



REVIEW ARTICLE

Biomass-fuelled combined heat and power: integration in district heating and thermal-energy storage

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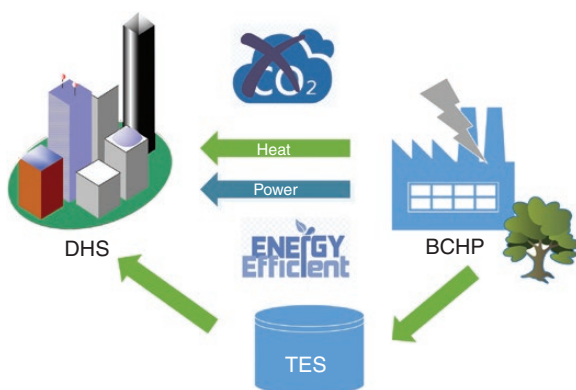
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Abstract

Conventional approaches towards energy-system modelling and operation are based upon the system design and performance optimization. In system-design optimization, the thermal or mechanical characteristics of the systems providing for the heat or electricity demands were derived separately without integration with the energy source and without interaction with demand, which results in low-efficiency energy performance. This paper presents a key review on the integration of biomass-powered combined heat and power (BCHP) systems in district-heating systems as well as coupling with thermal-energy storage. In BCHP design, the appropriate sizing of the associated components as part of the district-heating system is very important to provide the optimal dispatch strategy as well as minimized cost and environmental impact while it co-operates with thermal-energy storage. Future strategies for the feasibility, evaluation and integration of biomass-powered energy systems in the context of district systems are also studied.

Graphic abstract



Keywords: energy storage; biomass; combined heat and power (CHP); district heating; mathematical programming; optimization

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Introduction

Biomass has long been used for energy sources; however, using biomass in combined heat and power (CHP) applications is problematic in the supply chain, its processing as well as its conversion. There are many parameters affecting its effectiveness for energy purposes. Low energy-conversion efficiency has deterred operators from relying on biomass-powered energy systems. This is one of the reasons for the low share of biomass compared to other resources in energy generation. Biomass exists in solid, liquid and gaseous forms. Solid biomass could itself be transformed into a biofuel in liquid or gaseous forms via methods such as pyrolysis, Fischer-Tropsch synthesis, synthetic natural-gas production and torrefaction [1]. Fig. 1 shows the application of biomass in the energy sector where the main focus of this study will be on the simultaneous production of heat and electricity with biomass as an environmentally friendly source. Climate change has encouraged the usage of the CHP concept via district-heating systems (DHS) with the use of renewables, especially biomass. Today, its characteristics, such as a low purchase price, still make it a viable option for delivering distributed or centralized energy generation [2].

The main components of a biomass-powered CHP, denoted by BCHP, installation can be categorized as feedstock receiving and preparation, biomass conversion and finally power and heat production. The latter, as shown in Fig. 2, can be defined as the conversion of the steam or syngas into electric power and process steam or hot water. Biomass-fired CHP systems can produce heat or steam for application in industrial processes such as paper or pulp or for applications for space heating or hot-water demand in buildings, directly or by a thermal network in a district-heating design. The co-firing of biomass with other fuels in large CHP power plants has recently become increasingly common due to its higher efficiency. The co-firing notion in the biomass-fuelled CHP industry bears different meanings other than the CHP concept. While co-firing in the energy sector is translated into the simultaneous generation of the various sorts of energy, co-firing in biomass-powered systems means mixing biomass with fossil fuels (typically coal or natural gas) to substitute some portions of fossil fuels

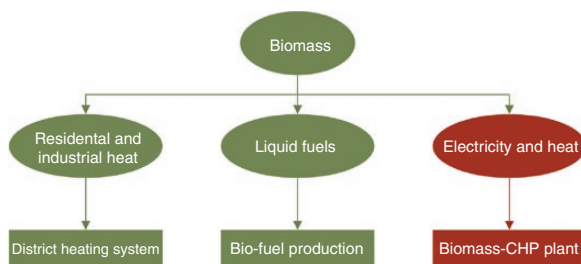


Fig. 1: Main applications of biomass as a source of energy and the focus of the current article

in boilers. It is the right choice for low-heat-content or wet and high-moisture-content biomasses, or where the environmental issues are highlighted. Woody biomass and pulp and paper wastes and residues are the main biomasses used in co-firing. Co-firing implicates using an *in situ* installation for a fossil-fuel-powered system with slight modification for biomass handling and processing. Approximately 55 GW of coal-fired capacity is accompanied by biomass co-firing in North America and Europe [3]. Fig. 3 shows three possible configurations of co-firing in biomass-fired CHP set-ups. In direct co-firing, biomass and another fuel (usually coal) are supplied into the CHP boiler. The burners may be shared or separate for biomass and the second fuel. In indirect configuration, solid biomass is converted into gas inside the gasification reactor and burned together with the second fuel. In a parallel set-up, biomass produces steam in a separate CHP boiler and generated steam is fed into the coal-fired boiler.

1 Goals and structure of this paper

An exhaustive analysis of the reported studies on biomass-fired CHP and their applications in district heating and other heat-supply chains with or without storage are related to design methodologies, optimization modelling, simulation techniques, as well as various prospects. The novelty of this review paper relies on the combination of BCHPs with DHS and integration of thermal-energy storage (TES) for efficiency enhancement. Fig. 4 illustrates the structure of the current review paper. The first part deals with the importance of TES as part of integrated BCHP systems. The second part focuses on the modelling and optimization of BCHPs into DHS, while the third part emphasizes the design and technical considerations of BCHPs. Finally, an overview of the current and future situations of BCHP integrated systems is provided. It includes the specifications of the integrated CHP into DHS and TES such as biomass feedstock, technologies, operating cycles and fluids, optimization approaches and utilized techniques, identification of the critical parameters in their optimization, technological options for biomass conversion and energy conversion in CHP and district systems, and an overview of the current trends and the evolution of the integrated biomass-powered CHPs.

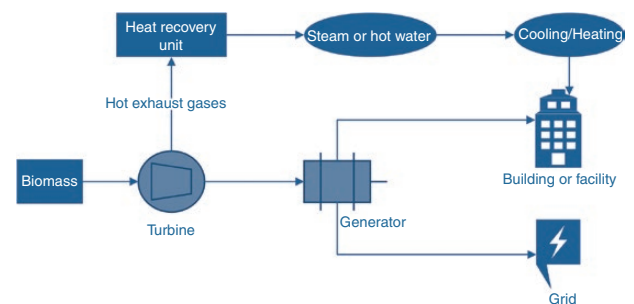


Fig. 2: Main components of a biomass-driven CHP

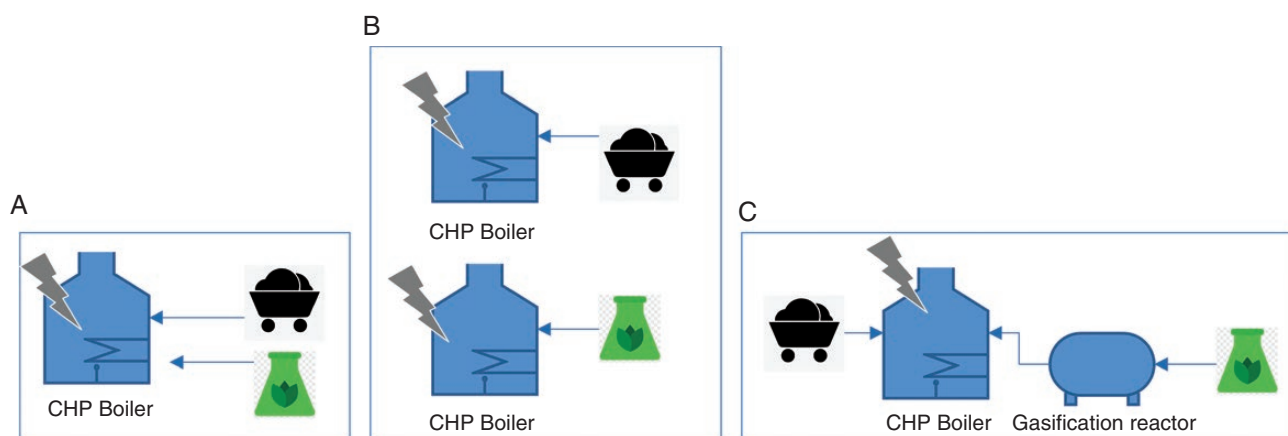


Fig. 3: Configurations of biomass co-firing in CHP plants: (a) direct, (b) parallel and (c) indirect.

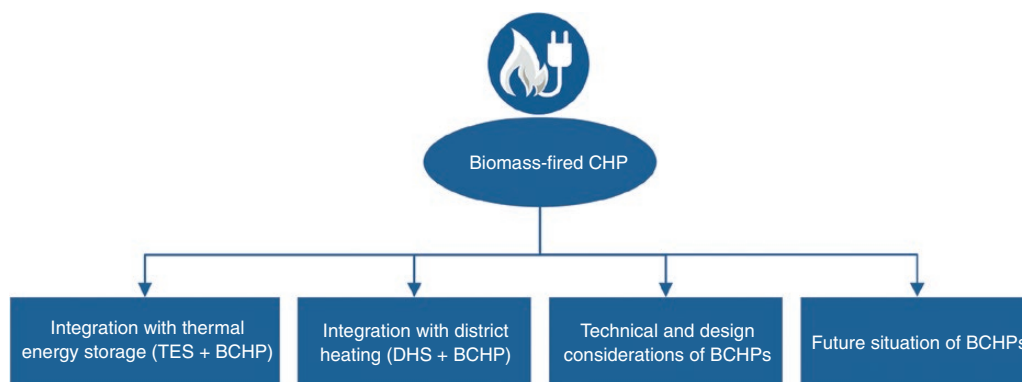


Fig. 4: Structure of the current review article

2 TES: application to BCHP-driven systems

BCHPs have the flexibility to incorporate energy-storage systems [4–7]. Energy storage can also be a solution to increasing the reliability and versatility of BCHP systems in normal and emergency situations [6, 8].

The heat-transfer medium is a very essential parameter, especially when the BCHP plant is integrated with a high-temperature storage system, in particular for phase change material (PCM) TES. It directly impacts the capacity specifications and optimal operation of the BCHP system. Ayyappan *et al.* reviewed the most common solid and liquid mediums for sensible heat storage with their physical, chemical and thermodynamic characteristics [9] for various temperatures based on the production range of BCHPs. The solid-state media that have been investigated are of metal and non-metal materials, such as sand-rock minerals, reinforced materials, reinforced concrete, cast steel and magnesia fire bricks. The most considerable disadvantage of the solid-state media is that their heat capacities are rather low, while they profit from lower costs in comparison with other materials, especially when large heat storage is needed for the BCHP. For the technical and economic reasons, such

as simplicity of use, lower costs and flexibility, to be integrated with biomass in BCHPs, water tanks have long been used and their efficiency has been a topic for research. Techniques such as water-temperature stratification have been applied along with insulation to enhance the heat efficiency for BCHP systems [10].

In the case that the biomass-CHP unit heats up air for space heating in a district-heating system, thermo-hydraulic analysis with air as the operating fluid in the storage-coupled CHP plant is important. In Ref. [11], the researchers mathematically analysed a heating system equipped with an air-packed-bed TES that used ceramic bricks for bedding to store solar energy or output heat from the BCHP unit. The temperature ranges and air volumes were subject to analysis for optimal economic performance. Various mathematical modelling ideas, with material properties and thermo-hydraulic parameters, were also investigated.

If the BCHP plant as part of the district is accompanied by passive design of the district's buildings, the PCM storage as part of the structure can store energy from both the CHP system and passive gain. As an example, Kenisarin *et al.* analysed and compared the organic and inorganic PCMs such as paraffin, fatty acids and hydrated

salts as part of the building's structure for energy-storage control from different sources such as solar and BCHP [12]. The materials they studied are among the most widely used PCMs [12]. In their research, 15 full-sized buildings containing PCMs were compared. The results showed that using PCM in buildings led to increasing efficiency by better control over the storage of various sources by mitigating air-temperature variation and peak-demand-hour shifts [12]. A similar approach is applied by the researchers in Refs [13–15]. Techno-economic analysis of two storage systems intended for use in micro-CHP was the subject of research by Mongibello *et al.* The heat-transfer medium in this research was water and sodium acetate trihydrate as a PCM, saving the heat during electricity generation. By a techno-economical approach, the research aimed to optimally size two latent and sensible heat-storage systems for micro-CHP systems in two residential buildings [16]. Their research exhibited that using PCM storage results in larger heat exchangers than sensible heat-storage systems.

Operational and cycle optimization of BCHP-TES systems is another interesting topic that has drawn the attention of researchers. By a dynamic simulation methodology, the optimal storage capacity for various CHP biomass-boiler operational statuses such as boiler on-time, boiler off-time and maximum boiler output temperature was evaluated by Wang *et al* [17]. The optimal heat-storage capacities for low, medium, intermittent, variable and high heat-demand profiles were optimized [17]. A hybrid power system consisting of solar-biomass subsystems equipped with thermal storage for heat recovery was thermodynamically analysed and techno-economically optimized by Pantaleo [18]. In this research, a wood-chips biomass-fired boiler equipped with a bottoming Organic Rankine Cycle (ORC) and solar panels was integrated and thermal storage was used as a linkage between the top and bottoming cycles. The size of the TES via a genetic algorithm (GA) was optimized and resulted in the fact that a hybrid biomass-solar system increases the system efficiency and flexibility. However, it inflicts costs that need incentives and supportive tariffs for justification [18]. In a techno-economic study by Sorrentino *et al.*, the heat demand of a commercial building was analysed to optimize the configuration and size of a biomass-fired boiler coupled with Organic Rankine Cycle and TES systems [19]. The molten-salt type of TES had been added to decouple the boiler from the Organic Rankine Cycle and avoid partial operational and low efficiency [19]. Pfeifer *et al.* focused on unused land in Croatia to evaluate the economic feasibility of biomass for combined cooling and CHP purposes with heat storage [20]. Based on scenarios, they analysed the economic behaviour of the biomass-fed poly-generation that was running 90°C TES with an efficiency of 80%. The heat generation of ≤ 30 MWt and electricity generation of ≤ 15 MWt were accounted for by system sizing. By the methodology used, they calculated the biomass price from farm-establishment, workforce and mechanization costs per

hectare of a farm [20]. Sameti *et al.* [21] worked on the optimized capacity of the thermal and electrical energy storage together with the supply side of a district-heating system to minimize both carbon emission and total operation and investment costs for grid-connected, stand-alone and net-zero energy systems. Several fuels including biomass are considered in the optimal solution. Coelho *et al.* techno-economically analysed the feeding syngas and biogas to a central receiver system for two base and hybrid cases in Portugal [22] including thermal storage. They compared various hybridizations of biomass and central receiver systems to find the case with a lower levelized cost. The simulation analysis for energy demand, solar fluxes and air cycles was run to evaluate the economy of the scale using various software. They delivered the optimal size for a central receiver system equal to 4 MWe. The used biogas in this study was supplied from wastewater treatment.

3 DHS: biomass-fired CHPs as the energy source

A district-heating system comprises a network of pipes, heat exchangers, pump houses and substations carrying heat from a power plant, in this study biomass-fired CHPs, to buildings. Hot water or steam carries the energy for the domestic or industrial hot-water supply to meet heating demands. Heat substations (heat exchangers) may be used to extract energy from the working fluid [23]. In addition to technology adoption, thermodynamic or mechanical parameters for designing CHPs in district-heating and -cooling systems, fuel selection, especially biomass for BCHPs, and its chemical and environmental issues emerge in the integrated biomass-fired CHP design. Therefore, some studies have focused on biomass-fuel/conversion technology selection as well as system configurations. Fuel selection involves a combination of biomass with fossil fuels such as natural gas, diesel or coal, or other renewable sources such as solar and wind energies [24]. A previous review evaluating different sources for district heating and cooling can be found in Ref. [25], especially by introducing challenges in fossil-fuel boilers and districts, and opportunities to use biomass for Swedish district heating.

In Italy, for a new nearly zero-energy district with BCHP close to Milan, the assessment of coupling photovoltaics (PV) and groundwater heat-pump systems as the weather-dependent and -independent generation unit is studied to achieve a fully renewable district-heating and -cooling system [26]. In another study, the implementation of district heating driven by BCHP units in rural areas in the continental areas of Spain is investigated. Because of the considerable numbers of unoccupied or partially occupied buildings in rural areas, the methodology is successfully applied for ~500 rural municipalities with a population of >1500 inhabitants [27]. In another study in Italy, an evaluation is carried out in terms of technical considerations and the performance of several BCHP-driven district-heating

units fed by wooden chips and several improvements and drivers were proposed [28].

Researchers in Ref. [29] employed an optimization tool to demonstrate the impact of conversion technologies delivered by the DHS under different operational strategies of BCHPs on the costs and demands of costumers. As a conclusion, for optimal results, DHS modelling should focus on synthesis, design and operations, as shown in Fig. 5. At the synthesis level, designers identify the configuration of the DHS system and its components by illustrating the system layout, including linear, radial, loop, mesh or tree-shaped networks. The geographical and geotechnical constraints for a DHS are incorporated in this phase, accounting for excavation, space required, trench depth, pipe elevation and energy source. In the design phase, the models involve the energy-supply profile from BCHPs, its operation temperature range, operating fluid flow inside the BCHP, insulation and pipe materials, and other hydraulic and mechanical parameters. These characteristics are well researched, as reported in recent studies [30]. In the operational phase, the system control to ensure the optimized delivery of energy from BCHPs is considered [31]. In this phase, the energy-dispatch or return-temperature mechanism is targeted to achieve optimized values for flow rates, optimal feeding of biomass, temperatures, time schedules of pump operation or the activation order of the substations [32].

Sartor *et al.* [33] used geometrical modelling in which a steady-state 2D simulation was performed to identify heat-loss patterns; on that basis, they provided the optimized utilization time for a biomass power plant as the BCHP serving a DHS. This optimization results in the best temperature and flow mechanisms for dispatching control of the heating network. Powell *et al.* investigated DHSs and heat storage with a dynamic programming approach to identify the best time sequence of the heat-storage charging/discharging. The strategies for optimization are categorized based on varying parameters, such as mass-flow and temperature values [34]. Jie *et al.* investigated four different strategies based on fixed or variable flow rates to minimize the sum of the annualized initial and operating costs for the hybrid BCHP supply system. They used a static approach, in which the provision of energy to consumers is based on a fixed, predetermined supply temperature [35]. Karschin *et al.* used the net present value of pipes and buildings in the Graph theory as the weights for calculating the delivered-energy cost by the CHP plants. By this approach, the pattern of the heating network and the user's connection BCHP-plant numbers and locations were

optimized. To model the DHS, they implemented Steiner nodes to account for the construction costs of the heating network and the revenue from selling heat to the connected nodes [36].

The literature review on the integration of BCHPs into DHS modelling indicates some pre-existing requirements for BCHP-system efficiency:

- including implementation in densely populated areas;
- using BCHPs with higher loading factors;
- full schedule capacity for BCHP operations;
- lower supply temperatures in BCHPs;
- de-centralization of generators by using micro-BCHPs;
- integration of heat storage with BCHPs as discussed in Section 3 of this article.

However, these requirements come with higher capital or maintenance costs. Moreover, there is a need to use optimal controls to minimize delays in satisfying the needs of distant users in the DHS network at the end points of the network. Such a delay could contribute to inefficiencies and mismatches between energy demand and BCHP production in the DHS [37]. Murugan *et al.* [38] surveyed the technologies to be employed in DHS and different fuels including biomass widely used in CHP and BCHP systems, from coal boilers to fuel cells and gas turbines for residential applications including district heating and individual utilizations. Several studies have also focused on small or micro-CHP or BCHP systems supplying energy for a small single building as the decentralized DHS. Due to limited studies on fuel cells and better functioning in electricity production, fuel cells are not typically used for heat-generation applications [39–41].

Different optimization techniques are used for the type of biomass fuel, the technology of BCHP and its size, from fuzzy or fuzzy-family programming to sensitivity analysis, while there are several options for the supply side of the DHS. These methods have also been combined with the life-cycle-assessment concept for BCHP and other co-production units [42, 43]. The intricate nature of these techniques highlights the necessity for solving software. Li *et al.* [44] used Aspen Plus to analyse the possibility of co-firing biomass (see Fig. 3 in Section 1 of this article) in a BCHP. They concluded that torrefied biomass would provide maximum efficiency and minimum emissions. In a similar study, Prakash *et al.* [45] used Aspen Plus to develop a process model for the gasification of various biomass as a fuel for BCHPs in a DHS. Other researchers used this software to optimize hybrid BCHP systems with other renewable and non-renewable sources in a DHS [46, 47].



Fig. 5: Interaction of DHS optimization with BCHP design

As an example, Rivarolo *et al.* [5] developed the Web-Based Economic Cogeneration Modular Program software to introduce a thermo-economic model for B CHP-plant configuration targeting smart poly-generation from natural gas as the non-renewable source. The thermo-economic approach is usually followed by a sensitivity analysis to arrive at the best set of design parameters [48].

A number of researchers have focused on the detailed operation of B CHPs as the heat and electricity source for a DHS network. Moharamian *et al.* and Ziebigket *et al.* used Engineering Equation Solver to solve a mathematical model to identify the optimal thermodynamic properties of a B CHP system in a DHS based on mass, energy and exergy balances [49]. Wang *et al.* [50] used Energy PRO software to model the co-production of solar energy with B CHP as the primary source of heat production in a DHS. Working fluid in both B CHP and DHS network is a significant factor in sensitivity analysis and efficiency enhancement. The fluid is selected according to thermodynamic, environmental and economic features. It should be cost-efficient, non-flammable, chemically stable and have no or low toxicity. Stijepovic *et al.* [51] analysed the impact of working fluids on the total efficiency and performance of B CHPs as a practical application for DHS. Invernizzi *et al.* [52] investigated the use of titanium tetrachloride as a novel working fluid that could provide a stable flow of $\leq 500^{\circ}\text{C}$, which can be used to supply industrial demands as well as providing heat for DHS at the same time.

Operational strategies of B CHPs to generate heat for DHS can be built based on three approaches [6]:

- a heat-tracking approach, which aims to set the system to provide heat and electricity at the required level or above;
- a fixed-point operation, which is based on rated or nominal values designed for maximum efficiency;
- a hybrid-operation strategy, which is a combination of the two approaches above.

Multi-objective optimization, which considers financial, technical and environmental objectives, is also used in DHS-connected B CHP-system optimization. Solving such problems requires powerful solvers with more intricate approaches. If the scales of objective functions are considerably different, normalization of objectives can be carried out [53]. Designers have widely implemented the GA and its decomposition techniques in multi-objective optimization. Designers can use the GA to construct a Pareto front by finding global and local solutions in an iterative fashion [54]. They can also employ life-cycle costing (LCC) for system financial analysis and optimization. With LCC, the total annualized costs for the whole service life of a system are calculated using net present value, the discounted payback period, internal rate of return or annuity factors [55].

A few studies have considered the application of both thermal-energy storage and biomass-driven districts at the same time for cogeneration (B CHP+DHS+TES). Verda *et al.* [56] examined the potentials of implementing heat

storage in a B CHP+DHS+TES configuration to reduce fuel consumption by optimal designing of the storage tank using a finite difference model for heating seasons. Franco *et al.* [6] used a multi-objective optimization model for optimum sizing and scheduling of a B CHP+DHS+TES system to maximize the operational share. They considered a number of scenarios for energy demand and system efficiency to identify an optimal time and start/turn-off pattern for the thermal storage. Noussan *et al.* technoeconomically analysed the optimal configuration of the biomass-fired Organic Rankine Cycle system integrated with DHS. The multiple-parameter simulation and sensitivity analysis were conducted based on the long-term operation of the existing district-heating system along with changing the component size. Maximum heat-storage capacity, primary energy saving and the payback period were the result of the research for various configurations [57]. A feasibility study for applying the TES with B CHP and DHS was carried out by Volkova *et al.* By scenario-based analysis, the influence of the TES size on the performance of the large-scale B CHP–DHS systems was evaluated. They showed that there is a strong relationship between electricity generation and subsidy policies [58]. In a study for a district-heating network in Belgium, a retrofit of an existing system including a B CHP unit and a TES is considered to find the best heat-storage capacity to reach the maximum environmental, economic and energetic objective functions [59]. Summary of the literature reported and reviewed in the above section is presented in Table 1.

4 Technical and design considerations of B CHPs

4.1 Prime movers for B CHPs

The prime mover for biomass-powered systems is the subject of the optimization to provide biomass as an appropriate fuel for B CHP energy supply whether in DHS applications or for other individual purposes. Steam turbines in extraction, back-pressure or condensing types, gas turbines in single or combined cycles, reciprocating engines in internal and external combustion sorts, and fuel cells are among the technologies used for this purpose. They are available in demonstrated or commercialized states for both large- and small-scale applications. Table 2 shows a taxonomy of the characteristics and comparison of the prime movers used in biomass-powered systems. Technology selection also has many subjects to be regarded for optimization. The exact analysis of the different technologies has been carried out in many approaches and for numerous pieces of research. Their range, operating fluids and operating cycles have been subjects of research. Researchers have analysed thermodynamic cycles such as the Rankine Cycle in CHP systems [49, 50, 53, 57].

Due to their features, primarily intended for small-scale applications in farms, remote villages or off-grid small buildings, they are suitable for cases near biomass

Table 1: A summary of the key literature on CHP–DHS systems and their characteristics

Approach	Energy source	Technology	Purpose	Authors	
Thermo-economic	<ul style="list-style-type: none"> ▪ Biomass ▪ Electricity ▪ Geothermal 	<ul style="list-style-type: none"> ▪ Boiler ▪ Steam turbine ▪ Gas turbine ▪ Ground-source heat pump 	<ul style="list-style-type: none"> ▪ Heat ▪ Electricity 	Li et al. [44]	
	<ul style="list-style-type: none"> ▪ Geothermal ▪ Sunlight ▪ Biomass 	<ul style="list-style-type: none"> ▪ Ground-source heat pump ▪ Solar ▪ Boiler ▪ Absorption chiller ▪ Organic Rankine-Cycle turbine 	<ul style="list-style-type: none"> ▪ Heat ▪ Cooling ▪ Heat ▪ Electricity ▪ Hydrogen 	Trillat-berdat et al. [60]	
	<ul style="list-style-type: none"> ▪ Biomass ▪ Natural gas 	<ul style="list-style-type: none"> ▪ Boiler ▪ Steam turbine 	<ul style="list-style-type: none"> ▪ Heat ▪ Electricity ▪ Cooling 	Sartor et al. [33, 59]	
		<ul style="list-style-type: none"> ▪ Boiler ▪ Steam turbine ▪ Gas turbine 	<ul style="list-style-type: none"> ▪ Heat ▪ Electricity 	Noussan et al. [57] Moharamian et al. [49]	
	<ul style="list-style-type: none"> ▪ Biomass 	<ul style="list-style-type: none"> ▪ Boiler ▪ Steam turbine 	<ul style="list-style-type: none"> ▪ Heat ▪ Electricity 	Prakash et al. [45]	
			<ul style="list-style-type: none"> ▪ Heating ▪ Electricity ▪ Cooling 	Lian et al. [62]	
	<ul style="list-style-type: none"> ▪ Typical fossil fuel 	<ul style="list-style-type: none"> ▪ Steam boiler ▪ Turbine 	<ul style="list-style-type: none"> ▪ Heat ▪ Electricity 	Ziebig [63]	
	<ul style="list-style-type: none"> ▪ Sunlight ▪ Natural gas ▪ Electricity 	<ul style="list-style-type: none"> ▪ Boiler ▪ Steam turbine ▪ PV cell ▪ Chiller 	<ul style="list-style-type: none"> ▪ Cooling ▪ Heating ▪ Electricity 	Ruan et al. [64]	
	<ul style="list-style-type: none"> ▪ Biogas ▪ Natural gas ▪ Diesel 	<ul style="list-style-type: none"> ▪ Microturbine 	<ul style="list-style-type: none"> ▪ Heating ▪ Electricity 	Pirkandi et al. [48]	
	LP	<ul style="list-style-type: none"> ▪ Natural gas 	<ul style="list-style-type: none"> ▪ ICE ▪ Gas turbine ▪ Chiller 	<ul style="list-style-type: none"> ▪ Cooling heat ▪ Electricity 	Ünal et al. [30]
		<ul style="list-style-type: none"> ▪ Natural gas ▪ Solar 	<ul style="list-style-type: none"> ▪ Chiller ▪ Gas turbine ▪ PV cells 	<ul style="list-style-type: none"> ▪ Cooling ▪ Heating ▪ Electricity 	Ondeck, et al. [32]
		<ul style="list-style-type: none"> ▪ Biomass ▪ Natural gas ▪ Heavy oil ▪ Solar 	<ul style="list-style-type: none"> ▪ Boiler ▪ Steam turbine ▪ Gas turbine 	<ul style="list-style-type: none"> ▪ Heating ▪ Electricity 	Wang et al. [17]
<ul style="list-style-type: none"> ▪ Natural gas ▪ Electricity 		<ul style="list-style-type: none"> ▪ ICE ▪ Steam boiler 	<ul style="list-style-type: none"> ▪ Heating ▪ Electricity 	Franco et al. [53]	
MILP`		<ul style="list-style-type: none"> ▪ Natural gas ▪ Electricity 	<ul style="list-style-type: none"> ▪ Chiller ▪ Steam turbine ▪ Boiler ▪ Solar ▪ PV cell ▪ Wind turbine ▪ Heat pump 	<ul style="list-style-type: none"> ▪ Cooling ▪ Heating ▪ Electricity 	Sameti et al. [65, 66]
		<ul style="list-style-type: none"> ▪ Restored heat ▪ Natural gas ▪ Electricity 	<ul style="list-style-type: none"> ▪ Organic Rankine Cycle ▪ ICE ▪ Microturbine ▪ Chillers ▪ Microturbine ▪ Steam boiler ▪ ICE 	<ul style="list-style-type: none"> ▪ Heat ▪ Heating ▪ Electricity ▪ Cooling ▪ Heating ▪ Electricity 	Stijepovic et al. [51] Rivarolo et al. [5]
		<ul style="list-style-type: none"> ▪ Microturbine ▪ Steam boiler ▪ ICE 	<ul style="list-style-type: none"> ▪ Cooling ▪ Heating ▪ Electricity 	Casisi et al. [67]	

Table 1: Continued

Approach	Energy source	Technology	Purpose	Authors
NLP	<ul style="list-style-type: none"> ▪ Fossil fuel ▪ Geothermal 	<ul style="list-style-type: none"> ▪ Ground-source heat pump ▪ Biomass ▪ Fossil fuel 	<ul style="list-style-type: none"> ▪ Heating ▪ Electricity 	Moret et al. [40]
	<ul style="list-style-type: none"> ▪ Biomass 	<ul style="list-style-type: none"> ▪ Boiler ▪ Gas turbine ▪ Bottoming Rankine Cycle ▪ Back-pressure steam turbines ▪ Gas engines ▪ Gas turbines in combined cycles 	<ul style="list-style-type: none"> ▪ Heat ▪ Electricity 	Jørgensen et al. [68]
	<ul style="list-style-type: none"> ▪ Sunlight ▪ Natural gas ▪ Chillers 	<ul style="list-style-type: none"> ▪ Solar ▪ Boiler 	<ul style="list-style-type: none"> ▪ Heating ▪ Electricity ▪ Cooling 	Buoro et al. [70]
	<ul style="list-style-type: none"> ▪ Natural gas ▪ Electricity 	<ul style="list-style-type: none"> ▪ Gas boiler ▪ Gas turbine ▪ Fuel cell ▪ Steam boiler ▪ Electric and absorption chillers 	<ul style="list-style-type: none"> ▪ Heating ▪ Electricity ▪ Cooling 	Jing et al. [71]
	<ul style="list-style-type: none"> ▪ Gas ▪ Coal 	<ul style="list-style-type: none"> ▪ Steam turbine ▪ Boiler 	<ul style="list-style-type: none"> ▪ Heating ▪ Electricity 	Golla et al. [72]

LP, linear programming; MILP, mixed-integer linear programming; NLP, nonlinear programming.

feed stocks. They are increasingly gaining attention for remote and isolated communities to be served as stand-alone DHS, either lacking an energy infrastructure or having high costs. Despite the similarity in all components with larger-scale applications, the modular system suffers from limitations. These limitations highlight some technologies and processes for being implemented in their utilization. For example, there are Stirling engines sizing from 500 W to 10 kW and small back-pressure steam turbines ranging from 100 kW to several megawatts are defined in modular systems, each of which has their benefits and disadvantages. The small steam modular systems have the lowest electricity efficiency, while the Stirling systems have the highest thermal and overall efficiencies. Another configuration is modular hybrid gasification/combustion, in which gas is produced in a chamber with a lower temperature of 550–800°C and is then combusted in a hot chamber up to 1300°C. This process reduces the need for cleaning and provides higher combustion quality. The advantages of modular systems are the simplicity of combustion, the high quality of gasification, using a low-heat-value biomass such as forest thinning and wood chips, and remote application. The disadvantages are low electricity efficiency, low electricity-to-thermal ratios, high costs and higher installation areas compared to gas-fired peer systems.

The optimization results provide the bedrock for comparison between the gasification and combustion techniques. The overall advantages of gasification over direct combustion can be summarized as efficient clean-up, lower heat loss in syngas generation, high-temperature and high-pressure syngas, higher temperature of the flue

gas, lower corrosion or slagging risks, heat recovery from the reaction zone and exhaust flue gas for drying biomass or incoming air, higher efficiencies of $\leq 80\%$ once integrated into CHP systems and lower capital cost.

4.2 Increasing B CHP efficiency

Flue-gas-condensation recovery has recently drawn attention in biomass-fuelled CHP design due to increased efficiency. This process plays a key role in B CHP units, as it is able to connect the cleaning of flue gas and wastewater treatment, which results in higher efficiency of simultaneous heat and electricity generation [73], as shown by Fig. 6 at the DHS level. Zajaks et al. performed the theoretical feasibility of using flue gas at 130°C to feed heat to a district-heating system at low temperature by driving a heat pump [74]. A waste-heat-recovery system through latent heat was designed by Terhan and Comakli from a 60-MW DHS boiler at a university campus by water-vapour condensation. An economic analysis is followed by the design to evaluate the payback period [75]. Mudasar et al. investigated the viability of a theoretical thermodynamic cycle, ORC cycle, based on the flue gas of a biomass-fuelled boiler and designed a new B CHP cycle for domestic power production for rural areas based on a biogas-fired ORC cycle [76].

5 Future research situation of B CHPs

DHS and B CHP systems are also gaining momentum in the realm of smart-energy-system research and practice [77, 78]. Emerging energy systems are equipped with

Table 2: A taxonomy of biomass-energy-conversion technologies for CHP [49, 50, 53, 57]

Prime mover	Range (MW)	Integrated system	Output	Advantages	Challenges
<ul style="list-style-type: none"> • Steam turbine • Condensing boiler • Extraction turbine • Back-pressure turbine 	0.05–250	<ul style="list-style-type: none"> • Boilers • Absorption chillers 	<ul style="list-style-type: none"> • Electricity • Thermal power • Steam • Hot water • Hot air • Chilled water 	<ul style="list-style-type: none"> • Fuel versatile • Size versatile 	<ul style="list-style-type: none"> • Lower efficiencies and higher costs
<ul style="list-style-type: none"> • Gas turbines • Simple cycle • Combined cycle 	0.5–40		<ul style="list-style-type: none"> • Mechanical power • Compressors • Pumps • Fans 	<ul style="list-style-type: none"> • Lower costs • Higher efficiencies 	<ul style="list-style-type: none"> • Inlet-temperature limitation due to blade-material strength • Lower air-to-fuel mixture for biogas than for natural gas • Proposed further for landfill • And wastewater • Lower electrical efficiencies than larger gas turbines
<ul style="list-style-type: none"> • Microturbine 	0.03–0.25	<ul style="list-style-type: none"> • Recuperator 		<ul style="list-style-type: none"> • Simple design 	<ul style="list-style-type: none"> • Reduced maintenance compared to reciprocating engines • Alternators to process the electricity frequency
<ul style="list-style-type: none"> • Reciprocating Internal Combustion Engine (ICE) • Spark ignition • Engines • Compression ignition 	<5	<ul style="list-style-type: none"> • Desiccants • Engine-driven chillers 		<ul style="list-style-type: none"> • Low necessary modification • Less clean-up • Less expensive • Fuel diversity 	<ul style="list-style-type: none"> • Emergency standby or limited duty-cycle service • Air emission concerns (NOx and particulates) • High wear and tear • Higher O & M • Complex heat recovery • Not commercially developed for low British Thermal Unit gases.
<ul style="list-style-type: none"> • Reciprocating Internal combustion engine (ICE) • Stirling engines 	<0.2			<ul style="list-style-type: none"> • High thermal efficiency • Low emission • Low noise 	<ul style="list-style-type: none"> • Small capacities • Low electricity efficiency
<ul style="list-style-type: none"> • Fuel cells • Phosphoric-acid fuel cell (PAFC) • Proton-exchange-membrane fuel cell (PEMFC) • Molten-carbonate fuel cell (MCFC) • Solid-oxide fuel cell (SOFC) 	0.00005–2		<ul style="list-style-type: none"> • Electricity 	<ul style="list-style-type: none"> • High electrical efficiency (up to twice ICE) • Low emissions • No combustion • Very quiet 	<ul style="list-style-type: none"> • Very high cost • Low durability • Difficult maintenance • Clean-up technology for fuel cell in early stage • No experimental results • High cleanliness levels • PAFC: very hydrogen-rich, no methane • PEMFC: <10 p.p.m. CO • Early stage for commercialization

information-processing and predictive controls, and the integration of these technologies with fourth-generation DHSs enhances access to renewable-energy sources once considered infeasible due to low efficiency or unavailability. Biomass is one such renewable resource with lower economies of scale and supply-chain reliability and dispersion issues. Distributed energy-generation units offer increased potential for biomass by opting into supply resources that are closer to B CHP plants.

Smart energy generation, first defined for Denmark focusing on the transportation sector and bioenergy, is a holistic and cross-sectoral energy system, defined with characteristics such as: 100% renewable-energy systems, storage synergies across energy subsectors, exploitation of low-value energy sources. A comprehensive approach incorporates the domains in biomass-fuel supply and energy distributions through B CHPs so it has interfaces with low-temperature district heating, low-content energy sources, energy storage and previously less utilized technologies such as heat pumps, electrolyzers and liquid fuels for the transportation sector [79]. Traditional and modern approaches towards energy generation are illustrated in Table 3. Lower supply and return temperatures (50~60°C for modern DHS) in the thermal grid will offer added advantages in the heat-production side [80]:

- improved power-to-heat ratios in the B CHP units;
- efficient recovery of heat through flue-gas condensation;
- improved coefficients of performance for heat pumps;
- potential use of heat sources with lower temperatures (i.e. industrial);
- improved sunlight-to-fluid heat transfer in solar thermal collectors;
- higher capacities for TES.

As previously stated, B CHP approaches are going further towards co-production with other renewables. Renewables are of fluctuating supply, intermittent- and low-efficiency types and coupled with distributing networks, prone to energy loss, which calls for a shift from the undistributed fossil-fuel CHP towards the distributed micro- or full-sized B CHP [81]. A hybrid energy system that supplies energy from various sources has been defined to increase the flexibility of renewable-energy systems together with B CHPs. Such a huge shift towards efficient energy systems and fourth-generation DHS grids entails a great shift in the optimization of such systems, both for new requirements raised for the future and more complex objectives.

6 Conclusions

This study has provided a structured review of and insights into the existing literature on the modelling and integration of B CHPs into DHS, and applications of TES in B CHPs from design, configuration and operational perspectives.

The objective functions in the reviewed optimization models were primarily of a financial and environmental nature. Some other factors, such as the share of renewable sourcing, were also used in those analyses. The optimization has been carried out based on implicit and explicit approaches, which mostly included a parametric or sensitivity analysis. They could be based on either the thermodynamic, hydraulic, chemical or costing parameters and decision variables as a result of the focus on energy, exergy or financial analysis. In the case of biomass-powered energy systems, there were additional parameters and decision variables incorporated into the models as related

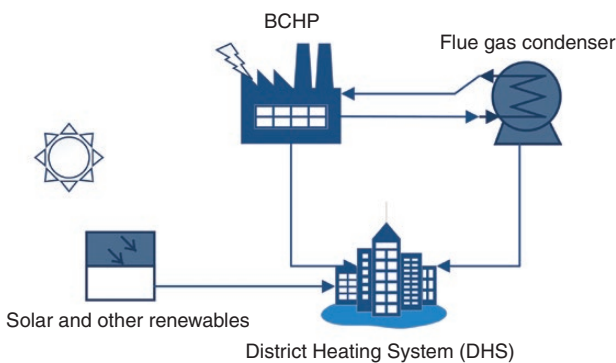


Fig. 6: Integration of flue-gas condenser with B CHP-driven district heating

Table 3: A comparison of conventional and modern approaches towards integrated energy-generation and -distribution systems at DHS

Component	Conventional approach	Modern
Resource	Fossil fuels	Renewables
Energy generation	Single-technology Combined heat and power (CHP)	Multi-generation Bioenergy
Technologies	Centralized energy conversion Combustion-based cycles Waste-heat recovery Seamless integration	Decentralized energy conversion Non-combustion-based cycles Storage Hybrid
Energy distribution	On-site grids Centralized	Off-grid Decentralized
Network temperature	High (>100°C)	Low (50~60°C)

to processing activities, moisture levels or chemical compositions.

Based on the reviewed literature, several issues and gaps are still in need of further research. Exergy analysis should be incorporated into all optimization modelling of BCHPs due to its impact on the final and real costs. In the case of direct combustion, optimization of the design and operation of a combustion chamber to improve its efficiency could reduce the exergy loss resulting from biomass-processing activities. The life cycle and supply-chain environmental impact of the biomass should be incorporated into DHS-CHP design, configuration and operation models. Despite introducing biomass as a carbon-neutral fuel, the environmental side effects such as particulates, poisonous by-products, resource depletion and soil fertility could be problematic, depending on the scale and location of the biomass facilities. Considering biomass as a zero- or low-carbon source of energy highly depends on the rate of plantation for the non-waste stream.

Syngas is generally of low heat value in comparison with fossil fuels, making challenges for its use in typical gas or steam turbines for BCHP-driven DHS. Therefore, mixing the syngas with natural gas or using a coal-fired subsystem has been investigated as a solution. It highlights the importance of incorporating sourcing strategies as decision variables in the supply-chain component of CHP-DHS optimization models.

Further, the economic feasibility of biomass-powered CHP-DHS systems is in line with the availability of carbon-reduction incentives, taxes or renewable-energy incentives. It is thus of particular importance to investigate the sensitivity of optimization models of CHP-DHS systems to such policies. Sensitivity analysis should avoid overestimation of the competitiveness and analyse system performance with varying incentives over time.

The research also emphasizes the multidimensionality of CHP-DHS systems, requiring models that incorporate several objectives (in the form of multi-objective optimization) or several targets (in the form of goal programming) in the design and operational optimization. These criteria are of a thermodynamic, hydraulic, chemical and financial nature. They can be prioritized by weighing factors depending on the preferences and priorities of decision-makers in line with budget limitations, the size of the served communities and the available technologies. Therefore, an explicit two-phase model could best serve CHP-DHS systems using biomass, in which a multiple-criteria decision-making step is used to arrive at the priorities of the objectives mentioned above. These weights will then be fed into a multi-objective optimization model to arrive at the optimal design, configuration and operating decisions.

There is also a need for a post-optimization assessment step, in which a supply-chain continuity model can be built using the reliability theory for the future operation of the DHS over its lifetime. In this regard, the outcomes of the optimization model will be associated with their

likelihood, measuring the chances of the optimal scenarios taking place, in case of uncertainties in the supply chain of biomass.

Conflict of Interest

None declared.

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