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Review of optimization techniques of polygeneration systems for building applications

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Abstract. Polygeneration means simultaneous production of two or more energy products in a single integrated process. Polygeneration is an energy-efficient technology and plays an important role in transition into future low-carbon energy systems. It can find wide applications in utilities, different types of industrial sectors and building sectors. This paper mainly focus on polygeneration applications in building sectors. The scales of polygeneration systems in building sectors range from the micro-level for a single home building to the large-level for residential districts. Also the development of polygeneration microgrid is related to building applications. The paper aims at giving a comprehensive review for optimization techniques for designing, synthesizing and operating different types of polygeneration systems for building applications.

1. Introduction

According to IEA [1], buildings are the largest energy consuming sector in the world, accounting for 32% of final energy use and equally important sources of CO₂ emissions. Polygeneration means simultaneous production of two or more energy products in a single integrated process. The typical energy products include electric power, heat and cooling. A larger potential of energy and emission savings have been recognized for polygeneration in building applications [2]. One viable way of exploiting the potential is through system optimization.

However, there are several challenges for polygeneration optimization for building applications. First, similar to applications in other areas such as utilities and industrial sectors, interdependence between different energy products makes system operations more complicated and production of different energy products need to be coordinated in an optimal manner [3]. Second, the scales of the systems range from micro-level to large-level [4]. There will be a significant difference between optimizing micro-scale systems and large-scale systems. Building integration of micro-generation systems is challenging because the loads are characterized by high diversity, stochastic nature and small quantity [5]. Third, driven by the development of sustainable buildings [1], utilization of renewable energy sources (RES) such as solar energy, wind power and biomass will be increased. Consequently, the system configuration varies significantly [6]. Finally, the concept of Smart Grid for power-only systems [7] has been extended to polygeneration systems, called Smart polygeneration microgrid (SPM) [8]. SPM can be applied in buildings. The techniques for optimizing polygeneration

3 Address for correspondence: Rong A Y, Department of Mechanical Engineering, Aalto University, 00076, Aalto, Finland. E-mail: aiying.rong@aalto.fi.
microgrids (PM) or SPM should be different from those for optimizing traditional polygeneration systems.

In literature, there are various surveys for polygeneration systems from different perspectives [3], [4], [9-11]. There are also surveys that address specifically the development of micro-polygeneration technologies and systems [12-14]. In this paper, we attempt to give a review for optimization techniques for polygeneration systems for building applications, focusing on micro-, small-scale as well as PM. The typical applications of medium- and large-scale systems are district heating and cooling (DHC) systems. Reference [15] reviewed the optimization techniques for such systems. Reference [16] reviews the design and optimization of microgrids in residential application from the viewpoints of distributed energy systems including both power-only and polygeneration systems.

The paper is organized as follows. Section 2 describes the system configuration of polygeneration systems for building applications. Section 3 describes PM for building applications. Section 4 describes the development of optimization techniques for polygeneration systems and classifies optimization techniques for joint design, synthesis and operation of both traditional polygeneration system and PM.

2. System configuration

Figure 1 shows a schematic diagram for a typical polygeneration system that generates electricity, cooling and heat for buildings. A typical polygeneration system consists of a power generation unit (PGU) or a prime mover, heat recovery system (HRS) and thermal activated technology (TAT) such as absorb chiller, adsorb chiller and desiccant dehumidifier and auxiliary devices (not shown in Figure 1) that increase the flexibility of the system such as energy storage, electric chiller, fuel driven chiller and heat pump.

![Figure 1. A schematic diagram of polygeneration system for building applications](image.png)

The high energy efficiency of a polygeneration system comes from utilizing otherwise waste energy in the process. From Figure 1, the waste heat in the process was recovered twice. First, the exhaust heat from PGU (power generation unit) can be directly used for heating water in the pipe and providing hot water for buildings. Second, the waste heat can be recovered by HRS and used to drive TAT to achieve further use of waste heat. The auxiliary boiler (AB) is used to provide additional heat for heating and cooling purpose if the excess heat in the system is not sufficient. The selection of the heating unit is associated with the design of the HVAC (heating, ventilation, air conditioner) system. It can be seen that TAT technologies play an important role in utilizing the low grade heat in the process and thus improve the energy efficiency of the system.

The design of a polygeneration system needs considering the types of technologies and capacity of devices in the system. A polygeneration system can be classified according to (a) prime mover, (b) TAT technology, (c) auxiliary device, (d) primary energy sources (solar, fossil fuel, biomass) and (e) energy products (cooling, heat, power, hydrogen, and syngas) in the system [6]. In terms of scales of
the system [4], the polygeneration system can be classified according to the capacity of electricity
generation: micro-scale (under 20kW), small-scale (20kW-1MW), medium-scale (1MW-10MW) and
large-scale (above 10MW). This classification is based on the type of prime movers. Fuel cell (FC),
Stirling engine (SE) and micro gas turbine (MT) are suitable for micro-scale and small-scale systems.
Traditionally, steam turbine (ST) and gas (combustion) turbine (GT) are usually for medium- and
large-scale systems. However, they can also be applied for small-scale systems. Reciprocating internal
combustion (IC) engine are applicable from micro-scale to medium- scale systems. Among all prime
movers, fuel cell is an environment friendly prime mover where the chemical energy from the fuel is
converted into electricity and water is the by-product. For remaining fuel based prime movers, CO₂ is
the byproduct if fossil fuel is used. All of these fuel based types can be RES based, e.g., powered by
solar energy or directly fueled by biomass or through biomass gasification [17]. RES can also be used
directly to generate heat such as solar heat collector or power such as wind turbine and solar
photovoltaics (PV).

The system configuration can be determined in the design stage by selecting proper types of prime
movers and other technologies as well as the capacity of prime movers and other technologies based
on the scale of the system. Once the system configuration is determined, operational strategies have
impact on the efficiency of the system. In addition, load profile also affect the efficient operation of
the system. To increase operational flexibilities and achieve the balance between supply and demand
for different energy products, one option is to install different types of storages as a buffer for energy
products. For traditional fuel based polygeneration systems, usually thermal energy storage (TES) are
used [18].

With integration of RES such as wind and solar power into the energy systems, in additional to
thermal storage, different types of electric storages (ES) such as battery and plug-in electrical vehicle
(PEV) charging stations can also be considered [19]. The other option is to introduce electric heat
pumps into the system to meet heat and cooling demands [20]. The efficiency of heat pump is higher
than electric heater or chiller (one unit electricity can produce 3 units of thermal energy). An electric
heat pump can work in both heating and cooling mode and thus can balance the load through years
(summer: cooling mode, winter: heating mode). Electric heat pump in conjunction with thermal
energy storage can increase additional flexibility to utilize RES and achieve power grid balance by
avoiding starting up thermal demand-driven polygeneration plants when there is large RES based
power production [21-23].

3. Polygeneration microgrid

Microgrids are small distributed energy systems integrating different distributed generation
technologies such as reciprocating IC engine, micro-turbine, gas turbine, small-scale steam turbine,
and fuel cell, photovoltaics (PV) and wind turbine, which can utilize local energy sources such as
natural gas, biomass, solar and wind, to produce power, heat and cooling for satisfying local energy
demands. When polygeneration technology is involved, the microgrid is called polygeneration
microgrid (PM) as shown in Figure 2. This configuration is similar to [24].

PM can operate either in a stand-alone mode or a grid-connected (utility grid in Figure 2) mode.
The polygeneration system in Fig 1 can be treated as a module connected to the microgrid in Figure 2.
It means that higher efficiency of polygeneration can be carried to microgrids [25] because the overall
electricity consumption of the absorb chiller is much lower than the compression (electric) chiller in
the conventional system [25]. Thermal energy and electric power are distributed separately via district
heating and cooling (DHC) network and local power network respectively and production of thermal
energy and electric power need to be coordinated. This means that the structure of PM is the same as
the microgrid for the power-only system in terms of power delivery. PM integrates DHC and power
distribution network and supplies both electric power and thermal energy to customers by a mix of
generator systems.

With integration of intermittent RES such as wind power and solar energy into microgrid, it is
natural to extend the concept of Smart Grids for power delivery to PM for power and thermal energy
delivery. On one hand, the higher efficiency of polygeneration can address sustainability issue more
reasonably by considering demands of both electricity and thermal energy simultaneously [3]. On the
other hand, polygeneration systems can provide additional flexibility to enhance the effectiveness and efficiency for power delivery and power utilization by exploiting the interdependence between different energy products in the polygeneration system [22], [23], as well as by utilizing auxiliary devices such as electric boiler and heat pump [21], [26]. This extension is called Smart PM (SPM) [8]. Infrastructure of PM and SPM may be the same. However, SPM is equipped with more advanced control and communication devices to facilitate the coordination of production for different energy products. More specifically, in SPM, the potential of thermal energy needs to be explored in depth. “Smartness” can be interpreted from different perspectives. For example, automatic adjustment, advanced control, accurate estimation, proactive coordination and integrated design.

4. System optimization

A polygeneration system is more complicated than a power-only system regardless of the scale of the system due to interdependence between different energy products in the polygeneration plant and production scheduling need to be done in coordination through different production, storage and auxiliary facilities in the system [3]. On the top of this, there are different technical, legal [27] such as the capacity, efficiency and self-consumption percentage of polygeneration installations and social considerations that need to be respected in practice. Moreover, to promote polygeneration technology for building applications, the eligibility criteria for introducing technology needs to be modified or carefully designed [28] because it is not easy for a micro- and small-scale polygeneration plant to operate as efficiently as a large-scale plant. Furthermore, the system operates in a dynamic environment full of uncertainty. For example, the power price or the fuel price as well as load profile for different energy products varies from hour to hour in each day. Finally, the output of some intermittent RES such as wind and solar energy is hard to control or predict due to the stochasticity caused by wind speed or solar irradiance.

4.1 Methodology development

Cost and energy efficiency is the driver behind the development of micro- and small-scale polygeneration system. The system can utilize local energy resources to produce different energy
products to meet the need of local customers. It can alleviate the dependency on imported energy resources to improve energy security. It can also reduce the energy loss due to the short distance between generation and the end user. Furthermore, it is suitable for serving the remote community which has no connection with the utility grid.

As compared with large-scale thermal systems where units for power, heat and cooling generation are subject to minimum up and down time constraints [29-32], micro- and small-scale systems can respond quickly and flexibly to load changes and market changes because generating units can be started up and shut down easily and quickly. Usually it is not necessary to consider such constraints [33]. However, it depends on the choice of the period length. If the period length is chosen to be 15 minutes, it is also necessary to consider minimum up and down time constraints [34]. Minimum down time (MDT) constraints indicate the necessary maintenance time after the unit is shut down while minimum up time (MUT) constraints indicate the need to minimize thermal stresses in the equipment which could otherwise arise.

However, such systems are prohibitively expensive [35] for building applications mainly due to the load profiles for buildings [36]. The cost and energy savings of the system can be achieved when thermal loads are sufficiently high and fully utilized [18]. The operating hours in the buildings are not long enough to recover the initial investment quickly. For example, thermal loads for residential buildings happen in the evening through early morning while the thermal loads for office buildings happen in the day time at office hours. In addition, the efficiency of the micro- and small-scale system may not competitive enough to gain market share as compared with domestic and commercial boilers in certain situations. Therefore, it is important to investigate different system configurations and operating strategies to make the system feasible, attractive and profitable. Different approaches such as simulation, thermodynamic analysis and optimization can be applied in designing, synthesizing and operating polygeneration systems. In practice, lots of effort is devoted to evaluating the performance of the system based on field tests, simulation and thermodynamic analysis due to complexity of the system. Reference [11] summarized development related to field test, simulation and thermodynamic analysis. It also touched the issues of optimization. The literature related to all these developments continues to grow. In the subsequent sections, we mainly focus on optimization approaches.

4.3 Overview of modeling and optimization based solution approaches
Optimization is one of the typical ways to deal with complicated systems. Optimization is a way to achieve the best possible performance criteria under certain conditions. Usually different types of mathematical models need to be constructed first to facilitate developing efficient algorithms or utilizing various standard optimization algorithms. The operating characteristics of a component can be either convex [37], [38] or non-convex [39]-[41]. Here the component refers to a device in the system. Convex characteristic means that if a component can operate on two points in a region, then it can also operate on the line segment connecting these two points. The convex characteristic represents a category of the “easy” optimization problem that is not difficult to find the optimal solution because the local optima is the global optima.

In terms of modelling techniques, reference [3] summarized three approaches. The first one is to apply general mathematical programming approach, including multi-objective optimization approach [42], [43] or thermodynamic modelling approach [44]. Thermodynamic models are used to describe or predict chemical and physical equilibria, which usually take nonlinear forms. The second one is to explicitly describe interaction between different components and the relationship between different energy products using input-output matrix [45-47]. The last one is to reformulate a general mathematical programming model of the component into the model with a special structure [48] according to extremal formulation [49]. Based on this modelling framework, power-only, heat-only and cooling-only components can be treated as a special case of polygeneration component model. Using this as basis, different types of efficient algorithms for single objective [50] and for multi-objective optimization [51], [52] can be developed for different system configurations.

Unit commitment (UC) is an important operational optimization problem in energy and power systems. UC determines the most efficient combinations of generation units to satisfy the demands for different energy products. UC problem can be modelled on the top of individual component (unit)
model by introducing binary variables indicating whether the plant is ON or OFF. This will result in a mixed integer linear [33], [34] or non-linear [53] model. The operational flexibility of the system can be achieved by coordinating with heat pump, energy storage with the schedules of UC to increase the share of RES while considering other uncertainties such as price and demand [26]. In terms of dealing with uncertainty, fuzzy programming [54], [55], Monte Carlo simulation [56], [57], robust optimization [58], stochastic programming [43], sensitivity analysis [27], Markov method [59], [60] and forecast [61] have been applied.

4.4 Optimization techniques for micro and small-scale polygeneration systems
Reference [62] provided a paradigm for design, synthesis and operation of the energy system based on optimization approaches. The first step is to determine the system superstructure. The superstructure for a polygeneration system (as shown in Figure 1.) can be interpreted as the layout of the components in the system as well as the technology choices and capacity for the corresponding component. The second step is to build an optimization model that combine techno-economic evaluation with life cycle analysis while considering uncertainty. This is equivalent to building a mathematical model that optimizes some performance criteria while respecting technical constraints and accommodating uncertainties over a planning horizon. Then life cycle assessment is conducted based on the model. The third step is to apply or develop efficient computational algorithms for solving the resulting mathematical programming model.

<table>
<thead>
<tr>
<th>Prime mover</th>
<th>Auxiliary device</th>
<th>Modelling</th>
<th>Solution</th>
<th>Reference</th>
</tr>
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<td>[83]</td>
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<td>'MILP'</td>
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<td>[56]</td>
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<td>'PSO'</td>
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*Tables 1 and 2 share the same notes. The notes appear at the end of Table 2.*
Table 2. Optimization techniques for multi-objective design and operation problems

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<th>Solution</th>
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<td><strong>Epsilon-c+forecast</strong></td>
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<td><strong>EC, ES, TES</strong></td>
<td><strong>MILP</strong></td>
<td><strong>NSGA-II</strong></td>
<td>[108]</td>
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</table>

*Fuel Cell.  
*b Gas Engine.  
*c Gas Turbine.  
*d reciprocating Internal Combustion engine.  
* Micro gas Turbine.  
*solar Photo Voltaics panel  
*f Stirling Engine.  
*g Steam Turbine.  
*h Electric Chiller.  
*i Electric Storage.  
*j Heat Pump.  
*k Thermal Energy Storage.  
*l Mixed Integer Linear Programming.  
*m Mixed Integer Non Linear Programming.  
*n Branch and Bound.  
*p Epsilon-constraint.  
*q Evolutionary Algorithm.  
*r Fuzzy Cognitive Map.  
*s Genetic Algorithm.  
*t Hierarchical Optimization.  
*u Life Cycle Analysis.  
*v Multiple Population Genetic Algorithm.  
*w Non-dominated Sorting Genetic Algorithm-II.  
*x Particle Swarm Optimization  
*y Sensitivity Analysis.  
*z Standard solver, e.g. CPLEX, LINGO, Excel solver

The overall problem can be formulated as a mixed integer linear or non-linear programming (MILP or MINLP) model. Reference [63] decomposed the problem at the three levels. Each level is associated with a subproblem, called synthesis, design and operation subproblems, respectively. The synthesis subproblem aims at identifying the components to be installed or to be excluded in the optimal lay-out. The problem can be formulated by an integer programming (IP) model by associating each component with a binary (0-1) variable indicating whether the component to be excluded or to be included in the optimal lay-out. The design subproblem aims at determining the optimal size/capacity of each component. Operation subproblem aims at optimization of the operating condition for each component based on the hourly load profile. For any energy system, these three subproblems should
be solved jointly to identify the system configuration (in terms of the layout of the component and the size of the component) and the corresponding operational strategy to achieve the best results where the components can be operated in a convenient manner [64].

In literature, some research addresses optimization of joint design (synthesis) and operation problem while other research focuses on operation optimization. Operation optimization can be handled separately when the system configuration is determined. At the same time, operation optimization also has effect on sizing of the component. For the traditional system, operation optimization is related to determining operational strategy. Two commonly used operational strategies are FEL (following electric load) and FTL (following thermal load). The primary concern of economic dispatch (ED) in FEL is to satisfy electric demand while the primary concern of ED in FTL is to meet thermal demand. However, both of them suffers from energy waste in certain conditions [4]. Then some advanced operational strategies need to be developed based on the system configuration and the objective of the system. References [4] and [11] summarized the development of different operational strategies.

For the PM, operation optimization is associated with determining control strategy. The most commonly used control strategy is model predictive control (MPC) strategy [65]. MPC uses a dynamic model to estimate future outputs over a prediction horizon based on preceding and future actuator commands. It attempts to compute the best sequence of future control commands to minimize some performance criteria, subject to a set of physical or policy constraints. It uses the principle of closed loop control theory to penalize the error between output and its reference value and the deviation of mean values from their nominal values as well as suppress rapid changes in input. The MPC is one of effective strategies to address the concerns of grid stability and load balance caused by the penetration of intermittent RES [66]. There are also other control strategies that use different predictors such as fuzzy logic based [67] and grey prediction based [68]. Real-time optimization and online control are major research themes related to operation optimization of the PM. The research follows this direction has started [69-72] and will continue in the future.

Here we mainly focus on joint design (synthesis) and operation problems. For the traditional polygeneration system, the system configuration more or less follows the structure of Fig 1, the major components include prime movers, HRS and TAT, i.e., prime movers associated with PGU and certain types of TAT are mandatory components. Auxiliary devices such as electric chiller, heat pump and thermal energy storage are optional. As we mentioned in Section 3, the traditional system is treated as a module in the PM. The PM should have more options for generators and storage facilities besides those mentioned in the traditional system because it needs to accommodate the penetration of intermittent RES. The additional components include PV panels, wind engine, electric storage such as battery and PEV. Therefore, we do not distinguish between PM and traditional system explicitly. The subtle difference can be reflected in the choices of prime movers and auxiliary devices in Table 1 and 2. Table 1 and 2 give single and multi-objective optimization techniques for design and operation problems respectively. In the reference column of two tables, the reference number appears bold if the problem is related to PM. The typical economic objective function is total cost which consists of investment cost and operational cost over a year. The investment cost includes the cost for purchasing equipment. The operational cost includes fuel cost and energy cost if there is a power exchange with main grid over the planning horizon. The additional objective may be related to CO₂ emissions and environmental impacts. In addition, the system energy efficiency and system reliability can also be used as an objective function. Multi-objective optimization approaches can address multiple conflicting objectives simultaneously and provide more realistic performance evaluation of the system.

5. Conclusion
Polygeneration is a promising technology to address efficient use of primary energy sources and CO₂ emissions for providing increasing energy demand requirements stimulated by economic development and population increase [111] due to its higher efficiency. Building sector accounts for one third of global energy consumption. The energy consumption can be reduced by increasing the efficiency of energy supply and by implementing efficient demand side management (DSM) [112]. DSM include two major activities, called demand response (load-shifting) and energy efficiency and conservation.
SPM plays a greater role in making DSM cost effective and convenient by providing two-way communication capabilities between customers and energy providers and real time information.

The sustainable development of the energy system drives the increasing use of local energy sources and local technologies to satisfy the energy demand. In this way, the environmental impact of energy production and use can be decreased. This leads to the paradigm shift for the energy system from the centralized production to distributed generation [113]. This is the reason why both micro- and small-scale polygeneration systems and RES based generation prosper. Main challenges for optimal design, synthesis and operation of polygeneration systems come from the requirements to increase the flexibility of integrating intermittent RES by selecting suitable system configurations, operating strategies and control strategies. It is expected that the development of SPM can enhance such capabilities effectively.

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