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Review

A Review on Green Cooling: Exploring the Benefits of Sustainable Energy-Powered District Cooling with Thermal Energy Storage

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Abstract: This paper examines the economic and environmental impacts of district cooling systems (DCS) that are integrated with renewable energy sources and thermal energy storage (TES). Typically, a DCS offers a highly efficient and environmentally friendly alternative to traditional air conditioning systems, providing cool air to buildings and communities through a centralized system that uses chilled water. However, the integration of renewable energy and thermal energy storage into these systems can further increase their sustainability and efficiency, reducing their dependence on fossil fuels and improving their ability to handle fluctuations in demand. The goal of this paper is to provide a comprehensive review of the current state of the art of renewable energy-driven DCS with TES integrated and to highlight the benefits and challenges associated with these systems. Finally, the findings of this paper offer valuable insights into the potential for renewable energy-powered district cooling systems to contribute to a more sustainable and efficient built environment.

Keywords: refrigeration; sustainability; cost-effective; vapor compressor cooling

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1. Introduction

Energy and the environment are considered two concurrent emerging global challenges today. This has led to increasing global commitment at all levels considering global warming and climate change, which is resulting in an irreversible impact across the globe. The environment is threatened by the influx of greenhouse gases (GHG), particularly CO_2-heightened radiation and heat sourced from fossil fuel combustion. Studies have shown that CO_2 is the major contributor to GHG emanating from rising heat waves and long-wave infrared radiation from the earth's surface [1,2]. The quest for better economic advantage and environmentally friendly cooling systems ignited the interest in exploring less energy consuming and high-performing district cooling systems (DCS) [3]. It has been established that approximately 17% of the total electricity generated is consumed by refrigeration applications and this inevitably led approximately 8% of total greenhouse gas (GHG) emissions to the environment. DCS technology has a direct impact on global warming, considering the rising heat waves heightened by greater energy consumption by the DCS. In response, renewable energy-powered cooling systems and thermal energy storage incorporated with vacuum centrifugal chillers (VCCs) were used as plausible options with high proficiency in terms of energy savings and minimal environmental impacts [4].

However, the generation and consumption of electricity for both domestic and industrial purposes contributed immensely to the rising heat waves in the environment. Consequently, this raises a lot of worry about the intensive energy demand in buildings considering accelerated consumption for comfort-driven purposes worldwide. On this note, substantial growth in energy consumption was recorded, by 20 to 40%, for domestic and commercial apartments in most advanced countries [5]. For instance, approximately 36%

of CO_2 emissions from Europe is from energy consumption by residential and commercial buildings, accounting for 40% of the output of the entire energy system [6]. Similarly, in Asia, approximately 35% of buildings consumed the total energy generated and a significant proportion of this energy is consumed for cooling and heating purposes across different parts of China [7]. In the same vein, 38.9% and 33% of the total energy consumed is utilized by the residential building sector in the United State of America (USA) and the United Arab Emirates (UAE), respectively [8]. Therefore, the negative impact of climate change can be slowed down through compromises in comfort, i.e., by reducing electricity consumption for heating and cooling. In this context, conventional standalone chiller plants installed in individual buildings, or industrial or commercial facilities were overworked. This led to the deployment of a district cooling system (DCS) that will contribute immensely to the significant energy reduction target and upscale maximum system efficiency. Figure 1 shows the common methods of heat production and energy sources linked to the technology period of the DCS.

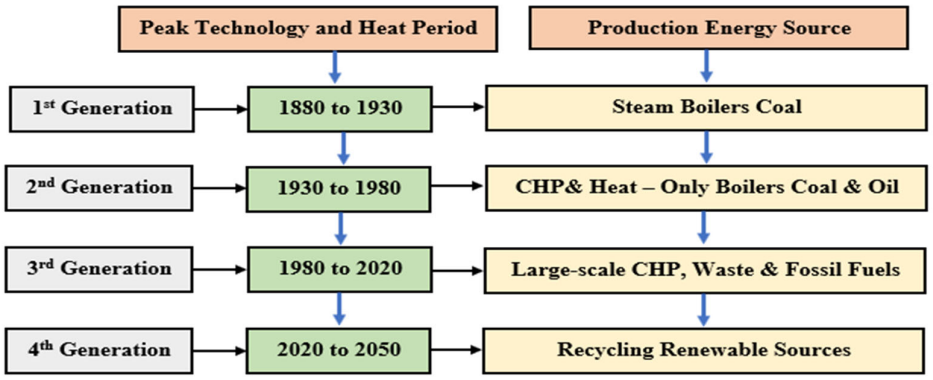


Figure 1. Production and energy sources for DCS.

In support of this claim, a DCS offers advantages such as a lower energy demand compared to on-site cooling systems (conventional), due to large-scale central water-cooled chiller plants for a given cooling system, efficient and flexible capacity, peak-period saving potential, a lower unit cost of cooling, low maintenance and cost-effectiveness, reduced environmental emissions, etc. [9]. Further, the technology would reduce damages linked to transmission, enhance productivity conversion, support the integration of other technologies, and foster sustainability and economic viability [8,9]. As a contemporary developed technology, DCS are used in areas flooded with high-density buildings due to their high cooling efficiency. Moreover, the technology is used to supply energy for space cooling and dehumidification [10,11]. DCS are tailored towards meeting and satisfying the energy demand for cooling purposes for an energy distribution network within a confined marketplace [12,13]. A DCS involves decentralization and centralization, where the former is more suitable for large-scale regions. Energy transformation occurs in diverse buildings. However, a moderately small capacity building is preferred, where advanced energy technologies are assembled outside the building for convenient energy flow in the direction of the building through the DCS network [13–15].

However, more cooling systems are being heavily used as we adapt to hot climatic conditions experienced in many countries on the one hand, and more heating systems are being equally engaged in colder zones. As a result of this heavy load, the conventional DCS is incapable of meeting and sustaining the changes in today's society that are often circumscribed by high energy consumption [16–18]. This compelled the integration of TES tanks with VCC systems in DCS plants [19,20], and the integration of renewable energy resources into DCS [2] to boost the efficiency of the process and improve the economic gains of the process. Consequently, the integration of renewable energy resources into DCS has taken center stage in the research in this field in recent decades. With this development, renewable energy sources such as biomass, wind, solar, and geothermal energy were

identified as the most feasible technologies for DCS integration [12,15]. Nevertheless, issues linked to global warming and climate change are posing challenges to economic growth due to the limitations associated with fossil-based energy [20–22]. As a result, a hike in electricity bills and the possibility of fossil fuel exhaustion has led to revisiting the utilization of renewable energy sources to power cooling/heating systems [18,22]. The use of renewable energy will serve multiple benefits such as supporting energy security missions, decreasing the rate of GHG emissions, and ensuring dependable and affordable energy delivery [23]. Surprisingly, despite the above-mentioned advantages, reviews addressing the sustainability, economic and environmental benefits of DCS powered by the grid, renewable energy technologies integrated into DCS and thermal energy storage (TES) with VCCs incorporated are still lacking. Therefore, the objective of this work is to review the current state of the art of renewable energy-driven DCS with TES, examine the benefits and challenges associated with integrating renewable energy and thermal energy storage into DCS, and compare the performance of renewable energy-driven DCS with TES to traditional air conditioning systems. Moreover, this review also presents recommendations for the future development and implementation of renewable energy-powered DCS with TES and concludes by highlighting the potential for these systems to contribute to a more sustainable and efficient built environment.

2. District Cooling System (DCS)

A DCS is a centralized cooling system that provides cooling services to multiple buildings or facilities within a defined geographic area, such as a district, campus, or city. It is an energy-efficient alternative to individual cooling systems for each building, as it eliminates the need for each building to have its own cooling system [20]. DCS offers several advantages over traditional cooling systems, including higher energy efficiency, lower maintenance costs, and reduced environmental impact. It is particularly suitable for large commercial or residential developments, where a high demand for cooling is required [21]. As shown in Figure 2, the DCS comprises a cooling source, chillers, a distribution network, heat exchangers, and customer installations (buildings) [22]. In hot countries, for instance, high electricity consumption and resulting carbon emissions are two main concurrent challenges of the cooling sector. Similarly, countries located near the tropics, also known as the Gulf Cooperation Council (GCC) comprising Saudi Arabia, Kuwait, Bahrain, Oman, Qatar, and the United Arab Emirates, are known to be among the hottest with high climate changes [23,24]. Their electricity consumption is approximately 70% maximum with a minimum of 50% due to the air conditioning system in the GCC. It was projected that the cooling demand in this region will triple by 2030 compared to in 2010. However, the amount of electricity consumed in households, mainly for air conditioning, was recorded as 70%, 60%, and 36% in the Kingdom of Saudi Arabia, Oman, and the United Arab Emirates, respectively [25–28]. There is a similar scenario in Malaysia, where the air condition system is also considered to consume among highest amount of energy, accounting for 28 to 46% of the total electricity consumption [29]. Overall, it can be established that electrical power generation expansion needs to increase by approximately 60% to meet the air cooling sector's energy requirements [24].

Typically, in DCS plants, the need for each building to have its cooling production system is avoided through centralization of the supply from the plant. This minimizes high capital, and operational costs and affords ease of maintenance [30]. However, the management and distribution of chilled water to various end users have channeled a network monitored by a third party [31]. The higher efficiencies of the DCS through the utilization of centralized energy production plants led to a reduction in GHG emissions compared to the conventional system [32]. Therefore, in a bid to enhance the efficiency of DCSs in cooling technology, the incorporation of a TES tank with a chiller system and renewable energy integration were introduced. This allows for increased operational flexibility and enhances the optimization of the technology [33,34]. In this work, various renewable energy integration methods as well as the incorporation of TES with VCCs into DCS are discussed

in Sections 3, 3.1–3.5, 4, 4.1 and 4.2, respectively. The various environmental and economic benefits as well as the sustainability status of the two technologies are discussed. Moreover, the various contributions in terms of environmental, economic, and energy savings of the technologies under review are highlighted in Section 3.

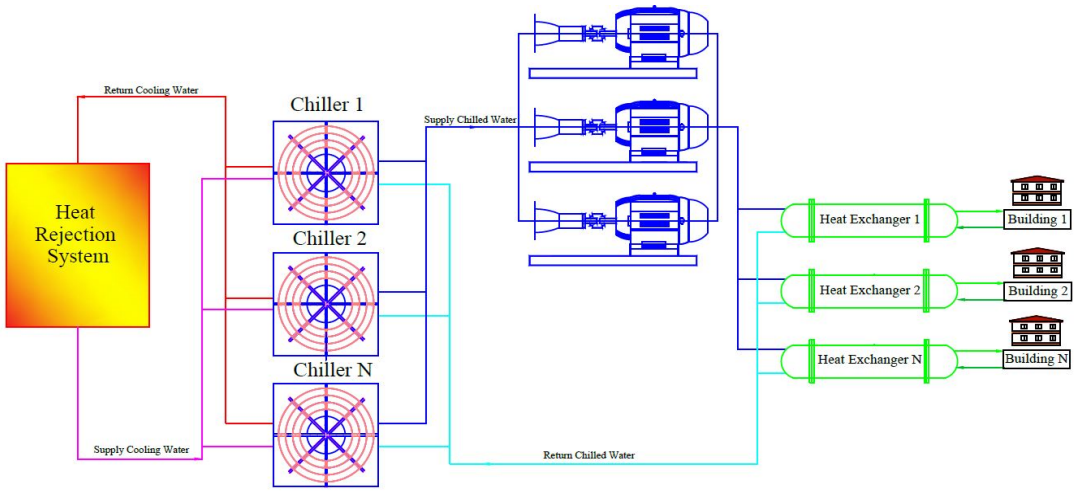


Figure 2. A schematic network of a typical DCS.

Types of District Cooling Systems

There are several types of district cooling systems, namely centralized DCSs which are large-scale systems that provide cooling to multiple buildings through a network of pipelines connected to a central cooling plant; decentralized DCSs that are small-scale systems that provide cooling to a single building or a limited number of buildings through a cooling plant [35]; hybrid DCS that are often a combination of centralized and decentralized systems, where cooling is provided through a combination of a central cooling plants and individual cooling units within the buildings; absorption chiller-based DCS use absorption chillers that are powered by waste heat or renewable energy sources to provide cooling [36]; chilled-water DCS are used as central cooling plants to generate chilled water that is then distributed to multiple buildings through a network of pipelines; direct-expansion DCS uses refrigerants to provide cooling, and the refrigerant is directly circulated through the building's air conditioning systems [37]. Table 1 presents the benefits and challenges of the various types of DCS.

Table 1. Benefits and challenges of different types of district cooling systems.

DCS Type	Benefits	Challenges	Reference
Centralized DCS	Improved air quality, high energy efficiency, reduced carbon footprint, and high initial investment.	Long-term maintenance costs and complex infrastructure.	[38]
Decentralized DCS	Flexibility to adapt to changing demand, lower initial investment, and lower maintenance costs.	Lower energy efficiency, higher energy consumption and costs, and limited cooling capacity.	[39]
Hybrid DCS	Combines the benefits of both centralized and decentralized systems and lowers energy consumption and costs.	Long-term maintenance costs and complex infrastructure.	[40]
Absorption chiller-based DCS	High energy efficiency, and reduced energy consumption and costs.	Dependence on waste heat or renewable energy sources and complex technology.	[41]

Table 1. *Cont.*

DCS Type	Benefits	Challenges	Reference
Chilled-water DCS	Reduced energy consumption and costs; reduced carbon footprint and high energy efficiency.	The high initial investment, complex infrastructure, and long-term maintenance costs.	[37]
Direct-expansion DCS	High energy efficiency, reduced energy consumption and costs, improved air quality, and minimized carbon footprint.	The high initial investment, complex infrastructure, and highly dependent on refrigerants and cooling fluids.	[42]

3. Renewable Energy Integration into DCS

The basis of scientific principles for the creation of a balance between the environment, energy, and sustainable power consumption lies within sustainable development requirements and resource utilization mechanisms, which are among the pivotal issues in today's modern society for economic and social development [43]. In this context, the irreversible increase in energy demand tied with ever-growing GHG emissions prompted the need for clean sustainable energy to relieve the crisis of high energy consumption and rising heat waves [44]. Therefore, the incessant liberation of GHG can be largely controlled with the integration of indigenous renewable energy resources into the DCS [45]. Accordingly, various co-renewable energy integration methods into the DCS are discussed.

3.1. The Use of Biomass Energy in DCS

The indiscriminate discharge of GHG emissions owing to excessive fossil fuel consumption aggravated the increasing climate change across the globe [26,27]. Therefore, energy from biomass is considered among the attractive alternative sources of renewable energy that are proficient and capable of fulfilling the ever-growing energy demand [28,29]. Biomass contributed up to 14% of the worldwide renewable energy consumed, with approximately 90% utilized in rural areas [30–32]. Biomass is a type of renewable derived from organic materials (plant or animal) that produce energy after burning. For instance, biomass is sourced from forest-based, agriculture biomass, and waste-based feedstocks [33–37]. During photosynthesis, solar energy is stored in biomass. Of the 2×10^{12} energy stored during photosynthesis, only 0.5% by weight is used as a crop for food for humans. Biomass is processed to improve its quality for energy generation and to reduce pollution [38–51]. Techniques such as pyrolysis, Fischer–Tropsch synthesis, synthetic natural gas production, and torrefaction are used for this. Energy generation from processed biomass is an active area of research and optimization, with a structured review by Masoud et al. [52], incorporating thermal storage. Designing and optimizing biomass-based systems are challenging due to factors such as moisture content, working fluid, operating cycle, char and tar production, and gas-to-biomass ratios [53]. Research on biomass processing and energy conversion is being carried out from various angles to make biomass-based systems more affordable and reliable. To achieve this, many aspects such as cost and technology, as well as chemical, thermodynamic, and environmental factors, need to be considered. Ahmadi et al. [54] studied the impact of energy and energy efficiency on the cost and CO_2 emissions of biomass-fueled energy systems using a thermodynamic model. Moharamian et al. [55] compared three configurations of a mixed biomass–natural gas energy system in terms of technology and economics and evaluated the sensitivity of the hybrid systems in an organic Rankin cycle setting, with changes in energy generation pathways. Studies have shown that lower amounts of CO_2 and carbon monoxide are emitted from biomass combustion compared to burning fossils. This CO_2 can be reused after the biomass is burned, thus making it carbon neutral [56,57]. Thermochemical and biochemical processes are two options for converting stored energy in biomass and the choice of which is tied to a particular type of application [58]. The applicability of using biomass energy in a DCS is such that the heat generated by the utilization of the biomass is used to cool the absorption chiller. Subsequently, insulated pipelines are used for the

circulation of the cooled air into different parts of the building facility and are often maintained at a particular temperature throughout the process.

Therefore, one potential substitute for conventional air-cooling systems is liquid cooling, which involves transferring heat away from a computer or electronic device using a liquid, typically water, rather than air. In a liquid cooling system, water is pumped through a closed loop system that includes a water block, which is a heat sink that is in contact with the electronic device generating heat. As the water flows through the water block, it absorbs heat and carries it away from the device. The heated water then flows through a radiator, where the heat is dissipated into the air, and the cooled water is pumped back into the water block to repeat the cycle [4,11]. This approach offers solution-based modules such as a GHG reduction strategy, energy saving, and sustainable energy supply in this integrated system [59]. Other applications of biomass-based cooling systems can provide heat or steam for industrial processes such as paper or pulp production, or heating and hot water needs in buildings through direct means or a thermal network in district heating systems. The combination of biomass with other fuels in big power plants is becoming more prevalent due to improved efficiency. The term "co-firing" in the biomass industry has different interpretations. In the energy sector, it refers to the simultaneous production of various forms of energy, whereas in biomass-powered systems, it means blending biomass with fossil fuels (usually coal or natural gas) to partially replace fossil fuels [60]. Further, waste derived from biomass incineration is used to power absorption chillers; in this way, the waste is judiciously transformed into value-added products rather than ending in landfills. Moreover, this process saves energy consumption by 60% and decreases the CO_2 emissions rate per unit of cooling compared to other conventional compression chillers [61]. Rentizelas et al. [62] proposed the development of an increased biomass supply chain for possible use in DCS. According to the authors, the development offers advantages such as cost savings and efficiency, and reduces warehouse effects [62].

3.2. The Use of Solar Thermal Energy in DCS

The increase in energy consumption worldwide is expected to raise CO_2 emissions by 60% by the end of 2030 [63,64]. The compelling internal cooling demands, particularly during winter seasons for mainly thermal comfort, are said to be the reason behind this [65]. This has led to the overwhelming response by scientists worldwide towards the exploration of abundant solar energy, which is known to be readily available all year round on most of planet earth [66]. Applications of high solar energy radiation in DCS, domestic cooking wares, water heating, electricity generation, and refrigeration are foreseeable with multiple benefits [67]. Therefore, installation of thermally driven cooling machines using solar energy will support meeting the cooling demands experienced during the hot season/period. Most importantly, this cooling system offers improved efficiency in terms of energy consumption and minimizes environmental consequences as compared to vapor compression machines [68]. Thus, climate change mitigation and an energy-balanced target would considerably upscale the contribution of solar energy. In this way, the cooling demand experienced during the hot season can be substantially addressed using the supplied energy obtained from solar thermal (ST) technologies [2]. Moreover, ST energy can potentially replace fossil fuels and complement the energy needed for hot water and cooling inside buildings.

Therefore, ST-driven DCS consist of solar thermal collectors connected to thermally driven chillers for space cooling in buildings [69]. ST technology is also known as green cooling technology and works based on the principle of converting solar radiation into heat energy [70]. Hence, thermally driven absorption chiller machines are used to generate heat energy required for cooling using this technology. Installation of ST technology is increasing due the ease and efficiency of the cooling process [71]. Further, thermally activated absorption chiller machines for cooling are regarded as environmentally friendly owing to zero GHG emission with no effect on the ecosystem. As such, ST-integrated DCS are being considered for commercial use [67]. Additionally, ST collectors can be

used to supply DCS absorption chillers with low thermal heat requirements. Therefore, ST energy-driven DCS are attractive alternatives in countries with low local supply of fossil fuels.

3.3. The Use of Geothermal Energy in DCS

Geothermal energy is a thermal form of energy found in the earth's crust, formed because of the formation planet and the radioactive decay of materials. This form of energy is derived from the earth's central core at a depth of 6437.376 km from the earth's outer surface. However, the high temperature on the earth's central surface is mainly due to the decay of radioactive particles [2]. Geothermal energy is renewable and obtained from within the earth, used directly for heating and electricity generation. Geothermal energy is considered different from other renewables due to year-long availability and use at any time of the day. Moreover, this form of energy contributes substantially to safeguarding the atmosphere and preserving public health from risks emanating from emissions of burning fossils [46]. A natural temperature gradient from higher to lower sources normally exists based on the second law of thermodynamics. Thus, heat moves towards the outer surface of the earth with approximately 42 million thermal megawatts. However, in a geological process also known as plate tectonics, some of this thermal heat is reserved at temperatures and depths for commercial applications [2].

Typically, in geothermal reservoirs, water is used as the most common fluid for heat transfer. Additionally, geothermal reservoirs for power production use a direct heating system with low and medium temperatures [72]. Some of the merits of this process include the relative abundance, zero competition for land requirements, fewer atmospheric pollutants, and that it is completely independent of weather conditions, making it more viable compared to other renewable technologies [73]. Moreover, proven sustainability, low cost, and cleanliness are some of the advantages that set the bar higher for using geothermal energy in DCS. This has ignited interest in the growing use of geothermal energy [74].

3.4. The Use of Solar Photovoltaic Systems in DCS

Solar photovoltaic systems have been opted as a non-polluting and sustainable route of electricity generation [75]. In view of the increasing rate of energy consumption globally, low-cost, sustainable, and reliable energy sources are ingredients for sustainable economic growth and development [76]. In this process, incident solar radiation is used for power generation using photovoltaic solar cells. Therefore, solar energy has the potential of meeting the economic energy need for electricity and other purposes. No chemical or mechanical work is required in the conversion of solar energy to electricity. As a result, solar energy-driven electricity has zero emissions, thereby making it the most environmentally friendly energy compared to other renewable resources [77]. However, despite high proficiency and the environmentally friendly benefits offered by solar photovoltaic (PV) systems towards addressing the lingering energy crisis, its high cost is considered a major limiting factor to its large-scale use. To address this, incentives in the form of financial support and tax-free import waivers need to be granted to companies as a way of inspiring/motivating more investment in solar PV systems [78]. Additionally, the ease of installation with cheap maintenance labor as compared to other power generation systems increase investment in solar PV systems [79]. Other benefits include zero risk, safe use, low maintenance costs, and high durability [80]. It is forecasted that the PV-powered electricity share will be more than 20% across the world by 2050 [81]. However, Sunanda et al. [82] reported that the amount of solid waste produced from the disposal of solar panels has not been accurately determined, and this will become a problem for the photovoltaic energy sector in the future. The waste from end-of-life solar panels is harmful to the environment and has the potential to produce 300-fold more toxic waste than nuclear plants.

Therefore, the integration of solar PV into DCS could minimize GHG emissions emanating from heating and cooling systems. Thus, a net-zero energy building is that in which the building system is completely serviced by renewable energy resources [83].

Consequently, building systems for cooling purposes are highly enriched with solar PV-generated electricity to achieve the electricity load. In most designs, integrating solar PV into the DCS serves as a primary energy source while grid electricity is a secondary energy source [84]. With this, solar PV systems can significantly contribute to the cooling energy requirements in buildings via the support of artificial lighting systems and visual comfort, guaranteeing healthy natural lightening and producing solar electricity and solar heat at the same time [85,86]. In addition, the building cooling system will be supported by solar PV for both residential and district systems with a single central control unit. Therefore, due to the efficiency, cheapness, and abundance of solar energy for integration into DCS, increased adoption of the technology among residential, commercial, and government establishments is witnessed.

3.5. The Use of Surface Water in DCS

Surface water is considered a sustainable source of energy capable of fulfilling the bulk energy consumption demand of cooling and heating systems in buildings. This type of energy resource has the maximum capacity and is often regarded as the most frequently utilized in DCS [12]. Studies have shown that numerous DCS located in coastline cities across the world utilize deep seawater as a cold source of energy. With this, solar energy is absorbed by the surface and bottom (below 500–1000 m) of the ocean with a temperature of approximately 25–30 and 4 °C, respectively [83]. In deep seawater, the DCS scheme functioned with numerous benefits including huge energy savings of approximately 90% and is cost-effective, ecologically safe, and available for as long as needed [2]. However, in the world's tropical oceans, seawater temperatures decrease with depth, due to the presence of the deep-water ocean hot sink because of issues linked to climate change.

Typically, within the tropical zone, the temperature is approximately 8 and 4 °C, slightly colder, at approximately 700 m and 1000 m in depth, respectively. However, if cool water is available in ample amounts, DCS chillers are not required. With this free cooling technology, the energy requirements of the DCS will significantly reduce [12]. As shown in Figure 3 of deep sea cold water, heat exchangers are used for the passage of the deep cold seawater from the surface to the central DCS plant [87]. Therefore, its abundance and ease of accessibility make it readily available and suitable for integration into DCS. Moreover, this technology offers the potential of supporting the required thermal comfort during hot seasons to residential, commercial, industrial, and government institutions/establishments. The economic viability of this process coupled with its increased efficiency make this process an attractive alternative for DCS to foster the sustainability of cooling technology.

3.6. The Economic and Environmental Analysis of Renewable Energy-Driven Systems for Cooling

The economic and environmental impacts of renewable energy-driven district cooling systems are significant and complex [84]. On the economic side, these systems offer cost savings over traditional air conditioning systems through their centralized design, reduced energy consumption, and lower maintenance costs. However, the initial investment required to implement these systems can be significant, and the long-term financial benefits depend on factors such as energy prices, government incentives, and system performance [88]. On the environmental side, the integration of renewable energy sources can greatly reduce carbon emissions by district cooling systems, as well as lower the impact of climate change [89]. However, a summary of the economic and environmental gains of renewable energy-driven systems for cooling is presented in Table 2. Harnessing the power of renewable energy systems can significantly reduce their greenhouse gas emissions and contribute to a more sustainable energy system. Furthermore, renewable energy sources are considered reliable and less susceptible to fuel shortages, price fluctuations, and other supply chain disruptions, making district cooling systems more reliable and less vulnerable to unexpected interruptions. Additionally, the use of these systems helps reduce dependence on finite fossil fuel resources and promote a more sustainable energy future by improving the stability of the energy system and reducing the need for backup power

from fossil fuels [66]. Overall, the economic and environmental impacts of renewable energy-driven district cooling systems are highly positive, but they are also subject to many uncertainties and challenges. To fully understand the benefits and drawbacks of these systems, further research and development are needed to assess their performance in different conditions and environments and to identify best practices for their implementation. In conclusion, the use of renewable energy-driven systems for district cooling can result in both economic and environmental benefits, making them a promising solution for sustainable energy production.

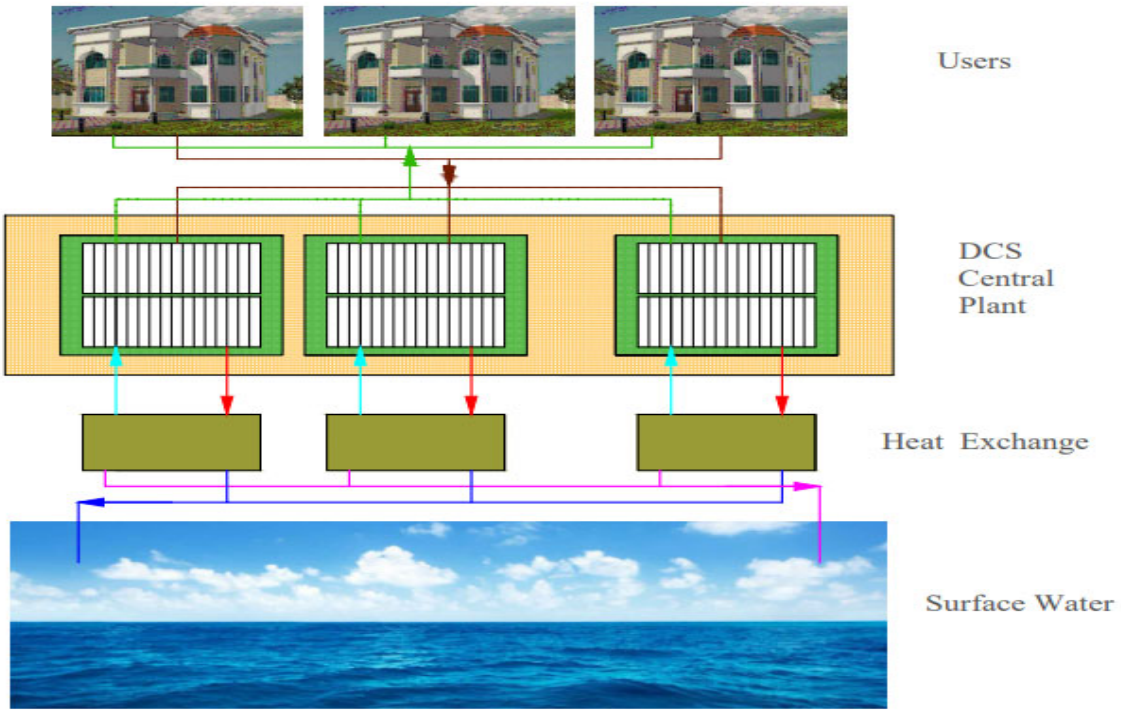


Figure 3. A modified version of the DCS using surface water; copyright by Elsevier 2019 [2].

Table 2. The economic and environmental advantages of incorporating DCS with various green energy systems.

Renewable Energy Type	Economic	Environmental	Ref.
Biomass energy integration into DCS	• Lower cost: Biomass-based materials are typically less expensive than traditional fossil fuels, reducing the operating costs of district cooling systems. • Renewable energy source: Biomass is a renewable energy source, reducing dependence on finite and expensive fossil fuels. • Its unlimited availability makes it cheap. • Job creation: The use of biomass in district cooling systems can stimulate the growth of local biomass production and processing industries, creating new jobs and economic benefits in rural areas. • Local availability: Biomass is often readily available in local areas, reducing transportation costs and energy losses associated with long-distance fuel transportation.	• It is safe and produces lower amounts of GHG. • Biomass is linked to a reduced risk of wildfire and an increase in sustainable ecology. • Reduced emissions: Biomass-based materials produce lower amounts of greenhouse gas emissions compared to traditional fossil fuels, improving air quality and reducing the carbon footprint of the district cooling system.	[90,91]

Table 2. *Cont.*

Renewable Energy Type	Economic	Environmental	Ref.
Solar thermal energy integration into DCS	• Reduce power consumption, thereby lowering electric bills. • Lower energy costs: By using solar thermal energy, a district cooling system can reduce its dependence on traditional fossil fuels and lower its overall energy costs. • Improved energy security: Solar thermal energy can provide a local and renewable source of energy, reducing dependence on imported fuel and improving energy security. • Boost to the local economy: The integration of solar thermal energy into district cooling systems can create jobs and stimulate local economies, as well as increase demand for local goods and services.	• It is pollution free, with no GHG emissions after installation. • Decreased greenhouse gas emissions: Solar thermal energy is a clean and renewable energy source which reduces the emissions of greenhouse gases associated with fossil fuels.	[70,82,92]
Geothermal energy integration into DCS	• Reducing overdependence on imported energy, thereby decreasing the trade deficit. This in turn promotes the growth of an in-house healthy economy.	• The combustion of fossil fuels on site is dramatically lowered or eliminated. • Offers a significant reduction in GHG emissions and the environmental damage associated with non-renewable resource extraction.	[93]
Solar photovoltaic integration into DCS	• Offsets electricity-associated costs. • Requires little maintenance and is easily customized.	• Minimal air pollution, thereby enhancing the long-term health of humans. • Passive and active systems with the option to also provide cooling during warmer seasons using absorption chillers.	[94]
Surface water energy integration into DCS	• Waste accumulation benefits.	• Supports the circular economy through waste conversion to value-added products.	[70]

4. Vapor Compression Chiller Integration into Thermal Energy Storage

4.1. Thermal Energy Storage (TES)

The poor cooling performance of DCS led to the deployment of TES to assist in storing chilled water during times that require less cooling. This works by discharging cold energy to meet the cooling loads, particularly at peak demand. Integrating a TES tank into a DCS setup helps improve operational efficiency, enhance the life span of the DCS, and reduce high tariff charges for peak and off-peak periods of the day [95,96]. Therefore, the workload of the electricity grid in the DCS is supported through the deployment of TES, leading to lower energy consumption, and reducing the cost of refrigeration using high electricity consumption due to transitioning to off-peak hours. Moreover, TES technology uses water as its storage medium, which is readily available with high thermal capacity, thereby making this process economically viable and sustainable. Another promising feature is the lower technical complexity of the water storage medium in connecting networks of the DC system [97]. Further, ice storage is another storage medium that utilizes the latent heat of ice, thus resulting in a smaller storage volume [98]. Comparatively, the use of ice storage demands little storage space and a low evaporation temperature for production, leading to lower plant efficiency in cold energy production. On the other hand, higher temperatures affect the efficiencies of water-based storage tanks through increases evaporation, increased stratification, and acceleration of build up scale and deposit inside

tanks. Most importantly, the literature revealed that the environmental impact is reduced by approximately 40% following the integration of TES into the DCS [64]. Nevertheless, the efficiency of TES is also enhanced by the integration of a vapor compression chiller (VCC) but cost inevitably increases.

4.2. Vapor Compression Chillers (VCCs)

A vapor compression chiller (VCC) is a mechanical device/compressor that uses steam, electricity, or gas turbines in the refrigeration process and is often installed to supply chilled water to TES for charging purposes [99]. The process involves lowering the temperature in an enclosed space by extracting heat and dispatching it to a designated place [100]. The VCC system is composed of a compressor, an evaporator, a condenser, and an expansion valve as shown in Figure 4. Typically, the process involves the circulation of the refrigerant around the system, followed by high pressure condensing, with the evaporator vaporizing the refrigerant as the vapor pressure becomes lower [101]. However, the compression and expansion of the refrigerant are often facilitated by the compressor and expansion valves and, subsequently, the condenser serves to repel the heat from the refrigerant vapor. Studies have shown that data mining, simulations using different software, and data analytics are used to quantify energy saving and ultimately improve the energy efficiency of VCS in buildings. Further, other modeling tools reported in the literature include the grey box, which combines the qualities of both the physics-based and data-driven models [102]. Therefore, the energy efficiency of VCCs can be measured using different indicators such as the energy efficiency ratio (EER), the integrated part load value (IPLV), the seasonal energy efficiency ratio (SEER), and the seasonal coefficient of performance (SCOP) that involves seasonal chiller operations and capacity modulation. Therefore, the efficiency of the VCC and its overall performance is computed using the COP and the cooling load from measurements of electricity consumption is quite simple, thus the surrounding conditions and the chiller technology determine the COP value [103].

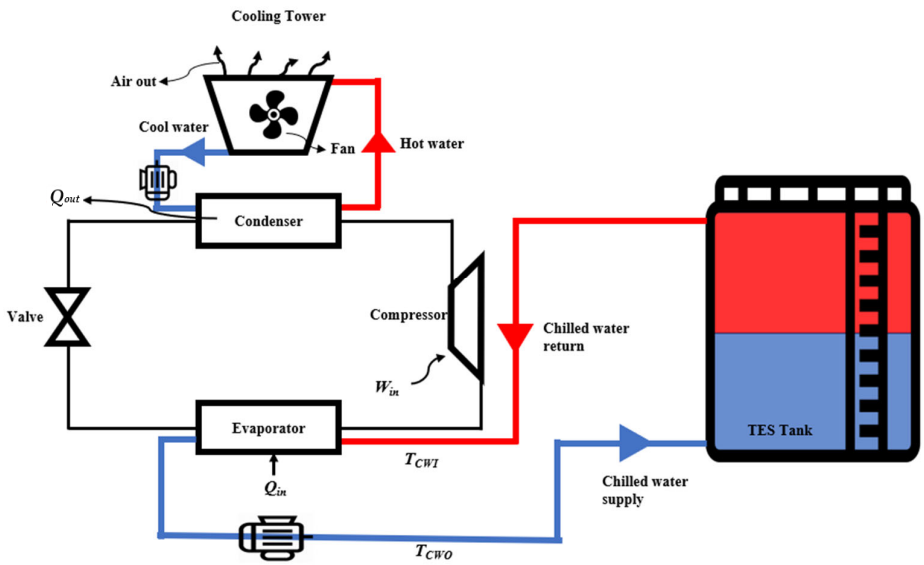


Figure 4. Schematic diagram of a vapor compression system adapted from [20].

Overall, the benefits of VCC/TEC integration into DCS are:

- Enhanced control and monitoring of industrial processes, leading to improved efficiency and reduced waste.
- Reduced dependence on fossil fuels and reduced greenhouse gas emissions.
- Optimization of energy consumption, reducing costs and further benefiting the environment [96].
- Economic and environmental benefits for selected countries as presented in Table 3.

Table 3. Environmental and economical advantages of implementing DCS, incorporating renewable energy sources, and integrating VCC/TEC into DCS outlined for certain countries.

Country	Energy Source/ Integration	Environmental Benefit	Economic Benefits	Reference
District cooling system				
Hong Kong	DCS powered by grid	Has no environmental gain	Lowere electricity consumption by the DCS especially for an ice storage system with 60% chiller priority. This in turn reduces the electricity tariff.	[102]
	✓	✓	Approximately 80% of the annual operating cost of DCS with ice storage compared to DCS optimized using a conventional method.	[103]
USA	✓	✓	In 2015, a sum of USD 421,434 was realized in one week (i.e., 1–7 July) as profit from the sales of electricity from the grid to cooling system stations and other heating sales.	[104]
Turkey	DCS powered by grid using coal-fired power plants	Lower emissions (not quantified)	No economic benefit was recorded.	[105]
Kuwait	DCS powered by grid using Natural gas	There is a 50% annual reduction in CO_2 emissions	The relative cost per ton-hour for cooling was reduced by approximately 53%.	[9]
District cooling system using renewable energy				
Saudi Arabia	DCS powered by solar system integration	• Minimal emission of GHG • Lower heat emissions	• Investment into the solar-driven system was improved, leading to more investment in the technology. • The lowest investment cost is recorded through the deployment of solar systems.	[106]
	✓	CO_2 emissions are reduced by an average of 500 tons (i.e., 70%) and 1400 tons per year relative to DCS with a centralized electrical compression chiller cooling plant	• The primary cost of the solar field, storage tank, and chillers is reduced through the system component size optimization. • The overall cost of DCS with PTC-driven double-effect absorption chillers is approximately 30% lower than that of DCS with ETC-driven single-effect absorption chillers.	[36]
Singapore	DCS powered by PV electric system integration	CO_2 emissions would be reduced by an average of 19.7% from 2020 to 2050	An estimate of three hudred and thirty million dollars, was earmarked for DC grid investment of the Singapore 2050 energy system, which is projected to save by up to 32.7% energy.	[107]
Sweden	DCS powered by biomass	Zero CO_2 emissions	Not reported.	[108]
Dubai	DCS powered by solar system integration	Not reported	Non-quantified economic savings associated with reduced electricity consumption, reduced peak demand charges and reduced CC investment costs.	[109]
District cooling system using vapor compressor cooling/thermal energy storage				
Malaysia	DCS integrated by TES/VCC	Lowest CO_2 emissions, reduced by approximately 40% as recorded by TES	Approximately 40% savings.	[20]

5. Conclusions and Future Research Priorities

This study reports the economic and environmental impact of DCS and the integration of renewables and TES with VCCs into DCS. This study identified a cost-effective, energy-efficient, and environmentally friendly cooling technology. The report also compares the

benefits of different cooling technologies, such as better comfort and reliability, as well as reduced maintenance and operating costs. However, traditional DCS technology has drawbacks, including high energy demand and excessive CO_2 emissions from fossil fuel combustion. To address these issues, the integration of renewable energy into DCS is proposed to minimize costs and reduce carbon accumulation. The implementation of solar energy in DCS in Saudi Arabia and Dubai reportedly led to a 35–70% reduction in their carbon footprint. Meanwhile, the integration of bioenergy into DCS is widely adopted in Finland and Sweden, in line with their green energy policies. In conclusion, the integration of renewables into DCS offers a feasible solution because it is efficient, cost effective, and environmentally friendly. Additionally, the integration of information processing and predictive control technologies will improve access to previously impractical renewable energy sources such as biomass, which has lower economies of scale and reliability challenges in the supply chain. Distributed energy generation units have greater potential for biomass by utilizing local supply resources. Lastly, the integration of TES with VCCs into DCS was reported to have been adopted and used successfully in Malaysia. This technology was also found to have offered an economic advantage of an approximately 40% cost reduction compared to DCS alone, which in turn reduces energy consumption and environmental impact. Overall, it can be established that the use of renewable energy technologies has the most significant influence on the system's environmental performance. Overall, this study highlights the potential for renewable energy-driven district cooling systems with thermal energy storage to contribute to a more sustainable and efficient built environment. Moreover, the challenges and uncertainties associated with these systems, and the need for further research and development to fully realize their potential, have been presented. Although renewables are considered expensive in some respects, policies such as tax import waivers and other incentives by the government would go a long way in upscaling the broader utilization of renewables. In conclusion, the following recommendations were made for the use of DCS technology.

- Increase government incentives: Encouraging the development and implementation of renewable energy-powered district cooling systems with thermal energy storage through government incentives such as tax credits, subsidies, and grants can help to overcome the initial investment hurdle and increase the adoption of these systems.
- Improve energy storage technology: Advances in energy storage technology, such as increased capacity, reduced cost, and improved performance, will play a key role in the future development and implementation of renewable energy-powered district cooling systems.
- Encourage public–private partnerships: Encouraging public–private partnerships between government agencies, utility companies, and private sector organizations can help to pool resources and expertise and increase the speed and scale of deployment of these systems.
- Develop new financing models: Developing new financing models, such as energy performance contracting and energy service companies, can provide innovative ways to fund the development and implementation of renewable energy-powered district cooling systems with thermal energy storage.
- Enhance public awareness and education: Raising public awareness and education about the benefits and potential of renewable energy-powered district cooling systems with thermal energy storage can help to build public support and drive demand for these systems.
- Implement smart grid technologies: Integrating smart grid technologies, such as demand response and energy management systems, into renewable energy-powered district cooling systems with thermal energy storage can help to optimize energy consumption, reduce energy waste, and improve system efficiency.
- The focus should be tailored towards exploring synergy among the co-technologies of DCS, renewables, and TES with VCC-integrated systems to effectively overcome many problems associated with the technology.

- Deployment of modern learning tools such as machine learning to forecast the rate of energy efficiency and consumption in the building: This creates an avenue for comparison between the predicted results and the conventional results to detect possible defections.
- A holistic approach to sustainability evaluation should be incorporated in the environmental and economic assessment of the various technologies.
- Strategies for incremental development in terms of the challenges of system efficiency, cost, and sustainability would help these technologies become more viable in the nearest future.

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