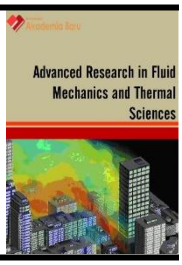
Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879



An Overview of Polygeneration as a Sustainable Energy Solution in the Future

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ARTICLE INFO

Article history:
Received 10 January 2020
Received in revised form 21 May 2020
Accepted 26 May 2020
Available online 15 August 2020

Keywords:
Sustainable energy; system design; sustainability; energy solution; polygeneration system

ABSTRACT

Better systems can be produced from various utility outputs that are integrated to make choices. The emergence of polygeneration after triggers and cogeneration can be used as sustainable solutions, making it possible to utilize resources optimally, efficiently and environmentally friendly. Polygeneration can be conceptualized with several possibilities because, theoretically, the working system has been well received as contained in some literature. Various scientific works have reported that the input and output vary greatly. The results of experimental analyses and prototypes developed have also been widely investigated and reported. Optimization tools that are based on the function of each objective are also used as a step to develop polygeneration effectively and efficiently. Polygeneration assessment has multidimensional criteria and their definitions can be applied based on cases with specific objectives. The main objective of this article is to comprehensively review the various literature available to investigate the status of polygeneration for renewable and sustainable energy solutions in the future. Various possible logical and predictable future works on polygeneration are also discussed at the end of this article.

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https://doi.org/10.37934/arfmts.74.2.85119

1. Introduction

The main input and growth and civilization of the world economy are energy sources [1,2]. The availability of primary energy contained in nature has several differences and their respective uses, however, the safest forms are used and benefits, such as secondary energy for power generation [3–7]. Therefore, technology for converting other energy into electricity is very important since conventional fuel is a resource that has a high heat pillar with a long period of time available. In general, power plants still use fossil fuels [3,4]. Worldwide, the electricity sector is still dominated by large-scale power plants, such as ultra-mega and mega power plants. However, as fossil fuels continue to run low, limited and included CO_2 greenhouse gas emissions become the main problem for the power plants [8–10]. To make better use of resources, it can be done by increasing efficiency so that indirect environmental degradation can also be reduced. However, the saturation of the steam-based power cycle to increasing efficiency depends on the material being developed. The gas-vapor combination cycle, in essence, has significantly increased efficiency so that the impact on the environment is minimal because the type of fuel used can be limited specifically for this plant. A combined cycle of integrated gasification (CCIG) and coal can also be used for this cycle. CO_2 from CCIG capture is an option in limiting or reducing CO_2 through coal. However, it has a very large connection to the efficiency resulted. To date, sustainable development has been considered as one of the most rational goals for the long term. The use of energy from the results of conversion into aspects and objectives on an ongoing basis is very important. Optimal use of resources, management of requests, efficient improvement, etc. are things that should be done as soon as possible. This is a different aspect of sustainable energy use. The limited availability of resources, as well as various environmental impacts and long-term use of fossil fuels, cannot be fulfilled because of the depletion in the last few decades [11–14]. However, during the transition, the renewable energy from fossil fuels in their use must also be ensured to be more environmentally friendly and more efficient.

Sustainable energy solutions can be utilized with polygeneration systems because the fuel used can vary for several utilities [15–18]. Increased overall efficiency is very significant with the system design on the integration of several sub-systems that can be done efficiently. In addition, the use of alternative fuels to utilize resources can be increased by making appropriate fuel changes or mixing conventional fuels. Higher efficiency with the use of suitable fuels can reduce environmental impact. Utilities found in conventional fuel-based polygeneration which is used for gas/liquid fuel synthesis can also reduce CO_2 emissions [19–22]. The output of the utility will determine the optimal use of available resources. In addition, it is also possible to integrate hybrid systems for renewable and non-renewable resources with an optimum capacity [23–26]. Research or investigation on polygeneration has been available in some literature. Investigations regarding multigenerational used for distributed applications have been carried out by Chicco and Mancarella [18]. The purpose of the investigation is to meet the heating power, power (CCHP) and hybrid cooling. An overview of models and assessment techniques for distributed multi-utility generation is generally presented by [27–29]. An investigation into the potential of hybrid power plants with well-integrated solar biomass in several desalination and cooling techniques has also been carried out by Sahoo *et al.,* [30]. Research on this desalination technique has been carried out in India [30]. Sustainable energy solutions with the use of distributed polygeneration have also been investigated by Rong and Lahdelma [31]. In the review, they mainly focus on the angle of optimization. Meanwhile, expanded polygeneration with tri generative syntax (CCHP) has been investigated by Murugan and Horak [32,33]. The process with integrated systems is polygeneration in providing input to utilities that are one unit, so that it can produce multi-utility systems efficiently. The design of polygeneration properly and correctly can increase energy efficiency, increase economic benefits, reduce waste and emissions by implementing a system of increased complexity [16,18,32]. Biomass-based polygeneration from the sun has various advantages such as reducing carbon emissions, increasing energy efficiency and overcoming the problem of scarcity of fossil fuels compared to stand-alone units. The outermost regions which are decentralized with polygeneration can increase energy access in areas that are difficult to access electricity [18]. Meanwhile, coal-based polygeneration is very beneficial for the use of carbon for environmental and economic perspectives [34,35]. Thus, energy efficiency can be improved by polygeneration to save resources.

The power generation system can be obtained from the use of fuel energy as shown in Figure 1.1. While at the same time, the wastes are disposed into the environment in the form of exhaust gases, hot water waste, etc. In addition, the utility and electric heat contained in the cogeneration plant is produced as shown in Figure 1.2. The output of the resulting plant is a truthful factory as shown in Figure 1.3. This output is in the form of heating, electricity and cooling. Production results from various utilities from one factory or from several resources can be called polygeneration or multigenerational as shown in Figure 1.4. Other outputs from polygeneration, such as chemicals, are independent from the available energy service system [36,37]. The combination of several processes can be called polygeneration because the design is very important and varies in intensity. To produce various outputs from polygeneration, it can be done with multiple and single inputs so that an assessment of its performance is very important. This performance measurement can be done with a matrix type, and it is very important to be carried out continuously on multi-dimensional aspects [23,30]. Polygeneration is the energy that can produce various utilities from only one factory. Previous studies of polygeneration have been conducted and reported [38–40]. This polygeneration is carried out by utilizing coal with the aim of producing electricity, thermal energy, liquid hydrogen and nitrogen gas which are designated at the request of the Kennedy Space Center.

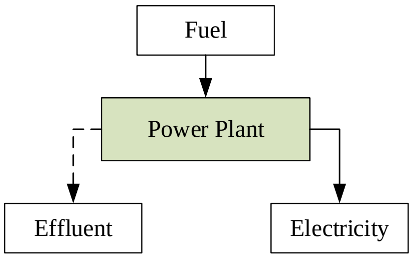

Fig. 1.1. Power Plant

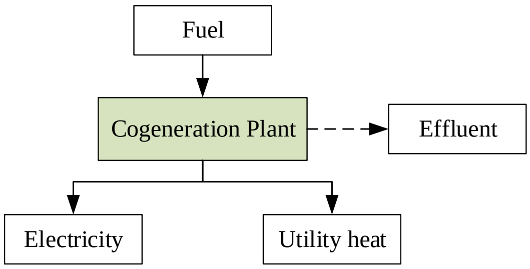

Fig. 1.2. Cogeneration Plant

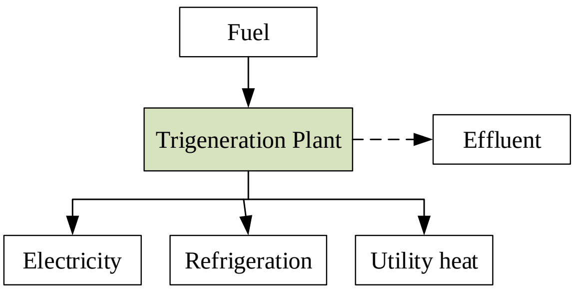

Fig. 1.3. Trigeneration Plant

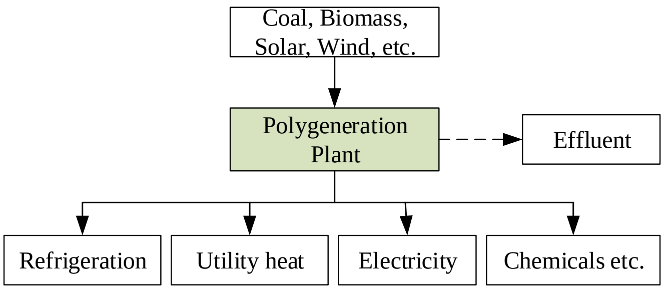

Fig. 1.4. Polygeneration Plant

Fig. 1. Resource for Power generation, cogeneration, trigeneration and polygeneration

The research on polygeneration has also been carried out by several partners funded by the European Commission [40,41]. The research is named as (POLYSMART) which aims to investigate various technological feasibility of polygeneration and market potential in the world and in Europe itself. Various forms and types of polygeneration are found in some literature as illustrated in Figure 2. The existing polygeneration operations are not carried out on a commercial scale. While the polygeneration system available in the literature is the largely theoretical study and has not been found in the form of experiments. The simulation and modelling of polygeneration in the review of this article are shown in Table 1.

Table 1
Development and simulation of polygeneration

Electricity converting devices	Types of energy input	Outputs/Application	Purposes	Ref.
CCGT	Municipal solid Waste and Natural gas	Fuel for Transportation and Electricity	Techno-economic modelling	[54]
CCGT	Coke oven gas and Coal	Methanol, Dimethyl ether and electricity	Modelling System	[56]
CCGT	Agricultural waste	Ethanol, Power, chill and heat	Design Process with (Aspen Plus simulation)	[57]
CCGT	Shale gas	Ethylene and Power	Design Process with (Aspen Plus simulation)	[58]
CCGT	Coconut fiber	Desalinated water, Power, Chill and Heat	Design Process with (Aspen Plus simulation)	[59]
CCGT	Coal	Utility heat, Power and Urea	Design Process with (Aspen Plus simulation)	[60]
CCGT	Coal gasifier Gas and Coke-oven gas	DME, Electricity and Methanol	Optimization and Simulation with Aspen Plus	[61]
CCGT	Coal	Power and Methanol	Optimization and Simulation with Aspen Plus	[62]
CCGT	Coal	Cooling, Power and Heating	Optimization with Multi-objective	[63]
CCGT	Natural gas	Methanol and Power	Design System	[64]
CCGT	Syngas	Methanol and Power	Small and medium-sized process design	[65]
CCGT	Coal	Power and Natural gas	Analysis of Exergy	[66]
CCGT	Coal	Methanol and Electricity	Design Optimal (MINLP)	[67]
CCGT	Coal	Power and H_2	Modelling (dual looping cycle of chemical substances)	[68]
CCGT	Lignite	Tar and Electricity	For Simulation	[69]
CCGT	Coal	Power, H_2, Ammonia and Urea	Modelling of Economic	[70]
Turbine Steam	Coal	Electricity, Ammonia and SNG	Evaluation of model and economy	[71]
Turbine Steam	Biomass	Ethanol, Power and Heat	Analysis of Exergy	[72]
Turbine Steam	Biomass	Power, Ethanol and Heat	Drying process influence	[73]
Turbine Steam	Biomass	Power, Ethanol and Heat	Simulation with Aspen Plus	[74]
Turbine Steam	Sugarcane	Ethanol, Sugar and Electricity	Optimization of Exergy	[75]
Turbine Steam, Gas Turbine and Fuel Cell	Coal, Biomass and Natural Gas	Captured CO_2, Electricity, H_2 and Heat	Optimization with Multi-Objective	[76]
Turbine Steam and Gas Turbine		Methanol, Power and DME	Chemical changes	[77]
Stilling Engine, Gas Turbine and Fuel Cell,	Energy Solar and Natural Gas	Cooling Fresh Water, Electricity and Heating	Optimization and Design	[25]

PV	Energy Solar	Electricity, Heating and Cooling,	Model, simulation and optimization of Thermoeconomic	[78]
PV	Solar PV/T	Hot Water, Space Heating, Electricity and Chilling,	Dynamic simulation and optimization of Thermoeconomic	[79]
PV	Biomass and Solar PV/T	Fresh Water, Power, Heating and Cooling	Analysis of Exergy	[80]
PEM fuel cell and PV	Biomass, PV, Solar Thermal and PEM fuel cell	Electricity, Heating and Cooling	Simulation and performance assessment of TRNsys	[81]
Fuel cell with solid oxide	Hydrogen and Syngas	Heating and Electricity	Simulation and Design	[82]
Fuel Cell and Wind Turbine	Energy Solar and Wind Energy	H_2, Electricity and water	Optimization and Simulation	[83]

Classification based on the type of energy sources of input, output, devices for energy conversion and objectives in this paper is also described in Table 1. The energy inputs to polygeneration shown in this table are renewable and non-renewable energies that produce electricity, cooling, liquid fuel, heating, drinking water, cooling, gas, etc. Polygeneration can be configured with some variations, especially for energy input and output. Conversion from primary to secondary energy can be done with different energy conversion devices depending on the configuration and technology and socio-economic choices made.

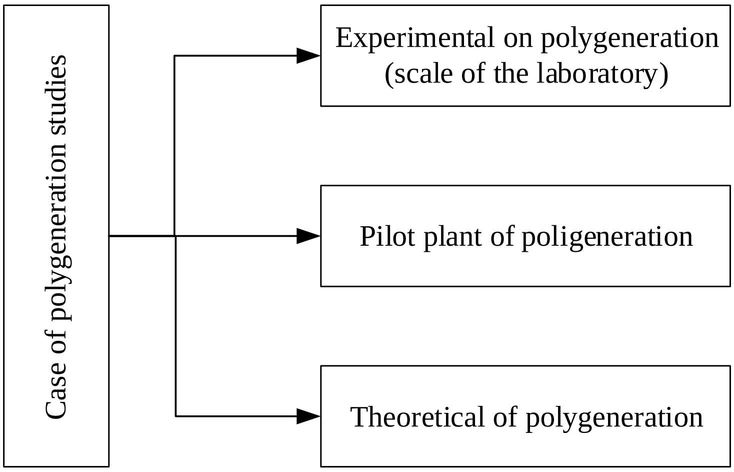

Fig. 2. Classification of polygeneration articles in several previous articles

In several studies of polygeneration, pilot plants have been tested and considered. The polygeneration pilot plant designed by conducting experiments and investigations at 190 kW was reported by Ma *et al.,* [42]. Electric power developed from polygeneration as well as for cooling, clean water and food preparation has also been investigated by Hossain *et al.,* [43]. Compression engines are built in the plant and run on factory oil with an engine power of 9.9 kW. The face of polygeneration energy is specifically designed for people in remote areas who can solve various problems with maintenance and operations related to the electricity production system autonomously [44,45]. The system built is very flexible and strong in operating for different conditions. Investigations and comparisons of experimental results on real-time management of smart micro-grids have also been carried out by [46–48]. The investigation on the results of the analysis is carried out only by looking at from the perspective of the environment and the economy.

The main drivers of different polygeneration performance curves have also been investigated and measured [49,50]. Internal combustion engines, micro-turbines, refrigeration catchments and SOFC-hybrid systems were selected for prime movers as the main facilities created in this study. The pilot plant from the results of the polygeneration process developed by pyrolysis has been tested on a laboratory scale by conducting several developments [51–53]. Improvements to the scale of the results of the polygeneration process have been reported by several researchers before. The polygeneration pilot plant developed in Spain was carried out by Ortega *et al.,* [54]. The results of development carried out by operations through polygeneration are destined for electricity, cooling and heating. Sun-based polygeneration investigated by conducting experiments has also been carried out [31,55]. The polygeneration experiment designed at the plant is developed for the production of cold water intended for air conditioning, domestic hot water which is utilized from heat recovery and clean water through membrane utilities.

This comprehensive review of the study of polygeneration with various results has been reported in several kinds of literature from previous studies. This includes systems for local resources that can be distributed on a small or large scale with the aim at and focus on more efficient polygeneration (including fossil fuels). In addition, the discussion also includes different types of input on hybrid systems with renewable and conventional fuels. The benefits of polygeneration include outputs to energy services such as heating, cooling, electricity, etc. In addition, the output from polygeneration such as drinking water, fertilizer, gas and liquid fuels, etc. are also discussed in this study. The objective function for optimizing polygeneration with different boundary conditions using mathematical tools has been discussed. The operation and control of the polygeneration prototype that has been discussed in some literature are also discussed in this study, however, with different cases and results.

2. Type Fuel for Polygeneration

Polygeneration has a varied range of fuel inputs that can be applied. Most decentralized factories have adequate supply of energy at the local level [23,31,84–86]. The plant design of polygeneration to date has only focused on the use of coal [86–89], even though renewable-based polygeneration has a higher capacity. In some cases, polygeneration has been chosen and used because it has the desired output. The inputs refer to the production of liquid fuels that use biomass or coal as their input [87,90–92]. In addition, there are also some inputs that can be used as in [93,94]. However, the determination of input resources has previously been determined such as the utilization of local resources, and the output of this polygeneration is chosen based on its configuration. The display of various inputs in the form of fossil fuels such as natural gas and coal as well as renewable-based fuels and mixtures from various sources are shown in Figure 3 [31,32,95,96].

The selected polygeneration input must be suitable for the purpose of mapping the specified resources. An increasing country's GDP has a direct impact on energy consumption. In 2000 to 2015, the average electricity consumption throughout the world increased 2.1% [97]. On the other hand, energy supply from conventional fuels still dominates the increase in GHG emissions by 47% [98]. Therefore, the energy demand for the community can be met by reducing GHG emissions so that a sustainable energy system needs cannot be avoided and are very necessary. Thus, the features of a sustainable energy system must at least be available (such as; efforts to reduce GHG emissions, economic viability and maximum utilization of resources). Specifically, the discussion of the polygeneration system has been largely discussed [14,15,99]. The design of the energy system must initially assess the availability of resources very carefully, in this case, renewable energy because of its intermittent and dilute nature. Renewable energy cannot be carried away at any further place in producing energy; this is significantly different from fossil fuels.

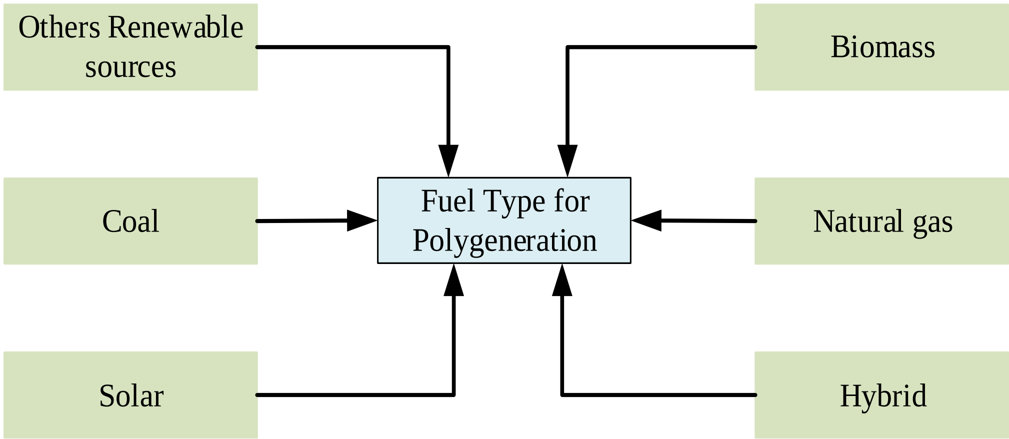

Fig. 3. Type Fuel for Polygeneration

A brief description of the energy scenario found in several countries in the world from renewable energy to the total electricity mix is shown in Table 2 [98]. The largest share of renewable energy can be observed in three countries including India, China and the US. Socio-economic-political conditions and types of energy resources have increased renewable energy compared to other countries. A polygeneration system can be well designed since the right resource mapping is very important. This study reports the type of resource mapping by taking from several countries that are sampled, especially in India. The maximum energy consumption in India has been carried out and applied to the industrial sector, transportation and housing. It is because the large part of these sectors are still dominated by fossil fuels.

Table 2
Scenario energy brief of the world's various countries

Country	China	United States	India	United Kingdom	South Africa	Australia	Egypt	Norway
Total consumption of energy (Mtoe)	3101	2196	882	179	138	126	80	32
Total consumption of electricity (Mtoe)	423.1	110	88.3	27	17.8	19	12.5	2.7
Renewable electricity percentage (%)	24.7	13.8	14.1	26.3	3.3	15.2	8.9	97.9

2.1 Biomass Based Polygeneration

Solid fuels, such as biomass, have similarities with coal, such as hydrocarbons consisting of lingo-cellulose and cellulose. However, the complexity involved in gasification and combustion is different during operations [100–106]. Tar formation and ash fusion are the main problems that arise [107–111]. The investigations regarding tar burning and tar cracking have also been carried out before [112–115]. Biomass conversion is principally thermo-chemical and utilizes syngas so that the results are very similar to coal even though they have different qualities. Thermochemical conversion of biomass can be carried out with two different options between pyrolysis and gasification [116–118]. Power production for the polygeneration scheme in producing power, heating, cooling and ethanol is shown in Figure 4. Biomass-based polygeneration is one of the most important aspects because it can produce both gas and liquid fuels for transportation [119–122]. Thermoses ethanol production from the results of the syngas process as is illustrated in Figure 5. Biofuels can be converted from biomass through biochemical routes, so this option can be considered more promising. The production process through biochemistry against bioethanol, alcohol and gas is higher because it is safer and easier. However, the type of biomass, the effectiveness of algae, the quality of catalysts, etc. can determine variations on biofuel production [123–127]. First-generation biofuel production is controversial in food and energy security [128–130], because the production of biodiesel and bioethanol in this process uses corn, sugar, etc. [131,132]. Meanwhile, in the second generation, biofuels are produced using biomass such as organic waste, wood, plants, etc. Therefore, the biofuel process using this waste does not have significant obstacles to food security. Biofuel production has been increased significantly in the third generation [133–135]. Integration of carbon storage and capture can be done with various biofuel production processes, so that the net negative system is obtained with biofuel produced in the fourth generation [136].

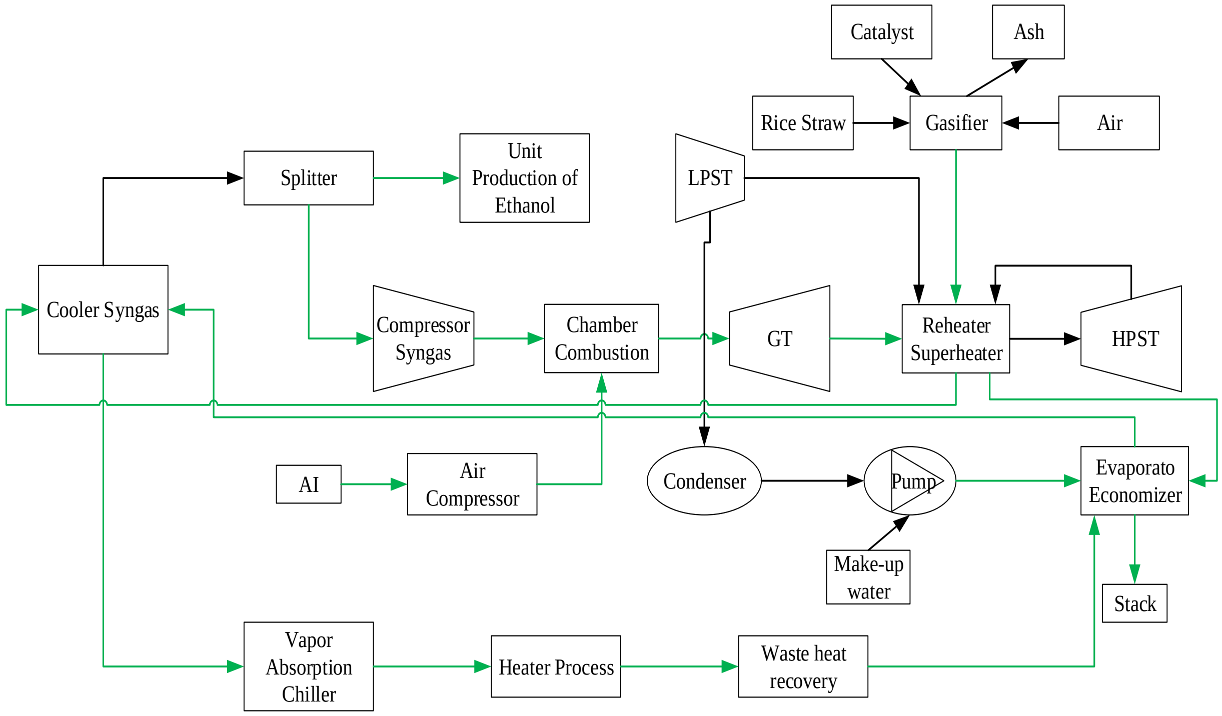

Fig. 4. Schematic diagram of polygeneration process

Agricultural waste is the largest source of biomass with no influence on food security [137,138]. The energy resources processed from agricultural waste have very good potential [139–143]. The thermochemical properties found in this waste vary more depending on the type of plant used [144–146]. The properties contained in biomass have different potential, so it is very suitable in the process of producing different biofuels for electricity generation. Meanwhile, in remote/rural areas, the availability of agricultural waste needed is very limited. Therefore, the main need for producing electricity is a supply of biomass [91]. Each year, the production and manufacture of waste greatly vary [147,148]. During the harvest period, waste can be produced in very large quantities specifically for seasonal crops such as rice. Waste can also be produced from several food processing industries such as sugarcane bagasse produced from agricultural crops because the availability of this waste is available in concentrated areas. Meanwhile, plants such as coconut have less waste available. Agricultural wastes that are used in a certain way have different variations depending on the type of waste used. The absence of geographical location and the practice of local communities are different socioeconomic reasons. The heating value contained in agricultural waste is quite sufficient for the biofuel process. Thus, this process can be used as a better-added value compared to advanced technology [145,146,149]. The use of rice straw as heating, ethanol production by thermochemical, biochemical or electricity generation are the examples of possible implementation. Technology development by utilizing this waste for energy sources has many challenges [109]. This waste can be utilized through decentralized technology with appropriate development [150–152]. However, this concentration can occur if agro-industrial waste such as sugarcane bagasse is centralized. Technology developed by utilizing agricultural waste as an energy resource is more appropriate since the availability and local energy needs are more likely to secondary energy for sustainable energy solutions, especially in rural areas in the future [43]. A summary of polygeneration with complicated biomass is described in Table 3. Types of various biomass inputs with the conversion process of output from polygeneration are also described in Table 3. It can be reported that the use of biomass as an energy source for polygeneration input by utilizing biofuels such as DME, ethanol, methanol, etc. in polygeneration are very important outputs [153–157].

Table 3
Description of biomass hybrid and based biomass for polygeneration

Inputs	Product	Biomass conversion process	Year	Ref.
Bio-Oil and Coal	Chemicals and Power	Thermochemical	2013	[158]
Hemicellulose, Lignin and Cellulose	Pyrolysis oil and Char	Pyrolysis Thermochemical	2013	[159]
Palm oil residues	Electricity, Bio-diesel, Steam and Pellet	Biochemical	2013	[160]
Biomass	FT Diesel, Ethanol, DME and Biogas	Thermochemical and Biochemical	2014	[161]
Biomass (switchgrass), solar energy focused	Heat, Electricity and H_2	Gasification Thermochemical	2015	[162]
Fiber of coconut	Heat, Power, Chill and Desalinated Water	Gasification Thermochemical	2015	[59]
Waste from tobacco	Oil, Gas and Char	Pyrolysis	2015	[154]
Biomass and Coal	Methanol and Power	Gasification Thermochemical	2011	[163]
Biomass, Coal and Heavy Oil	FT liquids, Power, H2, Methanol and Urea	Gasification Thermochemical	2011	[38]
Solid waste	Hydrogen, Heat, and Power	Digestion Biochemical	2013	[164]
Farming straw	Polygeneration pyrolysis	Torrefaction	2014	[165]
Agricultural straws (stalks of cotton)	Liquid oil, Char and biogas	Pyrolysis Torrefaction	2016	[155]
Solar energy and Biomass	Power and Methanol	Gasification Thermal	2015	[166]
Rice husk and Cotton stalk	Woody vinegar, Charcoal, Woody tar and Biogas	Pyrolysis	2016	[167]
Stalks of cotton, stalks of rape, stems of tobacco, rice and bamboo	Gas fuel of high quality, liquid oil enriched with phenols, carbon adsorbent, biochar	Pyrolysis	2016	[153]
The shell of the pine nut	Chemicals, Biochar and bio-oil	Pyrolysis	2016	[155]
Biomass	Chemicals, FT fuel and DME	Gasification Thermochemical	2011	[168]
Sugarcane	Electricity, Sugar and Ethanol	Biochemical	2011	[75]
Pongamia and Jatropha	Electricity, food, cold storage and clean water	Biochemical	2013	[43]
Biogas	Electricity, potable water for cooking fuel	Digestion	2014	[169]

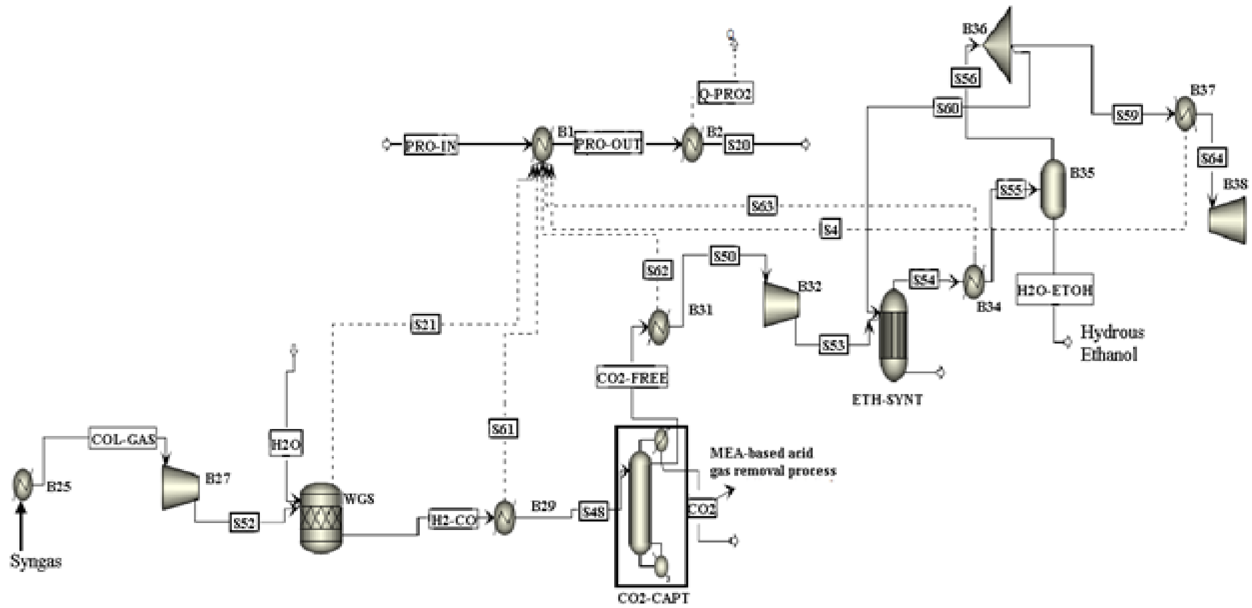

Fig. 5. Thermo-chemical method of processing of ethanol

2.2 Biofuel for Polygeneration

Bio-fuel methanol can also be used as polygeneration for renewable energy. Methanol produced from biomass is very suitable to be used as polygeneration other than coal, solar energy and other energy. The production of methanol for polygeneration has been carried out in a research by [170]. However, the research is a coal-based polygeneration system intended to produce methanol and electricity. Electricity and methanol productions from renewable energy using natural gas-based polygeneration systems have also been evaluated [64]. The results of their research show that the new system can save about 6% energy than a system with a single product. The polygeneration system by producing biofuel by utilizing heat as one of the by-products can provide cooperation between the transportation sector and district heating [161,171]. DME and FTD productions are two technologies that can be used for biomass gasification. The configuration scheme is shown in Figure 6(a) is a process for biofuel production. Production of this type can generally be carried out in a number of steps: pretreatment, gasification through thermochemistry into synthetic natural gas (SNG), increasing SNG, purification and synthesis of biofuels [172–174]. Exothermic is a process that opens the possibility to be able to use excess heat in the production of DH or combined heat and power (CHP). The scheme shown in Figure 6(b) is the simplified result for the ethanol production process based on SSF. The process for this stage is pretreatment, in which biomass is converted into pulp. Then, the slurry is cooled using a flash, then the pH is neutralized and diluted first. The SSF process is carried out with yeast obtained from the cultivation results in the slurry and then the ethanol is separated by distillation and dehydrated [175,176].

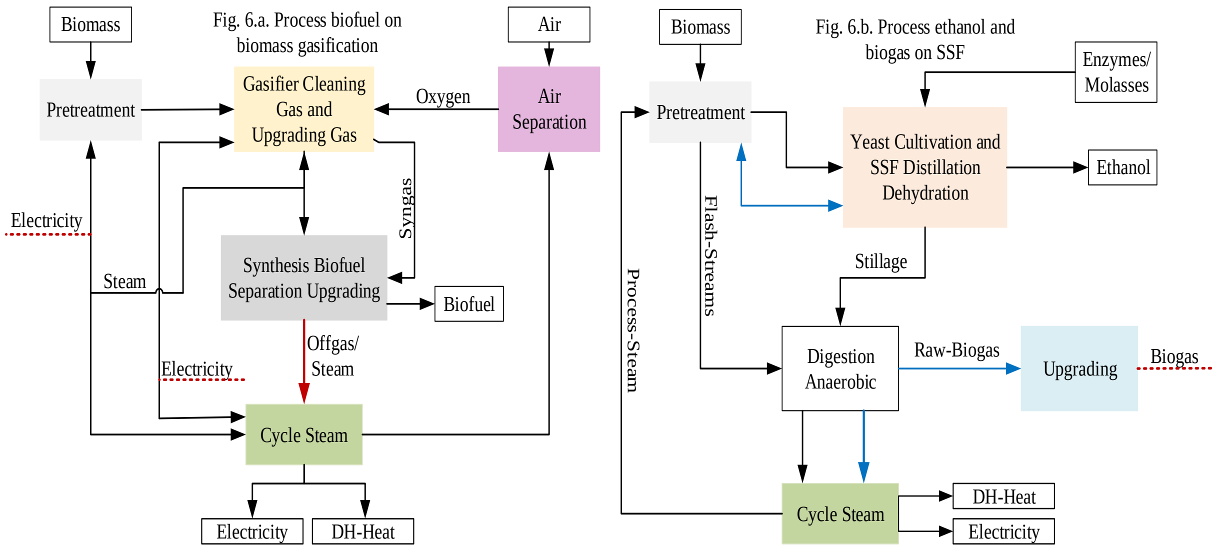

Fig. 6. Biofuel production schematic biomass gasification and ethanol/biogas processing on SSF

2.3 Solar and Coal for Polygeneration

One of the renewable energies found throughout the world is solar energy in which has different intensity in each country. This solar energy can replace conventional energy dependence in a number of countries [157,177]. To harness energy from the sun, this can be done by polygeneration. However, the solar energy input for polygeneration is very difficult to achieve due to its lower energy concentration [178]. The uniformity of solar energy which is carried out in some cases regarding to renewable energy such as fuel cells and biomass is carried out to produce utility outputs as shown in Figure 7.

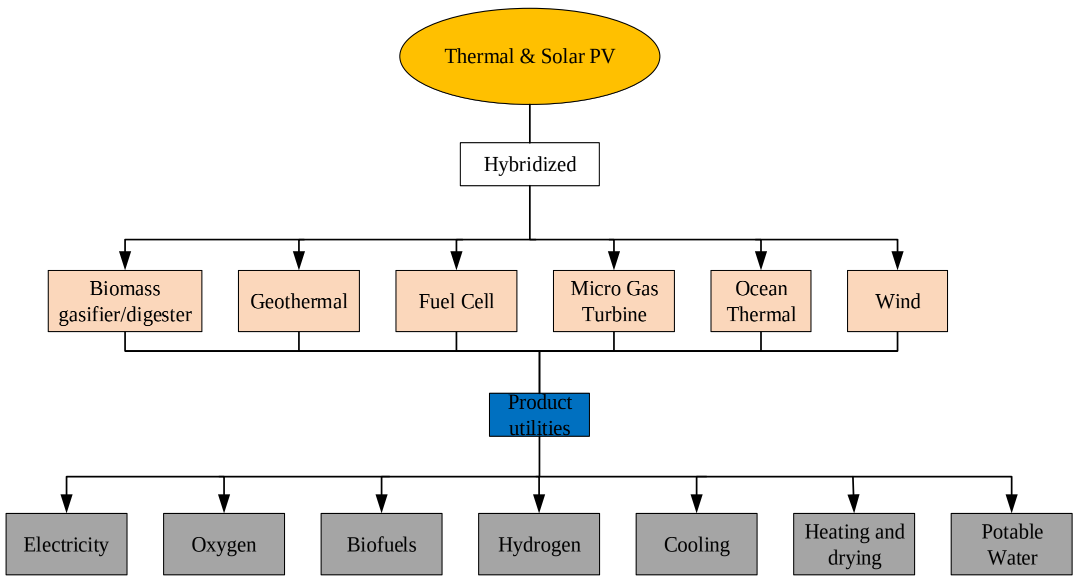

Fig. 7. UTM-LST delta wing VFE-2 profiles

Fuel cells and biomass gasifier are renewable energy sources with the result of a combination of photovoltaic or solar thermal collector shown in Table 4 [179–181]. Table 4 describes the various applications of solar thermal collectors by comparing solar photovoltaic collectors found in polygeneration systems. Hybridized fuel cells in polygeneration have produced electricity with cooling, drinking water and heating as an output from utilities. Hybridization systems in biomass polygeneration, in general, can produce biofuels such as methanol, ethanol, etc. In addition, outputs such as electricity, cooling, heating are some of the results. Energy storage capacity can be reduced by hybrids from polygeneration, so that their utilization has the potential to be efficiently used as an energy source [182].

Table 4
System of hybridized solar polygeneration

Input	Hybridization type	Product	Solar thermal	Solar PV	Year	Ref.
Biomass, Energy Solar & Natural Gas	A network of natural gas and gasification of biomass	Heating, Electricity, fresh water & cooling	Yes	No	2011	[25]
Energy Solar & Coal	Coal gasification	Heating, energy, hydrogen, oxygen and hot water	Yes	No	2013	[183]
Energy Solar	The fuel cell of PEM	Heating, Electricity & Cooling	Yes	Yes	2012	[178]
Energy Solar	Engine Heat	Heat & Electricity	Yes	Yes	2008	[184]
Solar and wind energy	Wind turbine, micro grid based on wind turbines	Heating, Electricity & Cooling	Yes	No	2013	[179]
Solar and vegetable oil	The engine that is fuelled by vegetable oil	Heating, Electricity & Cooling	Yes	No	2012	[185]
Energy Solar	Fuel cell with solid oxide	Heating, Electricity & Cooling	Yes	No	2011	[186]
Biomass & Solar	Biomass gasifier	Electricity, refrigeration, hot water, warm air	Yes	No	2015	[187]
Solar & geothermal energy	Geothermal well	Energy, drying and cooling	Yes	No	2014	[188]
Solar and biomass production	Biomass gasifier	Electricity, Refrigeration, Heating & Water	Yes	No	2015	[29]
Micro-gas turbine solar assisted	Nano turbine gas	Energy, Hot Water & Cooling	Yes	No	2014	[189]
Solar and biomass production	Biomass gasifier	Methanol & Electricity	Yes	No	2015	[166]
Solar & geothermal energy	Geothermal well	Electricity, cooling, heating, heating and hot water for industrial use	Yes	No	2014	[190]
Solar & Geothermal Energy	Energy Geothermal	Heating, Cooling & Electricity	Yes	No	2017	[191]
Natural Gas & Energy Solar	The whole cogeneration network is paired with a cogeneration gas turbine	Electricity, Cooling, Hot Water in The Building	Yes	Yes	2014	[78]
Solar & Geothermal Energy	Geothermal energy	Power, desalinated water, heating, refrigeration	Yes	No	2017	[192]
Biogas & Solar Energy	A digester's biogas	Electricity, Heating & Drinking Water Biogas	No	Yes	2015	[24]
Energy Solar	Organic Rankine Cycle	Heating, Electricity & Cooling	Yes	No	2015	[193]

Unrenewable energy sources, such as coal, can also be used as input in polygeneration. Coal energy can be utilized in two ways including gasification and direct combustion. Direct combustion system can be done by converting the value of coal heat into exhaust gas that is destined to process on different downstream sides, such as cooling, utility heating, electricity generation, etc. However, synthetic fuels and chemicals cannot directly be produced from this process. Synthetic liquids, chemicals and liquid fuels can be produced by gasification-based polygeneration which is more preferred [71,100]. The thermo-chemical properties, in this case, are analyzed by determining the coal's potential for chemical production. Gasification and direct combustion are likely to reduce CO_2 emissions [33,71,194]. However, carbon capture based on gasification based polygeneration is intended for pre-combustion. Another solution that can reduce CO_2 through chemical repetition and combustion of coal-based oxy-fuel in polygeneration [60,68]. Coal-based polygeneration at the plant has a greater capacity than renewable energy-based polygeneration.

3. Polygeneration Outputs

A lot of utilities can be generated from the design of polygeneration. The types of output contained in various kinds of literature include water, energy and material services [15,31,32]. The utilities used in some literature that have been reported are shown in Figure 8. However, the utility output from this polygeneration is chosen based on the input request from the required utility. To meet local needs, the output from decentralized polygeneration must be adjusted to the demand of the region itself. Therefore, it is not feasible to the output from this utility for transportation and transmigration over long distances [17]. A decentralized polygeneration scheme is shown in Figure 9. The polygeneration modelling of the utility supply must be adapted to local needs such as realized water, heating, cooling and electricity in rural areas. Biomass that can be used for polygeneration inputs is available at local factories, such as coconut fiber. In general, one of the outputs of polygeneration is electricity since secondary energy is the most needed/used.

Biomass and coal are the best sources for H and C [195–198]. Biomass and coal-based polygeneration, synthetic liquids and natural gas fuels can be used as additional output as previously discussed [93,199–202]. The output of polygeneration can be sulfur, ammonia, urea chemical fuels, etc., however, this is independent of the synthetic fuel used [60]. In addition, other outputs can also be water, cooling and heating. Household or industrial needs can also take advantage of the output of polygeneration including cooling at certain temperatures and loads [203,204]. In general, this cooler can be produced during the cooling process so that it absorbs steam that is integrated with waste heat. The cooling scheme in the process of producing steam is illustrated in Figure 10. Similarly, this scheme is also found in the use of heat in the room, industrial applications and for other food processes [205,206]. A very valuable utility to date is water, because, in recent years, scarcity and contamination of water have continued.

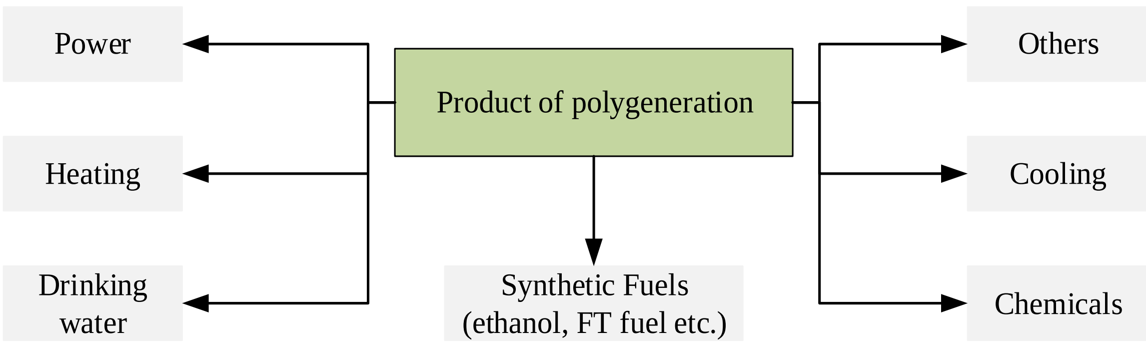

Fig. 8. Product of polygeneration

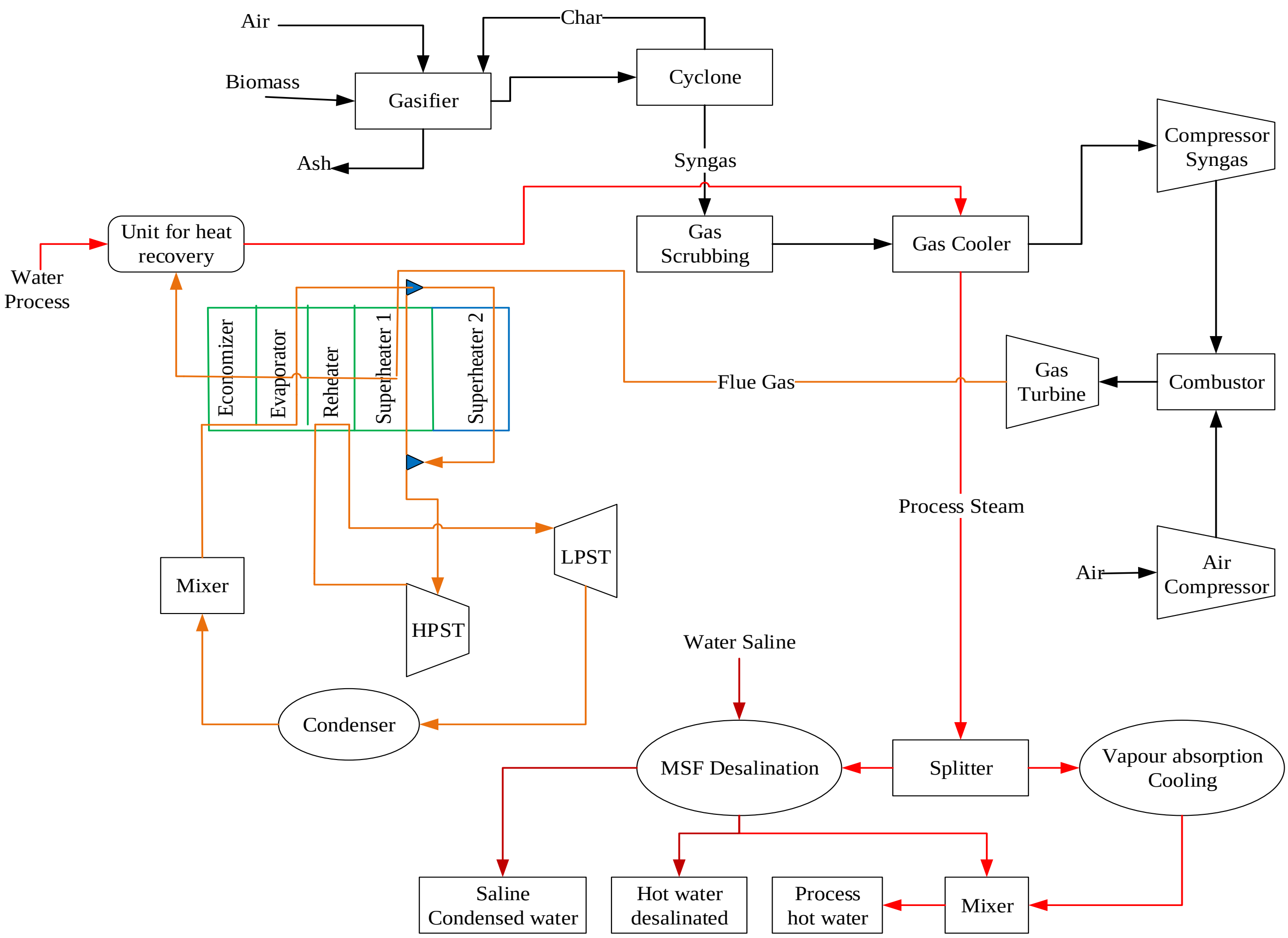

Fig. 9. Schematic diagram of a distributed coastal polygeneration

Desalination of the water purification process is a energy-intensive way. It can also be driven by power and heat movement [207,208]. In addition, water is needed for electricity generation. Therefore, water and energy are related and cannot be separated [209]. Processes with the use of heaters include multi-effect distillation (MED) and Multi-stage flash (MSF). Meanwhile, the process that is driven by using power is reverse osmosis (RO). The availability of waste heat is preferred to drive desalination [210]. The use of power to drive polygeneration in the water purification process can be done when electricity demand decreases. As a result, this polygeneration can be used for water production and stored in the future. In addition, fluctuating loads can be helped by polygeneration and water can be more economically and efficiently produced with multi-generation systems [211]. Input and configuration can determine the output of polygeneration by adjusting local needs and requirements. However, the fairness of the output must be able to provide thermodynamic performance, so that in the long run, its economic performance can be more feasible.

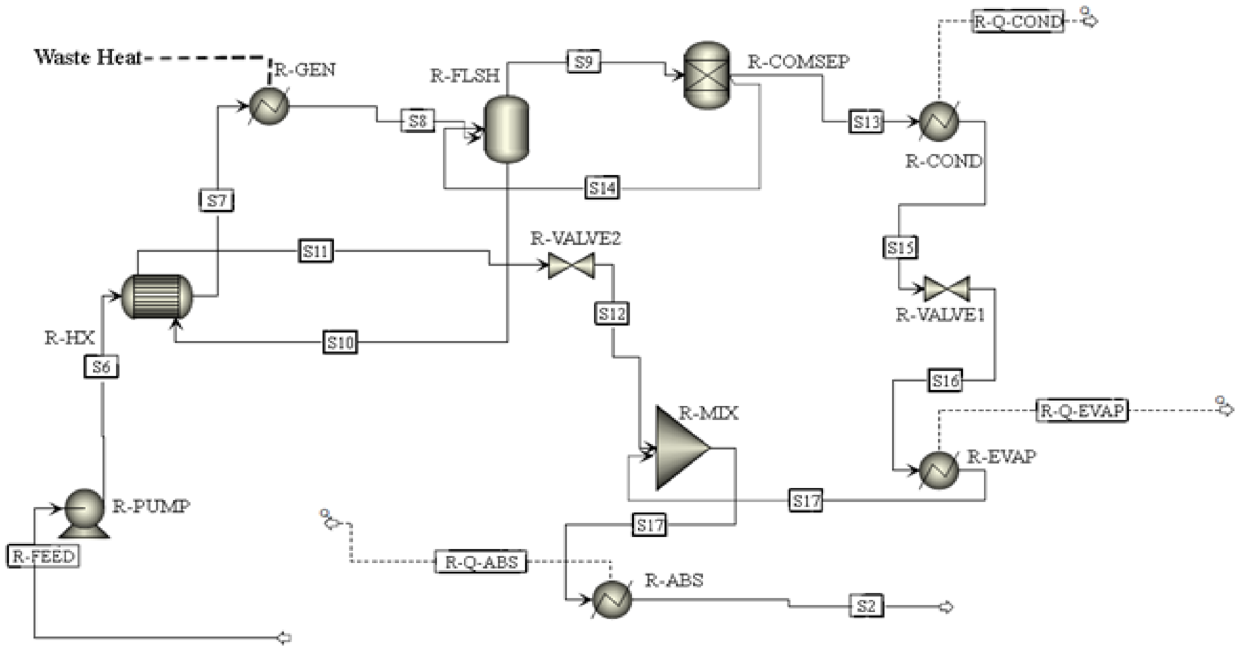

Fig. 10. Schematic diagram of the process of vapor absorption cooling

4. Optimization of Polygeneration

Multi-input and multi-output systems are processes that are found in polygeneration. The use of dual or single resources in polygeneration aims to minimize GHG emissions and costs without having to reduce the supply of needed utilities. Optimization with polygeneration has been available in several kinds of literature as described in Table 5.

Table 5
Numerical optimization in the development of systems for polygeneration

Input	Using Algorithm	Output	Year	Ref.
Energy coal	Optimization of mixed integer	Methanol & Electricity	2009	[218]
Energy Biomass, Coal & Natural gas	Linear mixed integer programming	Electricity & methanol	2007	[219]
Energy Solar & Natural gas	Nonlinear mixed integer programming	Heating, Electricity & Cooling	2011	[25]
Energy CHP prime mover	Multi-target optimization (MOO) with heuristic algorithms	Heating, Electricity & Cooling	2007	[220]
Power grid, pump, solar photovoltaic, main mover, and	A concept of expectation is constructed using both the deterministic model and the probabilistic model	Heating, Electricity & Cooling	2014	[221]
Energy Biomass	Multi-target optimization with MILP and Multi-target evolutionary algorithm	Heat & Electricity	2014	[222]
Energy Compressed fuel and air	The method for evolution	Electricity, ventilation, refrigeration and hot water	2012	[63]
Energy Biomass boiler, solar thermal power plant, heat processing CCHP	Pareto borders with the best possible trade between the principles of economics and exergy	Electricity	2015	[223]
Energy Solar & Natural gas	Optimization process	Cooling & Electricity	2015	[212]
Energy Solar & LPG	Particle Swarm Optimization	Heat & Electricity	2016	[224]

Polygeneration can be designed using numerical optimization techniques, where numeric is used to determine the suitability of the size of components and resources that are more prudent. Thus, the environment and the surrounding economy is maximally useful. The combined maximum is very possible to consider when the polygeneration process is designed. The use of multi-objective optimization techniques is done when the polygeneration system is designed [25,212,213]. The use of optimization contained in some research cases is still very limited [39,214,215]. The components contained in polygeneration can be determined by Mixed Integer Linear programming. In this case, there are several objective functions that must be maximized and minimized [216–218]. The use of Particle Swarm Optimization (PSO) algorithm and multi-objective evolution for non-conventional optimization techniques is used to get better results [63]. The discovery of solutions is often found in the use of unconventional techniques. The calculated optimization can be better produced by applying fuzzy logic.

5. The Capture of CO_2 in Polygeneration

Biomass and coal for polygeneration inputs have a pretty good chance of reducing CO_2 emissions as shown in Figure 11. Whereas carbon sequestration and capture are illustrated in Figure 12. CO_2 concentrations can be increased by coal-based polygeneration. CO_2 storage and capture must be equipped, so that sustainable energy can be achieved. During storage and capture of CO_2, the compression power and heat of the boiler function to consume energy. Mass and heat integration in polygeneration must be done with CCS integration so that overall energy reduction can be reduced. However, CO_2 capture can be produced to reduce the economic decline in carbon capture [18,33,158,225]. Carbon sources in the process of producing cystic fuels such as DME and methanol can also be produced from CO_2. Sometimes CO_2 occurs after a reaction during a shift in water gas (WGS). A large amount of H2 syngas can be produced so that it can maintain the ratio of H_2 and CO as shown in Table 6. H_2 and CO are very suitable for use in thermochemical synthesis fuels such as DME, methanol, ethanol, etc. sourced from biomass and coal. Coal-based polygeneration contained in the literature with a variety of CO_2 recovery and capture is illustrated in Table 6. CO_2 from the capture of polygeneration can save costs and is more efficient than using a CCS system. The polygeneration integration system can make utility heat available from a variety of different temperature sources. Utilization of heat with different temperatures can minimize the task of reboiler heat in the presence of polygeneration. In addition, the CO_2 used is very possible for polygeneration. In general, polygeneration is more efficient than independent units, because the use of mass heat is better with system integration and more efficient. CCS facilities for polygeneration can reduce GHG emissions substantially [136].

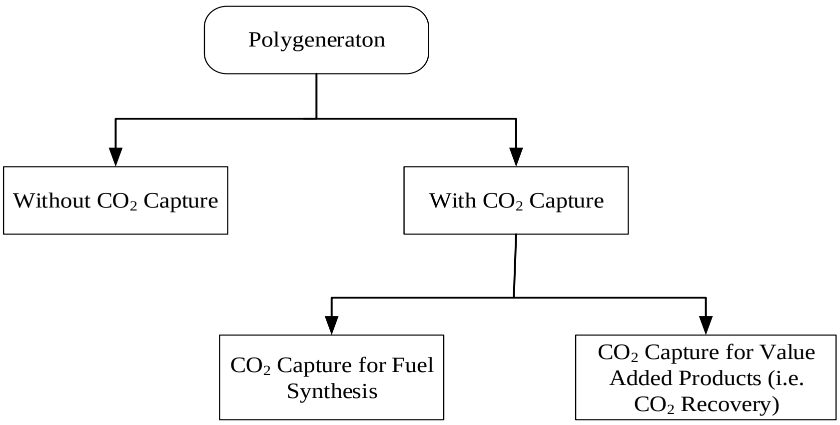

Fig. 11. Polygeneration produced with and without CO_2

Table 6
Summary of the CO_2 capture and recovery of polygeneration

The reasons for the capture of CO_2	Tools for collecting CO_2	Products	Year	Ref.
SOFC oil, natural gas reform, synthesis of methanol	During-combustion	Methanol & Electricity	2011	[226]
Production for H_2	During-combustion	Urea & Power	2015	[60]
CO_2 recycling and the synthesis of methanol	During-combustion	Methanol & Electricity	2011	[227]
The CCU for the synthesis of methanol	During-combustion	Methanol & Electricity	2013	[158]
Recovery for CO_2 and the synthesis of methanol	During-combustion	Methanol & Electricity	2011	[93]
Synthesis of methanol	During-combustion	Methanol & Electricity	2014	[66]
Increased concentration of H_2	During-combustion	Electricity, SNG & ammonia,	2015	[71]
The separation of H_2	During-combustion	Ammonia, Power, Urea & H_2	2016	[70]
Increased concentration of H_2	During-combustion	Hydrogen & Power	2015	[20]
Life cycle reduction of GHG emissions with reduced efficiency loss	Post-burning	Synthetic natural gas and electricity	2017	[228]
CCS	Post-burning	Tar & Electricity	2015	[69]
CCS	Oxygenated-fuel of combustion	H_2 & Power	2016	[68]

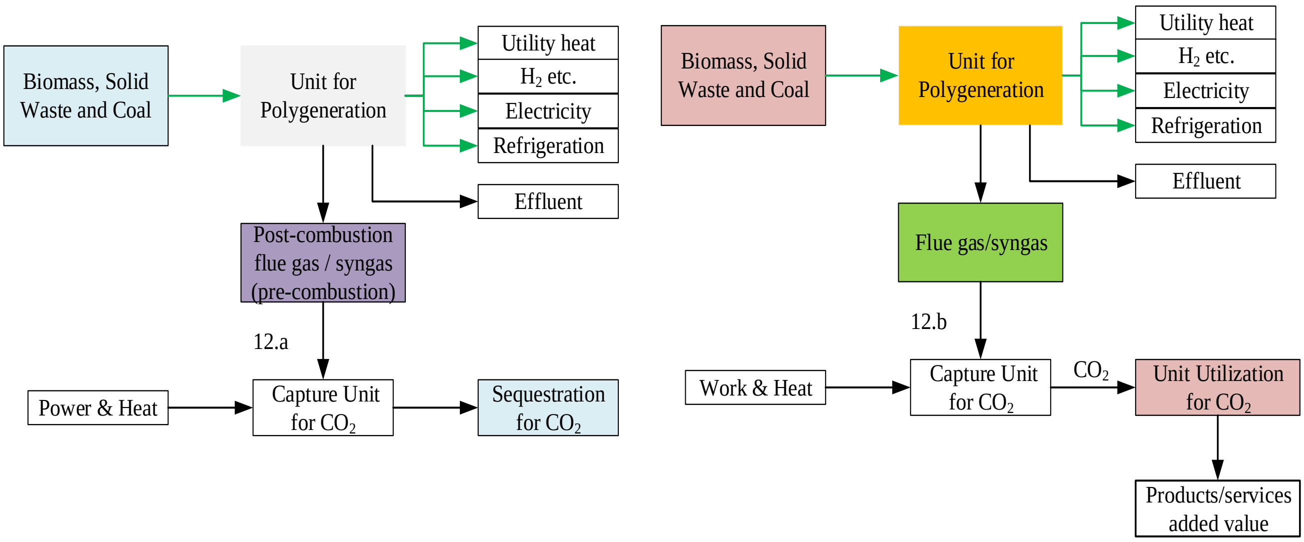

Fig. 12. (12.a) CO_2 captured polygeneration plant and (12.b) CO_2 captured and used polygeneration plant

3. Control of Polygeneration

Multi-input and output are system for polygeneration. However, the renewable energy source of the supply system is still disjointed, making the demands on its utility are also different. During the operation process, the use of intelligent controls makes it possible to request and supply as shown in Figure 13. Control and operating systems for polygeneration that have been available in some literature are described in Table 7. It can be concluded that the polygeneration plant has synchronized to all needs both in demand and supply. Coal-based polygeneration, wind, solar energy, etc. have been investigated in several cases. The load used throughout different years of the monarchy also greatly varies. So that at every polygeneration plant, the control system used is in accordance with its operational process. In general, the Predictive Control Model has largely been used for polygeneration [229–231]. The control application system for monitoring inputs originating from the surveillance and data acquisition (SCADA) control systems has been reported in several kinds of literature [232]. Systems analysis and application of fuzzy logic can give better results compared to the use of conventional control systems [182,233,234]. The use of programmable logic controllers (PLC) in several research cases has also been used. One of which is carried out on numerical computational techniques at an advanced level. The control system is needed so that intermittent renewable energy sources can be immediately met. Meanwhile, controlling with a PLC is very suitable for changing the control logic in a software application. As a result, errors that often occur can be minimized [235–237].

Table 7
Polygeneration process operation and control

The aim of the study	Strategy of optimization	Year	Ref.
Use of the Particle Swarm Optimization (PSO) algorithm to optimize the process	Comparison between the petri net approaches coupled with the ON/OFF approach. The petri net is used as a cognitive map activator	2013	[234]
Micro-grid polygeneration pair with CHP, together with solar and wind again	Model Predictive Control (MPC), Multi Commodity Matcher (MCM), Simplified Management Control (SMC)	2016	[47]
The integration of heat pump and co-generation plants is studied here	Optimal methods for predictive control	2013	[238]
The controllers are used to regulate the voltage and the micro grid frequency consisting of diesel generator, PV, storage system and inverters	Tertiary, primary and secondary operator	2015	[235]
The system is optimized in size using the PSO algorithm	The fuzzy management system of power logic (FMSPL)	2013	[234]
Integration of a micro grid of polygeneration with an existing grid of micro turbine powered by natural gas. The grid for polygeneration consists of PV, CSP, chillers for absorption, storage tank, etc.	Design predictive monitoring	2013	[239]
A dynamic optimization model is used to minimize costs and reduce CO_2 emissions.	MPC with the SCADA server	2015	[212]
The smart micro grid of polygeneration is connected to a data storage system for monitoring	Decentralized and centralized optimal control	2012	[240]
Provides the appropriate means (control systems) for the integration of renewable energy sources such as solar, wind, etc.	Smart grid integration with user cases by applying many modern control strategies such as automatic generation control demand side management, distributed management system, etc.	2014	[241]

Polygeneration has various input and output systems. Multi-objective optimization is needed so that the polygeneration system can be optimized. The availability of resources available locally determines the amount and type of output from polygeneration. Some systems that are processed can provide more efficient integration for social and economic matters. This integrity process is in the form of electricity generation, cooling, fuel synthesis, waste heat recovery, etc. To improve the overall process, performance is very dependent on the existing control system, so that the efficiency of polygeneration is needed. The control mechanism is needed to further the parameters of SCADA. One parameter fluctuation in the polygeneration system can absorb the production of the other, so that a more efficient system can be achieved. The more heat the solar collector is put into the chiller, so that the absorption carried out can produce a cooling utility. Some literature states that the purpose of polygeneration is for optimization [238,242,243]. The ant colony algorithm is an optimization system that is easier to understand as it is inspired by nature. In addition, differential evolution algorithms can also be used for multi-objective optimization for energy systems [244–246]. Efficient algorithms are often used by some researchers to produce smart energy systems that are more efficient. Conventional linear integer linear programming (MINLP) is an algorithm for optimizing bee colonies which has advantages as explained by [247–249]. In addition, the uncertainty of other parameters can be overcome by designing polygeneration systems from renewable resources. The control methods and the optimization of the polygeneration system must be more flexible [250–252]. Thus, the use of further control strategies such as the Predictive Control Model can be used to accommodate the best overall variation.

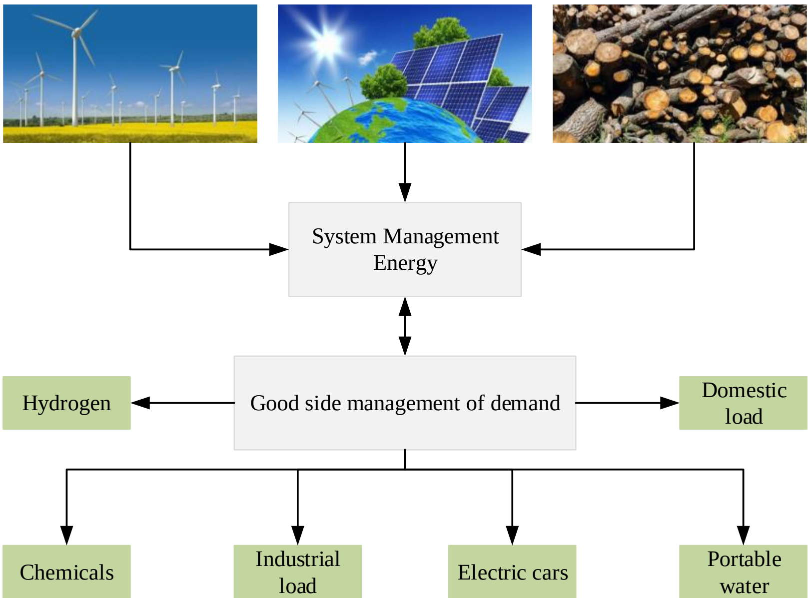

Fig. 13. Multi-generation intelligent control with multiple inputs

7. Conclusions

The depletion of fossil fuels and increasing CO_2 emissions to climate change have given challenges to a system of sustainable innovation. CO_2 emissions can be reduced by increasing efficiency in the optimal use of resources for sustainable energy systems. Several utilities can be integrated to produce various inputs to the polygeneration system. More efficient integration can produce high efficiency and environmentally friendly. This depends on the type of fuel used that is applied. In addition, the demand for utilities and appropriate resources and optimal management of resources is one of the main examples of sustainability. The theoretical description contained in some literature on the value of polygeneration has been discussed. However, the performance of experiments as well as the development of prototype designs is still very steps and difficult to find. The availability of local resources will determine the amount of capacity for the proposed polygeneration. On the other hand, coal energy for polygeneration is more feasible on a large scale and the benefits generated can increase utility output to reduce CO_2. Combining fossil fuels with renewable energy called hybrids has also been reported in some literature. The proposed polygeneration can have many inputs and outputs with optimal capacity standards to overcome more critical problems. The use of mathematical models for the optimization of polygeneration has also been reported in the literature. Multi-dimensional polygeneration performance is used to assess with different objectives. The overall review of polygeneration shows as an environmentally friendly and sustainable energy solution with natural resources that are more efficient and more environmentally friendly. Observations from the reviews available in the literature can be drawn as follows

i. Climate change and the continued depletion of fossil fuels have forced the review of sustainable energy development with high efficiency. Therefore, the utilization of existing resources can be optimized
ii. Polygeneration is a sustainable solution with a more efficient process of integrity from a variety of inputs and outputs and the availability of resources and utilities can be adjusted
iii. The polygeneration system that has been reported in some literature has shown the direction of future research on sustainable energy
iv. Modelling systems with objective function and optimization for the integration of coal-based renewable resources with the evaluated polygeneration performance are some good solutions
v. Biofuel-based polygeneration is a very appropriate choice for a long period of time and provides considerable opportunities for researchers in the future
vi. The development and design of prototypes with intelligent control and monitoring systems are some of the optimal solutions, as in the previous literature, and provides a good step for future research

Acknowledgement
The KEMENRISTEK DIKTI and Universitas Syiah Kuala, Research institutions and community service with the contract number of (64/UN11.2/PP/SP3/2018) supported this research.

Conflict of Interest
All authors declare that they have no known competing for financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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