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Optimal cost management of the CCHP based data center with district heating and district cooling integration in the presence of different energy tariffs

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A R T I C L E I N F O

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A B S T R A C T

Data centers are expected to be one of the major prosumers in energy networks because of their high electricity demands as well as being a possible source of waste heat energy utilization. A combined cooling, heat, and power (CCHP) system can be a perfect match with a data center for supplying the data center's less fluctuated, uninterrupted power and cooling demand. Moreover, CCHP based data center integration with regional district heating and cooling system can gain data center's excess heat, improve the efficiency of the primary energy sources, and give flexibility to district energy operators. This paper aims to offer a comprehensive energy cost management for a CCHP based data center that considers power, heating, cooling, and data center's excess heat utilization in the presence of hourly energy prices and varying outdoor temperatures. Mixed Integer Linear Programming (MILP) is used to determine a cost-optimized operational strategy for the overall system. The result shows that CCHP and regional energy integration to the data center decrease the overall energy cost of the operation while providing more flexibility to the data center and district energy network operators. Optimized operation of the CCHP system with the data center's excess heat recovery, district heating, and cooling integration can cut its annual electricity costs by 40.3% compared to the local operation of the CCHP based data center. Return of investment (ROI) is estimated to be in 6.6 years for additional required systems for the conventional data center.

1. Introduction

Data centers are energy-intensive buildings in commercial, telecommunicational, educational, and governmental facilities. A data center's concentrated energy consumption is 10–40 times higher than a regular office building [1]. The rapid increase in data traffic, data storage, cloud service, Internet of Things (IoT), and digital technology is also leading to a dramatic increase in demand of the data center industry. In 2014, data center's electricity consumption in the U.S. was estimated at 70 billion kWh, representing 1.8% of total U.S. electricity consumption [2]. In 2020, global electricity demand for data centers was estimated at 250 TWh, which is approximately 1% of global final electricity demand, and it is projected to increase to nearly 270 TWh by 2022 [3]. Due to the Covid-19 global pandemic, the internet infrastructure has been used heavily by relying on the existing data centers, and global internet traffic from February 2020 to mid-April 2020 increased by nearly 41% [3]. During the Covid-19 pandemic, Dutch data center operators observed a 1% to 4% rise in data center's energy consumption, while the total amount of consumed energy and total CO_2 emissions in the Netherlands dropped by 10% and 2.7%, respectively [4]. This contradiction shows that data centers can facilitate online workplaces and help to decrease global energy consumption. However, an increase in the new data center demand also increases the global energy demand. Hence, more energy-efficient data center solutions are crucial for future energy networks and society.

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Nomenclature

C_{dist_h} energy selling price for district heating energy [TRY/kWh]
C_{dist_q} energy selling price for district cooling energy [TRY/kWh]
C_{feed} surplus electricity selling price [TRY/kWh]
C_{grid} purchase price for electricity [TRY/kWh]
C_{ng} purchase price for natural gas [TRY/ Sm^3]
C_{ops} hourly energy cost of the overall operation [TRY]
C_{ops_chp} hourly energy cost of the CHP-fed operation [TRY]
C_{ops_grid} hourly energy cost of the grid-fed operation [TRY]
COP_{abs} coefficient of performance for absorption chiller [%]
COP_{ech} coefficient of performance for electric chiller [%]
COP_{hp} coefficient of performance for heat pump [%]
E_{abs} electricity consumption of absorption chiller (internal) [kWh]
E_{aux} electricity consumption data center's auxiliary systems [kWh]
E_{chp} input energy of CHP [kWh]
$E_{cooling}$ electricity consumption of data center's cooling system [kWh]
E_{CRAH} electricity consumption of computer room air handling [kWh]
E_{CT} electricity consumption of cooling tower [kWh]
$E_{e\_chp\_nom}$ nominal electrical energy output of CHP [kWh]
E_{demand} total electricity demand of the overall system [kWh]
E_{e_chp} electrical energy output of CHP [kWh]
$E_{e\_chp\_max}$ maximum electrical energy output of CHP [kWh]
E_{ech} electricity consumption of electric chiller [kWh]
E_{feed} surplus electricity for grid backfeeding [kWh]
E_{feed_abs} surplus electricity at absorption chiller mode [kWh]
E_{feed_frc} surplus electricity at free cooling mode [kWh]
E_{feed_ech} surplus electricity at electric chiller mode [kWh]
E_{frc} electricity consumption of free cooling operation [kWh]
E_{grid} electricity consumption from the grid [kWh]
E_{hp} electricity consumption of heat pump [kWh]
E_{IT} electricity consumption of IT devices [kWh]
E_{power_losses} electricity losses from power distribution [kWh]
E_{m_chp} output mechanical energy of CHP [kWh]
E_{pumps} electricity consumption of water-circulation pumps [kWh]
H_{abs} input heat energy for absorption chiller [kWh]
H_{chp} total waste heat energy of CHP [kWh]
H_{CRAH_fans} heat dissipation from CRAH fans: 8% of the total IT heat [kWh]
H_{dc} total dissipated heat in data center's whitespace [kwh]
H_{diss_chp} heat dissipation to ambient from CHP [kWh]
H_{dist} surplus heating energy for district heating [kWh]
H_{exh_chp} output heat energy of CHP's flue-gas exhaust [kWh]
H_{hp} heat energy output of heat pump [kWh]
H_{hw_chp} heat energy output of CHP's high-temperature water [kWh]
H_{IT} heat dissipation from IT devices [kWh]
$H_{lighting}$ heat dissipation from lighting fixtures: 0.5% of the total IT heat [kWh]
H_{lw_chp} heat energy output of CHP's low-temperature water [kWh]
H_{power_losses} heat dissipation from power infrastructure losses:3% of the total IT device's heat [kWh]
H_{rec} total heat energy recovery in data center's whitespace [kWh]
H_{waste} useful waste heat energy of CHP (utilized) [kWh]
$H_{waste\_nominal}$ nominal useful waste heat energy of CHP [kWh]
H_{wiring} heat dissipation from data wiring losses: 1% of the total IT heat [kWh]
H_{ng} natural gas heating value [kJ/m^3]
LF loading factor of CHP [%]
Q_{abs} cooling energy output of absorption chiller [kWh]
$Q_{abs\_nominal}$ nominal cooling energy output of absorption chiller [kWh]
$Q_{CT\_nominal}$ nominal cooling energy output of cooling tower [kWh]
Q_{demand} cooling demand of data center [kWh]
Q_{dist} surplus cooling energy for district cooling [kWh]
Q_{ech} cooling energy output of electric chiller [kWh]
$Q_{ech\_nominal}$ nominal cooling energy output of electric chiller [kWh]
Q_{frc} cooling energy output of free cooling operation [kWh]
Q_{gen} cooling energy generation of overall system [kWh]
V_{ng} natural gas consumption of CHP [Sm^3]
η_{m_chp} output mechanical efficiency of CHP [%]
η_{e_chp} output electrical efficiency of CHP [%]
η_{exh_chp} output flue-gas heat energy efficiency of CHP [%]
η_{hw_chp} output high-temperature water heat efficiency of CHP [%]
η_{lw_chp} output low-temperature water heat efficiency of CHP [%]

Abbreviations

CCHP combined cooling, heat, and power
CHP combined heat and power
CRAH computer room's air handling unit
DC district cooling
DH district heating
DMS geographical location coordinates by degree, minute and second
IT information technology
MILP mixed-integer linear programming
O&M operation and maintenance
TRY Turkish Lira (Currency for The Republic of Turkey)

Subscripts

$m1$, $m2$, $m3$, m4 different modes of the operations

Symbols

a variable to represent power mode is grid
b variable to represent power mode is CHP
m variable to represent cooling mode is electric chiller
n variable to represent cooling mode is absorption chiller
p variable to represent cooling mode is free cooling

1.1. Data centers and energy outlook

Electricity in data centers is consumed continuously by Information Technology (IT) devices in racks, electric chillers for cooling, lighting, and other auxiliary systems. This consumed electricity almost entirely converts to heat and it needs to be removed for the safer operation of IT devices [5]. IT devices in a data center require vast amounts of cooling energy. They are typically refrigerated by electric chillers that consume electricity to generate cooling energy with air-cooled or liquid-cooled cooling technology. Air-cooled technology is widely used in data centers. IT devices' power consumption is almost completely dissipated as heat in the data center's computer rooms (whitespaces). However, this excess heat energy is usually not utilized inspite of various possible heat recovery methods in the energy industry with their potential application to data centers [6]. Moreover, the data center's excess heat is expected to be classified as waste heat in the United Kingdom, so it can even be eligible for heat incentives as renewables. This development further encourages the reusing of excess heat in data centers [5].

Data center's excess heat can be recovered and reused with multiple methods, such as space and district heating, absorption chiller refrigeration, organic Rankine cycles, piezoelectric, thermoelectric, and biomass processing [5,6]. District heating is the most flexible and stable method of reusing air-cooled data center's excess heat [7]. Excess heat in the data center could be harvested from the return-air of the Computer Room Air Handling Unit (CRAH) at a temperature between 25 °C and 35 °C, as shown in Fig. 1. The main advantage of harvesting excess heat from CRAH return-air is that the excess heat recovery system will operate independently from the existing cooling system. Hence, the overall reliability and operation of the data center would not be impacted in case of a failure in the excess heat recovery system [8].

Data center's recovered excess heat is a type of low-temperature heat, and it needs to be upgraded by a proper heat pump approximately to a higher temperature between 60 °C and 90 °C, in order to be able to be used in existing district heating networks. In the future, more low-temperature district heating networks (LTDH) are expected to be installed to give more opportunity to low-temperature waste heat sources for using them in newly built houses, such as nearly zero energy buildings. This approach will allow the use of low-temperature heat energy without a heat pump, which will lead to a more efficient way of heat recovery. The municipality of Amsterdam has the ambition to expand its district heating network within the city, and it is planning to connect 27,000 homes to regional district heating networks by 2041. That district heating network will warm up about 41% of the totally new and existing buildings by utilizing the city's waste heat from the industrial facilities and data centers [9]. According to Amsterdam Metropolitan Area Data Center Strategy Report in 2020, a 1 MW data center can warm up to 500 homes with 54% heat recovery efficiency [10]. Fig. 2 shows how a data center can supply its excess heat to existing district heating networks. Facebook has started to recover its Danish data center's waste heat by connection to nearby district heating since July 2020. The data center currently warms up around 6900 homes, and it is expected to grow by 1700 homes, a total of 32,000 MWh of heating annually [11].

1.2. Data centers and CCHP integration

Data centers require continuous power and cooling. In conventional data centers, electric chiller's and IT system's electrical power consumption are provided from the power grid. Alternatively, a CCHP system can feed the data center's power and cooling demand by on-site generation. CCHP system consists of a combined heat and power (CHP) system and an absorption chiller producing cooling for data halls in a data center. In the conventional data center, waste heat occurs from its excess heat in data halls. Besides, in CCHP based data center, waste heat is composed of the data center's excess heat and CCHP's waste heat. Recent CHP systems in the industry generate an almost equal amount of power energy to heat energy (ratio between 0.95 and 1.01) [12]. Similarly, the data center's electrical power (kWe) and cooling (kWth) demands are almost equal, so the CCHP system is well suited to supply continuous power and cooling to the data center [13]. In contrast to traditional power plants, where 60% of primary energy is lost as heat to the environment, CCHP and its heat recovery system can utilize the waste heat with a total energy efficiency between 75% and 90% [14]. Fig. 3 shows the energy flow comparison of a grid-based and CCHP-based data center.

A CCHP based data center can operate at following operations:

CCHP and grid operation (normal operation):

When CCHP and grid exist, CCHP provides continuous electricity and cooling to a data center. Grid exists as a redundant source of power. If CCHP fails or is in maintenance, the data center's electrical demand will be supplied from the grid since it is an economical way of feeding data centers' electrical demand compared to on-site diesel emergency generators.

CCHP fails and grid fails (incident operation):

If CCHP and grid fail simultaneously, on-site diesel emergency generators will feed all the data center's electrical demand from power and cooling systems.

Data centers are classified by their infrastructure's redundancy

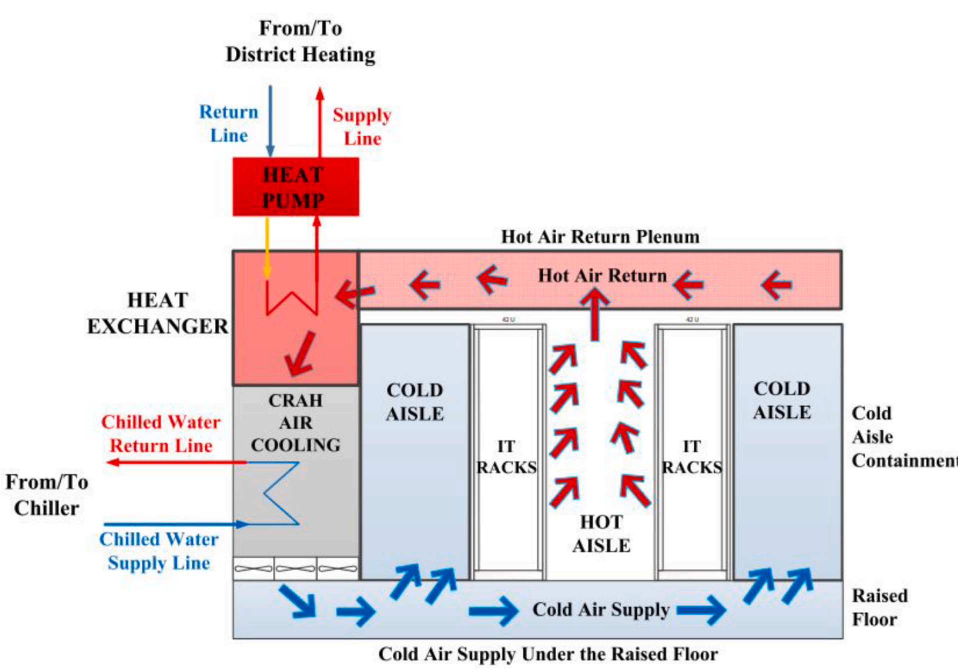

Fig. 1. Excess heat recovery system for air-cooled data center.

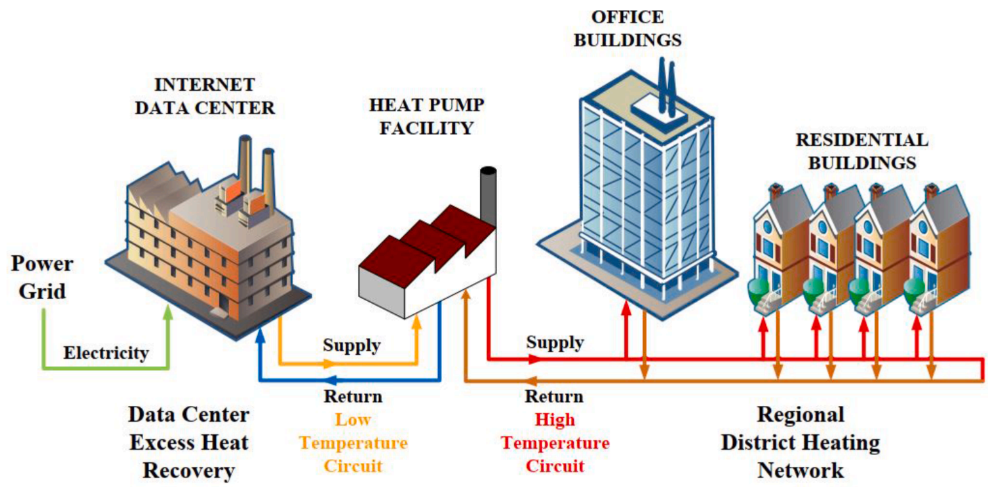

Fig. 2. Data center's excess heat (low-temp) recovery system integration to district heating network (high-temp).

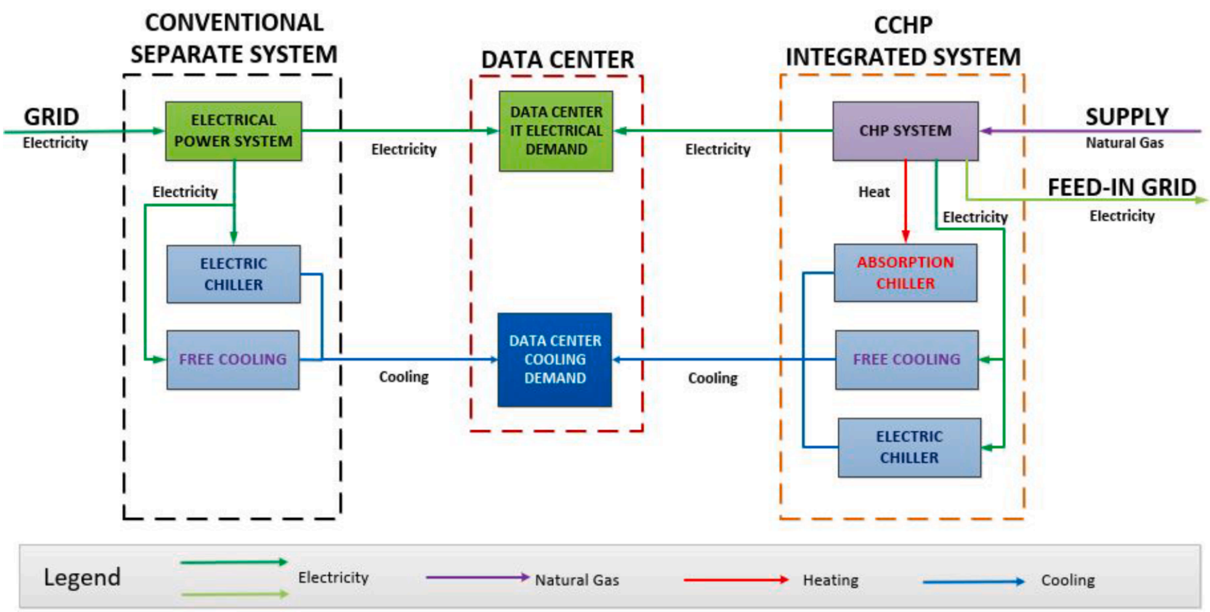

Fig. 3. Energy flow comparison of a grid-based and CCHP-based data center.

levels. While the Tier classification level is increasing from I to IV, redundancy level and reliability also increase. There are four nominated classes, and Tier-IV is the most reliable system class providing concurrent maintenance to the data center with its redundant topology. Angelis [15] proposed to increase the performance of a Tier-III data center by replacing one of the emergency diesel generators with CCHP. Industry-wide standards accept only the emergency generators with on-site fuel storage as a dedicated source of power supply. Angelis concludes that the requirements would not allow a replacement of emergency generators with a CCHP system, so this replacement is not recommended due to its impact on current industry-accepted Tier classifications. Keskin and Soykan [13] investigated the CCHP replacement with one of the grid connections for a Tier-IV data center. They show that CCHP replacement over one grid connection will not impact the Tier-IV topology, while it contributes to overall reliability, availability, and energy cost reduction.

CCHP systems are widely used in current district heating and district cooling networks. According to the International Energy Agency (IEA) report in 2012, heating and cooling energy consumption is accounted for nearly 46% of the total global energy consumption. Heat energy accounts for almost 50% of the end-use energy in Europe [16]. According to a recent strategy report by Heat RoadMap Europe [17], the aim is to enhance a share of thermal energy provided by district heating and cooling networks, from the current 13% up to 50% by 2050, through improvements in demand and supply management, waste heat reuse, thermal storage, and grid integration. In Finland, district heating accounts for about 50% of the total heating energy market and CHP plants supply almost 80% of district heating demand. Finland example and European Union Heat RoadMap show that CHP plays an important role in producing the district heat and it is beyond the out-of-date [5,17]. A data center with an integrated CCHP system can feed the district heating in winter and can satisfy the data center's cooling demand in summer. Furthermore, surplus heating or cooling energy can be sold anytime to a district heating and cooling network based on real-time energy prices. This operational strategy brings more flexibility to data center operators and district energy network operators in the region.

2. Literature review and contributions

CHP and CCHP research in the literature consists of the optimum system sizing, feasibility, performance assessments, modeling, optimal operation strategies, and other aspects of CCHP systems for various applications. CCHP's integration to residential buildings or district energy networks requires complex control and scheduling algorithms for the optimum cost of operation. Barun et al. [18] described the commonly used CCHP power management strategies. They used two types of load management which are: "Following the Thermal Load (FTL)" and "Following the Electrical Power Load (FEL)". Kim et al. [19] used MILP to find the optimal electrical, thermal outputs, and schedule the operational hours of the CHP with thermal storage. They demonstrated that an optimized operation of CHP with thermal storage could save 14% of operational costs. Saberi et al. [20] created a multi-objective model that aims to decrease the operational costs and carbon emissions in the presence of real-time demand response. The results showed that the operation cost was reduced by 3.97% and carbon emission by 2.26%, thanks to the real-time demand response implementation. Kialashaki [21] showed that a CCHP system could increase the economic benefit from 23% to 39% with an optimized operation and feed-in option by selling the surplus electricity back to the grid. Zhao et al. [22] investigated the optimal cost operation for a CCHP based microgrid system consisting of a wind turbine, photovoltaic cell, micro-gas turbine, waste heat boiler, and battery storage. The study demonstrates that under the optimal configuration of the grid-connected microgrid, the system's emission is much lower than the direct power purchasing from the grid.

In the literature, integration of CHP and CCHP systems for industry, some commercial, and residential buildings have been explored, but there is very limited research focused on their integration to data centers [23]. Data center-related studies mainly emphasized the internal consumption of CCHP power, heating, and cooling, or integrating renewables to CCHP systems. Therefore, the benefit of CCHP for a data center may vary based on the type of a prime mover e.g., fuel-cell, gas engine, gas turbine, and local energy prices. Xu and Qu [24] investigated a gas-turbine CCHP use in a data center under the assumption that all generation is consumed within the data center and without a district energy network connection. They concluded that the data center is a feasible match with the CCHP system. The CCHP system can reduce 31% of primary energy consumption, 45% of carbon dioxide equivalent emissions, and 46% of operational costs. Sevencan et al. [25] studied a fuel-cell-based CCHP use in a data center with Swedish energy market prices and weather conditions, but the results were not feasible for that case study due to the cost of the fuel cells. Keskin and Soykan [13] showed a 55% energy cost reduction when CCHP is used to supply data center's power and cooling demand in a warmer country with a relatively lower ratio of natural gas to electricity price (1:4).

Data center excess heat recovery system is also another way of energy saving from the waste heat, besides the CCHP's waste heat recovery. It is found beneficial in terms of power, carbon emission, and cost reduction. Some research papers focus only on reusing data center's excess heat and its connection to district heating. Huang et al. [7] indicated that the amount of data center's excess heat is enormous, and they estimate that 68% of the excess heat can be recovered. Davies et al. [8] analyzed the availability of the data center's excess heat recovery system and potential ways of reuse. Impressive results showed that 4100 tons of CO2e and nearly GBP 876,000 can be saved in one year at a 3.5 MW data center. Wang et al. [26] demonstrated that a large amount of energy and cost savings are possible when the 3.5 MW data center's excess heat recovery system is connected to a 70 °C district heating network. Wahlroos et al. [5] demonstrated that if major Finnish data center operators would connect the data center's excess heat to an existing district heating network, the heat pump investment payback would be five years. He et al. [27] indicated that the excess heat recovered from a 52.8 MW data center in China could save nearly 10% of the annual electricity for a data center. From the point of district heat network operator, the data center's excess heat recovery system is also found promising. Wahlroos et al. [28] simulated a district heating production together with possible excess heat recovery from industry and data centers in Espoo/Finland, according to actual data for 2013 and 2015. The study showed that if 60 MW waste heat can be recovered, 7.3% cost saving could be achieved for the district heat network operator. However, data centers produce a large amount of waste heat 24/7, which may not match the heating needs of the downstream heat consumers [29]. Hence, more efforts are needed to consider a data center as an energy prosumer, which can trade-off energy, supply heat and cooling to the district energy networks, while satisfying the energy demand at the facility, reducing the operational costs, and greenhouse gas emissions [28]. The utilization of CCHP's waste heat and data center's excess heat in district heating is widely applicable to colder regions with large heating demand. For warm or hot regions, district cooling could be a great opportunity for flexible use of CCHP based data centers in warmer regions.

In previous studies, many works focused on the CHP and CCHP systems which consider costs as a performance optimization criterion [21,30]. The economic performance of the CCHP system depends not only on the variation of load, but also on other items such as equipment performance characteristics for CHP unit, electric chiller, absorption chiller, pumps, energy prices, outdoor weather conditions, and operational constraints. Determining the optimal operational strategies by using an optimization technique is necessary due to hourly and seasonal fluctuations in a building's energy demands. In the literature, such research is limited, and there is a lack of comprehensive assessment of CCHP systems for data centers [24]. Thus, there is a need to fully investigate such scenarios improved by the data center's excess heat recovery system and regional energy network integration [7]. In this study, a developed energy management system will optimize the CCHP and cooling system operations while the data center's excess heat is recovered, final surplus heat, cooling, and power is sold to regional energy networks. Major contributions of this study are:

- Developing a comprehensive system, which considers the data center as a prosumer, and showing the importance of its role in regional energy networks.
- Designing a more realistic system that considers electric chiller, absorption chiller, and free cooling system.
- Operating the CCHP based data center with district heating and district cooling network integration by minimizing the overall energy cost.
- Analyzing the effect of data center's excess heat recovery system, integration of district heating and district cooling for a CCHP based data center in different cases.
- Indicating the economic benefit of the CCHP and regional energy integration for data centers as well as promoting the application of CCHP systems not only for cold-weather regions, but also for warm and hot-weather regions.
- Comparing the time-of-use tariff and single-tariff electricity prices impacts on the system scheduling, and total energy costs.
- Demonstrating the return of investment in years for each scenario by considering the investment, annual operational costs, and energy savings.

3. System modelling and calculations

The relations between energy sources and consumption nodes for CCHP based data centers with regional energy integration are shown in Fig. 4. A natural gas combustion engine is used in the CCHP system. Natural gas combustion engine CCHP system has a higher overall efficiency profile amongst the other types of CCHP systems. Natural gas is an attractive energy source due to its high availability, continuous, and less environmental pollutant specifications. Moreover, these natural gas engines are usually designed as multi-fuel sourced, which can also work with biogas. Hence, the natural gas engine CCHP system can offer more sustainable solutions and more flexibility to data center operators for the future.

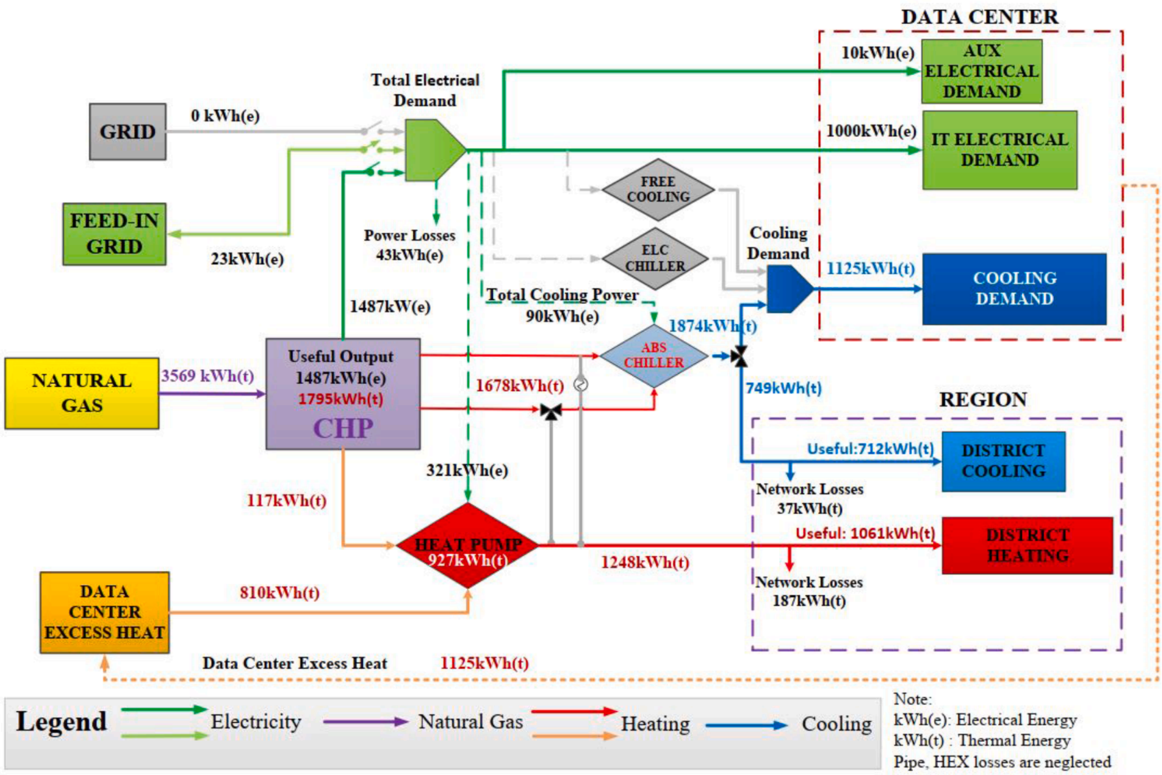

Fig. 4. Overall system schematic and energy flow.

In the data center cooling system, three cooling systems have been considered for the cooling supply. These are electric chiller, absorption chiller, and free cooling systems. Data center's excess heat and CCHP's waste heat are recovered as a cooling and heating energy source for the data center and regional demand.

Each component in Fig. 4 is modelled using mathematical equations based on the thermodynamic laws, formulas of energy, and efficiencies. Efficiency performance curves are used to find varying efficiencies of the components at different part loads [31]. These mathematical equations are supported with the manufacturer's efficiency datasheets to create a more realistic and successful system for the literature. Hence, the success of this system can provide a better evaluation to both data center investors and operators for their planning and future investments.

3.1. *Mathematical modelling of system components*

The system includes several components: CHP unit, electric chiller, absorption chiller, cooling tower, heat pump, circulation pumps, and CRAH unit. These components' mathematical outputs at varying conditions, load, and operation have been used in the optimization model. Additional descriptions of the notations, variables, and their corresponding units can be found in the above Nomenclature.

3.1.1. *Natural gas engine CHP unit*

A CHP unit consists of a gas engine and a synchronous generator that generates electricity and thermal heat energy while consuming natural gas. CHP's hourly natural gas consumption (V_{ng}) is captured from the manufacturer's datasheet based on the actual load and CHP's required input energy in kWh (E_{chp}) with the following formula:

$$E_{chp} = (V_{ng}\ x\ H_{ng})\ /\ 3600 \tag{1}$$

CHP's mechanical energy (E_{m_chp}) is found by multiplying the mechanical efficiency (η_{m_chp}) with CHP's input energy in kWh (E_{chp}):

$$E_{m\_chp} = E_{chp}\ x\ \eta_{m\_chp} \tag{2}$$

CHP's mechanical efficiency (η_{m_chp}) varies based on the actual load in percentage.

CHP's electrical energy (E_{e_chp}) is found by multiplying the electrical efficiency (η_{e_chp}) with CHP's mechanical energy (E_{m_chp}):

$$E_{e\_chp} = E_{m\_chp}\ x\ \eta_{e\_chp} \tag{3}$$

CHP unit generates thermal energy as a side-product in terms of flue gas exhaust heat (H_{exh_chp}), high-temperature water heat (H_{hw_chp}), and low-temperature water heat (H_{lw_chp}), while it is generating electricity. These heats can be recovered as useful heat to supply district heating, process heat, or steam. Dissipation heat from the engine (H_{diss_chp}) is not a useful heat with a 3% share of the total energy input and it is dissipated to the ambient. Thus, CHP's total waste heat (H_{chp}) is found by the sum of the following:

$$H_{chp} = H_{exh\_chp} + H_{hw\_chp} + H_{lw\_chp} + H_{diss\_chp} \tag{4}$$

Without dissipation heat, total useful waste heat (H_{waste}) is calculated by the sum of all other useful energy sources:

$$H_{waste} = H_{exh\_chp} + H_{hw\_chp} + H_{lw\_chp} \tag{5}$$

CHP's useful waste heat recoveries vary based on the actual part load of the CHP unit. Each heat efficiency (η) determines the different source of waste heat based on the CHP input energy (E_{chp}), and is calculated with the following formulas:

$$H_{exh\_chp} = E_{chp}\ x\ \eta_{exh\_chp} \tag{6}$$

$$H_{hw\_chp} = E_{chp}\ x\ \eta_{hw\_chp} \tag{7}$$

$$H_{lw\_chp} = E_{chp}\ x\ \eta_{lw\_chp} \tag{8}$$

On the other hand, (H_{lw_chp}) usually is not recovered in CHP applications due to its low-temperature, but this heat could be potentially recovered together with the data center's low-temperature excess heat (H_{dc}) by using a proper heat pump.

3.1.2. Absorption chiller unit

The absorption chiller can use CHP's exhaust heat and high-temperature water to produce cooling for spaces or processes. There are different types of absorption chillers in the industry for different purposes. A multi-source absorption chiller is used to capture exhaust gas (375 °C) and high-temperature (90 °C) water heat and convert them to chilled water (12 °C).

Absorption chiller's heat input (H_{abs}) is the sum of the CHP's exhaust heat and high-temperature water heat:

$$H_{abs} = H_{exh\_chp} + H_{hw\_chp} \tag{9}$$

Absorption chiller's cooling output (Q_{abs}) varies on the actual load. It is calculated by multiplying the coefficient of performance (COP_{abs}) with heat input (H_{abs}):

$$Q_{abs} = H_{abs}\ x\ COP_{abs} \tag{10}$$

COP value varies based on the actual load. Absorption chiller has an internal electricity consumption (E_{abs}) during the operation. This value has been added to total electricity consumption of the system's operation (E_{demand}).

3.1.3. Electric chiller unit

Water-cooled electric chillers are commonly used as cooling equipment in data centers. They produce chilled water that is supplied to CRAH units for providing cooling to IT racks in whitespace. There are different types of electric chillers and COP values of these chillers also vary based on the actual load and type of the machine.

Electric chiller cooling output energy (Q_{ech}) is a function of coefficient of performance (COP_{ech}) and electrical energy consumption of the chiller (E_{ech}):

$$E_{ech} = Q_{ech}\ /\ COP_{ech} \tag{11}$$

3.1.4. Cooling tower unit

When the outside ambient temperature is low, the data center's excess heat can be dissipated to the environment without the need for an electric or absorption chiller by free cooling. The indirect evaporative cooling tower is used to dissipate the heat to the environment during the free cooling operation. In this operation, the cooling system uses only the water circulation pump and cooling tower fans, so it consumes relatively less energy than an electric chiller or absorption chiller operation. Free cooling operation electrical consumption (E_{frc}) is the total electricity consumption of the pumps (E_{pumps}), CRAH (E_{CRAH}), and cooling tower (E_{CT}).

$$E_{frc} = E_{pumps}\ +\ E_{CRAH}\ +\ E_{CT} \tag{12}$$

3.1.5. Heat pump

An electric water-to-water heat pump is used to increase water temperature from low-temperature to high-temperature to be able to use low-temperature waste heat for district heating. The heat pump consumes electricity for its operation and the efficiency of the heat pump varies based on the load with an associated COP value.

The coefficient of performance value (COP_{hp}) is the ratio between heat pump heating output (H_{hp}) and heat pump's electricity consumption (E_{hp}). COP_{hp} value varies based on the actual load.

$$E_{hp} = H_{hp}\ /\ COP_{hp} \tag{13}$$

In our system, both the CCHP's low-temperature water heat and the data center's excess heat were recovered and utilized. This low-degree heat's temperature is increased to a higher temperature by a heat pump to utilize this heat in the district heating network. Besides, the described main components in the system, water pumps, CRAH fans, and a cooling tower consume electricity for the cooling system's water circulation. Those vary based on the partial load in percentage. According to cooling operations (electric chiller, absorption chiller, or free cooling), these auxiliary components' consumption has been added to total electrical consumption. However, other system components with relatively minor energy impacts on overall energy consumptions, such as pipes, valves, and heat exchangers, are neglected to simplify the overall system.

3.2. Energy demand and supply calculations

The overall system has eight main calculations related to one or multiple components in the last part. Table 1 shows the possible modes of the operations in CCHP based data center given in Fig. 4. System results have been calculated for all operating conditions are shown in Table 1. Results of the calculations are used in the optimization model as an input in finding the optimal electrical and cooling supply strategy based on the minimized cost function.

3.2.1. Electrical energy demand calculation

Data centers consume electricity mainly for IT racks' (E_{IT}), cooling generation ($E_{cooling}$) and auxiliary equipment (E_{aux}) such as lighting, small power, office use, etc. Total electricity consumption (E_{demand}) is the sum of these needs, heat pump's electricity consumption (E_{hp}) and electricity losses from power infrastructure (E_{power_losses}):

$$E_{demand} = E_{IT} + E_{aux} + E_{cooling} + E_{hp} + E_{power\_losses} \tag{14}$$

$E_{cooling}$ represents the total electricity consumption of the cooling system under the different operational status. It varies hourly during the year depending on the cooling demand of the data center and outdoor weather conditions:

$$E_{cooling} = \begin{cases} E_{ech}, & if\ electric\ chiller\ is\ On \\ E_{abs}, & if\ absorption\ chiller\ is\ On \\ E_{frc}, & if\ free\ cooling\ is\ On \end{cases} \tag{15}$$

3.2.2. Cooling energy demand calculation

Data Center's total heat dissipation is calculated based on the IT devices' heat dissipations (H_{IT}) and other heat dissipations (H_{others}). Other heat dissipations are the sum of heat dissipations from CRAH fan coils (H_{CRAH_fans}), lighting ($H_{lighting}$), wiring (H_{wiring}), and power infrastructure (H_{power_losses}) in whitespace [32]. Total dissipated heat (H_{dc}) is calculated as follows:

$$H_{dc} = H_{IT} + H_{CRAH\_fans} + H_{lighting} + H_{wiring} + H_{power\_losses} \tag{16}$$

This total dissipated heat must be extracted from the data center

Table 1
Mode descriptions.

Mode	CHP Operation	Cooling Supply System	District Heating Supply	District Cooling Supply
1	ON	Electric chiller	CHP exhaust, high-temperature water, Low-temperature water, data center's excess heat	Total absorption cooling
2	ON	Free cooling	CHP exhaust, high-temperature water, Low-temperature water, data center's excess heat	–
3	ON	Absorption chiller	CHP low-temperature water, data center's excess heat	Surplus cooling
4	OFF	Electric chiller or free cooling	Data center's excess heat	–

whitespace by cooling supply with the different cooling system by the electric chiller, absorption chiller, or free cooling. Hence, the data center's cooling demand (Q_{demand}) is equal to the data center's dissipated heat to maintain the temperature of the room in the advised temperature range:

$$Q_{demand} = H_{dc} \tag{17}$$

3.2.3. CHP electrical and heat energy supply calculations

CHP provides electrical energy (E_{e_chp}) and thermal heat energy (H_{waste}) based on a partial load or full load. Electricity and heat energy outputs vary based on the actual load factor (LF) of the CHP:

$$E_{e\_chp\_nom}(t) \geq E_{e\_chp}(t) \geq E_{e\_chp\_nom}\ x\ LF(t) \tag{18}$$

$$E_{e\_chp}(t) = E_{e\_chp\_nom}\ x\ LF(t) \tag{19}$$

$$H_{waste}(t) = H_{waste\_nominal}\ x\ LF(t) \tag{20}$$

3.2.4. Cooling energy supply calculation

Data center's cooling demand (Q_{demand}) is supplied based on three different systems: electric chiller, absorption chiller, or free cooling. Free cooling is possible when the outdoor temperature is relatively low and provides enough cooling without mechanical cooling. The free cooling operation has been determined by the outdoor wet-bulb temperature at a given data center's location.

If the electricity demand is fed from the power grid, the required cooling can be provided either from an electric chiller or free cooling. If the system operates with CHP, the absorption chiller can also provide cooling to the data center by converting CHP's heat output. In CHP operation, data center cooling demand (Q_{demand}) can be supplied from the electric chiller, absorption chiller, or free cooling.

$$Q_{demand} = \begin{cases} Q_{ech}, & if\ electric\ chiller\ is\ On \\ Q_{abs}, & if\ absorption\ chiller\ is\ On \\ Q_{frc}, & if\ free\ cooling\ is\ On \end{cases} \tag{21}$$

3.2.5. Grid feed-in electrical energy supply calculation

The data center's electrical energy demand depends on the electrical energy demand of IT racks and cooling systems. When CHP is turned-on, it can generate electrical energy as the maximum of its nominal electrical generation ($E_{e\_chp\_nom}$). If the data center's electrical demand is less than CHP's nominal electrical generation, the difference between actual generation (E_{e_chp}) and the data center's electrical demand could be sold back to the grid as surplus electrical energy. Total possible electrical surplus (E_{feed}) is calculated by subtracting the electrical demand from the energy generation:

$$E_{feed} = E_{e\_chp} - E_{demand} \tag{22}$$

3.2.6. Data center's excess heat recovery energy calculation

IT power consumption, lighting power, and CRAH's fan powers are almost converted to heat in a data center, and 100% of the heat could be recovered in theory. However, based on the studies and simulations in the literature, the results show that between 55% and 90% of the waste heat can be converted to useful heat [6,7,8,9,10,27]. Taddeo [33] created a simulation model in energy analysis software to determine the waste recovery potentials according to different heat recovery methods. Taddeo demonstrates that with the standard 18 °C server air supply, the average 860 kW heat of the 1200 kW reference data center's electrical consumption can be recovered by the CRAH return-air waste heat recovery method. Hence, a 72% heat recovery ratio has been used in our model, and accepted as a mid-case scenario of the literature for a data center's excess heat recovery system calculation:

$$H_{rec} = 0.72\ x\ H_{dc} \tag{23}$$

Heat cannot be transferred as efficiently as electricity over long distances. So, nearby heat demand is crucial for data center heat recovery system. Although heat losses in modern networks usually range from 5% to 10% of the produced heat, average heat losses are accepted as 15% in the latest Europe district heating network report due to aging of the district heating systems and heat leakages during the pipe failures [9,34]. Thus, in our calculations, the final consumer's useful heat recovery amount is decreased by 15% from the total district heating generation.

3.2.7. District heating supply calculation

Surplus heating (H_{dist}) can be supplied to the district heating network as shown in Fig. 4, according to modes in Table 1. Mode-1 and Mode-2 are the same for the district heating calculation. The amount of district heating supply is calculated for all modes as follows:

Mode-1 / Mode-2 ($m1/m2$): When CHP is operating but absorption chiller is not used, CHP's all waste heat can be supplied to district heating. This mode is usually used in winter when the outside temperature is low, and free cooling is possible. In this mode, the total district heat supply ($H_{dist\_m1/m2}$) is found by:

$$H_{dist\_m1/2} = 0.85\ x\ \left(H_{exh\_chp} + H_{hw\_chp} + H_{lw\_chp} + H_{rec} + \frac{H_{hp}}{COP_{hp}}\right) \tag{24}$$

Mode-3 ($m3$): When CHP is operating and absorption chiller is used, only CHP's low-temperature water (H_{lw_chp}) and data center's excess heat (H_{dc}) can be supplied to district heating. This mode is usually used in summer when the outside temperature is high, free cooling is impossible, and mechanical cooling is needed. In this mode, the total district heat supply (H_{dist_m3}) is found by:

$$H_{dist\_m3} = 0.85\ x\ \left(H_{lw\_chp} + H_{rec} + \frac{H_{hp}}{COP_{hp}}\right) \tag{25}$$

Mode-4 ($m4$): When CHP is not operating, cooling generation can be supplied from an electric chiller or free cooling. In this mode, all IT and cooling systems are fed from grid power, so district heating supply is only limited to the data center's excess heat recovery amount (H_{rec}). In this mode, the total district heat supply (H_{dist_m4}) is found by:

$$H_{dist\_m4} = 0.85\ x\ \left(H_{rec} + \frac{H_{hp}}{COP_{hp}}\right) \tag{26}$$

3.2.8. District cooling supply calculation

Data center's cooling demand (Q_{demand}) satisfaction is the first and unchangeable priority for a cooling generation, so the only surplus cooling (Q_{dist}) can be supplied to the district cooling network according to Table 1 at Mode-1 and Mode-3. Current district cooling networks are relatively newer than district heating networks in use. According to Calance's study [35], a maximum of 2% losses is observed in the district cooling network. According to The International Energy Agency report, system losses shall not exceed 5% of the total distributed cooling energy in sustainable district cooling systems [36]. Thus, the final consumer's useful cooling utilization is calculated by a 5% reduction from the CCHP's surplus cooling supply. The amount of district cooling supply is calculated as:

Mode-1 ($m1$): CHP in operation and electric chiller is used, data center's cooling demand is supplied by the electric chiller. Thus, the absorption chiller's total cooling generation can be supplied to the district cooling network. In this mode, the entire district cooling supply (Q_{dist_m1}) is found by:

$$Q_{dist\_m1} = 0.95\ x\ Q_{abs} \tag{27}$$

Mode-3 ($m3$): When CHP is in operation and an absorption chiller is used, only the surplus cooling generation from the absorption chiller can be supplied to the district cooling network. In this mode, the surplus district cooling supply (Q_{dist_m3}) is found by:

$$Q_{dist\_m3} = 0.95\ x\ (Q_{abs} - Q_{demand}) \tag{28}$$

4. Optimization model

A CCHP based data center with regional energy integration shown in Fig. 4 has been modelled and the data center is aimed to be operated based on cost optimization. Mixed Integer Linear Programming (MILP) is used to find the optimal operational modes by considering the low-cost operation of the overall system.

4.1. Objective function

We formulated the cost optimization of the problem to minimize the hourly energy cost of the data center as follows:

$$\min \sum_{t=1}^{8760} (C_{ops}(t)) \tag{29}$$

In the literature, power plant operation optimizations are solved by MILP and decision variables of the system. In this problem, variables become 0 or 1 as integer such as grid is on (a = 1), grid in failure (a = 0), CHP is on (b = 1), and CHP is shot down (b = 0) [37]. Hence, if we expand $C_{ops}(t)$ in the objective function in our problem, decision variables a and b can be placed in the optimization problem as follows:

$$\min \sum_{t=1}^{8760} (a\ x\ C_{ops\_grid}(t) + \ b\ x\ C_{ops\_chp}(t)) \tag{30}$$

where,

$$C_{ops\_grid}(t) = C_{grid}(t)\ x\ E_{grid}(t)\ -\ C_{dist\_h}(t)\ x\ H_{dist}(t) \tag{31}$$

$$\begin{aligned} C_{ops\_chp}(t) = {} & C_{ng}(t)\ x\ V_{ng}(t)\ -\ C_{dist\_h}(t)\ x\ H_{dist}(t)\ -\ C_{dist\_q}(t)\ x\ Q_{dist}(t) \\ & -\ m\ x\ C_{feed}(t)\ x\ E_{feed\_ech}(t)\ -n\ x\ C_{feed}(t)\ x\ E_{feed\_abs}(t) \\ & -\ p\ x\ C_{feed}(t)\ x\ E_{feed\_frc}(t) \end{aligned} \tag{32}$$

4.2. Problem constraints

The hourly cost of the operation is found according to the given input parameters with the following criteria.

Decision variables *a* and *b* define the operation mode, and the system can be either fed from the power grid or CHP unit. The following constraint is set to restrict the system to be fed from only one source:

$$a\ +\ b = 1 \tag{33}$$

Decision variables *m, n, and p* define the mode of the cooling generation mode. The system cooling demand can be supplied by absorption chiller, electric chiller, or free cooling. Free cooling mode (*p*) is only possible when the outdoor temperature is suitable. The following constraint is set to restrict the system to produce cooling only from one source:

$$m = n = 0 \quad \textit{if free cooling is available} \tag{34}$$

$$m + n = 1 \quad \textit{if free cooling is not available} \tag{35}$$

4.2.1. Data center's electrical energy demand satisfaction:

Data center's electrical energy demand must be satisfied either from grid or CHP. CHP has limit of power generation up to its nominal electrical energy ($E_{e\_chp\_nom}$) output:

$$E_{e\_chp\_max}(t) = E_{e\_chp\_nom} \tag{36}$$

To satisfy the data center's total electricity demand (E_{demand}), CHP electrical generation (E_{e_chp}) should be at least equal to electrical demand. Surplus electrical energy can be used for feed-in to grid:

$$E_{e\_chp}(t) \geq E_{demand}(t) \tag{37}$$

$$E_{feed}(t) = E_{e\_chp}(t)\ -\ E_{demand}(t) \tag{38}$$

The power grid has been accepted as an infinite electrical power source, but in grid operation grid shall be equal to demand. We specify the electrical consumption from the power grid equal to electrical demand:

$$E_{grid}(t) = E_{demand}(t) \tag{39}$$

4.2.2. Data center's cooling demand satisfaction:

The data center's cooling demand (Q_{demand}) is critical for its continuous operation. To satisfy this demand, cooling generation (Q_{gen}) should be at least equal to cooling demand:

$$Q_{gen}(t) \geq Q_{demand}(t) \geq 0 \tag{40}$$

Cooling demand must be satisfied by electric chiller (Q_{ech}), absorption chiller (Q_{abs}) or free cooling generation (Q_{frc}):

$$Q_{gen}(t) = m\ x\ Q_{ech}(t)\ +\ n\ x\ Q_{abs}(t)\ +\ p\ x\ Q_{frc}(t) \tag{41}$$

Maximum capacities of the cooling generation of the electric chiller, absorption chiller, and free cooling are determined by their nominal capacities:

$$Q_{ech\_nominal}(t) \geq Q_{ech}(t) \geq 0 \tag{42}$$

$$Q_{abs\_nominal}(t) \geq Q_{abs}(t) \geq 0 \tag{43}$$

$$Q_{CT\_nominal}(t) \geq Q_{frc}(t) \geq 0 \tag{44}$$

5. Results and discussions

CCHP based 1 MW data center located in Izmir, Turkey is used to analyze the results of different cases. Izmir city is located in Western Turkey at sea level (2 m) and the coordinates of the city are 38°25′08.6″N 27°07′43.4″E (DMS). Izmir is within the Mediterranean Climate Zone. Therefore, its summers are hot and dry, whereas winters are mild and rainy [38]. Fig. 5 shows the monthly temperature changes in Izmir during the year [39]. In Fig. 5, the grey bar displays the daily range of reported temperatures. Red ticks show the 24-hour-highs and blue ticks show the 24-hour-lows temperatures. Faint red lines represent the places over the daily average-highs, and faint blue ones show the daily average-lows temperatures. Table 2 shows the selected main components of the CCHP based 1 MW data center.

Six different cases described in Table 3 are determined to evaluate the optimal cost management impact of a CCHP based data center. In each case, another data center operation has been assessed. Case-1 and Case-2 have been simulated only for the grid-connected data centers widely used in the industry. The remaining cases (Case-3 through Case-6) have been simulated with CCHP integration with optimal cost management. All cases are analyzed for 8760 h in order to cover seasonal changes as well. Local hourly weather data, local energy prices, and fixed 1 MW IT power demand were taken as input for the six cases. From Case-1 to Case-5, hourly changing electrical prices for the electricity purchase and feed-in to the grid are used based on local time-of-use tariffs (T1, T2, T3). Additionally, single-tariff electricity prices are also simulated as Case-6. An example of the overall system's energy flow per hour in a daytime in Mode-3 is shown in Fig. 6. In this mode, the CHP and absorption chiller is in operation, the data center's excess heat is recovered, and surplus energy is sold to energy networks.

The annual energy cost of the operation is the sum of its hourly costs. Fig. 7 shows the annual energy cost comparison of the different cases, given in Table 3.

According to case results, the following conclusions have been found:

- The data center's excess heat recovery system can increase the total energy cost of the data center due to the heat pump's electricity

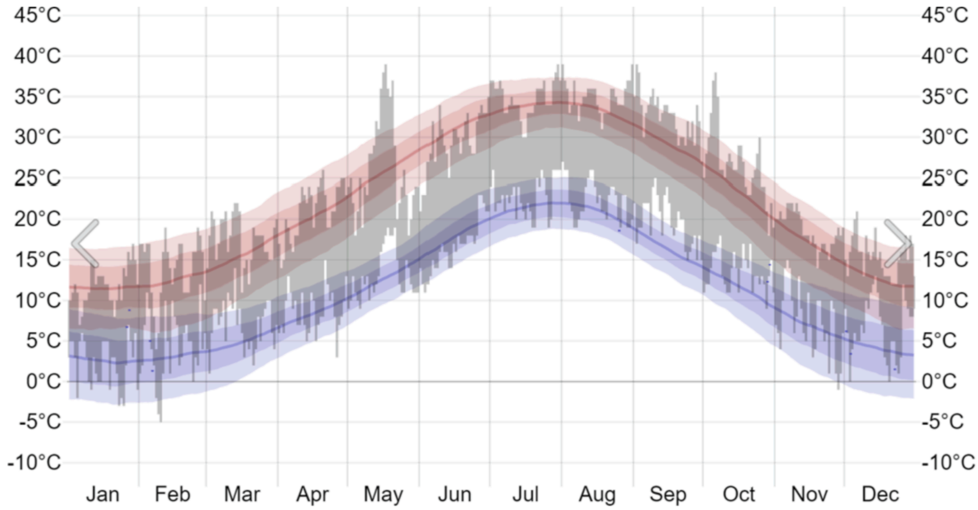

Fig. 5. Monthly temperature changes in Izmir during the year [39]

Table 2
Main components of sample 1 MW data center.

Main Components	Energy Values
CHP unit (with natural gas engine)	Nominal electric power: 1487kWe, Nominal input power: 3569kWth, Electrical efficiency: 41.7%, Thermal efficiency (including intercooler low temperature): 50.3%, Total CHP efficiency: 92%
Absorption chiller (multi-source, double effect)	Nominal output: 1758 kWth cooling, Input-1: 940 kWth heat, Input-2: 590 kWth heat,COP (Thermal): 1.15 (at 100% loading)
Electric chiller (Water-cooled, screw chiller)	Nominal cooling capacity: 1200 kWth, COP (Electrical): 5.36 (at 100% loading)
Heat pump	Nominal heating capacity: 1355 kWth, COP (Electrical): 4.2 (at 100% loading)
Cooling tower	Nominal cooling capacity: 1914 kWth, Tower fan power: 11 kWe
CRAH units	Nominal cooling capacity: 145.7 kWth cooling per unit, Total number of units: 8 pcs (N capacity), Fan power: 4.05 kWe per unit

Table 3
Case descriptions.

Cases	Data Center Operation	Data Center Excess Heat Recovery	Regional Energy Integration
Case-1	Grid operation	No	No
Case-2	Grid operation	Yes	District Heating
Case-3	CCHP or grid operation with optimal management	No	No
Case-4	CCHP or grid operation with optimal management	No	District Heating and District Cooling
Case-5	CCHP or Grid operation with optimal management	Yes	District Heating and District Cooling
Case-6	CCHP or grid operation with optimal management (With single-tariff electricity)	Yes	District Heating and District Cooling

consumption. Although the heat pump produces useful heating for district heating, the system was found not to be feasible only in Case-2 because of district heating's relatively low regional energy sales prices. The annual energy cost for data center's excess heat recovery (Case-2) increases by 5.1% compared to the standard data center operation (Case-1). Recovering the data center's excess heat is environmentally friendly, but the benefit of the system is highly dependent on regional electricity and district heating sales prices. This result further promotes the installation of low-temperature district heating networks (LTDH) in regions.

- CCHP based data center with the local operation (Case-3) can decrease the standard data center operation (Case-1) by 35.9%. In this case, CCHP supplied both the data center's electrical and cooling energy demand, so annual energy cost is decreased based on regional natural gas and electricity prices.
- CCHP based data center with data center excess heat recovery and regional energy integration (Case-5) increase the benefit of the use of CCHP in data centers. This data center can save 40.3% annual energy cost compared to CCHP based locally operated data center (Case-3). In this case, CCHP will be operated at full loads regardless of the local demand, so the benefit of the CCHP will be increased even in the summer by district cooling connection. This operation promotes the CCHP based data centers to be connected to regional energy hubs.
- CCHP based data center with data center excess heat recovery and regional energy integration (Case-5) can cut the total energy cost of the data center by 63.6% compared to the data center with excess heat recovery (Case-2). Thanks to surplus heat and cooling, surplus energy is sold to district heating and district cooling networks. These sales changed the data center's role to prosumer in the regional energy hub and saved on energy costs. The result shows that the CCHP application with data center excess heat recovery and regional energy integration (Case-5) is the most cost-efficient way of the data center operation.
- The annual energy cost difference between the time-of-use tariff (Case-5) and a single-tariff (Case-6) is found to be 1.2%. This result shows that single or time-of-use tariffs do not significantly impact the final energy cost. However, the time-of-use tariff causes the switching of the cooling system more frequently due to the changes in electricity prices during the day. Table 4 shows the operational hours of each cooling system according to different cases. In Case-6, the required cooling to the data center has been supplied either by free cooling or absorption chiller. Hence, the single-tariff is advised for the stable and reliable operation of the data center and the neglectable cost difference.

Fig. 8 shows the hourly cost of the overall operation for Case-6 and

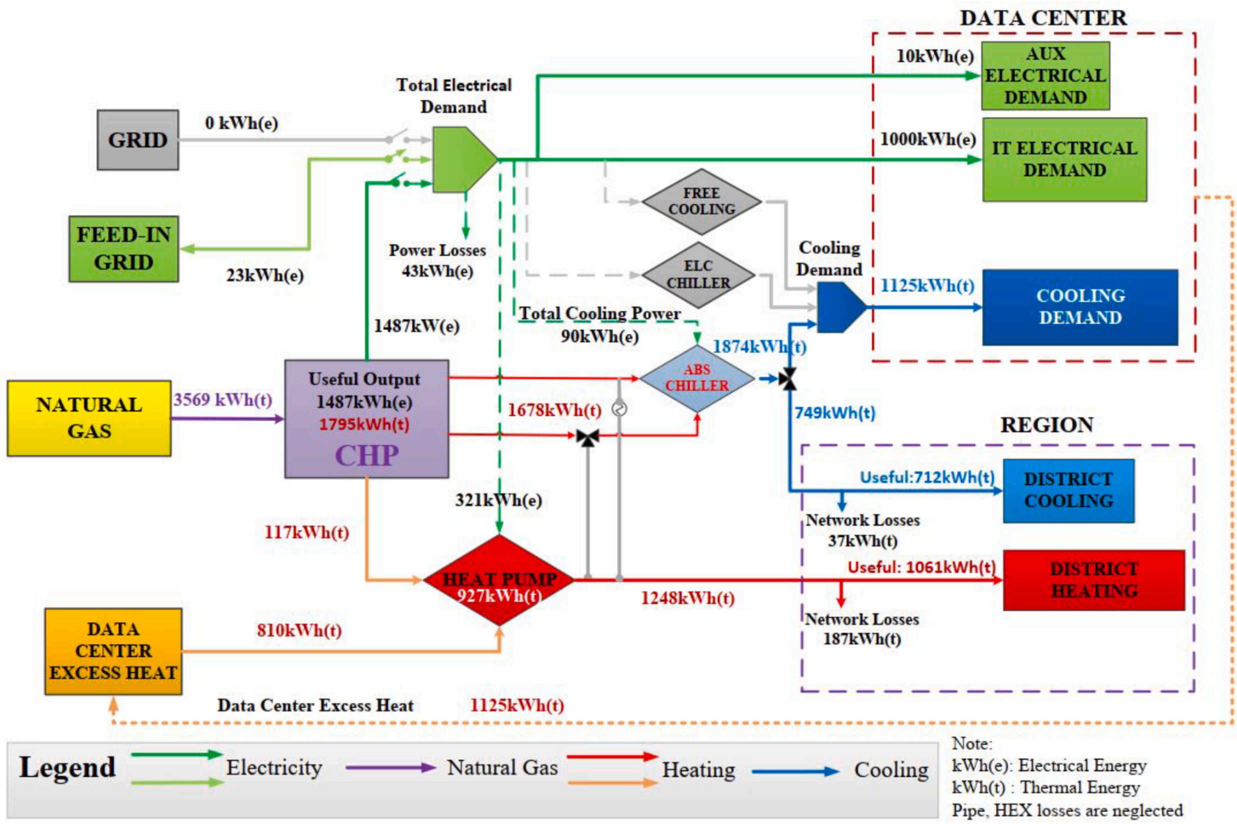

Fig. 6. An example of the overall system's energy flow when CHP and absorption chiller is in operation (Mode-3).

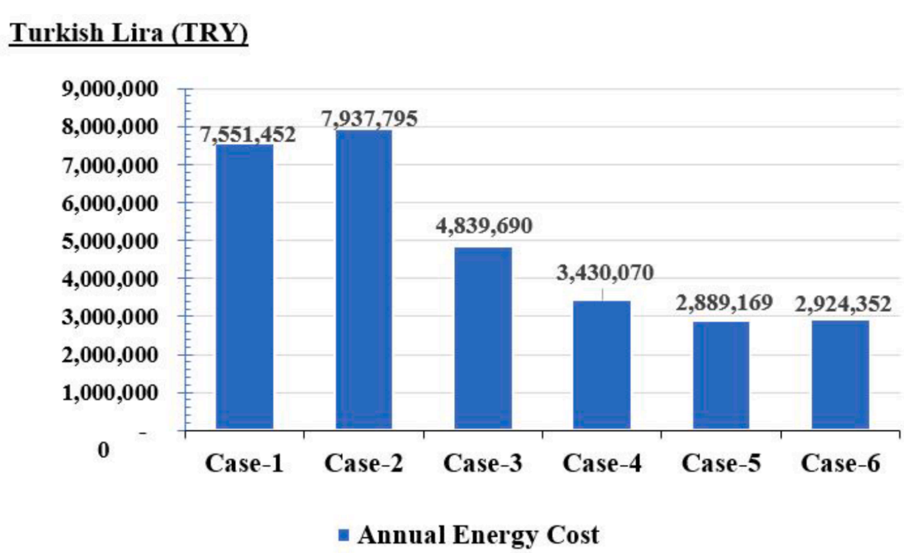

Fig. 7. Cost comparison of annual energy consumption for different cases.

natural gas to electricity price ratio changes during the year (8760 h). The graph shows that the hourly energy cost of the operation decreases when the natural gas to electricity price ratio also decreases. The hourly cost of the overall operation decreases on the 3rd and 4th quarters of the year according to the local energy price ratio.

CCHP is capital intensive and typically has more than 20 years of life, so we evaluate CCHP in longer terms. The investment cost of the CCHP and other required systems has also been investigated for the economics, and simple payback analysis for each case. Case-1 is a conventional data center, considered a base system, and other cases require additional system investments. Table 5 shows the capital, installation costs, and total investment cost of the additional systems for the conventional data centers to operate in different cases based on the reference cost information [40,41]. Installation cost is calculated as 15% of the capital cost.

A simple payback analysis is used to determine return of investment (ROI) in years for the potential feasibility of different cases with the following formula [42]:

$$ROI = \frac{Total\ Invesment\ Cost(TRY)}{Energy\ Saving(TRY/year)\ -\ O\&M\ Cost(TRY/year)} \tag{45}$$

Table 4
Annual operational hours of the cooling systems according to different cases.

Cases	Absorption Chiller Cooling Supply	Free Cooling Supply	Electric Chiller Cooling Supply
Case-1	0 h (No CHP)	4575 h	4185 h
Case-2	0 h (No CHP)	4575 h	4185 h
Case-3	3143 h	4575 h	1042 h
Case-4	2981 h	4575 h	1204 h
Case-5	3020 h	4575 h	1165 h
Case-6	4185 h	4575 h	0 h
		Total Annual Operational Hours	8760 h

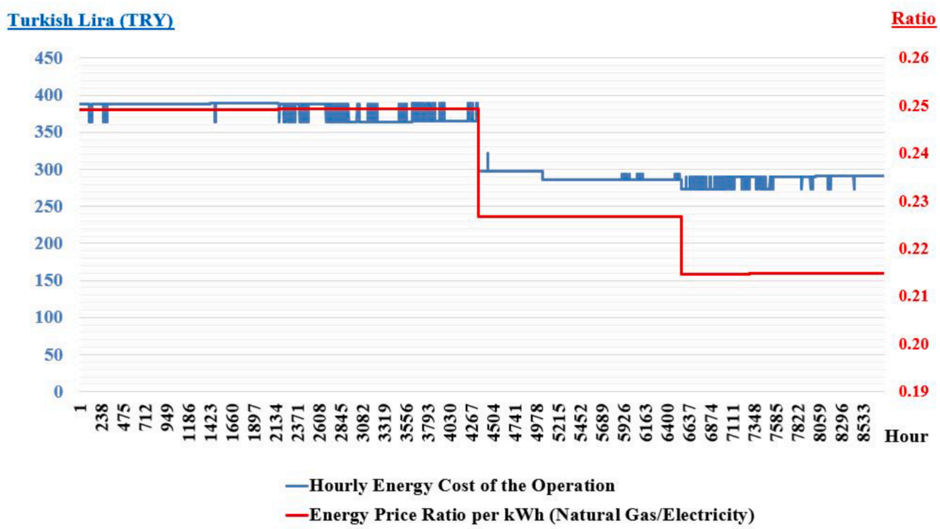

Fig. 8. Hourly energy cost changes during the year for optimized CCHP based data center operation with regional energy integration (single-tariff electricity).

Annual Operation and Maintenance (O&M) cost is calculated as 0.4% of the total investment cost. Table 6 shows the total investment and O&M cost, energy-saving, and ROI. ROI is the lowest when the data center's excess heat is recovered and CCHP based data center is integrated into the regional energy network, as in Case-5 and Case-6. Return of investment is estimated to be in 3.2 years only for the addition of data center's excess heat recovery system. In the best scenario, the return of investment is dropped from 8.7 years to 6 years when a local operation of the CCHP (Case-3) is changed to regional integrated operation and the data center's excess heat is utilized (Case-5). This result promotes the prosumer role of the data center.

On the other hand, energy prices for natural gas, electricity, district heating, and district cooling vary from time to time and region to region. Hence, CCHP's financial benefit and payback are sensitive to regional energy prices. Xu and Qu [24] investigated that the CCHP system with data center integration is profitable in San Diego due to the lower natural gas price and higher electricity price (ratio of 0.19). Ahn et al. [44] also demonstrate that CCHP system integration with district heating and cooling network reduced the operational cost in San Francisco (ratio of 0.22) and Boston (ratio of 0.27) due to the lower natural gas price to electricity price ratios. Fig. 9 shows Turkey's natural gas price, electricity price, and natural gas to electricity price ratio yearly changes from 2011 to 2021 [45,46]. Natural gas price to electricity price is relatively low and tends to decrease by years in the region. Thus, these energy prices promote the use of CCHP for data centers and district energy networks in Turkey. Recent natural gas reserve discoveries within the country would potentially support the low natural gas prices for the future in Turkey.

6. Conclusion

Most research published on energy awareness for data centers considers either excess heat recovery or CCHP use. This study has examined a comprehensive system for data centers, including excess heat recovery, CCHP utilization, free cooling, and district energy integration with energy trade-in opportunities.

We optimized the operation of the CCHP based data center with district heating and cooling integration by applying Mixed Integer

Table 5
Capital, installation and total investment costs of the additional systems for conventional data center.

Assets	Capital Cost (TRY)	Installation Cost (TRY)	Total Investment Cost (TRY)
CHP	14,040,000	2,106,000	16,146,000
Absorption chiller - only data center	3,172,000	475,800	3,647,800
Absorption chiller - data center and surplus district cooling	4,004,000	600,600	4,604,600
Heat pump - only data center's excess heat	2,184,000	327,600	2,511,600
Heat pump - CHP low-temperature heat and data center's excess heat	2,704,000	405,600	3,109,600
Heat exchangers - only data center's excess heat	156,000	23,400	179,400
Heat exchangers - only CHP	312,000	46,800	358,800
Heat exchangers - CHP and data center's excess heat	468,000	70,200	538,200

1 Euro (EUR) = 10.4 Turkish Lira (TRY) - yearly average ratio [43].

Table 6
Total investment, O&M cost, energy saving and ROI of the additional systems for conventional data center.

Cases	Total Investment Cost (TRY)	O&M Costs Annual (TRY)	Energy Saving Annual (TRY)	Return of Investment (Years)
Case-1	Base	Base	Base	Base
Case-2	2,691,000	107,640	-386,343 (No Saving)	Not feasible in terms of costs
Case-3	20,152,600	806,104	2,711,762	10.6
Case-4	21,941,816	877,673	4,121,382	6.8
Case-5	24,398,400	975,936	4,662,283	6.6
Case-6	24,398,400	975,936	4,627,100	6.7

1 Euro (EUR) = 10.4 Turkish Lira (TRY) - yearly average ratio [43].

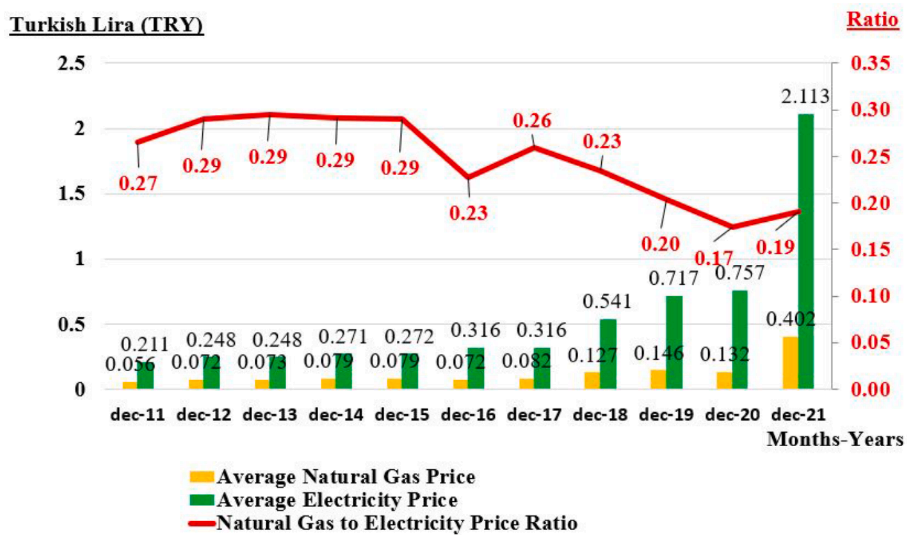

Fig. 9. Natural gas price, electricity price and natural gas to electricity price ratio changes from 2011 to 2021 for Turkey.

Linear Programming and studying different cases. In each case study, hourly energy tariffs and outdoor weather conditions are used to determine the optimized operation of the overall system. Calculation results show that the annual energy cost of the locally operated CCHP based data center can be reduced by 40.3% through a CCHP system with the data center's excess heat recovery, district heating and cooling integration. Time-of-use tariff and single-tariff are also compared for the CCHP based data center with regional grid integration. According to the results, the single-tariff and time-of-use tariff electricity prices' impact on the operational cost is neglectable. However, the single-tariff operation provides a more reliable and more stable operation due to requiring less switching of cooling system modes.

CCHP and other additional system investments require long-term evaluation in terms of the economics of the overall costs. When the data center's excess heat is recovered and CCHP based data center is integrated into the regional energy network with optimized scheduling, the return of investment could be in 6.6 years. This promotes and encourages the use of CCHPs in data centers.CCHP integration to a data center is a great success for its operation due to the match of the data center's continuous power and cooling demand, likewise the CCHP's continuous supply. CCHP integration to a data center decreases the grid dependency of the data center and helps to reduce its energy costs, according to the findings of the study. CCHP integration can combine a data center's excess heat recovery and promote using this waste heat for district heating and district cooling purposes. Moreover, regional energy integration changes the role of the data center from a consumer to a prosumer in a positive way.

The benefit of the CCHP system is highly dependent on regional energy prices. It has been proven that CCHP integration for a data center is more feasible and beneficial for a region where natural gas prices to electricity prices ratio are relatively low, such as in Turkey. This ratio tends to continue in Turkey today in a similar range as in the last decade, which positively promotes and supports the use of CCHP in data centers.

CRediT authorship contribution statement

Ilhan Keskin: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing, Software. **Gurkan Soykan:** Conceptualization, Methodology, Resources, Supervision, Project administration, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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