



# Polygeneration as a future sustainable energy solution – A comprehensive review



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## HIGHLIGHTS

- Developing future sustainable energy systems is critical.
- Polygeneration is such possible future option.
- A comprehensive review of published literature on polygeneration.
- Review includes design, assessment, optimization, control, etc.

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## ABSTRACT

Integrating multiple utility outputs to obtain better efficient system has been a good option. After cogeneration and trigeneration, polygeneration emerges as a possible sustainable solution with optimum resource utilization, better efficiency and environment friendliness. Several possible polygeneration has been conceptualized, performance assessed theoretically as available in literature. Both inputs and outputs vary in these reported works. A few prototype development and experimental result analysis are also reported. Several optimization tools based on objective function are used to develop efficient polygeneration. Assessment criteria of polygeneration are also multi dimensional and may be defined on a case to case basis with definite objective. In this paper a comprehensive review of available literature is done to assess the status of polygeneration as a possible sustainable energy solution. Possible future research in this field is also logically predicted at the end of this review.

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## 1. Introduction

Energy is a basic input for civilization and economic growth [1]. Though primary energy is available in nature in different forms and some of these are useful in that form, most convenient and useful form of energy is the secondary energy- specifically electricity [2]. Hence, technology for conversion of other forms of energy to electricity is very critical. As fossil fuels are high calorific value resources and have been available over a long period, most of the electricity delivering power plants use fossil fuels [2]. Thus power sector all over the world is presently dominated by large scale power generation from mega or ultra-mega capacity power plants. However, depletion of limited fossil fuel resources and emission of pollutants including greenhouse gases (specifically CO<sub>2</sub>) are the two major concerns regarding these power plants [3]. Increased efficiency is always preferred as it not only indicates better resource utilization but also decreases environmental degradation indirectly. However, steam based power cycles has reported saturation in efficiency and any increase of efficiency depends on material development. Though gas-steam combined cycle has a significant increase in efficiency and as a result less environmental impact, it has some restriction on type of fuel used for these plants. By coal gasification and using integrated gasification combined cycle (IGCC), coal can also be used in combined cycle. IGCC with CO<sub>2</sub> capture is the option for limiting CO<sub>2</sub> emission though using coal. However, this is associated with severe penalty in efficiency.

Presently, sustainable development is considered as the most rational goal. Energy conversion and use is a very important aspect of this sustainable goal. Optimum use of resources, efficiency enhancement, demand side management, etc is different aspects of sustainable energy use. Both from the viewpoints of limited resource availability as well as environmental impact, use of fossil fuels are not sustainable in the long run [4,5]. However, during transition from fossil fuels to renewable options, efficient and environment-friendly use of fossil fuels also has to be assured.

Polygeneration is considered as a possible sustainable energy solution that may use multiple fuels with simultaneous delivery of several utilities [6,7]. Overall efficiency increases significantly if the system design and integration of sub-systems are done efficiently. Moreover several alternative fuels may be used to improve resource utilization through proper fuel switching or mixing with conventional fuels. Environmental impact also reduces with higher efficiency as well as type of fuel used. Even CO<sub>2</sub> capture is a natural option for delivering several utilities in fossil fuel based polygenerations for liquid/gaseous fuel synthesis [8,9]. Depending on desired utility outputs and optimum use of available resources, hybrid systems integrating both renewable and non-renewable resources with optimum capacity may be also sustainable [10,11].

A few review papers which deal with polygeneration are available in literature. Chicco and Mancarella reviewed multigeneration for distributed application. This paper aimed to cater to the demands of combined cooling, heating and power (CCHP) mainly [7]. Mancarella reported an overview of models and assessment techniques of distributed multi-utility generation [12]. Sahoo et al. reviewed the potential and sustainability of solar-biomass hybrid power generation integrated with various cooling and desalination techniques. They have done this study in Indian context [10]. Rong and Lahdelma reviewed the role of polygeneration as a distributed sustainable energy solution. They reviewed from

the viewpoints of optimization. Murugan and Horak showed an overview of trigeneration (CCHP) and extended it to polygeneration [13].

Polygeneration is the process of system integration for delivering multiple utilities from a single unit to obtain an efficient multi-utility system. Though it increases system complexity, properly designed polygeneration enhances energy efficiency, reduces emission and waste, and increases economic benefit [6,7]. There are several advantages of polygeneration. Renewable energy say, biomass/solar based polygeneration reduces carbon footprint, resolves the problem of fossil resource scarcity and it increases energy efficiency compared to stand alone units. Decentralized polygeneration in remote areas also increases energy access to rural people [7]. For coal based system, polygeneration with carbon capture and utilization is beneficial from environmental and economic viewpoints [14]. Polygeneration increases energy efficiency and conserve resource.

In a power plant, electricity is produced from fuel energy (Fig. 1(a)). At the same time, effluents are rejected to the environment in forms of flue gas, hot waste water, etc. Similarly, electricity and utility heat are produced in cogeneration plant (Fig. 1(b)). When three outputs are produced from a single plant, it is called trigeneration plant (Fig. 1(c)). These outputs are electricity, cooling and heating. When multiple utilities are produced in a single plant from one or multiple resources, that plant is called multigeneration or polygeneration plant (Fig. 1(d)). Apart from energy services, chemicals may be outputs of polygeneration [15]. As polygeneration is a combination of multiple processes, design of polygeneration is important and it varies widely [15]. Polygeneration delivers multiple outputs by using single or multiple inputs. Hence, its performance assessment is also very crucial. This performance may be measured by different types of metrics and its sustainability assessment is critical from multi-dimensional aspects [10].

From the previous section, it is noted that polygeneration is an energy system to deliver multiple utilities from a single plant. Earlier study on polygeneration was reported by Kennedy Space Centre, USA [16]. This was a coal based polygeneration for producing liquid hydrogen, gaseous nitrogen, electricity and thermal energy to meet the demand of Kennedy Space Centre. A European Commission funded project with multiple partners was undertaken on polygeneration [17]. In this project POLYSMART, they studied different polygeneration systems, their technological feasibility and market potentials in European Union. The classification of the available literatures on polygeneration is shown in Fig. 2. Still these polygeneration are not operating at commercial scale. Most of the papers available in literature on polygeneration are based on theoretical studies. Summary of papers on different polygeneration Modeling and simulation is given in Table 1. Papers are classified according to sources of input energy, outputs, energy conversion devices and objectives are also shown in this table. From this table, it is noted that input energy to the polygeneration may be renewable or non-renewable and outputs are mainly electricity, heating, cooling, chemicals, liquid or gaseous fuels, potable water, etc. Configurations of the polygeneration vary widely. It mainly depends on input energy sources and outputs. To convert primary to secondary energy different energy conversion devices can be used as shown in Table 1 and these are selected depending on configurations and technological and socio-economical viewpoints.

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