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Polygeneration and Sustainable Energy System Development

Challenges and opportunities from optimization viewpoints

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Abstract— **A sustainable energy system is an integrated approach to supplying local energy demands from renewable energy or/and high-efficiency polygeneration energy sources. The approach can be seen as a development of the distributed generation concept. The main characteristics of a sustainable energy system are (cost) efficiency, reliability and environmental-friendliness.**

In this paper, we mainly discuss the role of the polygeneration in a distributed energy system and contributions of polygeneration in the sustainable energy system development. We also describe the characteristics of polygeneration plants to highlight the complexity of polygeneration technologies. In addition, we review the typical method for dealing with interdependence between different energy products for polygeneration and point out some practices in the industry may prevent the potential of polygeneration into full play.

Keywords— ***polygeneration; energy efficiency; distributed energy system; sustainable energy system.***

I. Introduction

Polygeneration means simultaneous generation of two or more energy products in a single integrated process. It is most widely used to describe the generalization of the idea of 'combined heat and power (CHP)' (i.e. the thermodynamically efficient use of fuel) in the form of systems which simultaneously produce electricity and useful heat, i.e., CHP is the basic form of polygeneration. It is an energy efficient technology that can make use of the excess heat that would be wasted otherwise in conventional condensing power production. Thus, it can save both fuels and emissions when compared to separate production of power and other energy products. It can find wide applications in utilities, district heating and cooling, large buildings and different industrial sectors such as pulp, paper, plastic, rubber, steel, chemical and food. Polygeneration is an essential component and renewable energy sources (RES) such as solar, wind, hydro power and heat pumps are a fundamental component of the sustainable energy system.

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A polygeneration plant can be fired by different types of fuels including both fossil fuels and biomass or powered by RES. To reduce CO_2 emissions for the fossil fuel based systems, an innovative dual-gas polygeneration system [1] that realizes the conversion and utilization of methane and CO_2 that would otherwise be directly discharged into the air. Considering the fact that fossil based technologies are currently dominant [2] for supplying heat and power all over the world and polygeneration is an important technology to improve the overall energy efficiency of heat and power production as well as utilization of CO_2, fuel mix (including biomass) [2, 3] is a viable option to implement the transition into future sustainable low-carbon energy systems. Encouragement of polygeneration from renewables will help to make progress towards both renewable heat (cooling) and electricity targets.

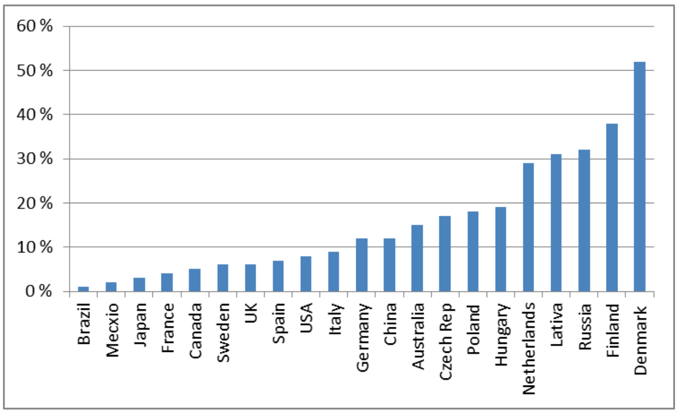

Fig 1. CHP share of national power production [4].

Currently, several countries in Europe such as Denmark, Finland, and the Netherlands [4] have successfully expanded the use of polygeneration to between 30-50% of total national power generation though polygeneration accounts for on the average only around 10% of global power generation as shown in Fig. 1. European Union (EU) promotes strongly polygeneration technology [5] and treats it as one strategy to combat climate change and to fulfil the EU commitment under the Climate Protection Protocol in Kyoto. In 2008, polygeneration accounted for 9% of total power generation capacity in USA. The USA government wants to counter high costs involved in energy production in the industrial sector caused by lack of inefficient implementation, by promoting the development of polygeneration on a national level [6].

However, the potential of polygeneration is far less into full play as expected. There are two reasons behind this. First, majority of companies operate polygeneration plants (e.g. CHP plants) according to a fixed power-to-heat ratio for easy control. This rigid operating mode imposes too strong correlation between heat and power generation and leaves fewer rooms for adjusting power output under the situation when heat generation is fixed. Second, the current energy policy in different countries to drive the sustainable energy development places too much emphasis on power generation. Various incentives to promote RES are causing a greater temporal and spatial imbalance between supply and demand. It means that current design, planning and policy-making methodologies fail to adequately consider the sustainability of different energy products in the system in coordination. Consequently, the equally important thermal energy (heating and cooling) is to a great extent neglected. In EU 27 countries, 42% of the final energy demand is heat [7]. Therefore, the heat and power has to be linked to make use of RES efficiently.

In this paper, we attempt to highlight the potential of polygeneration in the sustainable energy development as well as associated challenges. Section II describes the characteristics of a polygeneration plant. Section III reviews typical methods for dealing with polygeneration systems. We mainly focus on the challenges of considering polygeneration in the energy system from optimization viewpoints. Section IV discusses the role of polygeneration in distributed generation (DG) energy systems as well as the impacts of polygeneration on sustainable development. Section 5 gives a summary.

II. CHARCTERISTICS OF A POLYGENERATION PLANT

The energy sector is one of the core application areas in operations research and management science because energy systems are large and the activities associated with operations planning of the energy system are complex. The operation of polygeneration systems is more complicated than that for power-only systems because of interdependence between different energy products. Cost-efficient operation of polygeneration systems can be planned using an optimization model based on hourly load forecasts. Reference [8] surveyed and summarized plant characteristics of the CHP test systems in the literature based on gas turbines and combined gas and steam cycles. In sustainable energy systems, biomass will become a fuel option. Steam turbine based backpressure plants are one of options [9], which can combust biomass fuel directly. In addition, our past research [10] on polygeneration systems was mainly based on steam turbine. Here we illustrate plant configuration and plant characteristics of steam turbine based CHP. Fig. 2 shows a generic schematic steam turbine based CHP plant.

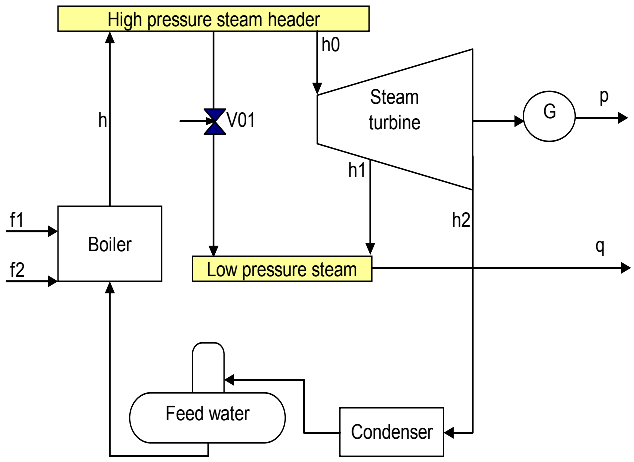

Fig.2. A generic schematic CHP plant

A. Convex plant characgteristics

Fig. 2 shows a traditional backpressure CHP plant with high-pressure steam input (h0) and lower pressure steam extraction (h1) and a condenser with lower-pressure steam input (h2). The reduction valve (v01) allows converting high-pressure steam to lower-pressure steam directly. p and q represent power and heat output respectively. The plant assumes a convex characteristic as shown in Fig. 3.

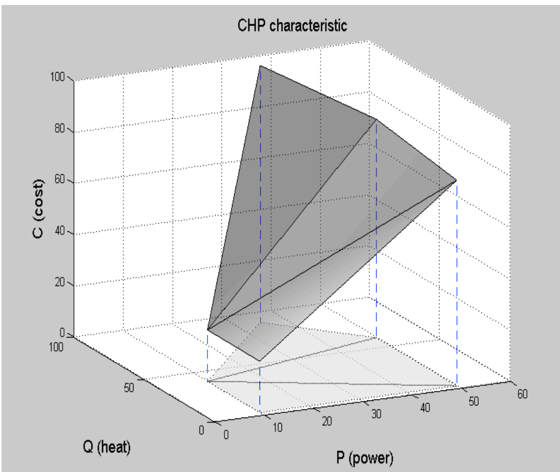

Fig. 3. Feasible operating region of a convex CHP plant

In a polygeneration plant, generation of different energy products follows a joint characteristic that defines the dependence between operating costs and generation of different energy products. The joint characteristic is far more complicated than a simple line (one special type of convex plant characteristic). A generic plant operates within a feasible region where there are much room to adjust power output for a given heat output as shown in Fig. 3. The plant is convex if the feasible operating region (characteristic area) is convex in terms of generation of different energy products and production cost is a convex function of generated energy products. Convexity of the region means that if the plant can operate at two different points, it can also operate at any point on the line segment connecting them. Convexity of cost function means that the operating cost is not higher than the corresponding linear combination of the operating costs at the endpoints.

Non-convex plant characteristics

The backpressure plant with condensing and auxiliary cooling options, gas turbine and combined gas & steam cycles can result in non-convexities of the plant characteristic or cost function. Fig. 4 illustrates the non-convex characteristic of a backpressure plant with auxiliary cooling options. The characteristic area is divided into three convex subareas: A1, A2 and A3. A1 is formed by extreme points 1, 8, 9, 2 and 3. This area includes the normal backpressure operation mode (line between points 1 and 2), gradual shift into condensing mode (area within points 1, 2 and 3) and the reduction mode (area within points 1, 2, 8 and 9). The non-convex area corresponding to the auxiliary cooling operating mode must be split into two convex sub-areas; A2 is formed by extreme points 1, 3, 6, 5, and 4 and A3 by points 2, 7, 6 and 3.

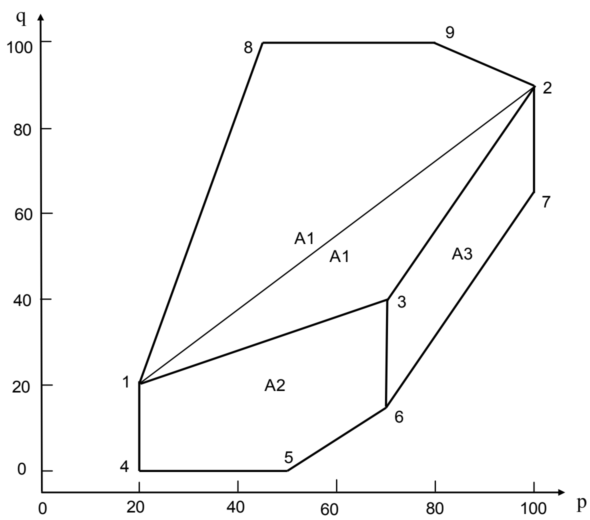

Fig. 4. The non-convex characteristic of a backpressure plant with auxiliary cooling options. p= power, q= heat

III. Typical Techniques for Handling Polygeneration Systems

Similar to power-only generation system, the non-linear, non-convex and combinatorial natures of polygeneration plants remain the challenge. The essential difference between polygeneration and power-only systems lies in the interdependence between different energy products. It implies that planning of different energy products should be done in coordination.

From modeling viewpoints, there are three ways to deal with the coupling relations between different energy products. The first one is to introduce explicitly coupling matrix between different energy products [11, 12]. The second one is to embed the coupling relation in describing the conversion process of different energy products [9, 13]. The last one is to embed the coupling relation in characterizing the feasible region of the polygeneration plants [10] as shown in Section II.

From solution approaches viewpoints, there are two ways to deal with the problem. One is to resort to general solution techniques including intelligent techniques such as evolutionary algorithms [9] and classical optimization approaches [11-13]. The interested readers can also refer to the comprehensive survey [8] in this aspect. The other is to apply specialized efficient solution algorithms [10]. The foundation for the specialized algorithm is to render the plant model with special structure by modeling the feasible region of plant in a special way. In this approach, a generic convex polygeneration plant as shown in Fig. 3 is the building block of the overall polygeneration system model. A generic (non-convex) plant can be encoded on the basis of the convex plant model according to convex partition [10, 15]. The components for providing single energy commodities can be treated as a special case of polygeneration plants.

IV. Role of Polygeneration in a Distributed Energy System

Distributed generation (DG) refers to energy generation at the point of consumption. Distributed energy systems (DES) represent a more reliable and sustainable alternative. Energy is produced locally and energy transmissions are avoided and thus energy losses can be reduced. Polygeneration and several other technologies utilizing RES such as solar power, wind power and hydro power are placed under the categories of DG technologies. Usually, DES implies integration of several small scale DG technologies. The storages associated with DG technologies are essential components for the DES such pumps storage for hydro power, wind pump for wind power, battery for solar power and thermal storage for polygeneration.

On the other hand, some of the above mentioned DG technologies will become central technologies if they are used for large scale generation because power transmissions are unavoidable to the remote users. For example, large scale hydro power and thermal power plants (including polygeneration plants) are components of the traditional central power systems.

Thermal energy (heat and cooling) and electric power are two main forms of energy products. The thermal energy must be generated and consumed locally because it cannot be transported economically over a long distance. Electric power is the most versatile and widely used form of energy and global demand is growing continuously. It can be balanced both globally and locally. The utilization of polygeneration technology can result in significant energy savings in case when both power and thermal heat are used. It means that the overall efficiency of power plants is determined mainly by the utilization of the thermal energy.

Generating power and heat on-site, rather than centrally, eliminates the cost, complexity, interdependencies, and inefficiencies associated with transmission and distribution. Energy efficiency plays an essential role in supplying energy demand in a sustainable, reliable and economic way, especially when the fossil fuels are used. In addition, fuel based (including biomass) polygeneration plants can be used to compensate for intermittent natures of renewable sources such solar power and wind power.

If polygeneration plants are powered by renewables, then the energy system can reach the target for renewable power and renewable heat simultaneously in cost-efficient way. In the literature, a sustainable energy system has been commonly defined in terms of its energy efficiency, its reliability, and its environmental impacts as commented by [16]. Therefore, polygeneration is an essential component for sustainable energy systems.

In addition, in parallel to the development of sustainable energy systems is the sustainable transition of European energy markets. The EU aims to fully integrate national energy markets in the near future, to give consumers and businesses more and better products and services, more competitive, and more secure supplies. In this situation, power transmission is necessary to connect the DES of the individual member countries and to share the RES and energy efficiency of polygeneration technologies at the EU level. It means that the sustainability should be evaluated from different perspectives.

V. SUMMARY

Polygeneration offers many benefits resulting from utilizing the excess heat that would be wasted otherwise. It provides both challenge and opportunities in the sustainable energy system development. To exploit the potential of polygeneration fully, the following comments are given.

First, there are two operating modes for a polygeneration plant. One is heat-led mode where the primary concerns are to satisfy heat demand and the other is power (electricity)-led where the primary concern are to satisfy power demand. Under deregulated power markets, the heat-led mode is favorable when the electricity can be freely traded on the power markets. In this situation, a key element of profitability of a polygeneration plant mainly depends on thermal heat (heating and cooling) demands and duration of thermal heat demands. This may be main reason why the companies operate plants according to fixed power to heat ratio because any volume of power can be sold on the markets. However, it should be realized that this scheme compromises the potential of polygeneration, especially for advanced production technologies that assume non-convex characteristics. For instances, fewer power can be generated when power prices are lower while more power should be generated when power prices are higher from viewpoints of energy companies.

Second, under the situation when fossil fuel based technologies are dominant for supplying heat and power all over the world [2], the role of polygeneration technologies cannot be overestimated for implementing the transition into future sustainable low-carbon energy systems. In addition, polygeneration is a viable option to implement sustainable heat and power when polygeneration is powered by renewables.

Finally, in a distributed generation system, the economic benefit of polygeneration may not be necessarily better than separate production of different energy products because usually the efficiency of small scale polygeneration plants is not high enough. This may be a barrier to promoting polygeneration if fossil fuel based technologies are used. However, it is a different story if CHP is powered by renewables. As commented by Finland [17], "Modern CHP is competitive on the market in relation to the separate production of heat and power. This is mainly due to the structure of our industry and the climate conditions." "CHP production is not particularly supported in Finland, with the exception of small scale CHP production based on RES, since small scale separate production is relatively more competitive than CHP production." It means that utilization of RES enhances the competitive edge of utilizing polygeneration technologies. The role of polygeneration will be strengthened in the course of the development of the sustainable energy systems. Efficient decision support tools for sustainable ploygeneration system planning remain demanding in the future.

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