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Review of optimization techniques of polygeneration systems for building applications

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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 CO_2 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

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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.

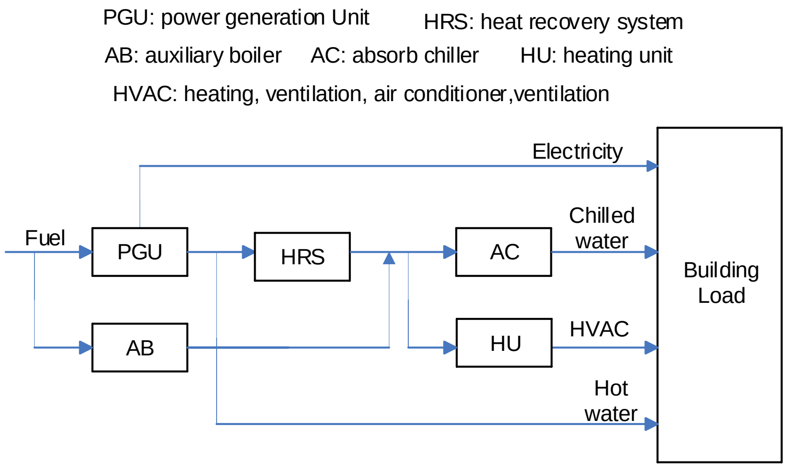

Figure 1. A schematic diagram of polygeneration system for building applications

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, CO_2 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.

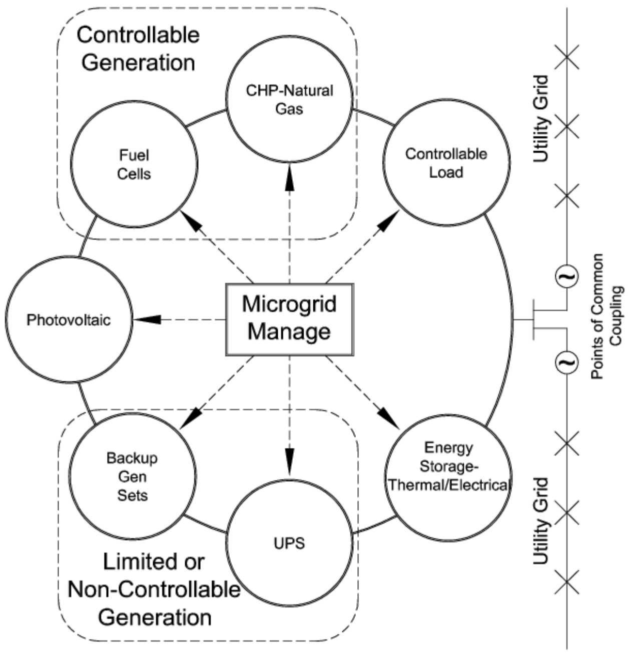

Figure 2. (Smart) Polygeneration microgrids

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.

[nc]**Table 1.** Optimization technique for single objective design and operation problems

Prime mover	Auxiliary device	Modelling	Solution	Reference
[c]GT,[d]IC,[e]MT,	[l]TES	[m]MILP	Robust	[58]
[c]GT	[i]EC	[m]MILP	[z]Standard	[74]
[d]IC	[l]TES	[m]MILP	[z]Standard	[75]
[c]GT, [d]IC		[m]MILP	[z]Standard	[76]
[a]FC, [c]GT, [d]IC,[e]MT	[k]HP	[n]MINLP	Bi-level	[77]
[a]FC,[d]IC,[e]MT,[g]SE	[l]TES	[m]MILP	[z]Standard	[79]
[b]GE		[m]MILP	[z]Standard +[u]LCA	[80]
[c]GT	[i]EC	[m]MILP	[z]Standard	[82]
[c]GT		[m]MILP	[z]Standard	[83]
[c]GT	[l]TES	[m]MILP	[z]Standard	[27]
[c]IC	[i]EC	[m]MILP	[z]Standard	[56]
[a]FC,[c]IC,[g]SE	[l]TES	[m]MILP	[z]Standard	[35]
[a]FC		Thermodynamic	Parametric study	[86]
[a]FC	[k]HP, [l]TES	[m]MILP	[z]Standard	[87]
[a]FC,[c]GT,[d]IC,[e]MT,[g]SE	[i]EC, [l]TES	[n]MINLP	Sequential	[88]
[a]FC,[c]GT,[d]IC,[e]MT,[g]SE	[i]EC, [l]TES	[n]MINLP	[z]Standard	[89]
[b]GE	[k]HP, [l]TES	[m]MILP	[z]Standard	[90]
[b]GE	[l]TES	[n]MINLP	[y]SA	[93]
[b]GE	[i]EC	[n]MINLP	[s]GA	[95],[96]
[c]GT	[i]EC, [l]TES	[n]MINLP	[x]PSO	[97]
[b]GE	[k]HP	[n]MINLP	[v]MPGA	[98]
[b]GE	[i]EC, [l]TES	[m]MILP	Graphic method	[100]
[a]FC		[m]MILP/[n]MINLP	[t]HO+[y]SA	[102]
[b]GE, [c]GT		[n]MINLP	Convexfication	[104]
[c]GT		Thermodynamic	[s]GA	[105]
[a]FC, [b]GE,[g]SE,[f]PV		[m]MILP	[z]Standard	[**106**]
[a]FC, [b]GE,[g]SE,[f]PV	[l]TES	[m]MILP	[z]Standard	[**107**]
[d]IC,[e]MT,[f]PV	[l]TES	[n]MINLP	[t]HO	[**109**]
[a]FC,[f]PV	[j]ES	[m]MILP	[t]PSO+[o]FCM	[**110**]

[nc] 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

Prime mover	Auxiliary device	Modelling	Solution	Reference
[a]FC		Thermodynamic	[q]EA	[73]
[e]MT	[i]EC	Thermodynamic	[s]GA	[101]
[b]GE	[k]HP,[l]TES	[n]MINLP	[s]GA	[99]
[c]GT	[k]HP,[l]TES	[n]MINLP	[s]GA	[85]
[c]GT,[h]ST	[i]EC,[l]TES	[n]MINLP	[s]GA	[103]
[b]GE	[i]EC	[n]MINLP	[u]LCA	[94]
[a]FC, [d]IC,[e]MT,[h]ST	[l]TES	[n]MINLP	[p]Epsilon-c+forecast	[83]
[c]GT, [d]IC	[i]EC,[k]HP,[l]TES	[m]MILP	Robust	[91]
[c]GT,[d]IC	[k]HP	[m]MILP	Heuristic	[92]
[d]IC	[i]EC	[m]MILP	[o]BB+fuzzy	[54]
[d]IC	[i]EC	[m]MILP	[p]Epsilon-c+fuzzy	[55]
[b]GE		[m]MILP	[p]Epsilon-c+[u]LCA	[81]
[b]GE, [c]GT		[m]MILP	[p]Epsilon-c	[78]
[d]IC, [e]MT, [f]PV	[i]EC, [j]ES, [l]TES,	[m]MILP	[w]NSGA-II	[**108**]

[a] Fuel Cell.
[b] Gas Engine.
[c] Gas Turbine.
[d] reciprocating Internal Combustion engine.
[e] Micro gas Turbine.
[f] solar Photo Voltaics panel
[g] Stirling Engine.
[h] Steam Turbine.
[i] Electric Chiller.
[j] Electric Storage.
[k] Heat Pump.
[l] Thermal Energy Storage.
[m] Mixed Integer Linear Programming.
[n] Mixed Integer Non Linear Programming.
[o] 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 supress 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 CO_2 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 CO_2 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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References

[1] IEA (International Energy Agency) 2013 *Transition to sustainable buildings by 2050*.
[2] IEA (International Energy Agency) *Cogeneration and district energy –sustainable technologies for today and tomorrow* Report. http://www.iea.org/publications/freepublications/publication/name, 805, en. html
[3] Rong A and Lahdelma R 2016 Role of polygeneration in sustainable energy system development—challenges and opportunities from optimization viewpoints *Renew Sustain Energy Rev.* **53** 363-72.
[4] Liu M, Shi Y and Fang F 2014 Combined cooling, heating and power systems: A survey *Renew. Sustain. Energy Rev.* **35** 1-22.
[5] IEA EBC (Energy in Buildings and Communities Programme) 2014 *Integration of microgeneration and related technologies in building*.
[6] Calise F 2011 Design of a hybrid polygeneration system with solar collectors and a solid oxide fuel cell: dynamic simulation and economic assessment *Int. J of Hydrogen Energy* **36** 6128-50.
[7] Tuballa M L and Abundo M L 2016 A review of the development of Smart Grid technologies *Renew. Sustain. Energy Rev.* **59** 710-25.
[8] Bracco S, Delfino F, Pampararo F, Robba M and Rossi M 2013 The University of Genoa smart polygeneration microgrid test-bed facility: The overall system, the technologies and the research challenges *Renew. Sustain. Energy Rev.* **18** 442-59.
[9] Chicco G and Mancarella P 2009 Distributed multi-generation: a comprehensive review *Renew. Sustain. Energy Rev.* **13** 535-51.
[10] Murugan S and Horak B 2016 Tri and polygeneration systems—A review *Renew. Sustain. Energy Rev.* **60** 1032-51.
[11] Cho H, Smith AD and Mago P 2014 Combined cooling, heating and power: A review of performance improvement and optimization *Appl. Energy* **136** 168-85.
[12] Dong L, Liu H and Riffat S 2009 Development of small-scale and micro-scale biomass-fuelled CHP systems – A literature review *Appl. Therm. Eng.* **29** 2119–26.
[13] Maghanki M M, Ghobadian B, Najafi G and Galogah RJ 2013 Micro combined heat and power (MCHP) technologies and applications *Renew. Sustain. Energy Rev.* **28** 510-24
[14] Sonar D, Soni S L and Sharma D 2014 Micro-trigeneration for energy sustainability: Technologies, tools and trends *Appl. Therm. Eng.***71** 790-6.
[15] Ortiga J, Bruno J C, Coronas A and Grossman I E 2007 Review of optimization models for the design of polygeneration systems in district heating and cooling networks *Comput Aided Chem Eng* **24** 1121-26.

[16] Liu P, Georgiadis M C and Pistikopoulosc E N 2013 An energy systems engineering approach for the design and operation of microgrids in residential applications *Chem Eng Res Des* **91** 2054-69.
[17] Raj N T, Iniyan S and Goic R 2011 A review of renewable energy based cogeneration technologies *Renew. Sustain. Energy Rev.* **15** 3640-80.
[18] Rong A, Lahdelma R and Luh P B 2008 Lagragian relaxation based algorithm for trigeneration planning with storages *Eur J. Oper Res*. **188** 240-57.
[19] Bracco S, Delfino F, Pampararo F, Robba M and Rossi M 2015 A dynamic optimization-based architecture for polygeneration microgrids with tri-generation, renewables, storage systems and electrical vehicles *Energy Convers Manag*. **96** 511-20.
[20] Danny Harvey L D 2006 *A Handbook on Low-energy Buildings and District-energy Systems: Fundamentals, Techniques and Examples* (UK: James and James).
[21] Meibom P, Kiviluoma J, Barth R, Barth H, Weber C and Larsen H V 2007 Value of electric boiler and heat pump for wind power integration *Wind Energy* **10** 321-37.
[22] Rong A and Lahdelma R 2016 An efficient model and algorithm for transmission-constrained multi-site combined heat and power system *Eur J. Oper Res* (minor revision)
[23] Rong A, Luh P B and Lahdelma R 2016 Dynamic programming based algorithm for the transmission-constrained multi-site combined heat and power system *ICPT 2016: 18th Int. Conf. Power Transmission* (accepted).
[24] Sellwood V 2015 Micorgrid and role of storage
[25] Bracco S and Delfino F 2015 The role of high efficiency trigeneration plants within sustainable smart microgrids: performance analysis and experimental tests *2015 AEIT Int. Annu.Conf. 1-6*
[26] Blarke M B 2012 Towards an intermittency-friendly energy system: Comparing electric boiler and heat bump in distributed cogeneration *Appl. Energy* **91** 348-65.
[27] Lozano M A, Ramos J C and Serra L M 2010 Cost optimization of the design of CHCP (combined heat, cooling and power) systems under legal constraints *Energy* **35** 794-805.
[28] Piacentino A, Barbaro C and Cardona F 2014 Promotion of polygeneration for buildings applications through sector- and user-oriented "high efficiency CHP" eligibility criteria *Appl. Therm. Eng.* **71** 882-94.
[29] Rong A, Hakonen H and Lahdelma R 2008 A variant of the dynamic programming algorithm for unit commitment of combined heat and power systems *Eur. J. Oper. Res* **190** 741-55.
[30] Rong A, Hakonen H and Lahdelma R 2009 A dynamic regrouping based sequential dynamic programming algorithm for unit commitment of combined heat and power systems *Energy Convers Manag*. **50** 1108-15.
[31] Rong A, Lahdelma R and Grunow M 2009 An improved unit decommitment algorithms for combined heat and power system *Eur. J. Oper. Res* **195** 552-62
[32] Bragin M A, Luh P B, Yan J H and Stern G A 2016 An efficient approach for solving mixed-integer programming problems under the monotonic condition *J Contr. Deci.* **3** 44-67.
[33] Collazos A, Marechal F and Gahler C 2009 Predictive optimal management method for the control of polygeneration systems *Comput. Chem. Eng.* **33** 1584-92.
[34] Bosman M G C, Bakker V, Molderink A, Hurink J L and Smit G J M 2012 Planning the production of a fleet of domestic combined heat and power generators *Eur. J. Oper. Res* **216** 140–51.
[35] Merkel E, McKenna R and Fichtner W 2015 Optimisation of the capacity and the dispatch of decentralized micro-CHP systems: A case study for the UK *Appl. Energy* **140** 120-34.
[36] Entchev E, Yang L, Ghorab M and Lee E J 2014 Performance analysis of a hybrid renewable microgeneration system in load sharing applications *Appl Therm Eng.* **71** 697-704.
[37] Lahdelma R and Hakonen H 2003 An efficient linear programming algorithm for combined heat and power production *Eur. J. Oper. Res*. **148** 141-51.
[38] Rong A and Lahdelma R 2005 An efficient linear programming model and optimization algorithm for trigeneration *Appl. Energy* **82** 40-63.
[39] Makkonen S and Lahdelma R 2006 Non-convex power plant modeling in energy optimisation *Eur. J. Oper. Res*. **171** 1113-26.

[40] Rong A and Lahdelma R 2007 An efficient envelope-based Branch and Bound algorithm for nonconvex combined heat and power production planning. *Eur. J. Oper. Res*. **183** 412-31.
[41] Liu P, Pistikopoulos EN and Li Z 2009 Global multi-objective optimization of a nonconvex MINLP problem and its application on polygeneration energy systems design *CMU-IBM Cyber-Infrastructure for MINLP*.
http://www.minlp.org/library/index.php (accessed Dec 2009)
[42] Liu P 2009 *Modeling and optimization of polygeneration energy systems* (London, United Kingdom: Department of Chemical Engineering, Imperial College).
[43] Chen Y 2013 *Optimal design and operation of energy polygeneration systems* (United States of America: Department of Chemical Engineering, Massachusetts Institute of Technology).
[44] Yu Z, Han J and Cao X 2011 Investigation on performance of an integrated solid oxide fuel cell and absorb chiller tri-generation system *Int. J of Hydrogen Energy* **36** 12561-73.
[45] Chicco G and Mancarella P 2009 Matrix modelling of small-scale trigeneration systems and application to operational optimization. *Energy* **34** 261–73.
[46] Geidl M and Andersson G 2007 Optimal power flow of multiple energy carriers *IEEE Trans Power Syst* **22** 145-55.
[47] Liu M, Shi Y and Fang F 2013 Optimal power flow and PGU capacity of CCHP systems using a matrix modeling approach *Appl. Energy* **102** 794–802.
[48] Lahdelma R and Rong A 2005 Efficient re-fromulation of linear cogeneration planning model ed. M.H. Hamza *Proc. of the 24th IASTED Int. Conf. Modeling, Identifi. Contr* 1-6.
[49] Dantzig G 1963 *Linear programming and extensions* (NJ, USA : Princeton University Press)
[50] Rong A 2006 *Cogeneration planning under the deregulated power market and emissions trading scheme* (Finland: Department of Information Technology, University of Turku).
[51] Rong A, Figueira J R and Lahdelma R 2014 An efficient algorithm for bi-objective combined heat and power production planning under the emission trading scheme *Energy Convers Manag* **88** 525-34.
[52] Rong A, Figueira J R and Lahdelma R 2015 A two phase approach for the bi-objective non-convex combined heat and power production planning problem *Eur. J. Oper. Res* **245** 296-308.
[53] Hawkes A D, Brett D J L and Brandon N P 2009 Fuel cell micro-CHP techno-economics: Part 1 – model concept and formulation *Int. J. of Hydrogen Energy* **34** 9545-57.
[54] Mavrotas G, Demertzis H, Meintani A and Diakoulaki D 2003 Energy planning in buildings under uncertainty in fuel costs: The case of a hotel unit in Greece *Energy Convers Manag.* **44** 1303-21.
[55] Mavrotas G, Diakoulaki D, Florios K and Georgiou P 2008 A mathematical programming framework for energy planning in services' sector buildings under uncertainty in load demand: The case of a hospital in Athens *Energy Policy* **36** 2415-29.
[56] Mavrotas G, Florios K and Vlachou D 2010 Energy planning of a hospital using Mathematical Programming and Monte Carlo simulation for dealing with uncertainty in the economic parameters *Energy Convers Manag.* **51** 772-31.
[57] Li C, Shi Y, Liu S, Zheng Z, Liu Y 2010 Uncertain programming of building cooling heating and power (BCHP) system based on Monte-Carlo method *Energ Buildings* **42** 1369–75.
[58] Akbari K, Nasiri M M, Jolai F and Ghaderi SF 2014 Optimal investment and unit sizing of distributed energy systems under uncertainty: A robust optimization approach *Energ Buildings* **85** 275-86.
[59] Aval S M M, Ahadi A and Hayati H 2015 Adequacy assessment of Power systems incorporating building cooling, heating and power plants *Energ Buildings* **105** 236-46.
[60] Luh P B, Yu Y, Zhang B, Litvinov E, Zheng T, Zhao F, Zhao J and Wang C 2014 Grid integration of intermittent wind generation: A Markovian approach *IEEE T Smart Grid* **5** 732-41
[61] Fuentes-Corte L F, Santibanez-Aguilar J E and Ponce-Ortega J M 2016 Optimal design of residential cogeneration systems under uncertainty *Comput Chem Eng* **88** 86-102.
[62] Gong J and You F 2015 Sustainable design and synthesis of energy systems *Curr Opin Chem Eng* **10** 77-86

IOP Conf. Series: Earth and Environmental Science **40** (2016) 012026 doi:10.1088/1755-1315/40/1/012026

[63] Piacentino A, Barbaro C, Cardona F, Gallea R, and Cardona E 2013 A comprehensive tool for efficient design and operation of polygeneration-based energy microgrids serving a cluster of buildings. Part I: Description of the method *Appl Energy* **111** 1204–21.
[64] Piacentino A and Cardona F 2007 On thermoeconomics of energy systems at variable load conditions: integrated optimization of plant design and operation *Energy Convers Manag* **48** 2341–55.
[65] Banta L, Rossi I, Traverso A and Traverso AN 2014 Advanced control of a real smart polygeneration microgrid *Energ Proc* **61** 274-7.
[66] Rossi I, Banta L, Cuneo A, Luigi Ferrari ML, Traverso AN and Traverso 2016 A Real-time management solutions for a smart polygeneration microgrid *Energ Convers Manag* 112 11–20
[67] [Kyriakarakos G, Dounis A I, Arvanitis K G and Papadakis G 2012 A fuzzy logic energy management system for polygeneration microgrids *Renew Energ* **41** 315-27.
[68] Kyriakarakos G, Dounis A I, Arvanitis K G and Papadakis G 2013 Intelligent demand side energy management system for autonomous polygeneration microgrids *Appl Energ* **103** 39-51.
[69] Matics J and Krost G 2008 Micro combined heat and power home supply: Prospective and adaptive management achieved by computational intelligence techniques *Appl Therm Eng* **28** 2055-6.
[70] Basu A K, Bhattacharya A, Chowdhury S, and Chowdhury S P 2012 Planned scheduling for economic power sharing in a CHP-Based Micro-Grid *IEEE Trans on Power Syst* **27** 30-8.
[71] Gu W, Wu Z , Bo R, Liu W , Zhou G, Chen W and Wu Z 2014 Modeling, planning and optimal energy management of combined cooling, heating and power microgrid: A review *Int J Elec Power* **54** 26-37.
[72] Zhang Y, Zhang T, Wang R, Liu Y and Guo B 2015 Optimal operation of a smart residential microgrid based on model predictive control by considering uncertainties and storage impacts *Solar Energy* **122** 1052-65.
[73] Ahmadi P, Dincer I and Rosen MA 2013 Performance assessment and optimization of a novel integrated multigeneration system for residential buildings *Energ Buildings* **67** 568-78.
[74] Ameri M and Besharati Z 2016 Optimal design and operation of district heating and cooling networks with CCHP systems in a residential complex *Energ Buildings* **110** 135-48.
[75] Anatone M and Panone V 2015 A model for the optimal management of a CCHP plant *Energy Proc.* **81** 399-411
[76] Arcuri P, Florio G and Fragiacomo P 2007 A mixed integer programming model for optimal design of trigeneration in a hospital complex *Energy* **32** 1430-47.
[77] Arcuri P, Beraldi P, Florio G and Fragiacomo P 2015 Optimal design of a small size trigeneration plant in civil users: A MINLP (Mixed Integer Non Linear Programming Model) *Energy* **80** 628-41.
[78] Bracco S, Gabriele Dentici G and Siri S 2013 Economic and environmental optimization model for the design and the operation of a combined heat and power distributed generation system in an urban area *Energy* **55** 2014-24.
[79] Brandoni C and Renzi M 2015 Optimal sizing of hybrid solar micro-CHP systems for the household sector *Appl Therm Eng* **75** 896-907.
[80] Carvalho M, Serra L M and Lozano M A 2011 Optimal synthesis of trigeneration systems subject to environmental constraints *Energy* **36** 3779-90.
[81] Carvalho M, Lozano M A and Serra L M 2012 Multicriteria synthesis of trigeneration systems considering economic and environmental aspect *Appl Energy* **91** 245-54.
[82] Romero A, Carvalho M and Millar D L 2014 Application of polygeneration optimization techniques for a hospital in North Ontario *Trans Canad Soci Mech Eng* **38** 45-62.
[83] Fuentes-Corte L F, Santibanez-Aguilar J E and Ponce-Ortega J M 2016 Optimal design of residential cogeneration systems under uncertainty *Comput Chem Eng* **88** 86-102.
[84] Lozano M A, Ramos J C, Carvalho M and Serra L M 2009 Structure optimization of energy supply systems in tertiary sector buildings *Energy Buildings* **41** 1063-75
[85] Lythcke-Jørgensen C, Adriano Viana Ensinas AV, Münster M and Haglind F 2016 A methodology for designing flexible multi-generation systems *Energy*

http://dx.doi.org/doi: 10.1016/j.energy.2016.01.084
[86] Najafi B, Mamaghani A H, Baricci A, Rinaldi F and Casalegno A 2015 Mathematical modelling and parametric study on a 30 kWel high temperature PEM fuel cell based residential micro cogeneration plant *Int. J. Hydrogen Energy* **40** 1569-83.
[87] Ren H and Gao W 2010 A MILP model for integrated plan and evaluation of distributed energy systems *Appl Energy* **87** 1001–14.
[88] Rubio-Maya C, Uche J and Martínez A 2011 Sequential optimization of a polygeneration plant *Energy Convers Manag* **52** 2861–69.
[89] Rubio-Maya C, Uche-Marcuello J, Martínez-Gracia A and Bayod-Rújula A A 2011 Design optimization of a polygeneration plant fueled by natural gas and renewable energy sources *Appl Energy* **88** 449–57.
[90] Wu Q , Ren H, Gao W and Ren J 2016 Modeling and optimization of distributed energy supply network with power and hot water interchanges *Appl Therm Eng* **94** 635-43.
[91] Piacentino A and Cardona F 2008 EABOT – Energetic analysis as a basis for robust optimization of trigeneration systems by linear programming *Energy Convers Manag* **49** 3006–16.
[92] Piacentino A and Cardona F 2008 An original multi-objective criterion for the design of small-scale polygeneration systems based on realistic operating conditions *Appl Therm Eng* **28** 2391–404.
[93] Ren H, Gao W and Ruan Y 2008 Optimal sizing for residential CHP system *Appl Therm Eng* **28** 514-23.
[94] Jing Y, Bai H and Wang J 2012 Multi-objective optimization design and operation strategy analysis of BCHP system based on life cycle assessment *Energy* **37** 405-16.
[95] Wang J, Jing Y and Zhang C 2010 Optimization of capacity and operation for CCHP system by genetic algorithm *Appl Energ* **87** 1325–35.
[96] Wang J, Zhai Z, Jing Y and Zhang C 2010 Optimization design of BCHP system to maximize to save energy and reduce environmental impact *Energy* **35** 3388-98.
[97] Wang J, Zhai Z, Jing Y and Zhang C 2010 Particle swarm optimization for redundant building cooling heating and power system *Appl Energ* **87** 3668–79.
[98] Zeng R, Li H, Jiang R, Liu L, and Zhang G 2015 A novel method based on multi-population genetic algorithm for CCHP–GSHP coupling system optimization *Energy Convers Manag* **105** 1138–48.
[99] Zeng R, Li H, Jiang R, Liu L, and Zhang G 2016 A novel multi-objective optimization method for CCHP–GSHP coupling systems *Energ Buildings* **112** 149–58.
[100] Qin C, Tang J and Zhang Y 2015 An efficient algorithm for CCHP system sizing and an operational optimization model based on LP *J Nat Gas Sci Eng* **25** 189-96.
[101] Abdollahi G and Sayyaadi H 2013 Application of the multi-objective optimization and risk analysis for the sizing of a residential small-scale CCHP system *Energ Buildings* **60** 330–44.
[102] Gamou S, Yokoyama R and Ito K 2002 Optimal unit sizing of cogeneration systems in consideration of uncertain energy demands as continuous random variables *Energ Convers Manag* **43** 1349–61.
[103] Kavvadias KC and Maroulis ZB 2010 Multi-objective optimization of a trigeneration plant *Energ Policy* **38** 945–54.
[104] Savola T and Fogelholm CJ 2007 MINLP optimisation model for increased power production in small-scale CHP plants *Appl Therm Eng* **27** 89–99.
[105] Ghaebi H, Saidi MH and Ahmadi P 2012 Exergoeconomic optimization of a trigeneration system for heating, cooling and power production purpose based on TRR method and using evolutionary algorithm *Appl Therm Eng* **36** 113-25.
[106] Mehleri E D, Sarimveis H, Markatos N C and Papageorgiou L G 2012 A mathematical programming approach for optimal design of distributed energy systems at the neighbourhood level *Energy* **44** 96-104.
[107] Mehleri E D, Sarimveis H, Markatos N C and Papageorgiou L G 2013 Optimal design and operation of distributed energy systems: Application to Greek residential sector *Energy* **51** 331-42.

[108] Guo L, Liu W, Cai J, Hong B and Wang C 2013 A two-stage optimal planning and design method for combined cooling, heat and power microgrid system *Energ Convers Manag* **74** 433–45.
[109] Rivarolo M, Cuneo A, Traverso A and Massardo A F 2016 Design optimization of smart poly-generation energy districts through a model based approach *Appl Therm Eng* **99** 291-301.

[110] Karavas C P, Kyriakarakos G, Arvanitis K G and Papadakis G 2015 A multi-agent decentralized energy management system based on distributed intelligence for the design and control of autonomous polygeneration microgrids *Energ Convers Manag* **103** 166–79.
[111] Serra L M, Lozano M A, Ramos J, Ensinas A V and Nebra S A 2009 Polygeneration and efficient use of natural resources *Energy* **34** 575–86
[112] Marechal F, Favrat D and Jochem E 2005 Energy in the perspective of the sustainable development: The 2000 W society challenge *Resour Conserv Recy* **44** 245-62.
[113] Manfren M, Caputo P and Costa G 2011 Paradigm shift in urban energy systems through distributed generation: Methods and models *Appl Energ* **88** 1032-48.