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Role of Polygeneration in Sustainable Energy System Development

Challenges and opportunities from optimization viewpoints

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Abstract

A sustainable energy system can be treated as a development of the distributed generation concept. It meets energy demands locally from renewable energy or/and high-efficiency polygeneration production technologies, and is characterized by energy and cost efficiency, reliability, and environmental-friendliness.

Distributed energy systems typically use renewable energy resources to supply all energy demands, such as heat, cooling, and electric power in an integrated way. However, it seems that too much emphasis is placed on power and associated renewable energy-based power technologies for dealing with sustainability issues in public discussion and the research community. Often, equally important thermal energy (heat and cooling) and polygeneration are ignored. Polygeneration is an energy-efficient technology for generating simultaneously heat and power as well as other energy products in a single integrated process. Energy efficiency contributes significantly to CO_2 emission reduction.

This paper discusses the role of polygeneration in a distributed energy system and the contributions of polygeneration to the development of sustainable energy systems. The paper also stresses that efficient decision support tools for sustainable polygeneration systems are important to achieve sustainability. First, the joint characteristic of a polygeneration plant that defines the dependency between different energy products is reviewed. Then, typical methods for dealing with polygeneration systems are reviewed. The review attempts to highlight the complexity of polygeneration systems and potential of polygeneration systems to adjust output of different energy products. Next, the challenges of sustainable polygeneration energy systems are discussed. Then some practices for operating polygeneration plants are discussed.

Keywords: Polygeneration; energy efficiency; distributed energy system; sustainable energy system.

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List of Abbreviations

CGSC	Combined gas and steam cycle(s)
CHP	Combined heat and power
DC	District cooling
DES	Distributed energy system(s)
DG	Distributed generation
DH	District heating
DHC	District heating and cooling
ED	Economic dispatch
EU	European Union
IEA	International Energy Efficiency
IGCC	Integrated gasification combined cycles
ORC	Organic Rankine Cycles
PTHR	Power-to-heat ratio
RES	Renewable energy source(s)
SES	Sustainable energy system(s)
UC	Unit commitment

1. Introduction

The IEA (International Energy Agency) study on energy technology scenarios [1] showed that energy efficiency accounts for the largest share of all options for CO_2 emission reductions, including CO_2 capture and storage. This means that energy efficiency plays an important role in the development of the sustainable energy system (SES). Polygeneration is an important energy-efficient production technology and combined heat and power (CHP) production is the basic form of polygeneration. Polygeneration is the simultaneous generation of two or more energy products in a single integrated process. It can be seen as a generalization of CHP production. CHP production means that electric power and useful heat are produced simultaneously, by utilizing further the excess heat that would otherwise be wasted in conventional condensing power production. Taking CHP as an example, the efficiency of a steam turbine is typically 20-38% for power generation only, but 80-90% when useful heat is also produced. For a fossil-fuel-based CHP plant, the fuel and emission savings vary from 10% to 40% depending on the production technologies originally used by the substituted system [2]. If more useful energy products can be derived from the excess heat (e.g., cooling energy), the overall energy efficiency of polygeneration can be improved further [3, 4]. Polygeneration 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.

The utilization of renewable energy sources (RES) such as solar, wind, hydro and biomass energy is fundamental to SES development. A polygeneration plant can be fired by different types of fuels including both fossil fuels and biomass. A polygeneration plant can also be powered by RES. Reference [5] reviewed different types of RES-based polygeneration technologies, including biomass-based, solar-energy-based, fuel-cell-based and waste-heat-recovery-based. The waste heat recovery aims at reusing the otherwise waste heat in different industrial sectors. Biomass can be either directly used or through gasification to fire polygeneration plants. To reduce CO_2 emissions of a fossil-fuel-based-system, reference [6] proposed an innovative dual-gas polygeneration system, which realizes the conversion and utilization of methane and CO_2 that would otherwise be directly discharged into the air. Considering that fossil-fuel-based technologies are currently dominant [7] for supplying heat and power all over the world, and polygeneration is an important technology to improve the overall efficiency of energy production as well as to utilize CO_2, the mix of multiple fuels (including biomass) [7,8] is a viable option for implementing the transition into future sustainable low-carbon energy systems. Encouragement of polygeneration from renewables will help make progress towards both renewable heat (cooling) and electricity targets. As commented by [9], a substantial increase in energy efficiency also forms an important cornerstone of a sustainable energy policy.

Currently, though polygeneration accounts for, on average, only around 10% of global power generation, as shown in Figure 1, several countries in Europe, such as Denmark, Finland, and the Netherlands have achieved the use of polygeneration to 30-50% of the total national power generation [10]. Reference [11] presented the implemented policies of the European Union (EU) in the broader field of energy, which includes seven categories: renewable energy, energy efficiency and savings, internal energy markets, security of energy supply, environmental protection, nuclear energy, and research and development. At present, global warming and fossil fuel depletion are driving the development of SES around the world. Consequently, mitigation of environmental impacts and the improvement of energy efficiency become a new focus for energy production and investments. The EU strongly promotes energy-efficient polygeneration technology [12] and treats it as one strategy to combat climate change and to fulfill the EU greenhouse gas emission commitments under the Climate Protection Protocol in Kyoto. In 2008, polygeneration accounted for 9% of the total power generation capacity in the USA. The US government attempts to promote the development of polygeneration on a national level [13] to cut down high energy production costs in the industrial sector, resulting from using traditional, inefficient production technologies. Also, other countries in the world have introduced different support mechanisms to facilitate the deployment of polygeneration [14].

<Figure 1 is around here>

However, the potential of polygeneration is far less utilized as would be expected. There are two reasons for this. First, a majority of companies operate polygeneration plants (e.g. CHP plants) according to a fixed power-to-heat-ratio (PTHR) for easy control. This rigid scheme imposes an excessive restriction between heat and power generation and leaves less room for adjusting power output in the situation where heat generation is fixed. Second, the current energy policy in different countries to drive sustainable energy development places too much emphasis on power generation. Various incentives to promote RES are causing a greater temporal and spatial imbalance between the supply and demand of power. Electric power is a perfect energy form except that it can only be stored directly at an extremely high cost. The storage cost is currently about 170 €/kW for electricity and 0.5-3 €/kW for thermal energy [15]. This 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 (heat and cooling) is to a great extent neglected. In 27 EU countries, 42% of the final energy demand is thermal energy [1]. It seems that the cooling demand in the EU 27 has a tendency to increase, and almost all individual cooling systems (excluding district cooling (DC)) are utilizing electricity now [16]. This demonstrates the need to shift to non-electric cooling systems (i.e., DC networks). Therefore, the thermal energy and electric power has to be linked to make use of RES efficiently. In this situation, polygeneration should have an opportunity to play its role [17].

To address sustainability issues properly, it is important to consider polygeneration technologies in energy systems. Polygeneration systems are more complicated than power-only systems because of interdependence between different energy products. This may be one of the major reasons for simplification of characteristics for polygeneration in practice. Optimization is one of the most effective approaches for dealing with complex systems. The development of SES reshapes optimization problems from generation, transmission, and distribution to management strategies. Polygeneration is mainly associated with generation optimization and related to decision making about production strategies of energy systems. Model based methodologies have been widely used to support decision making in the energy sector. Reference [18] reviewed the role of optimization modeling techniques in SES. In SES, production strategies should be centered around the impacts of energy production and energy consumption on the environment. Production strategies are designed and implemented through different levels of production planning over a time horizon (day, week, month, or year), including long-term strategic planning, medium-term tactical planning and short-term operational planning. Long-term planning determines capacity investments and types of production technologies to invest in. Medium-term planning determines the allocation of fuel and emission allowance as well maintenance schedules of the system. Short-term planning (scheduling) is associated with unit commitment (UC), economic dispatch (ED) of committed plants, and bidding strategies in the market. The ED is the basic problem associated with all levels of planning problems. It shows that efficient operation of polygeneration systems is important.

This paper attempts to highlight the potential of polygeneration in the development of SES as well as associated challenges. The paper also stresses the importance of developing efficient decision support tools for system optimization and energy management. Section 2 reviews polygeneration technologies, the characteristics of polygeneration plants, and optimization approaches for dealing with polygeneration systems. Section 3 discusses the challenges of sustainable polygeneration energy systems and associated optimization problems. Section 4 gives comments on the practice of operating polygeneration plants. Section 5 discusses the contributions of polygeneration on the development of SES. Finally, section 6 provides visions for SES development.

2. Methodologies for dealing with polygeneration systems

Efficient decision support tools are highly required for energy system planning for at least two reasons. First, the energy companies need to respond quickly to the changing energy markets. Second, scenario-based risk analysis is one of the commonly used methods to deal with uncertainties. The analysis requires handling a large number of scenarios within a reasonable time limit. As mentioned before, the operations of polygeneration systems are complicated by the interlinked process of producing multiple energy products and challenged by advanced production technologies, which require sophisticated techniques to handle.

A polygeneration system may not only consist of generation facilities but also non-generation components. Generation facilities include polygeneration plants and plants for separate provision of different energy products, such as traditional condensing power plants, heat plants (boilers), and cooling plants (chillers). With the penetration of RES, the generation facilities can include RES-based power (heat)-only production technologies, such as wind power, solar power (heat) and hydro power, as well as RES-based polygeneration technologies [5]. Non-generation components include various bilateral contracts and demand side management (DMS) components for different energy products. The DMS [19] fosters the efficiency of the system through modification of demand patterns, i.e., encouraging energy consumers to shift demands from peak hours to off-peak hours via various incentive mechanisms. The shift is equivalent to introducing “virtual generation facilities” from the demand side. In the following, we review polygeneration technologies. We then review the characteristics of polygeneration plants. Finally, we review optimization approaches for dealing with polygeneration systems.

2.1. Polygeneration technologies

Polygeneration technologies can be classified from different perspectives. In terms of output of energy forms, the basic energy forms are electric power and heat. The efficiency of the polygeneration technology results from the utilization of the excess heat that would otherwise be wasted in the process. Other useful energy forms or products can be produced by making use of the excess heat as illustrated in [20]. Cooling energy can be produced by installing thermally activated technologies, such as absorb or adsorb chillers. Fresh water can be produced by installing distillation facilities. Also, the bio-refinery can be treated as a kind of polygeneration technology. It is a facility designed for combining biomass conversion processes and devices to produce fuels, power, and chemicals from biomass. The concept of a bio-refinery is similar to traditional petroleum refineries, which produce multiple fuels and chemicals from crude oil [21]. The fuels and chemicals derived from bio-refineries have the potential to reduce the dependence on the petroleum refinery based on products.

Next, in terms of engines and turbines used to generate electric power, power is generated by combing an engine or a turbine with an electricity generator. The two most widely used turbines are the combustion (gas) turbine and steam turbine. These two types of turbines are suitable for large or medium-scale polygeneration plants. The size range is 0.5MW—250MW for the gas turbine and 0.5MW—500MW for the steam turbine. Steam turbines can use virtually all types of fuels and mainly combust solid fuels such as coal and nuclear fuels in practice. Gas turbines can combust gaseous fuels, such as natural gas or liquid fuels (e.g. different type of petroleum products). Turbines and engines suitable for small and medium-scale polygeneration plants include internal combustion engines (10-5000 kW), micro turbines (1-1000 kW), Stirling engines (up to 100 kW), and fuel cells (0.5-1200 kW). A fuel cell is one of the promising choices for an emission-free generation of electricity, because hydrogen is used as fuel and water is a by-product. The detailed discussions about engines and turbines can refer to [22]. To improve the efficiency of electricity, combined gas and steam cycle (CGSC) technology has been developed [23]. For small-scale polygeneration plants, it is worth mentioning the development of ORC (Organic Rankine Cycles). The ORC uses organic chemicals as working fluids instead of water. The ORC can operate at lower temperatures and pressures than a conventional steam turbine and thus can utilize low-grade heat in the process and improve the efficiency of electricity generation. This makes it suitable for small-scale or micro-scale polygeneration plants. For RES-based polygeneration technologies, the current development mainly focuses on small-scale or micro-scale technologies [5, 24].

2.2. Characteristics of polygeneration plants

Reference [25] surveyed and summarized plant characteristics of CHP test systems in the literature based on gas turbines and CGSC. In SES, biomass will become a fuel option. Steam turbine-based plants are one of the options [24, 26], which can combust biomass directly. In addition, our past research [27] on polygeneration systems was mainly based on steam turbine. Here we illustrate plant configuration and plant characteristics of a steam turbine-based CHP from [27].

<Figure 2 is around here>

2.2.1. Convex plant characteristics

Figure 2 shows a traditional backpressure CHP plant with high-pressure steam input (h0), 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 Figure 3. The corner points in the figure are called extreme points.

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 (e.g. fixed PTHR for a CHP plant), a special type of convex plant characteristic, which a majority of energy companies apply in practice.

As discussed later in Section 4, this scheme can only guarantee the efficient operation of plants under certain conditions. A polygeneration plant should operate within a feasible region, where there is much more room to adjust power output for a given heat output, as shown in Figure 3. In a convex plant, both the feasible operating region and the cost function are convex. The detailed discussion about the convex characteristic is shown in [27, 28]. From optimization viewpoints, the convex characteristic is easy to handle, because it is not difficult to operate plants in an optimal manner to obtain the most beneficial result. In addition, it is the foundation for modeling advanced production technologies as illustrated in the next subsection. Furthermore, it is the building block for modeling polygeneration systems.

<Figure 3 is around here>

2.2.2. Non-convex plant characteristics

The backpressure plant, with condensing and auxiliary cooling options, gas turbine, and CGSC, can result in non-convexities of the plant characteristic or cost function. Figure 4 illustrates the non-convex characteristic of a backpressure plant with auxiliary cooling options. A well-known technique to handle non-convex characteristic is convex partition. The characteristic area in the figure can be partitioned into three convex subareas: A1, A2, and A3. A1 contains extreme points 1, 8, 9, 2, and 3. It represents the combination of the normal backpressure operation mode (line between points 1 and 2), the condensing mode (area formed by points 1, 2, and 3), and the reduction mode (area formed points 1, 2, 8, and 9). A2 and A3 represent the auxiliary cooling operating mode. A2 includes extreme points 1, 3, 6, 5, and 4, and A3 points 2, 7, 6, and 3. The non-convexity of the plant shown in Figure 4 comes from the operating costs. In other cases, the non-convexity may come from the operating region. Each subarea can be treated as a convex component.

<Figure 4 is around here>

2.3. Optimization approaches for dealing with polygeneration systems

Here we review typical techniques for handling polygeneration systems. Similar to power-only generation systems, the non-linear, non-convex, and combinatorial features 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 the planning of different energy products should be coordinated.

In terms of modeling, there are three ways to deal with the coupling of production of different energy products. The first is to explicitly introduce a coupling matrix between different energy products [29, 30]. The second is to embed the coupling of production of different energy products in equations for describing the conversion process of different energy products [26, 31, 32]. The last is to embed the coupling of production of different energy products in characterizing the feasible region of the polygeneration plant [27] as illustrated in Figures 3 and 4.

In terms of solution approaches, there are two ways to deal with the problem. One is to apply general solution techniques, including intelligent techniques, such as evolutionary algorithms [26] and classical optimization approaches [29-32]. The interested readers can also refer to the comprehensive survey [3, 25, 33, 34] in this aspect. The other is to apply specialized efficient solution algorithms [27]. The foundation for the specialized algorithm is to render the plant model with special structure by reformulating the general model in a special way [35]. Using this approach, a convex polygeneration plant model [27,28,36,37] is the building block of the overall polygeneration system model, and the convex model can be formulated as an extremal problem [38] according to the convex combination of extreme points as shown in Figure 3. A non-convex plant can be encoded on the basis of the convex plant model according to convex partitioning techniques as illustrated in Figure 4. The detailed models can be referred to [27, 39, 40]. The components for providing a single energy product as well as non-generation components, such as bilateral contracts and DSM components, can be treated as a special case of polygeneration plants. In this way, polygeneration systems can be modeled using a unified modeling technique.

3. Challenges of sustainable polygeneration energy systems

In the previous section for reviewing techniques for dealing with polygeneration systems, we mainly focus on how to deal with the interdependence of energy products for polygeneration systems. In this section, we will identify new problems in the context of sustainable energy development and discuss possible optimization techniques for dealing with the problem.

Growing concerns of environmental impacts of energy production and utilization of RES encourage the development of smart grid (computerized power grid) [41]. Smart grid equips advanced functions of automatic metering, controlling, and adjusting energy loads using digital information and modern communication technology. Smart grid is designed to improve the current power grid and to achieve the goal of sustainability, characterized by cost and energy efficiency, reliability, and environmental friendliness [42]. On one hand, sustainable energy development promotes the development of distributed energy systems (DES) and advocates consumption close to the site of generation. The development attempts to reduce cost and improve reliability by eliminating the long-distance power transmission of conventional centralized power systems. On the other hand, the development encourages international integration of energy markets, where excess power of some countries can export to other countries to achieve competitive power supply. In this case, long-distance power transmission is inevitable. In the following, the challenges related to optimization are discussed at both the distribution level and transmission level.

3.1. Distributed polygeneration energy system

An SES can be viewed as a development of the distributed generation (DG) concept. DG refers to energy generation close to the site of consumption. Usually, the DES implies integration of several small-scale DG technologies. Polygeneration and several other technologies utilizing RES, such as solar power, wind power, and hydro power, are placed under the categories of DG technologies. The DES is developed in contrast to the conventional centralized power system. In the conventional system, power plants are located far away from end users, and long-distance power transmission networks are used to connect power generation and power consumption. Figure 5 illustrates the conventional power system (a) and DES (b). In the DES, energy is produced locally, and long-distance power transmissions are avoided; thus, energy losses can be reduced. The DES promotes the concept for self-sufficiency and reduces the dependence on the external energy supply. In this way, both the efficiency and reliability can be improved. When polygeneration technologies are involved, smart grid is often called smart polygeneration microgrid [43]. The microgrid can operate either independently or in conjunction with the normal power grid to meet the demand of different energy products.

<Figure 5 is around here>

Such systems integrate district heating (DH), district cooling (DC) and electricity generation islands, which are connected by a private network. The power demand can be met by a local generation plus power exchange via a private network. Within the DES, the power exchange can be treated as an internal exchange, because the distance of power transmission is usually short, and in most cases, power exchanges bypass the normal power grid. Reference [43] listed the basic components of such systems, including different generation facilities, storage facilities, and thermally activated cooling technologies. Generation facilities include a micro-polygeneration gas turbine, polygeneration internal combustion engine, Stirling engine, photovoltaic field, and micro-wind mill. Storage facilities include electrical vehicle recharge station, electrical battery storage, and thermal storage. Thermally activated cooling technologies include an absorption chiller and adsorption chiller.

There are two challenges for such systems. The first challenge is related to the intermittent (stochastic) nature of RES based power technologies such as solar power and wind power. The grid penetration of wind power need considering the impact of stochastic nature of wind power on the system and thus need to handle stochastic UC [44, 45]. In the current study the second challenge is the focus, i.e., the dynamic nature of the problem caused by charging and discharging of different types of storage facilities. Thermal storage has been used in conventional polygeneration systems [46] to even out the short-term variation of thermal load. Thermal storage can also be used as a DSM component. The thermal energy, especially cooling energy, can be prepared and stored in storage at off-peak hours and released into the DHC network from storage during peak hours. In the smart polygeneration microgrid [47], thermal storage remains an essential component. In addition, the utilization of RES power-only technology may cause temporal and spatial imbalance between power demand and power supply. In this situation, electricity storage is one of the ways to handle the problem. This will results in polygeneration systems with different types of storage facilities [48].

3.2. Power transmission network

As just mentioned, the DES advocates self-sufficiency, but it does not exclude the possibility of connecting a normal (long-distance) power transmission network if the power exchange can improve the overall efficiency of the system. Under certain circumstances, it is necessary for the DES to operate in conjunction with normal power grid. For example, the large-scale penetration of electric power generated from RES, such as wind farms, will cause power excess in some countries [49]. One viable option is to export excess power to neighboring countries via a long-distance power transmission network. In this situation, power exchange is beneficial if the marginal cost of power production in other countries is higher. On the other hand, in parallel to SES development is the sustainable transition of European energy markets. The EU aims to fully integrate national energy markets in the near future so that the RES and energy-efficient technologies can be shared at the EU level, while guaranteeing the competitive and secure supplies of electric power. Therefore, it is necessary to connect DES through the power transmission network. Notice that this connection maintains the sustainability of the DES, because cost and efficiency of the system is improved. In addition, power transmitted over the network is that from the RES and thus reduce emissions. Furthermore, power network synchronizes power generation and power demand, which is a key feature of smart grids [50].

3.3. Optimization approaches for dealing with sustainable polygeneration systems

Typical techniques for operating polygeneration systems with storage are dynamic optimization based approaches [48], mixed integer linear programming approach [51], as well as different decomposition and relaxation techniques [52]. Therefore, Lagrangian relaxation technique [46] for dealing with conventional polygeneration systems with storage is still applicable in the context of SES development In addition, to respond quickly to real-time (e.g. market) changes, an interactive approach for tuning control and optimization techniques may be more practical [47].

In a case where it is necessary to connect DES with a power network, a new combined polygeneration and power transmission problem needs considering. In the power network, each DES can produce thermal energy products (heat and cooling) to satisfy local demand, while the power demand can be met by local production plus power exchange via the network. There is no research specifically addressing this problem. However, it is possible to develop specialized efficient algorithms by exploring the structure of a combined polygeneration and network model, similar to approaches pursued by our previous research [27, 53].

This problem is different from the conventional generation and transmission problem [54], where only the central power plant has generation capability, and power can only be transmitted from the central plant to end users. In this new problem, all DES have generation capacities, and power should be transmitted from DES with smaller marginal cost of power production to DES with larger production power cost. The marginal cost of power production for each DES needs to be determined dynamically when demands of other energy products are satisfied.

4. Practice of operating polygeneration plants and associated problems

The utilization of polygeneration technology can achieve significant energy savings in the case when both power and thermal heat are used. Therefore, the overall efficiency of power plants is determined mainly by the utilization of the thermal energy. Energy efficiency plays an essential role in supplying energy demands in a sustainable, reliable, and economic way, especially when fossil fuels are used. Different storage facilities can provide a buffer for temporal imbalance for different energy products. Thermal storage [46, 47] especially makes it possible to operate polygeneration plants at the most fuel-efficient load.

4.1. An example

As shown in Figure 1, Finland is one of the leading countries in the world to apply CHP technology. Both the industrial structure and cold climate conditions in Finland facilitate the deployment of polygeneration technologies. The pulp and paper industry is one of the major industries in Finland. Pulp production and paper drying are two energy-consuming processes. It is required that the power plant provides steam (heat) at correct pressure and temperature. Usually, steam is available from a steam turbine and electricity can be produced simultaneously. As production increases, more heat is needed and more power is generated. The pulp and paper industry is one of the industrial sectors that CHP technology can apply to reduce energy consumption significantly and achieve both fuel and emission savings. Cold climate means that the duration of the heat load is long. This facilitates the application of CHP in DH and improves the overall energy efficiency of the system.

Take Helsinki Energy as an example, it is one of the largest energy companies in Finland. The company serves a majority of the buildings (residential, commercial, and institutional) in the city via DH network. The DH system consists of polygeneration plants, heating plants, and thermal storages. About 90% of the heat demand in the city is covered by district heat (DH), CHP plants cover over 90% of the DH heat production, and the overall efficiency of CHP plant is over 90% [55]. CHP plants can meet the heat demand of the city in the spring, summer, and autumn. In the winter, additional heat demand is satisfied by heating plants. Thermal storage (water tank) is used to store heat produced by CHP plants at night when the heat demand is low. In the morning when heat demand is high, the heat from the storage will be released into the DH network.

Under certain circumstances, CHP plants can operate according to fixed PTHR (refer to the line connecting points 1 and 2 in Figure 4), because this scheme simplifies the control while maintaining high energy efficiency. However, this scheme requires that one of the following conditions should be met to achieve high efficiency. First, the power demand is roughly a fixed percentage of the heat demand. Second, the power demand can be met flexibly with different sources. Finally, the power can be traded freely on the power market (deregulated power market). In the latter two cases, power demand does not impose a restriction on power and heat generation of the CHP plant.

4.2. Down sides of fixed PTHR

There are usually two operational modes for a polygeneration plant. One is (thermal) heat-led mode, where the primary concern is to satisfy thermal heat demand and the other is power (electricity)-led, where the primary concern is to satisfy power demand or to maximize revenue from power sales. As commented by [23], both heat-led and electricity-led operation strategies may result in wasting a certain amount of energy. Under deregulated power markets, the heat-led mode is favorable when the electricity can be freely traded on markets. In this situation, a key element of profitability of a polygeneration plant mainly depends on both the volume and duration of thermal heat demands. This may be the main reason why companies operate plants according to a fixed PTHR, because any volume of power can be sold on the markets. In this case, the benefit of polygeneration should be evaluated based on revenue from power sales. Therefore, it should be realized that a fixed PTHR scheme may compromise the potential of polygeneration, especially for advanced production technologies that assume non-convex characteristics. For instance, less power can be generated when power prices are lower, while more power should be generated when power prices are higher, from the viewpoint of energy economics. In the power-led operational mode, it is critical to utilize the ability to adjust power output for serving peak power loads.

In addition, with the fixed PTHR scheme, it is easy to trap the plant in an inefficient state when the conditions mentioned in Section 4.1 are not satisfied. The satisfaction of one energy product can cause the excessive production of the other products. It is especially difficult for a stand-alone DES to operate efficiently using a fixed PTHR scheme when the demand patterns of different energy products do not assume linear relation. In such systems, the demands of all energy products must be satisfied by the system’s own production. Thermal storage can only alleviate imbalance of different energy products in a short period. It means that the operation of a polygeneration plant should deviate from the fixed PTHR line and operate at certain points in the region shown in Figures 3 and 4.

5. Contributions of polygeneration to SES development

The role of polygeneration cannot be overestimated in the course of SES development. Polygeneration contributes to transition and realization of SES.

First, currently, fossil fuels are major resources for providing heat and power all over the world [7]. According to the survey of the world energy council [56], the total primary energy supply by resources was not subject to significant change from 1993 to 2011. The fossil fuel dominated the supply and accounted for 82%. Especially, in large countries like China, the national economy heavily depends on coal [57]; the efficient use of a coal-based polygeneration system such as integrated gasification and combined cycle (IGCC) [58] is a viable option to implement SES. Also, the flexible fuel choices of polygeneration plants and the development of RES-based polygeneration technologies [5] make hybrid (a mixture of renewables and fossil fuels) polygeneration systems [59] contribute significantly to transition into future sustainable low-carbon energy systems.

Second, polygeneration plants can operate in conjunction with technologies such as heat pumps, thermodynamic cycles (e.g. ORC), and thermal storage [60,61], which can utilize low-temperature excess heat, such as condensed flue gases, to help reduce the cost and improve the efficiency of polygeneration plants. Consequently, the overall cost and energy efficiency as well as, the flexibility of polygeneration systems, can be improved. This configuration is attractive both in DHC and industrial sectors such as food, pulp and paper industries [60].

Third, polygeneration can achieve the goal of efficient use of biomass. The sources of biomass fuels are trees and crops, as well as residues and waste related to plants. Among all RES, biomass is one of the most attractive and promising choices for polygeneration technologies [62]. Reference [63] pointed out that biomass-fueled CHP plants are an attractive option in a region where it is easy to obtain wood chips. Although biomass belongs to the category of RES, it is different from other RES, such as wind and solar energy, in the sense that the latter are freely available each day and emission free. It takes some amount of time for plants to grow, and biomass fuels are usually not freely available. In addition, it remains a controversial issue about whether biomass is emission neutral or not. Some environmentalists contend that biomass is not emission neutral because its combustion can cause direct emissions into the air, while some biomass producers argue that biomass is emission neutral because it is an emission-neutral feedstock. No matter which views were held, from the energy economics viewpoints, the conversation and efficient use of biomass is important, similar to fossil fuel.

Finally, fuel-based (including biomass) polygeneration plants can be used to compensate for the intermittent nature of RES, such as solar power and wind power. If RES-based polygeneration plants are used, then the energy system can reach the target for renewable power and renewable thermal energy simultaneously in a cost-efficient way. According to analysis results of the integrated 3E (environment, energy and economy) model [9], increasing energy efficiency plays an important role in forming SES.

6. Visions for SES development

Polygeneration offers many benefits resulting from utilizing the excess heat that would be wasted otherwise. It contributes to the transition and the realization of the sustainable energy system.
To exploit the potential of polygeneration fully, the following comments are given.

First, the path towards SES should be diverse, according to the current infrastructure for providing energy, as well as major primary energy resources available in each country. An important step is to reduce imported resources and utilize local resources as much as possible. The utilization of polygeneration technologies can help attain this target. For countries with an abundance of fossil fuel, the efficient use of fossil fuel is a viable choice. In this case, polygeneration should be one of the major technologies to both save fuel and emissions. For countries with an abundance of biomass resources, polygeneration remains to be one of the major production technologies as mentioned before.

The biomass is abundant on the world scale, and its reserve ranks third after oil and coal [61]. In the remote rural areas where the access to fossil fuels is expensive and limited, but biomass is readily available, the demand for all energy products such as gas, heating, cooling and power can be met by hybrid use of biomass-based polygeneration systems and solar resources [64]. It is especially possible to satisfy increasing energy demand by increasing the supply of energy crops on surplus agricultural lands after food and feed production [65]. This should a viable option for SES development in developing countries. Similarly, it is also a viable option for developed countries. It seems that the EU pays particular attention to promote biofuel-fired polygeneration. According to [60], most of the biomass-fuelled CHP installations are located in Europe up to now.

As mentioned in [56], the consumption patterns of primary energy resources were more or less fixed in the past twenty years. Fossil fuel covered 82% of supply. It is projected that renewables will replace the fossil fuel supply in energy markets to make progress in the sustainable energy supply in the next ten years. The share of fossil fuel supply will decrease from 82% to 76%, while renewables other than hydro resources will increase from 11% to 16%. The remaining 1% is compensated by the increase of the nuclear supply.

Second, the scale of the DES should be appropriate (not too small) and the DES should seek a balance between the coverage area and cost and energy efficiency. “Distributed” is a form to organize the system, and cost and energy efficiency are the essence. In a DES, the economic benefit of polygeneration may not necessarily be better than that for separate production of different energy products, because the efficiency of small-scale polygeneration plants is usually not high enough. This may be a barrier to promoting polygeneration if fossil-fuel-based technologies are used. However, it is a different issue if polygeneration is powered by renewables or fueled by biomass. The policies for promoting polygeneration vary among the member states in the EU. For instance, Finland has taken the lead in applying polygeneration technologies in the world. It seems that Finland does not particularly support small-scale CHP production because of the lower efficiency. However, Finland encourages the installation of small-scale RES-based CHP production [66]. In Sweden, the highest investment grants have been allocated for biomass-fueled CHP plants [67]. Reference [68] reviewed small-scale biomass-fueled CHP plants in Sweden and Finland. In Finland, DH CHP plants are mainly fossil-fuel-based, and fossil fuels share 65% of fuel consumption. The utilization of biomass fuels showed a rapid increase in the past 10 years, reaching 18% in 2010. In Sweden, DH CHP plants are biomass fuelled. In Austria, there are socio-economic drivers for large urban biomass polygeneration development [69], which should complement small-scale polygeneration development in DES. This means that utilization of RES and biomass fuel enhances the competitive edge of utilizing polygeneration technologies. The role of polygeneration will be strengthened in the course of SES development.

Finally, efficient decision support tools [33] for sustainable polygeneration system planning become even more important in the future for several reasons. First, the intermittent (stochastic) nature of wind and solar power must be handled properly. Second, dynamic natures of different storage facilities need special attention. Third, optimization tools for real-time management [47, 70] need to be developed. Finally, it is necessary to develop optimization tools for addressing power transmission between DES, because such tools facilitate studying the impacts of the sustainable integration of European Energy markets on decision making about RES-based production technologies and energy-efficient polygeneration technologies. Three pillars are needed to achieve the sustainability of energy systems: increasing the share of RES in the global energy mix, increasing the share of energy-efficient polygeneration technologies in energy production, and developing efficient decision support tools for sustainable polygeneration systems.

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Figure caption

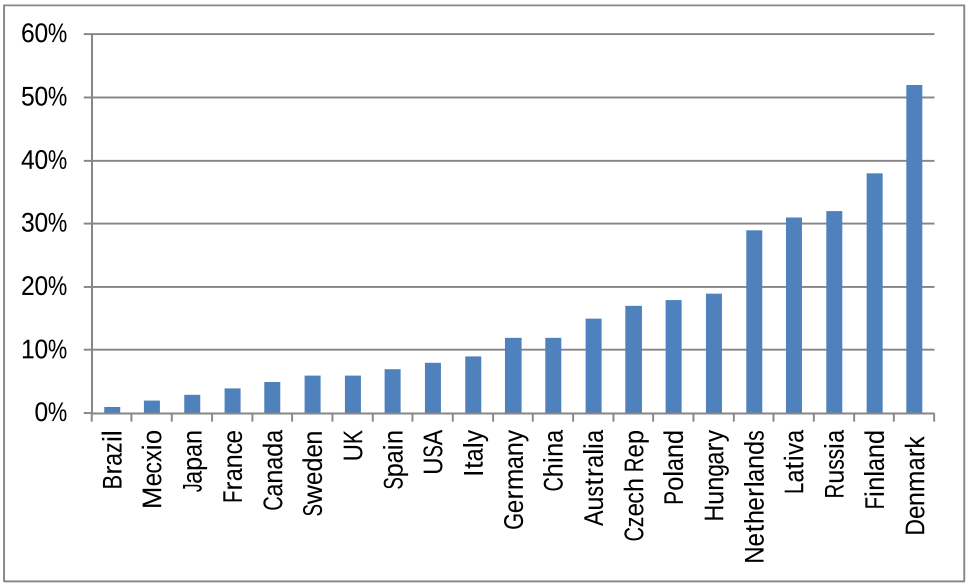
Figure 1. CHP share of national power production (from [10])

Figure 2. A generic schematic steam turbine based CHP plant (from [27])

Figure 3. Feasible operating region of a convex CHP plant (from [37])

Figure 4. The non-convex characteristic of a backpressure plant with auxiliary cooling options. p= power, q= heat (from [40])

Figure 5. Conventional central power systems vs distributed energy system incorporating CHP plants



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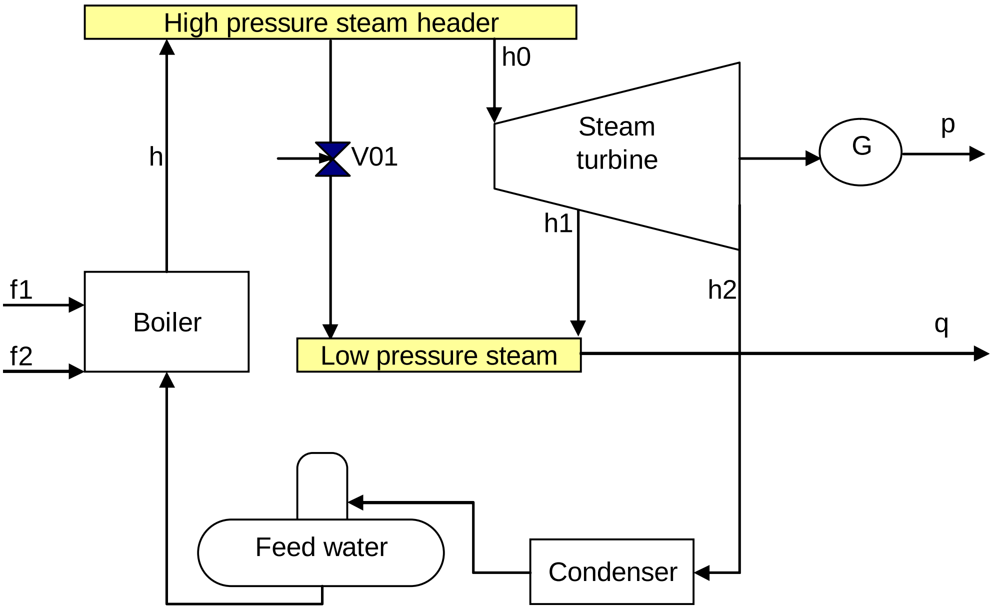

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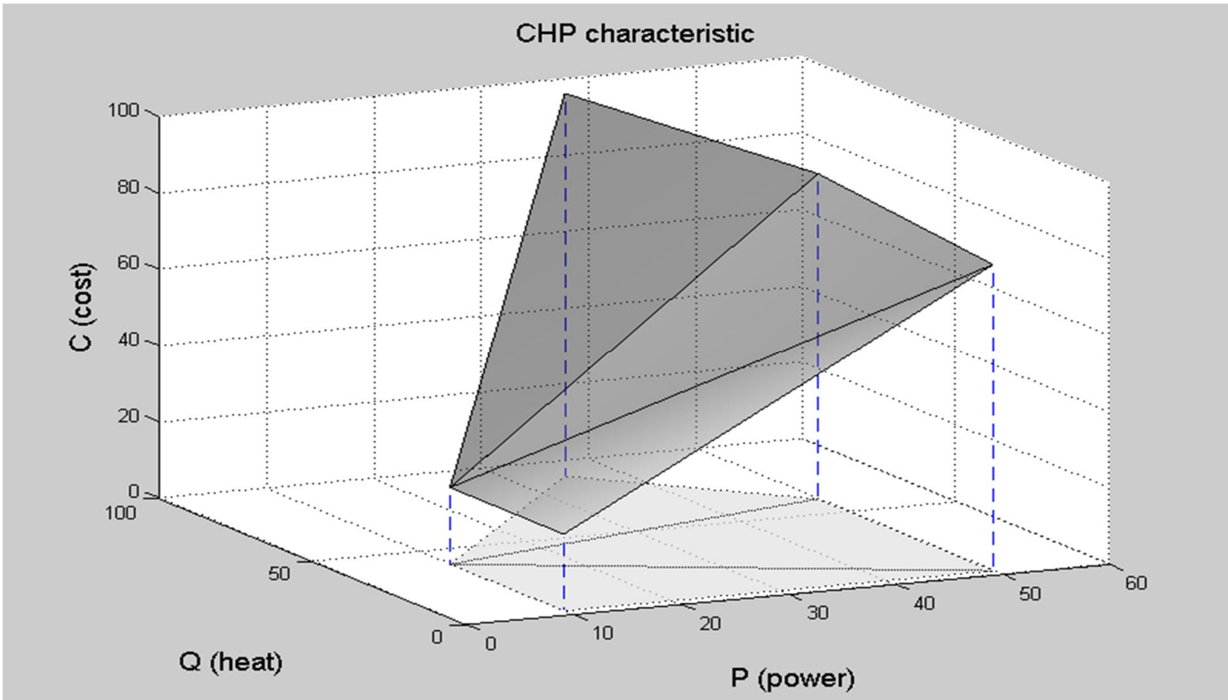
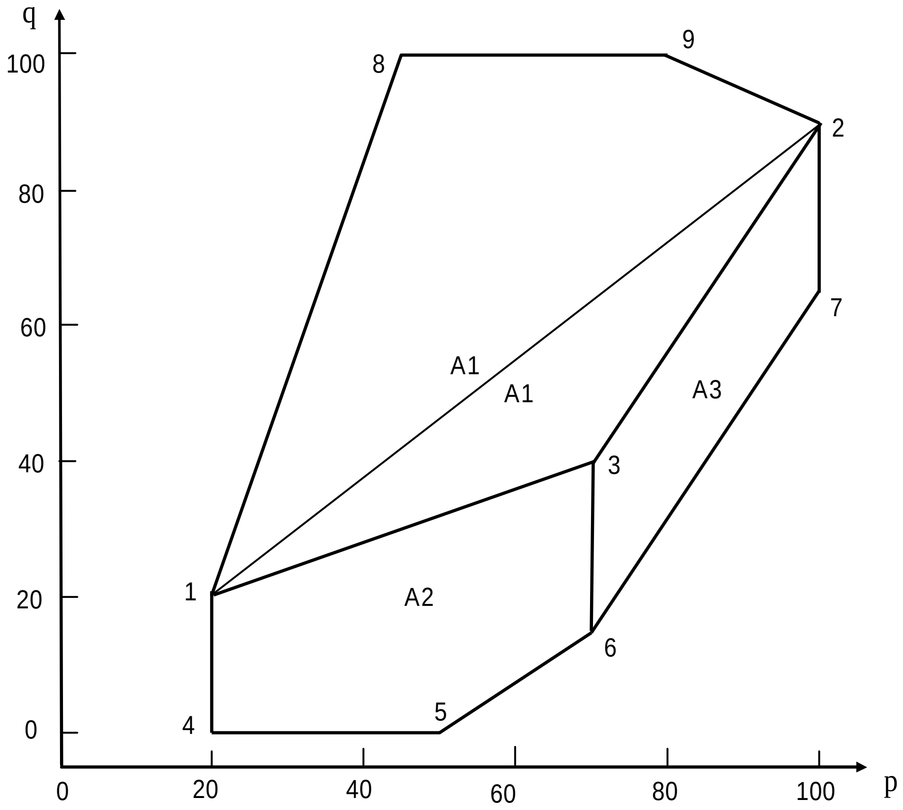


Figure 3. Feasible operating region of a convex CHP plant (from [37])



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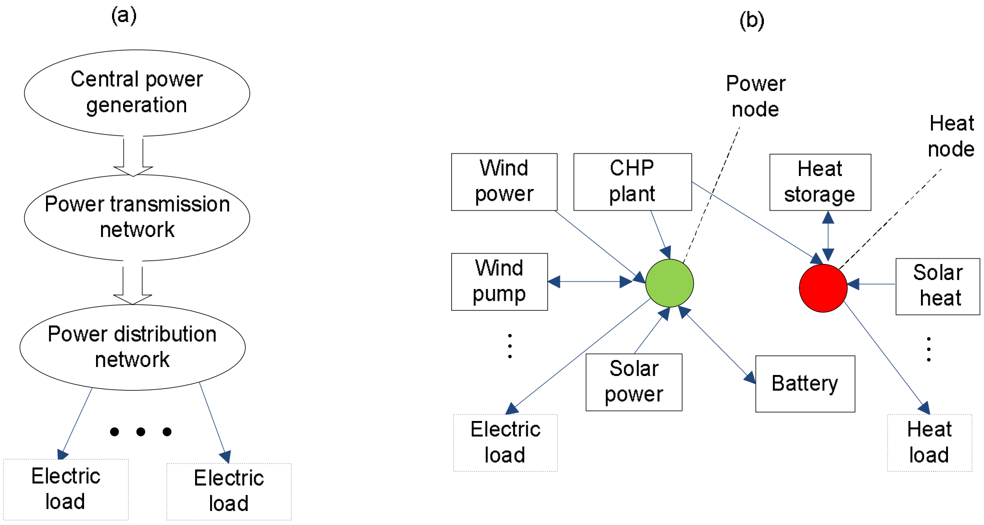

Figure 5 Conventional central power systems vs distributed energy system incorporating CHP plants