Micro combined heat and power

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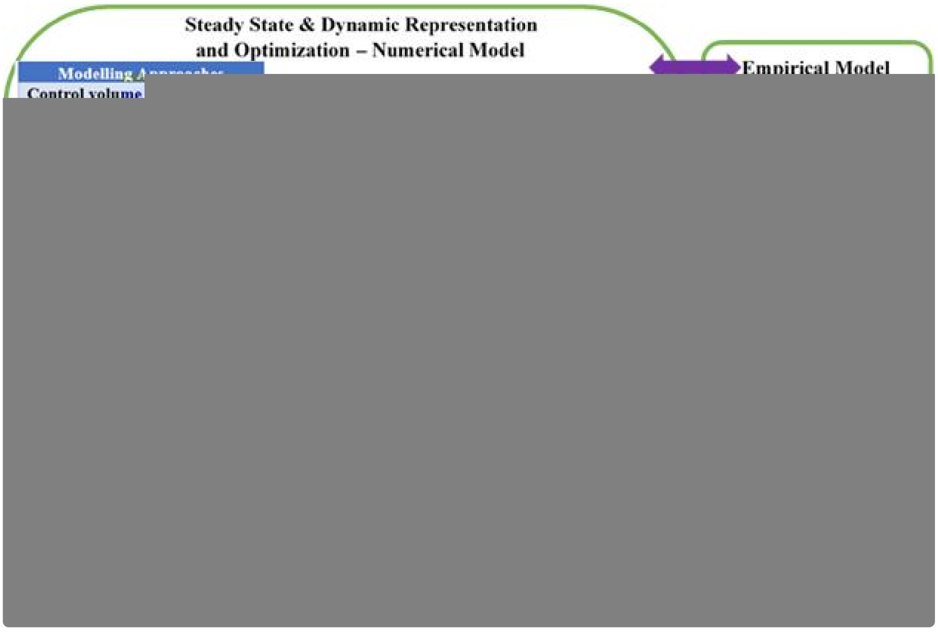
Micro Combined Heat and Power (µCHP) systems in a DG infrastructure can reduce a building's primary energy consumption, reduce carbon footprint, and enhance resiliency. The simultaneous production of electrical and thermal energy from a single fuel source at a high overall energy efficiency can reduce primary energy consumption while lowering greenhouse gas (GHG) emissions. A comprehensive overview of various modeling approaches adopted by international researchers is presented. The key objective is to present the state-of-the-art models and approaches while identifying opportunities for further refinement to expand the capabilities of such models for versatile applications.

Keywords: Micro combined heat and power ; Cogeneration ; Prime mover ; Primary Energy Consumption ; Engine ; Modeling



1. Introduction

The decentralized aspect of µCHPs can potentially reduce distribution losses while reducing the peak load burden on central power generation plants. Economic and population growth are the primary drivers of rising electricity demand and it is bound to increase further, especially as electric vehicles become commonplace. In fact, CHP technology is gaining ground as an acceptable energy provider at university campuses, industrial facilities, and as backup generation, according to a recent study [1]. The key market drivers contributing towards the growth of CHP technologies include lower operating costs, environmental regulations, resiliency, policy support, reliability, and utility interest. CHP reduces the burden on electric grid as well as the need for new transmission and distribution infrastructure while utilizing domestically available clean energy resources such as biomass and natural gas. Some of the major hurdles for the mass deployment of CHPs include value proposition to the utilities, user awareness, permitting and siting constraints, and general market uncertainties.

Cogeneration technologies including those of industrial and micro scale have been analyzed for their applications in buildings dating back to late 20th century [2]. The authors identified the hurdles for rapid deployment and adoption by utilities, industries, and governmental regulatory bodies. Suggestions were made for accelerating the implementation of these devices with a primary focus on research, fuels, economics, environment, industry-utility interface, and regulation. Some of these focal points are still relevant even though the suggestions were made almost four decades ago!

Given the significant potential of µCHP in buildings, we present in this paper a review of prior work in modeling µCHPs that use internal combustion engine (ICE) as the primary mover. Integration of these µCHP units as primary building energy resources requires good understanding of their performance in meeting the dynamic energy needs (thermal and electric loads) of the building influenced by users, seasons, climate, and the overall interaction with the grid. The key objective is to present the state-of-the-art thermodynamic models and their advantages, while identifying opportunities for further refinement to expand the capabilities of such models for versatile applications and ability to accept different prime power ICE based µCHP products.

2. Discussion

Based on the comprehensive review of past two decades of work, it can be concluded that the application of µCHP has been shown to reduce primary energy consumption coupled with environmental benefits associated with lower GHG emissions. However, the true savings were shown to be greatly influenced by the control mode adopted: thermal load following vs. electrical load following. Transient heat and power demand variations influenced the overall effectiveness significantly. Therefore, accurate prediction of µCHP output under steady-state as well as transient operating conditions is critical to developing µCHP control schemes and determining the economic viability of their applications. Several researchers developed and tuned the models and approaches to predict the behavior of specific equipment and their integration into buildings. Due to the complexity of the physical processes that take place to produce power in ICE, first principle modeling of µCHP is impractical to implement for building applications. It would require level of details that are usually not available to users. Therefore, all µCHP energy simulation models fall into either grey-box or black box category. Both categories require the availability of performance data of the µCHP system under investigation for calibrating the parameters of the model. Grey-box models are more versatile. The same set of equations can be directly used for different µCHP systems and can be easily modified to accommodate differences in system topography. Black-box models on the other hand are easier to develop. However, a black-box model architecture that is developed for certain system may not apply to a different system.

A summary of the modeling strategies, optimization approaches, benefits and advantages of different studies discussed in Section 2 is outlined in the table below:

Prime Mover, (kW)	Energy Storage	Approach/Methodology	Advantages	Optimization	Ref
Combustion Engines, Fuel Cells (<15 kW_e)	Hot water storage tank	Control Volume. Model calibration with empirical data	Simplicity, reliability if empirical data is utilized	Thermal capacitance and conductance optimization with GenOpt	[3]
ICE, 5.5 kW_e	Simulation in TRNSYS, ESP-r, Energyplus	Annex 42 model-based control volume approach	Non-traditional calibration procedure—using optimization tools	single- and multi-objective optimization algorithms	[4]
ICE, 6 kW_e	Hot water tank	Annex 42 modelling approach. Electric load following mode	Detailed calibration methodology, Transient mode considerations	GenOpt optimization approach	[5] [6]
ICE, 6 kW_e	Variable capacitance hot water storage tank	TRNSYS dynamic platform, control volume approach	Parametric study similar to 14; Sensitivity of energy flow with variable thermal storage volume	Electrical and thermal load following modes of operation to optimize the savings	[7]
Otto cycle Engine, 4 kW_e	Hot water storage tank, stratified model	TRNSYS component-based model.	Detailed transient test approaches and their implications on model reliability	Model tuned to match simulated outputs with experimental results	[8]
ICE, 25 kW_e, CCHP	TRNSYS hot water storage tank module-based model	Modified Annex 42 approach with additional control volume preventing overheating via bypass loop	Models ability to operate in manual, thermal priority and electrical priority modes. High level of model detail and calibration methodology	Dynamic simulation model without the need for any optimization	[9]

Prime Mover, (kW)	Energy Storage	Approach/Methodology	Advantages	Optimization	Ref
Reciprocating Gas Engine, 1.3 MW_e	Thermal storage tanks	Dynamic and steady-state performance data from an operating plant was used to develop the model using engineering principles	Reliable dynamic performance prediction	-	[10]
ICE, <50 kW_e	Thermal and Electrical Storage	Six different components (including user demand) in the CHP were independently modeled	Implementation of delay subsystem yields high transient performance reliability.	Optimal thermal and electrical energy storage-based configurations. Simplified representation of dynamic effects	[11] [12]
Otto Engine, 125 kW_e	Stratified thermal storage module	Three different levels of stratification were modeled along with all energy flows	Influence of temperature level in the tank on energy efficiency and economics is modeled	-	[13]
ICE-ORC Hybrid, 2.5–5 MW	None	ODEs representing conservation laws while using reliable heat transfer correlations such as Wiebe, Woschini, and Annand	Provides guidelines on suitable ICE designsfor waste heat recovery projects	Whole system optimization framework.	[14]
Generic CHP Model	Flexible design consideration	Based on Mixed-Integer Non LinearProgramming (MINLP)	Generic dynamic modeling approach. Provides guidelines for system definition, and specification.	Generic, low computational effort framework	[15]
ICE, 15 kW_e	Waste heat recovery and direct utilization	Modeled according to the continuity, momentum, and energy equations through 1D thermo-fluid dynamic characterization	Flexible waste heat recovery system with multiple temperature levels of thermal output	Optimal sizing of the polygeneration plant based on flexible heat recovery	[16]
Otto Engine, 4 kW_e	Stratified storage tank model	TRNSYS component based model, calibrated with empirical data	Application of commercial software to design, optimize and validate a complete residential building CHP system	TRNSYS optimization	[17]
Hybrid ICE-Stirling, 85 kW_e	Direct heat utilization	Zero-dimensional mathematical model with single zone consisting of operating fluid as the thermodynamic system	Simplified system representation with high reliability	Electrical output optimization via waste heat utilization in secondary power generation unit	[18]
Biogas-Diesel ICE, 3.5 kW_e	No thermal storage	Artificial Neural Network (ANN) based approach while minimizing the RMSE value	Reliable engine performance prediction showing the electrical and thermal outputs	Iterative selection data optimization for ANN design optimization.	[19]
3MWe, polygeneration system	None	Open Problem Table (OPT) combining pinch analysis with MILP	Novel approach for complex systems containing multiple sources and sinks	MILP model with multiple decision variables	[20]

3. Conclusions

Based on the reviewed work, the authors suggest a closer look in to the following topics to help cement the µCHP as an efficient and resilient energy source to address the growing needs of the population driven by economy and new energy consumers entering the marketplace (e.g., electric vehicles). Thorough consideration of the following aspects in the model is recommended for enhancing the reliability and predictability of a global µCHP model:

- Develop/refine models to address discrepancies associated with transient behavior—startup, cool-down, stand-by, interval between start and stop cycles, and delay time in these transient conditions. These aspects have been shown to improve the thermal efficiency of the system and are crucial for a reliable model.

- Develop reliable schemes to analyze the performance of thermal and electric energy storage modules over a broad range of operating conditions. These models must be designed such that the integration-related discrepancies are accounted for appropriately.
- Properly account for condensation of the flue gas exhaust stream in the PM model as well as its integration with thermal storage model
- Simulation results have been proven to be impacted significantly by the time-step used in the model. This factor must be considered for developing the model and utilizing the calibration data in a meaningful form
- Broader operational and experimental results need to be collected to study and characterize the PM thoroughly
- Storage system model must balance the accuracy of the PM model
- System design approaches focusing on cold climate applications—µCHP systems are ideal resources for cold climate applications where the heat demand is high, and the grid resources are vulnerable
- Thorough consideration of the governing physics and chemistry of the model to improve the accuracy of complex systems
- Expansion of the µCHP model to integrate thermally driven heat pump technology for maximizing the energy efficiency
- Examination of co/trigeneration system models for applications in communities, non-residential buildings, and other large facilities
- Application of these models to address commercialization issues to help wider market adoption.

The last two decades developing reliable mathematical models of µCHP systems, their application in real world scenarios and understanding the complexities associated with integration into the building environment. Development opportunities surrounding the modeling of prime movers and their integration with energy storage technologies were identified by several researchers. Publically available software platforms have evolved to design, improvise, and develop reliable cogeneration simulation models which will aid in further development of reliable, efficient, and resilient µCCHP products.

Energy utilization in buildings is a challenging subject, influenced by the building's thermal and electrical demands, and primarily impacted by mismatch between the energy demand and supply. As a result, energy storage must be an integral part of the µCHP system to fully utilize the benefits of distributed generation. A fully integrated optimal µCHP configuration is underexplored as there are numerous possible solutions, which leads to the need to utilize software programs that help design the ideal system.

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