7th International Building Physics Conference

IBPC 2018

Proceedings

SYRACUSE, NY, USA

September 23 - 26, 2018

Healthy, Intelligent and Resilient
Buildings and Urban Environments

ibpc2018.org | #ibpc2018

A Review of Microgrid Energy Systems

Lei Gao, Yunho Hwang*, Reinhard Radermacher

Center for Environmental Energy Engineering, Department of Mechanical Engineering University of Maryland, College Park, MD, 20742, United States

*Corresponding email: yhhwang@umd.edu

ABSTRACT

Microgrid combined cooling, heating and power energy systems are under intensive investigation owing to expansion of renewable energy generation and development of advanced technologies in distributed energy generation. Multi-generation systems serve as one of the core parts in any microgrid energy systems. This review paper presents the summary of state-of-the-art technologies in these multi-generation systems. The first part introduces the energy structure based on energy sources and the latest renewable energy harvesting technologies for solar, biomass and geothermal energy. In the second part, prime movers, including small-scale ones used in a microgrid energy system, are summarized. The third part shows the expanded microgrid system configurations mainly for desalination. The fourth part describes the control and operation strategies for complex multi-generation systems. In the first three parts, insufficient investigation or research gaps are also pointed out. Overall, this paper systematically summaries recent progress in microgrid multi-generation system, and suggest future researches for designing and optimizing a microgrid energy system.

KEYWORDS

Microgrid, CCHP, Renewable Energy, Multi-generation, Prime Mover

INTRODUCTION

Combined cooling, heating and power (CCHP) microgrid system can increase energy efficiency by recovering waste heat and eliminating transmission and distribution losses as compared with separate individual systems. And it will naturally decrease the operation cost and greenhouse gas (GHG) emission because of the energy input saving. In addition, microgrid systems are more reliable than centralized power plants from natural and man-made disasters since renewable energy serves as a localized energy source in most of the systems (Ebrahimi, 2014). A conventional CCHP microgrid system can be divided into four sub-components as shown in Figure 1: energy source (top), energy conversion technologies (middle left), energy demands (middle right) and storage systems (bottom). Different from traditional energy sources, more renewable energy including wind, solar, geothermal and biomass have been utilized in microgrid systems. The upstream of microgrid system will highly influence the system configuration and technologies applied.

RENEWABLE ENERGY SOURCES

Available renewable energy applied in CCHP systems has expanded from solar to biomass, geothermal and wind energy. Solar PVs and thermal collectors are two methods used for solar energy powered CCHP, in which solar thermal part can be integrated into the system as heat source of various energy conversion components due to its flexible temperature range. Solar thermal energy is always serving as a heat source for ORC, ABC or direct heating in CCHP. Wang et al. (2016) show that the solar thermal integrated CCHP system is more energy efficient but less exergy efficiency than the solar PV integrated system. However, due to the intermittent and daytime-occur-only characteristics, CCHP systems powered by solar energy are sensitive to weather variation in its performance and cost change in its payback. Thus, accurate demand predictions and reliable control strategies are needed for efficient and effective solar integrated CCHP systems. While most of the research works considered parameters of solar PV as constant, Arsalis et al. (2018) provided detailed solar PV model experimentally validated in a CCHP system. Biomass as an alternative to natural gas has garnered researcher's attractions as it can produce more stable power than solar. In terms of structure, the biomass integrated CCHP system is similar to conventional one except that the fossil fuel is replaced by gasification subsystem. The increment of components and coupling within subsystems increases system complexity. Exergoeconomic analysis is the mainstream of biomass based system. Wang and Mao (2015) show that the biomass price greatly influence the product unit cost and the exergy cost of cooling water is the most sensitive among all the demand. However, the comparison of environmental and energy benefits between biomass powered CCHP system and conventional one has not been investigated sufficiently. Maraver et al. (2013) adopted ORC or Stirling engine to biomass-based CCHP system and found it is more favorable than stand-alone generation system in terms of the environmental aspect under small cooling-to-heating ratio. Nonetheless, the comparison is only limited to heat powered subsystems and other engines like gas turbines or internal combustion engines have been ignored. Similar to solar thermal energy, geothermal energy can be used to generate electricity. Figure 2 shows how geothermal energy is used in CCHP system. Kalina cycle is more utilized than ORC in system when geothermal is the only thermal source since the thermal efficiency is relatively low (Sun et al., 2017). ORC was used more often when solar thermal energy exists. The ground source heat pump is the most intensive investigation. Other researches were about supercritical CO_2 cycle power cycle, two-stage ORC cycle, combined with LNG gasification process. The utilization characteristics of geothermal in CCHP system is due to the lower temperature range. However, the pressure recovery of ground water has not been explored.

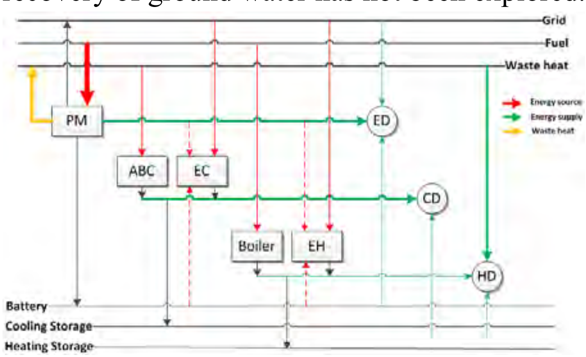

Figure 1. CCHP microgrid structure.

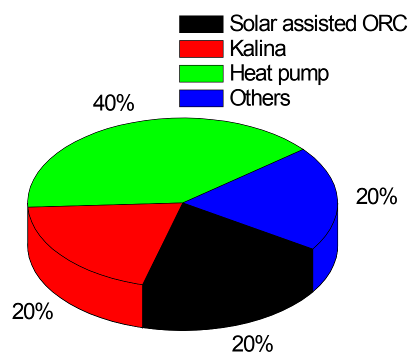

Figure 2. Research paper distribution of geothermal CCHP

PRIME MOVERS

Wu and Wang (2006) showed the characteristics, performance as well as economic information of main prime movers (PM), including steam turbine (ST), gas turbine (GT), microturbine (MT), internal combustion engine (ICE), Stirling engine (SE) and fuel cell (FC), utilized in CCHP microgrid system. The selection of prime mover in CCHP microgrid system varies based on the energy source, energy, environment and economic (3E) criteria. Wang et al. (2008) use multi-criteria (3E+society) to evaluate different PMs based trigeneration system and found gas turbine plus LiBr ABC is the best and SOFC based one is the worst. Ebrahimi and Keshavarz (2012) expanded this method to different climate regions. The results showed that the best to worst PMs are ICE, SE, separated system and MT, and climate difference has little influence for selection. However, there are only limited hierarchy criteria in the second layer, which would limit the application of this method. Khorasaninejad et al. (2016) combined several other fuzzy approaches to the second layers criteria for selection of PMs in ORC based CCHP system. This work found PV panel is the best PM and GT is the worst when every primary criterion (3E+society) are segmented into 16 to 5 sub-criteria. Roman and Alvey (2016) provided following hybrid load operation-based selection method among ICE, MT and phosphoric acid FC. However, the selection is only one layer, so it can only provide the selection in each sub-criteria. Moreover, selection of PMs in these papers is based on some fixed configurations and no consideration of operation strategies for different PMs. The truth is that different PMs have their own optimal subsystem configuration and operation strategies, there is no work based on this premise. In addition, PMs can be driven by renewable energy, there is little concern about the influence of renewable energy on selection.

For small size microgrid, FC, MT and SE are the main PMs in microgrid system based on the capacity range. Solid oxide fuel cell (SOFC) and proton exchange membrane (PEMFC) are the most common FC that are used in CCHP system, which can be seen from the distribution of published paper in Figure 3. Overall, FC based CCHP system has earned more attention recently. In system design and analysis, most of the research focused on energy saving potential and economic feasibility through parametric study. As for optimization, most of the work tried to solve multi-objective optimization through 3E criteria. Due to the research intensity and complex experiment setup, there is not much review work and test verification in this subtopic. The electricity to heat ratio for FC is relatively larger than conventional large-capacity PM, so it is sometimes insufficient to provide thermal cooling energy for ABC, however, the electric cooling can be designed in CCHP system, so there is need of comparison for FC based CCHP in which cooling is provided by ABC and EC.

Researchers have integrated MT integrated CCHP system based on cogeneration system since 2000. Figure 4 shows the research paper distribution from 2001 to 2018, in which ‘others’ includes dedicated investigation of MT and dynamic system modeling. Early stage research concerned about the system thermodynamic analysis, simple operation strategies and it always comes along with new system designs. Sugiartha et al. (2009) started to adopt 3E analysis in MT based CCHP system but no optimization analysis was provided until recent. Since MT is impaired under the variable ambient condition, so efficient and accurate system control is important for 3E benefits. However, there is not much work specified on control of MT based CCHP system. At last, limited research about combined cooling and power system is a special design in which heating demand is negligible compared with other two.

SE based system has not been explored much in recent research work. Limited investigators designed SE as supplementary PM in CCHP system to further improve energy efficiency of whole system (Ansarinasab and Mehrpooya, 2018). Other research chooses SE as main PM are all about system design and sizing. Kaldehi et al. (2017) designed a solar driven SE trigeneration system and mainly focused on the SE modeling and verification in different climate regions. However, when the authors tried to analysis the system performance, the thermal load was calculated based on ASHRAE standard, which is a fixed value and not reflects the actual demand. Thus it would not well suit for following electricity/thermal (FTL/FEL) load control strategies. Moghadam et al. (2013) use 3E criteria to optimize SE size under FTL/FEL. Nonetheless, auxiliary device or power is needed under these following strategies, so there is still some space for improvement of energy efficiency. Karami and Sayyaadi (2015) applied fuzzy-AHP decision-making method to choose the best optimization objective for different cities. However, the fuzzy-AHP method is subjective and depends on researchers’ experience, so objective method should be considered. Harrod James et al. (2010) provided a sizing method for SE in CCHP through parametric study, however, the optimization is single objective which is not sufficient for SE design and selection. Moreover, in the PM selection research mentioned above, SE is sometimes considered less competitive compared with other PMs when considering the capital cost. Overall, SE shows its developing potential in CCHP system and there is a need for more investigation of SE based CCHP, especially in related to the economic analysis.

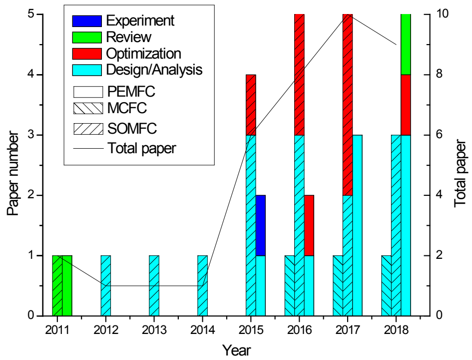

Figure 3. Research trend of fuel cell.

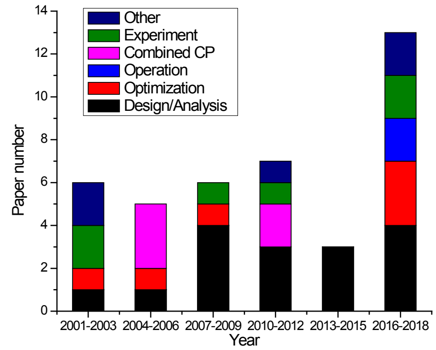

Figure 4. Research trend of microturbine.

SYSTEM CONFIGURATIONS

Desalination is an additional function that has been enriched in CCHP microgrid systems, especially for shipboard application. The system efficiency can be further improved. Shu et al. (2013) developed a fresh water producing CCHP system based on shipboard ICE. Mohammadi and Mehrpooya (2017) designed a desalination integrated CCHP system, which can provide 46.8 kW power, 451 kW heating, 52 kW cooling and 0.79 kg/s potable water, and optimal operational parameters were decided based on the sensitive analysis. Sadeghi et al. (2017) designed a novel multi-generation system for producing power, cooling and fresh water by adopting ejector and humidification /dehumidification desalination technology. The optimal exergy efficiency can reach 17%. Najafi et al. (2014) presented 3E modeling of a solid oxide fuel cell–gas turbine (SOFC–GT) hybrid system integrated with a multi-stage flash (MSF) desalination unit. The optimal design leads to an exergetic efficiency of 46.7% and 9 years payback period. However, the practical water demands have not been reflected in these researches. Besides, the most of these systems are not CCHP based and seldom provide optimal control strategies.

CONTROL AND OPTIMIZATION

The CCHP system optimization problems are always attributed to the multi-objective problem since almost all the investigations consider not only energy savings but also payback time and greenhouse gas emission reduction. The most common optimization algorithms used in CCHP system are genetic algorithm (GA) (Zhang et al., 2018), particle swam optimization algorithm (PSO) (Luo and Fong, 2017a) and differential evolution algorithm (DEA) (Yao et al., 2017). The optimization of system control strategy has a great impact on system operation performance. The control strategies have gone from fixed pattern like following thermal load and following electricity load (Fumo et al., 2011) to model predictive control (Rossi et al., 2016) and discrepancy consideration (Luo and Fong, 2017b).

CONCLUSIONS

This review paper summarizes recent progress of CCHP microgrid systems from energy source, prime mover, system configuration, system control and optimization points of view. First, other renewable energy such as biomass and geothermal have been considered in microgrid systems in addition to conventional available distributed energy sources such as solar thermal and PV. Exergoeconomic analysis is the mainstream in biomass powered systems, and energy and environmental effects should be investigated more as compared with other conventional energy sources. There exists research gap for pressure recovery in geothermal powered microgrid system. Second, research works related to MT, SE and FC are summarized in this paper. Current selection of prime movers is based on fixed system configuration which is not designed for various PMs. In addition, renewable energy should be considered when selecting PMs. FC, MT, and SE based small-scale CCHP microgrid systems focus on thermodynamic analysis and optimization through 3E criteria. There is a lack of experimental validation. Third, a mirogrid system has expanded its function to desalination for further improving energy efficiency. However, the system becomes more complex and is not clear whether water demand is met when integrated with CCHP system. Last, the control and optimization work on the microgrid CCHP system has contributed to improving the performance. The control has upgraded from simple strategies to comprehensive and real-time ones.

REFERENCES

Ansarinasab, H., and Mehrpooya, M., 2018, Investigation of a combined molten carbonate fuel cell, gas turbine and Stirling engine combined cooling heating and power (CCHP) process by exergy cost sensitivity analysis: *Energy Conversion and Management*, v. 165, pp. 291–303.

Arsalis, A., Alexandrou, A.N., and Georghiou, G.E., 2018, Thermoeconomic modeling of a small-scale gas turbine-photovoltaic-electrolyzer combined-cooling-heating-and-power system for distributed energy applications: *Journal of Cleaner Production*, v. 188, pp. 443–455.

Ebrahimi, M., 2014, Combined cooling, heating and power: decision-making, design and optimization: Elsevier, Waltham, MS.

Ebrahimi, M., and Keshavarz, A., 2012, Prime mover selection for a residential micro-CCHP by using two multi-criteria decision-making methods: *Energy and Buildings*, v. 55, pp. 322–331.

Fumo, N., Mago, P.J., and Smith, A.D., 2011, Analysis of combined cooling, heating, and power systems operating following the electric load and following the thermal load strategies with no electricity export: *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, v. 225, no. 8, pp. 1016–1025.

Harrod James, Mago Pedro J., and Luck Rogelio, 2010, Sizing analysis of a combined cooling, heating, and power system for a small office building using a wood waste biomass-fired Stirling engine: *International Journal of Energy Research*, v. 36, no. 1, pp. 64–74.

Kaldehi, B.J., Keshavarz, A., Safaei Pirooz, A.A., Batooei, A., and Ebrahimi, M., 2017, Designing a micro Stirling engine for cleaner production of combined cooling heating and power in residential sector of different climates: *Journal of Cleaner Production*, v. 154, pp. 502–516.

Karami, R., and Sayyaadi, H., 2015, Optimal sizing of Stirling-CCHP systems for residential buildings at diverse climatic conditions: *Applied Thermal Engineering*, v. 89, pp. 377–393.

Khorasaninejad, E., Fetanat, A., and Hajabdollahi, H., 2016, Prime mover selection in thermal power plant integrated with organic Rankine cycle for waste heat recovery using a novel multi criteria decision making approach: *Applied Thermal Engineering*, v. 102, pp. 1262–1279.

Luo, X.J., and Fong, K.F., 2017a, Control Optimization of Combined Cooling and Power System with Prime Mover of Solid Oxide Fuel Cell-gas Turbine for Building Application: *Energy Procedia*, v. 105, pp. 1883–1888.

Luo, X.J., and Fong, K.F., 2017b, Development of multi-supply-multi-demand control strategy for combined cooling, heating and power system primed with solid oxide fuel cell-gas turbine: *Energy Conversion and Management*, v. 154, pp. 538–561.

Maraver, D., Sin, A., Sebastián, F., and Royo, J., 2013, Environmental assessment of CCHP (combined cooling heating and power) systems based on biomass combustion in comparison to conventional generation: *Energy*, v. 57, pp. 17–23.
Moghadam, R.S., Sayyaadi, H., and Hosseinzade, H., 2013, Sizing a solar dish Stirling micro-CHP system for residential application in diverse climatic conditions based on 3E analysis: *Energy Conversion and Management*, v. 75, pp. 348–365.
Mohammadi, A., and Mehrpooya, M., 2017, Energy and exergy analyses of a combined desalination and CCHP system driven by geothermal energy: *Applied Thermal Engineering*, v. 116, pp. 685–694.
Najafi, B., Shirazi, A., Aminyavari, M., Rinaldi, F., and Taylor, R.A., 2014, Exergetic, economic and environmental analyses and multi-objective optimization of an SOFC-gas turbine hybrid cycle coupled with an MSF desalination system: *Desalination*, v. 334, no. 1, pp. 46–59.
Roman, K.K., and Alvey, J.B., 2016, Selection of prime mover for combined cooling, heating, and power systems based on energy savings, life cycle analysis and environmental consideration: *Energy and Buildings*, v. 110, pp. 170–181.
Rossi, I., Banta, L., Cuneo, A., Ferrari, M.L., Traverso, A.N., and Traverso, A., 2016, Real-time management solutions for a smart polygeneration microgrid: *Energy Conversion and Management*, v. 112, pp. 11–20.
Sadeghi, M., Yari, M., Mahmoudi, S.M.S., and Jafari, M., 2017, Thermodynamic analysis and optimization of a novel combined power and ejector refrigeration cycle – Desalination system: *Applied Energy*, v. 208, pp. 239–251.
Shu, G., Liang, Y., Wei, H., Tian, H., Zhao, J., and Liu, L., 2013, A review of waste heat recovery on two-stroke IC engine aboard ships: *Renewable and Sustainable Energy Reviews*, v. 19, pp. 385–401.
Sugiartha, N., Tassou, S.A., Chaer, I., and Marriott, D., 2009, Trigeneration in food retail: An energetic, economic and environmental evaluation for a supermarket application: *Applied Thermal Engineering*, v. 29, no. 13, pp. 2624–2632.
Sun, Y., Lu, J., Wang, J., Li, T., Li, Y., Hou, Y., and Zhu, J., 2017, Performance improvement of two-stage serial organic Rankine cycle (TSORC) integrated with absorption refrigeration (AR) for geothermal power generation: *Geothermics*, v. 69, pp. 110–118.
Wang, J.-J., Jing, Y.-Y., Zhang, C.-F., Shi, G.-H., and Zhang, X.-T., 2008, A fuzzy multi-criteria decision-making model for trigeneration system: *Energy Policy*, v. 36, no. 10, pp. 3823–3832.
Wang, J., Lu, Y., Yang, Y., and Mao, T., 2016, Thermodynamic performance analysis and optimization of a solar-assisted combined cooling, heating and power system: *Energy*, v. 115, pp. 49–59.
Wang, J., and Mao, T., 2015, Cost allocation and sensitivity analysis of multi-products from biomass gasification combined cooling heating and power system based on the exergoeconomic methodology: *Energy Conversion and Management*, v. 105, pp. 230–239.
Wu, D.W., and Wang, R.Z., 2006, Combined cooling, heating and power: A review: *Progress in Energy and Combustion Science*, v. 32, no. 5–6, pp. 459–495.
Yao, E., Wang, H., Wang, L., Xi, G., and Maréchal, F., 2017, Multi-objective optimization and exergoeconomic analysis of a combined cooling, heating and power based compressed air energy storage system: *Energy Conversion and Management*, v. 138, pp. 199–209.
Zhang, J., Cao, S., Yu, L., and Zhou, Y., 2018, Comparison of combined cooling, heating and power (CCHP) systems with different cooling modes based on energetic, environmental and economic criteria: *Energy Conversion and Management*, v. 160, pp. 60–73.