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Environmentally Constrained Optimal Dispatch Method for Combined Cooling, Heating, and Power Systems Using Two-Stage Optimization

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Abstract: The reliance on coal-fired power generation has gradually reduced with the growing interest in the environment and safety, and the environmental effects of power generation are now being considered. However, it can be difficult to provide stable power to end-users while minimizing environmental pollution by replacing coal-fired systems with combined cooling, heat, and power (CCHP) systems that use natural gas, because CCHP systems have various power output vulnerabilities. Therefore, purchasing power from external electric grids is essential in areas where CCHP systems are built; hence, optimal CCHP controls should also consider energy purchased from external grids. This study proposes a two-stage algorithm to optimally control CCHP systems. In Stage One, the optimal energy mix using the Lagrange multiplier method for state-wide grids from which CCHP systems purchase deficient electricity was calculated. In Stage Two, the purchased volumes from these grids were used as inputs to the proposed optimization algorithm to optimize CCHP systems suitable for metropolitan areas. We used case studies to identify the accurate energy efficiency, costs, and minimal emissions. We chose the Atlanta area to analyze the CCHP system's impact on energy efficiency, cost variation, and emission savings. Then, we calculated an energy mix suitable for the region for each simulation period. The case study results confirm that deploying an optimized CCHP system can reduce purchased volumes from the grid while reducing total emissions. We also analyzed the impact of the CCHP system on emissions and cost savings.

Keywords: absorption chiller; combined cooling; heating; and power; emission; microturbine

1. Introduction

Scheduling for conventional generation units has generally focused on economic dispatch to satisfy the system load at the lowest cost based on the optimal transmission and operation. For example, cost minimization defined by the United States Energy Policy Act (2005) aims to provide energy reliably to the consumer through capacity and cost awareness when operating power generation and transmission facilities [1]. Fossil fuel use increased dramatically from the beginning of the industrial revolution and is used throughout global industry, with enormously increased emissions as a result. For example, SO_2 prevalence, which increases acid rain, gradually increased in China in the period 2001–2015. Consequently, China implemented a five-year plan to reduce SO_2 emissions by 8% during 2011–2015 with a subsequent 15% reduction in the period 2016–2020 [2]. NO_x emissions have also increased 3-6-fold worldwide due to anthropogenic activity [3], and greenhouse gas (GHG) concentrations have increased due to reckless development plans that were formulated without regard for the environmental impact [4]. The New Zealand (NZ) Clean Air Act (1990) highlighted how to dramatically reduce SO₂ emissions generated by electricity generation [5], with the New Zealand government implementing a plan in 2007 to replace 90% of the electricity sector with renewable energy by 2025 for national energy power production [6]. Moreover, research on European regions presents pollutant



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). emissions (e.g., SO_2 and NO_x) as a result of generation through mean-varying models and argues for the importance of using natural gas over conventional fossil fuels [7].

Recent electricity generation research has expanded economic dispatch to consider environmentally constrained equal and unequal constraints. Among currently commercialized generators, combined heating and power (CHP) systems generate highly efficient energy by jointly generating useful heat and electrical energy from natural gas. For example, microturbines (MTs) achieve a 65–75% efficiency [8] by reusing CHP waste heat using absorption chillers (ABCs) and using renewable energy from photovoltaic (PV) systems. Many studies have examined policies that aim to reduce emissions from existing generators and to increase electricity efficiency and heat energy efficiency.

Generally, ABC, MT, or PV systems combine cooling, heating, and power (CCHP), and the impact of the CCHP and PV systems on power grids with renewable energy generation have been widely analyzed [9]. Ogunjuyigbe et al. [10] minimized CO₂ emissions, life cycle cost, and dump energy using distributed generation rather than large diesel generators and implemented the genetic algorithm (GA) for grid-embedded PV, wind, split diesel, and battery hybrid energy systems for residential buildings. Bernal-Agustín et al. [11] considered costs and emissions simultaneously, applying the Pareto evolutionary algorithm to a multi-objective design with isolated hybrid systems (e.g., PV, wind, and diesel). CCHPs were preferred as efficient systems for this desired power combination. Other studies have considered the improved energy efficiency and minimized emissions and costs associated with CCHP systems. Ren et al. [12] proposed a mixed-integer nonlinear programming model and examined the optimal storage tank size and the key components for residential CHP systems while minimizing annual costs and CO₂ emissions to meet energy policies. Kim et al. [13] considered the energy efficiency and economic sensitivity for CCHP systems used in residential, commercial, and industrial buildings using HOMER software, and analyzed the effects of the CCHP system on economic efficiency, and environmental aspects. Ren et al. [14] proposed a hybrid combined cooling heating and power system integrated with solar and geothermal energies and obtained the Pareto-optimal solutions for the configurations of a hybrid system. Wang et al. [15] defined the flexibility of hybrid CCHP systems and constructed a multi-objective optimization model considering flexibility while analyzing the influence of flexibility on system performance.

Previous studies aimed to minimize CO₂ emissions while satisfying electric power demand, but they rarely considered NO_x, another GHG, or SO₂, which causes acid rain. Moreover, water is another resource that ought to be reduced. Hence, no previous study has considered dispatch models for CHP systems that have simultaneously considered (CO₂, SO₂, NO_x) and water usage, and ABC usage. CCHP systems usually have a relatively small capacity compared with conventional power generation units and have a limited reliability in relation to the provision of sufficient power for the total load required for a region since they are not normally used for centralized power generation. Therefore, residential communities with CCHP systems commonly purchase electric energy from the power grid. For example, the Georgia Power company produced power for USD 24.70/MWh and purchased energy at USD 43.3/MWh (175% increase) in 2015 [16]. Therefore, the energy required from the power grid should be minimized or optimized when designing CHP systems. However, it is difficult to determine the exact quantities if the source state or national-wide grid cannot be properly modeled.

Therefore, this paper calculates the energy mix values appropriate for the considered metropolitan area using a two-stage optimization to determine the corresponding generation percentages. We minimized emissions and costs, fully reflecting their environmental impact, considered the energy mix in the region, and included CO_2 , SO_2 , and NO_x emissions and water usage within the proposed objective function. Thus, this study not only optimized the weighting coefficients for the objective function but also the optimal energy mix. We considered a case study to examine the reduced emissions using the objective function with weight coefficients. Generation units with reduced CO_2 emissions often also reduce SO_2 and NO_x emissions, but these can sometimes be increased. Thus, it is essential

to add weighting factors for reducing SO_2 and NO_x (e.g., where soil pollution is severe due to acid rain).

This paper considered not only the reductions in CO_2 , SO_2 , and NO_x emissions and water consumption for a specific reason using equal or adjusted weights, but also verified the proposed CCHP optimization algorithm validity based on the achieved emission reductions. Stage One calculated the optimal energy mix using the Lagrange multiplier implemented in MATLAB for state-wide grids (specifically, Georgia USA). Stage Two used the Atlanta, Georgia energy mix as an input and then optimized the CCHP systems in the area every hour through a complete year (8760 h).

The current study proposes an algorithm to reduce the costs and emissions for CCHP systems connected to residential customers in a metropolitan area. Residential communities with CCHP systems may purchase electric energy from an external grid, e.g., a state or national-wide grid, to cover CCHP generation capacity limitations. The proposed two-stage optimization determined the optimal generation percentages appropriate for the CCHP system using an objective function to simultaneously minimize emissions and costs. An ABC model was also included in the proposed method to provide more feasible optimization and to maximize the effects of the CCHP system. These algorithms can also contribute to the development of power generation planning software that considers weighted costs and environmental emissions.

The proposed method can be also applied to case studies for CCHP systems used in small electric and thermal energy hubs below 1 MW, and as an effective methodology to more accurately determine the impact of CCHP systems for specific regions connected to the grid.

The remainder of this paper is organized as follows. Section 2 defines the problem statement and Section 3 presents the CCHP system, generator, emission, and objective function modeling. Section 4 proposes the two-stage optimization method with weight coefficients to minimize CO_2 , SO_2 , and NO_x emissions, and water consumption. Section 5 discusses a case study and the simulations for the Georgia, USA grid and the Atlanta area, obtaining the optimal energy mix using the proposed two-stage optimization. Finally, Section 6 summarizes and concludes the paper.

2. Problem Statement

Since economic and environmental dispatches are generally enforced at the grid level, dispatches to the metropolitan level have limitations. We propose a two-stage optimization method that can achieve optimization at the metropolitan level, which aims to install optimized CCHP systems in small areas. For this purpose, we assume two scenarios:

- MTs used in CCHP systems can operate at their highest capacity for the primary power load;
- (2) MTs can operate at optimal efficiency for the simulation period to minimize the proposed objective function.

Figure 1 shows the modeled and simulated CCHP system to achieve energy efficiency optimization for the Atlanta area case study. For example, outputs from generators G_1 to G_4 (corresponding to hydroelectric, nuclear, coal, and gas generation) were calculated from their known generating costs or using the optimal generation dispatch algorithm. MTs provide electrical and useful heat energy, and their waste heat energy can also act as input energy to ABCs, i.e., waste heat energy can be recovered using ABCs to cool air and water, which is subsequently used for cooling and heating loads. The proposed two-stage optimization shows that the effect of the recovered cooled air on cooling demand, mostly generated at the highest prices, can dramatically reduce peak demand during summer. The heat energy that MTs cannot supply during winter is provided by gas facilities.

The objective of this study was to analyze the impact of the CCHP system on emissions and cost savings and to optimally schedule the CCHP systems suitable for a metropolitan area. Therefore, this study modeled six coal-fired, two nuclear, thirteen gas-fired, one hydro, and two small plants for the Georgia, USA grid [17,18]. We proposed a two-stage

optimization to determine the required energy purchased from the grid that CCHP systems could not provide. After determining the state-wide grid energy, we downscaled that energy mix to the metropolitan residential community grid for Atlanta, USA, including the CCHP system.



Figure 1. Residential home example including CCHP systems.

3. Combined Heat and Power and Emission Output

3.1. Combined Heat and Power System

A CCHP system includes MTs and ABCs. MTs generate heat, as well as electrical output, and CCHP systems usually use this waste heat as input to an ABC to generate chilled air or water, which is then used for cooling loads. Since the average generating costs of CCHP systems are higher than those of conventional generators (e.g., coal-fired, or nuclear plants), a CCHP system is often prominent at the peak hours, rather than at the baseload. For example, on the hottest days of summer, the demand for cooling loads increases significantly. In this situation, the possibility of replacing the demand for cooling loads with the output of ABCs increases so that energy efficiency can be maximized. This means that users of CCHP systems can purchase less electric energy from the grid. Chilled air or water recovered from the waste heat of MTs can increase energy utilization and total efficiency. CCHP systems also generally offer advantages in environmental pollution emissions since they use natural gas, which releases relatively fewer emissions than other fuels. CCHP efficiency is highly dependent on local weather and climate, hence we used thermal load profile data on average weather conditions (e.g., typical meteorological year data) in the case study in the United States.

3.1.1. Microturbines

Generally, MTs use natural gas as fuel. We selected the C65 (65 kW) capstone model as an example MT, assuming a residential community with 1700 residents (669 households) and installed six C65 MTs with a total capacity = 390 kW, i.e., 14.1% total peak electrical load [13]. Figure 2 shows inputs and outputs of the MT, where we used least-squares to linearize the relationships between input (fuel consumption) and output (electrical energy) for the first order and presents the actual measured trends in representative intervals applied to this study.

$$P_i = a_i F_{natural gas, i} + b_i \tag{1}$$

where P_i is MT power output (kW), and $F_{natural gas, i}$ is fuel consumption (L/h).

For example, the considered C65 MTs generates 65 kW of electrical power and 120 kW of thermal power (approximately 408,000 BTU) [19]. Table A1 (Appendix A) shows the detailed parameters for C65 MTs.



Figure 2. Typical microturbine input and output characteristics.

3.1.2. Absorption Chillers

The ABC produces chilled air or water using MT waste heat. ABC generated heat output P_{ABC} has a loss coefficient = 0.75 and a pipe loss coefficient = 0.9 [20]. Using the chilled water to supplement the cooling load reduces the required electrical power purchased from the grid for the cooling load. Let P_{Total} be total power required from the load, and P_{ABC} the cooling load offset from ABCs. Then, the power required from the grid is:

$$P_{Supply} = P_{Total} - P_{ABC} \tag{2}$$

3.2. Generator and Emission Modeling to Develop Optimization Algorithms

This paper implemented optimization algorithms by modeling each generator and emission source using the Lagrange multiplier method.

3.2.1. Steam Turbine Generation

Figure 3 shows an input–output model of the generating unit *i*, which burns fossil fuel, can be formulated as a function of its output [21], and approximated as the following cubic equation:

$$F_i(P_{Gi}) = P_{Gi}H_i(P_{Gi}) = a_i + b_i P_{Gi}$$
(3)

and

$$C_i(P_{Gi}) = f p_i F_i = a'_i + b'_i P_{Gi} + d'_i P_{Gi}^3, \tag{4}$$

where:

 F_i = the fuel input of generating unit *i* in MBtu/h P_{Gi} = the net power output of generating unit *i* in MW C_i = total operating costs in USD/h

 fp_i = the equivalent fuel price of generating unit *i* in USD/MBtu



Figure 3. Typical fuel-cost curve for steam generation [13].

3.2.2. Hydroelectric Unit

Figure 4 presents an input–output model for a hydroelectric unit with a constant head can be approximated by first- and second-order equations [22]:

$$q_{i} = q_{i}(P_{Hi}) = \begin{cases} a_{Hi} + b_{Hi}P_{Hi} \text{ for } 0 \le P_{Hi} \le P_{Hi,saddle} \\ c_{Hi} + d_{Hi}P_{Hi} + e_{Hi}P_{Hi}^{2} \text{ for } P_{Hi,saddle} < P_{Hi} < P_{Hi,max} \end{cases}$$
(5)

where:

 q_i = the water discharge of unit *i* or during interval *i* in acre-ft/h P_{Hi} = the hydroelectricity generation of unit *i* in MW



Figure 4. Hydroelectric unit power generation.

3.2.3. Emissions Output

Figure 5 presents generation unit emission outputs for SO_2 , NO_x , and CO_2 and water evaporation can be estimated as cubics [23], respectively:

$$EO_{SO_{2},i}(P_{Gi}) = ef_{SO_{2},i}F_{i} = \alpha'_{SO_{2},i} + \beta'_{SO_{2},i}P_{Gi} + \gamma'_{SO_{2},i}P_{Gi}^{3},$$
(6)

$$EO_{NO_X,i}(P_{Gi}) = ef_{NO_X,i}F_i = \alpha'_{NO_X,i} + \beta'_{NO_X,i}P_{Gi} + \gamma'_{NO_X,i}P_{Gi}^3,$$
(7)

$$EO_{CO_{2},i}(P_{Gi}) = ef_{CO_{2},i}F_{i} = \alpha'_{CO_{2},i} + \beta'_{CO_{2},i}P_{Gi} + \gamma'_{CO_{2},i}P_{Gi}^{3},$$
(8)

and

$$WO_{Water,i}(P_{Gi}) = ef_{Water,i}F_i = \alpha'_{Water,i} + \beta'_{Water,i}P_{Gi} + \gamma'_{Water,i}P_{Gi}^3;$$
(9)

where EO_i , ef_i , F_i , and WO_i are the emission outputs (kg/h), the emission factors (kg/MBtu or gallons/MBtu), fuel input (MBtu/h), and water output (gallons/h) for unit *i*, respectively.



Figure 5. Emission output.

3.3. Objective Function

The proposed method optimizes the generating unit costs and pollutants (CO₂, SO₂, NO_x, or water) with the weighting factors [24]. Users can perform various optimization simulations according to the target by resetting the weighted factor.

$$Minimize \left[W_{cost}C(P_G) + \sum_{i \in \{SO_2, CO_2, NO_X, Water\}} W_i EO_i(P_G) \right], \tag{10}$$

where:

 W_{cost} = weighting factors of grid generation units

 W_i = weighting factors of objective function *i* from 0 to 1

The sum of the weight factors is 1:

$$\sum_{i \in \{Cost, SO_2, CO_2, NO_X, Water\}} W_i = 1, \tag{11}$$

and specific costs or emissions can be more weighted to reflect the practical case.

The algorithm applied in this paper is based on the Lagrange function with the Lagrangian multiplier λ ,

$$L = F_T + \lambda \varnothing \tag{12}$$

and

$$\frac{\partial L}{\partial P_i} = \frac{dF_i(P_i)}{dP_i} - \lambda \left(1 - \frac{\partial P_{loss}}{\partial P}\right),\tag{13}$$

where F_T is the total cost to supply the indicated load, P_i is the electrical power generated by unit I, P_{loss} is the transmission network loss, and \emptyset is the energy balance, including losses.

3.4. Typically Generation Allocation Algorithms with Lagrange Multiplier

Figure 6 shows the flowchart for the traditional generator allocation. Inputs include appropriate geographical regions, load profiles, generator types, and generation costs. The optimization of economic dispatch proceeds once the initial values are set.



Figure 6. Traditional generation allocation process.

4. Proposed Two-Stage Optimization

This paper analyzed the effects of a CCHP system in Atlanta, USA using the proposed two-stage optimization, focusing on yearly average costs and environmental emissions savings for CCHP systems. We assumed that Atlanta installed 390 kW (6×65 kW) CCHP systems with a peak demand = 2.7 MW (4.13 kW per household, 669 households) for any given year [17,18]. We acquired the electric energy mix purchased from the grid in hourly

time intervals throughout the year to analyze the effects of the CCHP system on electrical and thermal energy. However, generation economic dispatch that usually determines the electric energy mix for large-scale conventional generators (i.e., six coal-fired, two nuclear, thirteen gas-fired, and hydroelectricity plants on the Georgia, USA state grid) is not usually applied to small-scale units (e.g., CCHP units with tens of kW or less capacity) because the available generation unit heat rates for economic dispatch are in the order hundreds of MW or above. Thus, we ran simulations on the state-wide grid with hundreds of MW or GW units in two stages to determine the detailed electric energy mix.

Figure 7 shows that the proposed optimization approach explicitly considered four environmental emissions and shows the CCHP system compared with the traditional approach (Figure 6). The two-stage optimization method extended from the Atlanta area to the state of Georgia, i.e., we computed the state-wide energy mix, then reduced that onto the Atlanta area for optimization. Thus, the two-stage approach enables dispatch for small areas (Atlanta, GA, USA).



Figure 7. Proposed two-stage optimization process.

4.1. First Stage Optimization

The first stage optimization extended the capacity of the MTs of the Atlanta area from 2.7 MW to 16.1 GW for the state of Georgia [17,18], modeling six coal-fired, two nuclear, thirteen gas-fired, one hydro, and two small plants. Thus, detailed and accurate energy mix values were obtained from simulations at the Georgia state level during one year in hourly intervals.

4.2. Second Stage Optimization

After determining the state-wide grid energy mix, we reduced the size to fit the Atlanta area. Energy mix values reflected the accurate energy purchases from the grid that CCHP MTs cannot provide. The case study used the proposed method to analyze the impact of CCHP systems on energy efficiency, cost variations, and emissions savings.

Figure 8 shows the proposed two-stage optimization process. MT capacity in Atlanta was multiplied by 5963 (\approx 16.1 GW/2.7 MW). Generation resource allocation simulations on the state-wide grid with these MTs of an increased size were performed over one year in hourly intervals. Detailed state-wide generation resource allocation algorithms are available elsewhere [9,24], and we modeled the MTs as gas-fired generation units. Figure 8 shows an example energy mix = gas-fired 39%, hydro 2%, coal-fired 34%, and nuclear 25%, representing the percentages of the peak loading condition during the day. The energy mix was reduced to the Atlanta area to determine the accurate amount of energy purchased from the grid.



Figure 8. Transformation of generation proportions in two-stage optimization.

5. Case Study

The energy mix for the CCHP system's region must be calculated to optimize the CCHP system for small areas. Optimized CHP systems can reduce purchases from the grid. The CCHP systems were optimized with either economical or environmental constraints.

This case study demonstrates the validity of the energy mix values obtained from the first optimization: the Georgia state-level economic dispatch. The second optimization simulation for the Atlanta unit was performed on the energy mix obtained from the first step. The case study results confirm that the optimized CCHP system reduced energy usage and environmental emissions.

5.1. Case Study A: First Stage Optimization in Georgia

Case study A shows the dispatching algorithm (or the generation resource allocation algorithm) operation for CCHP systems and the minimization of the impact of the CHP system on the environment. The results verified the developed algorithm's validity.

5.1.1. Electric and Thermal Load Profile

Demand (or load) varies momentarily with customer demand. In particular, the thermal load profile is strongly connected to weather conditions. This case study used the following load data for the proposed dispatch algorithm, which included the CHP system. Figures 9 and 10 detail a residential community with 1700 residents or 669 households with data collected in hourly intervals from Open Energy Information (OpenEI) [17,18]. Load profiles (Figure 9a,b) show an electric demand peak = 1 p.u. (2.7621 MW) on 1 August and a load factor = 0.360 (\approx 0.9962/2.7621), where 0.9962 MW is the mean electric demand over the year. Similarly, Figure 10a,b show a thermal demand peak = 1 p.u. (8.8849 MW) on 12 February and a load factor = 0.103 (\approx 0.9142/8.8849). The load factor is the ratio of the average demand (or load) over a year to peak demand.



Figure 9. Yearly electric load profiles for the Atlanta area.



Figure 10. Thermal load profiles for the Atlanta area.

5.1.2. Daily Generation Profiles

Figure 11a,b show the optimized results and the minimization of cost and environmental emissions through generation resource allocation algorithms for peak days (peak = 16.1 GW) over one year for the Georgia grid. The import value is responsible for 9.60% of the total demand in the generator optimization allocation to minimize costs, and six upscaled MTs are responsible for 1.29%. On the other hand, an imported generation value = 33.92% and six up-scaled MTs = 1.21% are required to reduce environmental emissions. The imported generation increases due to the maximum capacity constraint for the thirteen gas turbines [16,18] to minimize emissions release in Figure 11b. Thus, we determined the import value (purchased energy) required for a peak day and the optimized

12 of 20



CHP system capacity for cost and environmental emissions to meet overall demand, where the import value is related to the gas-turbine units.

(**b**) To minimize emissions

Figure 11. Daily profiles on a peak day in the Georgia, USA state grid.

5.1.3. Weekly Generation Profiles

Figure 12 shows the weekly profiles including the peak day (1 August). Summer peak days have more cooling load demands than other days. The power generation from the CHP systems and other generators in peak summer times exhibit similar trends as extensions from the daily profiles in Figure 11.



(**b**) To minimize emissions

Figure 12. Weekly profile including the peak day for the Georgia state grid.

5.2. Case Study B: Second Stage Optimization in Atlanta

Table 1 shows the generation costs for the Atlanta area CCHP system [25–27], based on the Georgia Power Company's 2015 annual report, comprising the inputs for the proposed algorithm. Thus, the power generation unit costs can be replaced and applied at any time not only for the Atlanta area, but also for other regions.

Figure 13 shows the electric energy demand for a peak day (1 August), with peak demand = 2762.10 kW. Demand comprises cooling, fan, heating, light, equipment, and unknown loads. Cooling demand is chilled air or water from running ABCs. Table A2 (Appendix A) shows the detailed emission data for each generator type (coal, gas, nuclear, hydro, and CHP) [28–33].

Type for Electricity	Cost (USD/MWh)	
Coal	45.5	
Nuclear	7.8	
Gas	24.7	
Purchased (imported)	43.3	
Microturbine	39.11	
Solar (community)	40.14	
Type for thermal	[USD/MWh]	
Thermal gas price	48.11	

Tal	ole	1.	Generation	costs	for A	tlanta	area	as i	input	25-27].
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Figure 13. Original electric demand for peak day in Atlanta area [13].

5.2.1. Generation Profile

Figure 14 shows the daily effects of the optimized CHP system on generation, where the CCHP system was optimized to minimize emissions. ABCs can recover cold air or water during the summer by recycling waste heat. The CCHP system can generate 390 kW (=65 kW × 6), or 0.1444 p.u. electric power and recover 485.32 kW (=4,048,000 BTU × $6 \times 0.75 \times 0.9$) or 0.18 p.u. from the ABC [15]. Thus, the CCHP system produces total power = 875.32 kW or 0.32 p.u. The CHP system uses natural gas, which emits fewer GHGs than coal-fired generation units. Thus, the CCHP system was required for almost 24 h (Figure 14a). On the other hand, since the CHP system uses relatively more expensive fuel than coal-fired and nuclear generation units, the operating time of the CCHP system is low in order to minimize costs. Figure 14a,b were simulated under the same conditions.

Figure 15 shows the output duration curve of the CCHP system, optimized to minimize emissions (CO2, SO2, NOx, and water) with equal weights (i.e., wi = 25%) for one year. Table 2 shows the utilization rate and operation time to minimize either all emissions or only CO2. Approximately 92.5% MTs were utilized and 15% MTs operated at full capacity (e.g., for peak hours).

Table 2. Utilization rates and operation times for minimizing emissions.

	Min Only CO ₂	Min All Emissions
Operation time per year (hour)	23	8125
Utilization rate (%)	0.26%	92.75%





Figure 14. Daily generation profile for a peak day in the Atlanta area.



Figure 15. Duration curve when minimizing emissions over one year.

5.2.2. Electric and Thermal Energy Savings

Figure 16 shows the annual average electric energy purchased from the grid and the thermal energy purchased from the gas facility (e.g., boilers). The bar color corresponds to conditions: orange indicates the absence of the CHP; blue, green, and gray correspond to full-blast, optimal minimized costs, and optimal minimized emissions scenarios, respectively. For example, Figure 16a shows a 48.8% saving in electrical energy under the full-blast condition; whereas green and gray exhibit 0.03% and 30.6% savings compared to operations without CHP systems, respectively. Similarly, Figure 14b shows the thermal energy savings = 32.9%, 0.0%, and 15.6% for the blue, green, and gray bars, respectively. Thus, Figure 16 confirms that the proposed method can be used for generation dispatch to minimize generation costs, emissions, or combined costs and emissions.



(a) Electric energy savings



Thermal Energy from Boiler in MWh/year/household

(**b**) Thermal energy savings

Figure 16. Annual energy savings (ABCs available).

5.2.3. Emissions Savings

Figure 17 shows the four emission source reductions individually, where the bar color represents the same MT conditions as in Figure 16. Figure 17a shows CO₂ reductions = 33.1%, 0.6%, and 55.1% compared to conditions without a CHP system. Although CO₂ decreased in all conditions, to minimize emissions, optimal-blast conditions show the most significant reduction, as expected. Figure 17b shows SO₂ reduction = 57.2% and 40.5% reductions for full and optimal-blast (minimize emissions) cases. However, the optimal-blast (to minimize costs) case (green bar) exhibited a 1.8% increase. Thus, optimal-blast (minimize costs) cannot reduce SO₂. Figure 17c,d shows NO_x and water reductions follow the same pattern as for SO₂. Thus, we verified the proposed algorithm's effectiveness from annual energy and emissions savings results as shown in Figures 16 and 17.



(a) CO₂ savings



(**b**) SO₂ savings



(c) NO_x savings



(d) Water savings

Figure 17. Annual emissions savings.

6. Conclusions

This study proposed a two-stage optimization algorithm and performed a case study to analyze the impact of a CCHP system including ABCs and MTs on a metropolitan area power supply system. We also applied the proposed optimization to the generation resource allocation algorithm explicitly considering CO_2 , SO_2 , and NO_x , emissions and water usage.

The case study for Atlanta optimized the impact of various pollutant emissions to comply with the global power generation trends. Moreover, global trends such as microgrids and smart cities require optimization studies of various generator allocations for small areas. The proposed two-stage optimization provided an effective methodology to determine more accurately the impact of the CCHP system on areas that not only install small generation units (kW or less) but are also connected to a larger grid (e.g., the grid of the state of Georgia in United States). The analysis presented here can help design optimal CHP capacity to meet economical or environmental needs for specific regions.

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Abbreviations

absorption chiller
combined heat and power
combined cooling heat and power
genetic algorithm
greenhouse gas
microturbine
per unit
photovoltaic

Appendix A

Tables A1 and A2 show the characteristics for type C65 MTs; and CO₂, SO₂, NO_x, and water emissions, respectively.

Table A1. Parameters associated with C65 MTs [19].

Rating	65 kW
Electrical efficiency (lower heating value)	29%
Combined heat and power efficiency	Up to 90%
Exhaust temperature	309 °C (599 °F)
Compatible fuels	Natural gas, liquid fuels, sour gas, etc.

	Coal	Gas	Nuclear	Hydro	СНР
CO_2 (kg/kWh)	$8.8800 imes 10^{-1}$	4.9900×10^{-1}	$2.9000 imes 10^{-2}$	0	$3.0255 imes 10^{-1}$
SO_2 (kg/kWh)	$6.0781 imes 10^{-3}$	$2.3133 imes10^{-6}$	0	0	$3.0391 imes 10^{-6}$
NO_x (kg/kWh)	$2.5401 imes 10^{-3}$	$9.0718 imes10^{-6}$	0	0	$5.8967 imes 10^{-5}$
Water (gallon/kWh)	$6.7000 imes 10^{-1}$	$2.7500 imes 10^{-1}$	$6.2000 imes 10^{-1}$	18	0
Water (L/kWh)	2.536225	1.040988	2.346954	68	0

Table A2. Generation type emission levels [28–33].

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