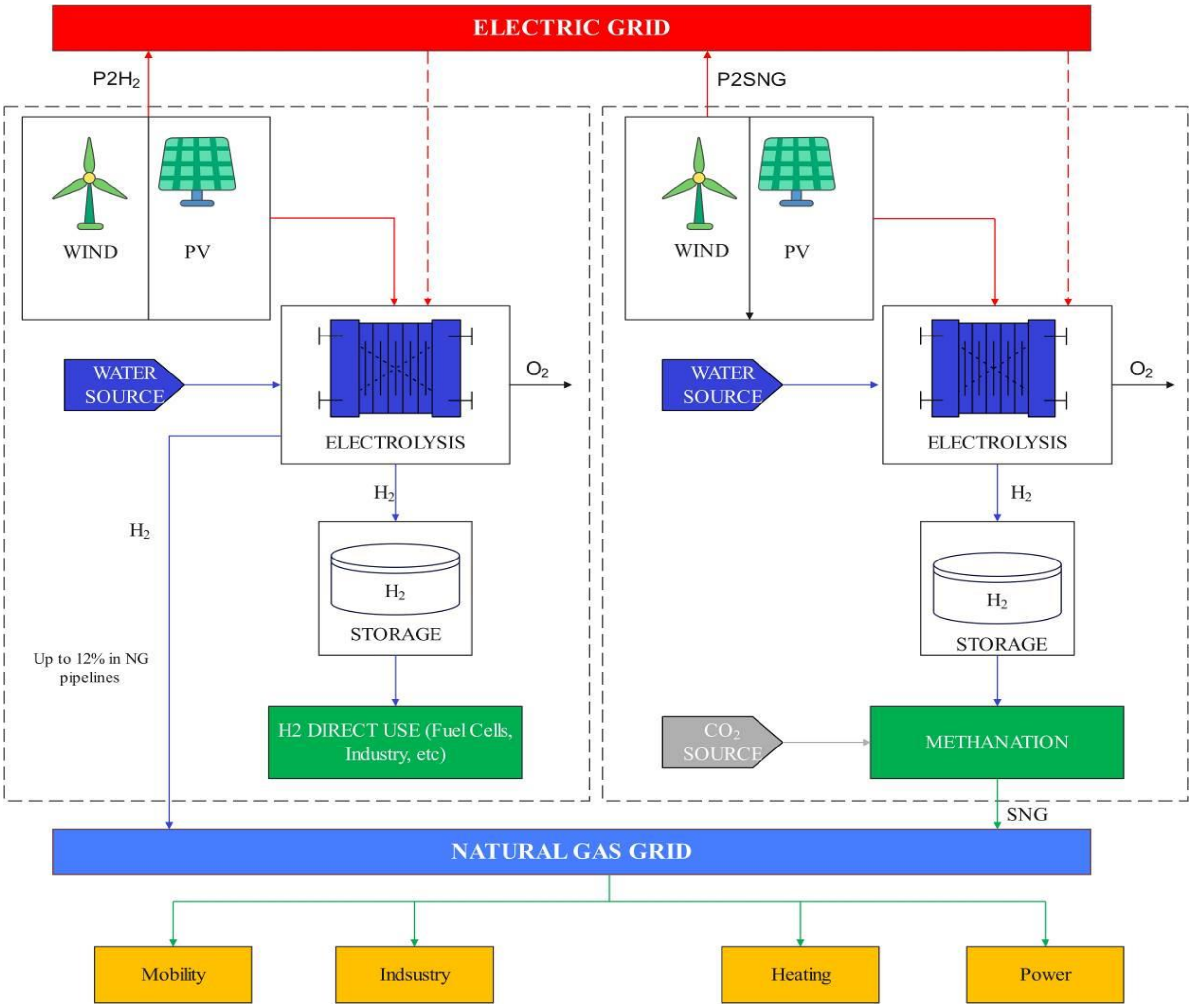

Figure 1. Power to gas notion [3]

As it is shown in Figure 2, SNG is produced in the thermo-chemical process by several steps. The first one is gasification, in which a solid carbon source is transformed into a producer gas, its primary species including H2, CO, CO2, H2O, CH4 and higher molecular weight hydrocarbons and impurities such as hydrogen sulfide and hydrochloric acid. Gas cleaning and conditioning are another steps to achieving precise gas composition and obtaining optimal conversion rates by removing particulates and catalyst poisons. Steam reforming and water gas shift reactions are the most usual stages in the conditioning step, which are presented in Eqs. (1) and (2).

$$C_xH_y + xH_2O \leftrightarrow xCO + \left(x + {}^{y}/_{2}\right)H_2 \qquad \Delta H^{\circ} > 0 \tag{1}$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H^{\circ} = -41\ kJ/mol \tag{2}$$

The third step is an exothermic process, so-called methanation, which is indicated in Eqs. (3), (4) and (5), comprises the reaction of hydrogen with carbon dioxide or carbon monoxide, in conjunction with catalyst, at high pressure and temperature to engender synthetic methane and water [6,7].

$$3H_2 + CO \leftrightarrow CH_4 + H_2O \quad \Delta H^{\circ} = -206\ kJ/mol \tag{3}$$

$$4H_2 + CO_2 \leftrightarrow CH_4 + 2H_2O \quad \Delta H^{\circ} = -165\ kJ/mol \tag{4}$$

$$2CO \leftrightarrow C + CO_2 \quad \Delta H^{\circ} = -173\ kJ/mol \tag{5}$$

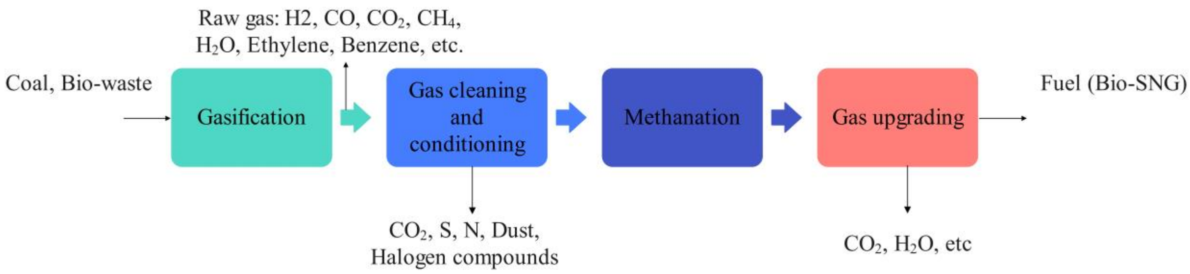

Figure 2. Conversion pathways of solid carbon source to synthetic fuel also is known as Bio-SNG [6-8]

If the ratio of the reactants H2/CO is three or more, the reaction of carbon monoxide and hydrogen takes place, producing methane and water (Eq. (3)). Yet, the producer gas gained from gasification has a ratio between 0.3 and 2, which is deficient for an appropriate conversion and the almost enduring performance of the catalyst. So the water gas shift reaction (WGS, Eq. (2)) is applied to adjust the ratio. The Boudouard reaction (Eq. (5)) has significance too on the grounds that carbon on the catalyst surface plays an important role of intermediate in the methanation proceeding [6].

SNG can be considered the most suitable alternative option for the replacement of NG as long as it keeps the main properties of combustion. Study [9] sets out the properties in entirety. Table 1 highlights some aspects of NG and SNG at 20°C and 101.3 kPa. According to it, by taking the heat value of both gasses into account, 1 m3 of SNG is equivalent to 1.49 m3 of NG. Moreover, while NG's density is lower than air, SNG's density is higher than it. Another aspect is related to stochiometric air, which needs to be 13.9 m3/ m3 of SNG in the burning system.

Methane produced in a P2G system can be regarded as "green", and consumers can opt to use it rather than fossil gas, which is quite possible to be eager to pay an additional fee for it. The government can encourage the consumers to shift their habitual usage of fossil fuels to the synthetic gas. Germany, Italy and Switzerland have proposed an overview to justify the use of SNG in transportation and heating. In Germany and Switzerland, for example, financial support is allotted to the specific use of SNG, and in Italy it is designated to the just injection of SNG into the natural gas network [4,10].

Table 1. The main properties of natural gas and synthetic natural gas [9]

PROPERTIES	UNIT	Natural gas	Synthetic natural gas
Gross caloric value	kj/m^3	39356	58841
Net caloric value	kj/m^3	36006	53629
Specific gravity	None	0.636	1.411
Density	kg/m^3	0.763	1.696
Stochimetric air	m^3 air/ m^3 gas	10.3	13.9

In the future, the profit of the P2G methanation plant will be concerned with the operation hours in a particular year, electricity price and CO2 sources. Thus CO2 price will increase or the introduction of a quota for green gas will be exerted [2,4]. There are diverse points of view about the price of natural gas in nearly future. According to [11], the price will not experience a noticeable change. Reference [12] claims that there are excessive crude oil and natural gas can be extracted in cheap ways.

Other reports assert contrasting approaches. For instance, the World Energy Outlook 2017 [13], anticipates a dramatic rise in the cost for the following 25 years. It also provides the forecast of natural gas price in various regions, including the EU, where it is projected natural gas price will cost twice as much in 2040 as in 2016.

Due to the increasing rate of gas consumption in developing economies and the rise in international oil prices, since 2020 gas import price has seen a progressive rise, and it is anticipated to reach 27.07 and 30.99 €2017/Mwh in 2030 and 2050, respectively. It is postulated that further unconventional gas reserves, mainly shale gas, have been becoming accessible massively on a global level, developing the gas supply basis. On the other hand, higher production costs are attributed to these resources compared to routine low-cost ones, in which a gradual depletion will happen [14]. However, it has been reported that the SNG production processes cost much more than those for natural gas, and it depends on the price of electricity. So by taking expected renewable electricity supplies into consideration, it is required to survey potential electricity supply and annual fluctuation for an extended time frame, in order to the optimization of the P2SNG design for distinct regions. Furthermore, the durability of the plant's own production should be assured for a certain period of the year, and consultation with Energy Meteorology expert may be essential. What is remarkable in the process is the existence of a strong likelihood of compensation for the costs by production and injection of the SNG to the gas distribution grid, producing oxygen, waste heat recovery and also reduction of emission (20-25 €/t CO2). Undeniably, oxygen is a worthwhile product that is essential for diverse sectors. Regarding the sale of oxygen, the action of filling a bottle with high-pressure oxygen and transporting it, yield extreme cost. On top of that, the cost of medical oxygen is much higher. As it is mentioned earlier another plus point of the SNG process is the making of oxygen via electrolysis, which is purer and versatile, including technical, analytical and medical aims[2].

Waste heat recovery (WHR) is another beneficial method to the way to European and worldwide goals on the decarbonization of the economy and pollution reduction. Although renewable electricity energy has been increasing, forecasts anticipate this rate will not fulfill the global energy demand by 2050. Traditional generation and renewable sources which imply combustion like biofuel, power- to- gas and power-to-fuel technologies with their WHR possibility will engender the rest of the demand [15]. For generating power, one can consider such cycles as organic Rankine cycle (ORC), conventional and inverted Brayton cycle (IBC), supercritical and transcritical CO2 (sCO2 and tCO2).

Reusing waste heat from the methanation process to meet energy demands during critical moments can be determinative for high annual efficiency achievement. Furthermore, the generated SNG from the methanation process needs dehydration and cooling, which means the injection of the dry SNG is mandatory to make it utilizable. So this step is considered as a heat source and drawing benefit from that leads to increase system efficiency. Many studies have revealed the positive consequences of heat integration due to the enhancement of energy efficiency of the PtSNG technology [16]. Schaaf et al. [17] indicated that the utility of generated heat during the methanation process as heating up the reactor's feed and the supplement of the electricity needs to plant operation, completely sufficed the required energy. Additionally, the author proposed an option for the excessive heat not recovered internally, for utilization in several sectors such as district heating, power generation, etc. Buchholz et al. [18] assessed the techno-economic feasibility of the PtSNG process coupled with a Lignite-fire power plant (LPP), in which the waste heat in the methanation plant was recovered as steam and used in LPP and CO2 absorption unit, resulted in the efficiency of the PtSNG system to be literally 54%. Anghilante and Lefebvre [19] researched the possibility of integration between released heat in the reactors of the methanation process and high-temperature electrolysis. The calculated overall plant efficiency was about 68%, which was considerably higher than those in other literatures. Candelares et al. [16] studied the waste heat from a PtSNG plant during the operation hours integrated with wind energy that was recovered by the means of a two-tanks diathermic oil circuit. The recovered heat was used as the compensation for the heat losses of methanation reactors, during the hot-standby condition, and as it is depicted in Figure 3, contained two options. The first one was the transfer of the accumulated heat from the diathermic oil to a hydrogen stream in order to satisfy the required thermal energy for the reactors during the standby periods. In the second option, a power cycle (ORC) exploited retrieved heat to produce electricity to be stored in batteries to recompense the heat losses of reactors during the hot-standby hours, as well as to meet the ancillary equipment energy needs.

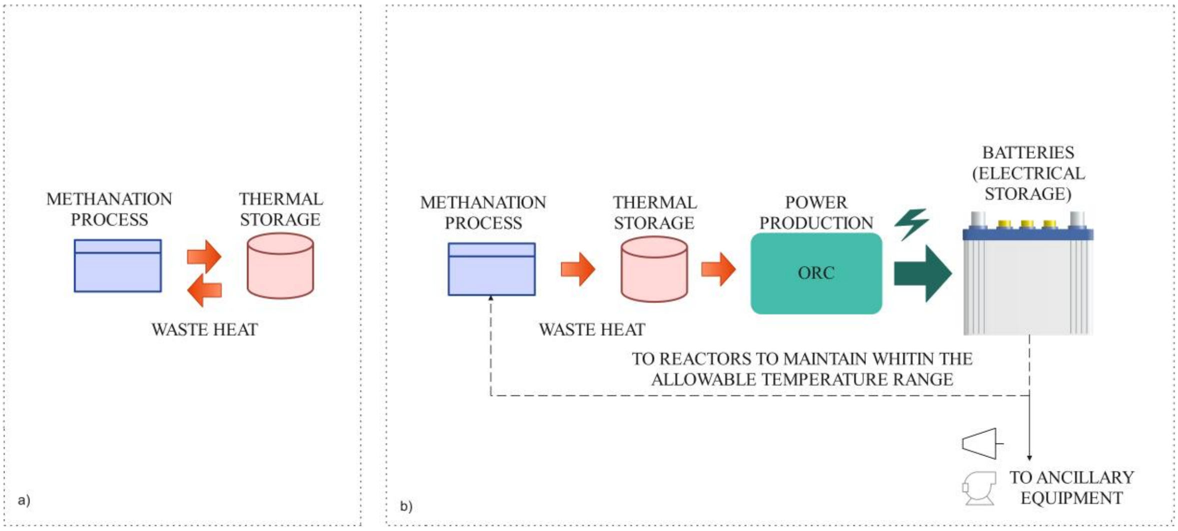

Figure 3. Pathway of stored waste heat energy in the two forms of thermal and electrical energies [16]

Spazzafumo [20] presented a method to obtain valuable electric power and SNG. Figure 4 depicts the plain schematic of the generic layout of the method. A flow of oxygen had stemmed from the electrolysis process was fed to a gasification unit, where partial oxidation of biomass was carried out. Then, the obtained syngas was directed to the power unit, which could be two suitable options, either gas turbines or internal combustion engines (ICE). Yet, the high temperature of oxycombustion was an objectionable issue that could be controlled by adding steam and/or carbon dioxide. The major components of the exhaust gas were predominantly steam and carbon dioxide. Recompression and separation were the next stages, the offshoots of the separation unit entailed three flows: a diluent flow to control combustion temperature, a water flow to the electrolysis, and a carbon dioxide flow to the SNG production process. According to the results, system efficiency ranged from 0.52 to 0.58. In another study, Spazzafuma and Frigo [21] complied with the same layout of the preliminary study, but with more accurate specifications of ICE behavior along with specific software, the AVL Boost, to achieve more precise and trustworthy results. In this study, two series were investigated. In the first series of simulation, the syngas was expanded to atmospheric pressure, which directly entered the IBC (Base layout), but in the second one, a water gas shift unit (WGS) or a methanation unit (MET) were applied to the downstream of partial oxidation of biomass to yield more carbon monoxide conversion. Results revealed that cogeneration efficiency for Base, MET and WGS layouts were 0.691, 0.71 and 0.673, repectively.

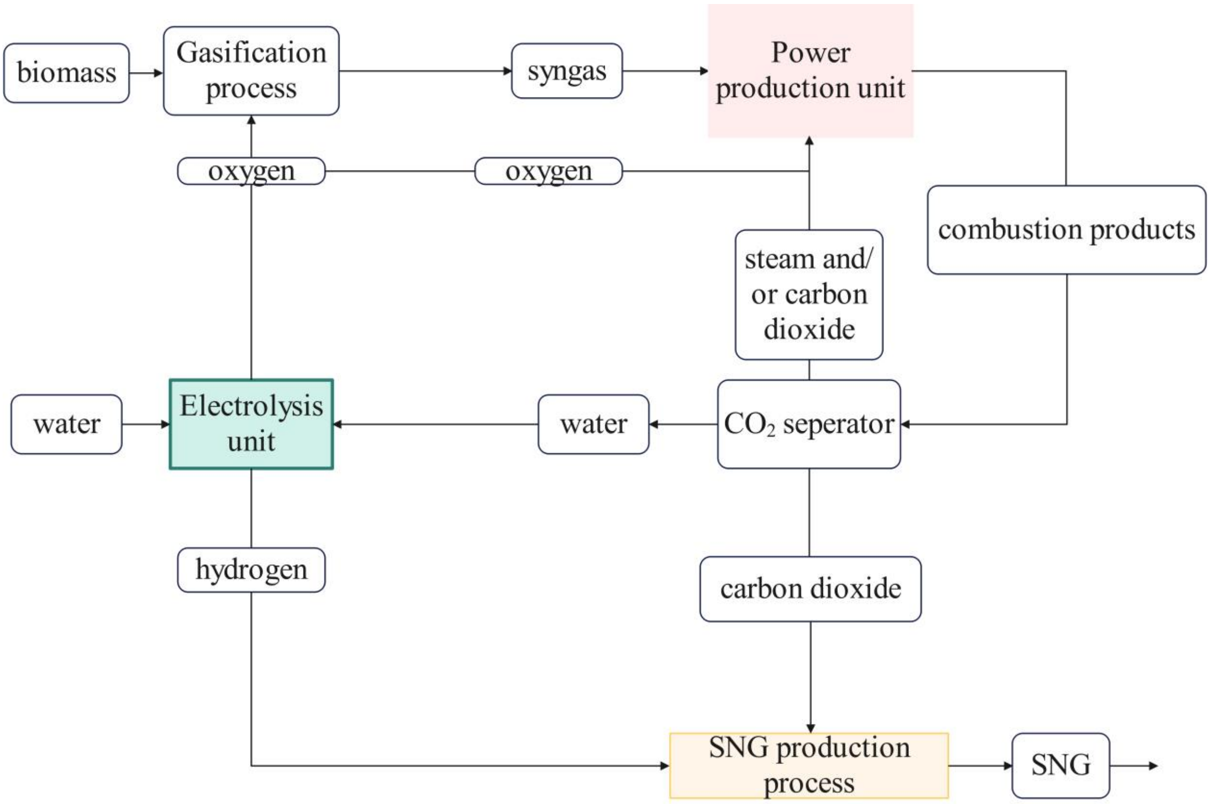

Figure 4. Simplified diagram of the generic layout, presented by Spazzafumo [20,21]

Methanol is regarded as an excellent organic solvent and staple to produce a great number of valuable chemical substances. The development and the optimization of methanol synthesis are becoming increasingly more alluring, in particular, syngas to methanol (STM) process. Zhuang et al. [22] presented a combined system of the STM and Kalina cycle (KC) with the objective of the recovery of the waste heat caused by the STM process. A schematic diagram of the Kalina cycle and the syngas to methanol process are illustrated in Figures 5 and 6. As is visible in Figure 6, the compression of the syngas feedstock took place in diverse steps. After the preheating, the syngas entered the reactor for reaction, followed by cooling. Then it was separated into the flash tank. At top of the flash tank, before mixing with feedstock, the unreacted gas carried on reacting, and at the bottom of the flash tank the concentrated methanol liquid mixture was extracted. The study presented a novel simultaneous optimization procedure that followed two steps: the first step was the optimization of primary parameters of the STM process and the KC in order to achieve the maximum amount of net power output of the combined system, and the second step objective was to minimize the number of heat exchangers. The KC and the STM process were simulated in Aspen Plus, and their heat integration was performed with MATLAB by the transfer of the simulation result. According to the results, the net power output of the combined system was inversely proportional to the reaction pressure. The obtained optimal value for the inlet temperature of the reactor and the maximum amount of the net power output were 180 °C and 15206.3 kW, respectively.

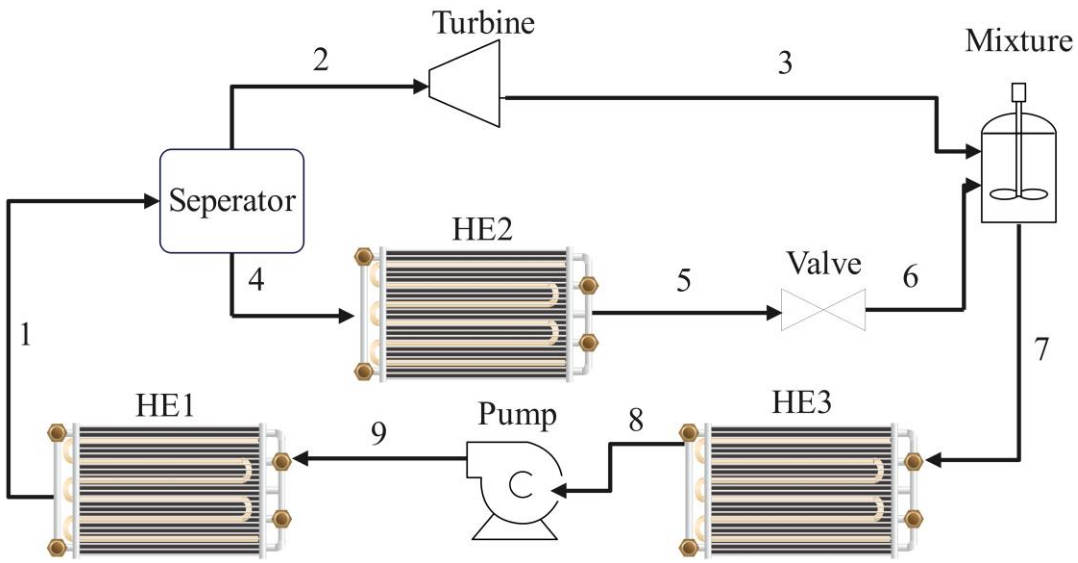

Figure 5. Shematic diagram of KC [22]

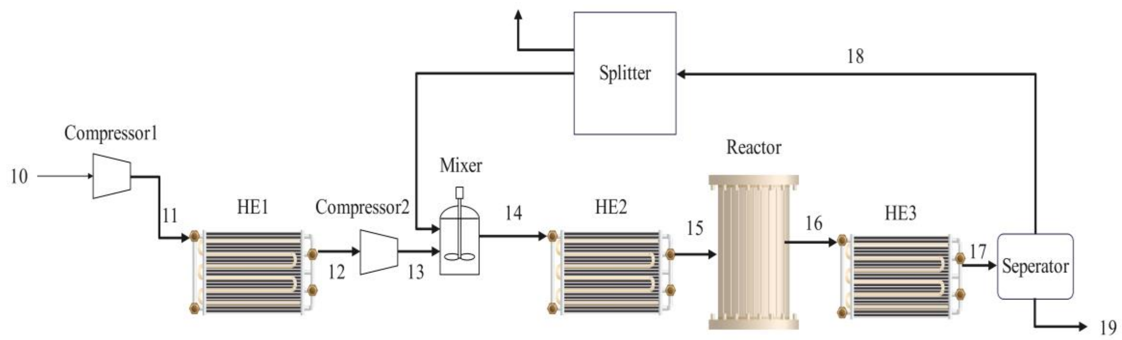

Figure 6. Syngas to methanol process [22]

All of the mentioned studies are relevant to the different methods of the recovery of waste heat due to the power- to- gas/fuel technology. Obviously, such utilization of waste heat is not limited to just this process. Su et al. [23] classified 12 usual industries that have a gigantic portion in the waste heat based on their temperature. In this study, also different approaches to waste heat recovery were reviewed, and summary and comparison of their performance and layout were conducted. Additionally, there was a discussion about the existing and possible restrictions in current research and future perspective.

Overall, the integration of heat in the SNG production process is mainly with the electrolysis unit, CO2 absorption unit, or the compensation for the heat losses of methanation rectors. Moreover, there are various technologies to retrieve the waste heat to produce the power such as ORC, IBC, sCO2, and tCO2. So the waste heat of the SNG production process can be regarded as the heat source for such power cycles. The present study aims to propose a combined system including an SNG production system by TREMP method and different cycles to produce power via waste heat of the process.