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Review

Sustainable District Cooling Systems: Status, Challenges, and Future Opportunities, with Emphasis on Cooling-Dominated Regions

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Abstract: A review of current and future district cooling (DC) technologies, operational, economic, and environmental aspects, and analysis and optimization methodologies is presented, focusing on the demands of cooling-dominated regions. Sustainable energy sources (i.e., renewable, waste/excess electricity and heat, natural/artificial cold) and cooling/storage technology options with emphasis on heat-driven refrigeration, and their integrations in published DC design and analysis studies are reviewed. Published DC system analysis, modeling, and optimization methodologies are analyzed in terms of their objectives, scope, sustainability-related criteria, and key findings. The current and future development of DC in the Gulf Cooperation Council (GCC) region, a major developing cooling-dominated market, is examined more specifically in terms of current and future energy sources and their use, and economic, environmental, and regulatory aspects, with potential technical and non-technical solutions identified to address regional DC sustainability challenges. From the review of published DC design and analysis studies presented, collective research trends in key thematic areas are analyzed, with suggested future research themes proposed towards the sustainability enhancement of DC systems in predominantly hot climates.

Keywords: district cooling; space cooling; air-conditioning; hot climate; thermally activated cooling; sustainable energy; Gulf Cooperation Council

1. Introduction

Energy sustainability, security and climate change are major threats of today's and future generations. Substantial reductions in anthropogenic greenhouse gas (GHG) emissions must be an integral part of sustainable energy production and use to limit the global rise in ambient temperatures over the coming decades [1]. Emissions reduction over the next two decades will be challenged by a projected 33% increase in global primary energy demand over the coming 25 years, 70% of which are anticipated to arise from the electricity sector [2]. This demand growth will be mainly contributed by the industrialization and electrification of non-OECD (Organization for Economic Cooperation and Development) economies, particularly China and India [2].

Buildings are responsible for approximately a third and 50% of global energy and electricity uses, respectively, and 20% of energy-related GHG emissions [1]. Approximately 99% of air-conditioning and refrigeration loads worldwide are met by electricity. The associated annual electricity demand (and carbon dioxide (CO_2) emissions) has tripled between 1990 and 2016, and currently represents 10% of global electricity use [3]. This demand is expected to triple again to 6200 TWh by 2050 in the baseline International Energy Agency (IEA) scenario, with 70% of this rise attributable to residential users, unless effective energy conservation and efficiency measures are adopted [3]. This growth will take place essentially due to rises in population in developing economies that are in hot-climate regions, and seek improved comfort (i.e., India, China, Indonesia, the Middle East) [3]. The cooling energy consumption of typical buildings in hot and hot/humid climates is up to three times higher than in moderate climates [1]. Furthermore, space cooling loads in hot climates are typically characterized by large seasonal and daily variations, that induce strain on electricity grids. Whereas air-conditioning represents on average 14% of peak electricity demand worldwide [3], in hot climates such as in for example the Gulf Cooperating Council (GCC) region, where the deployment of district cooling (DC) is discussed as part of this article, this demand represents approximately 50% [4,5] and up to 70% [3,5] of total and peak electricity consumptions, respectively. (The GCC comprises six Arabian states, namely Bahrain, Kuwait, Qatar, Oman, Saudi Arabia, and the United Arab Emirates (UAE). The GCC region extends over 2,500,000 km^2 area, with a population of 52.7 million in 2015 [6].) Similarly, in South Asian regions, where the energy demand of residential/service buildings accounts for approximately 60% of total energy consumption, approximately 44% and 50–57% of residential and commercial/office building electricity consumption is associated with space cooling [7]. Building cooling requirements will be exacerbated by climate change, as reflected by the measured augmentation in the number of cooling degree days in several regions [8]. Additional factors that contribute to a growing building cooling demand include building architectures, rising internal heat loads, and urban heat island effects.

At present, most air-conditioning loads worldwide are met by conventional on-site cooling systems (Figure 1a), consisting of either window units (i.e., split systems) applied in single rooms, apartment units or small buildings, or central air-cooled or water-cooled chillers, which tend to be located on the rooftop or basement of large buildings. In such systems cold energy is produced and distributed at the end-user's site [9]. The efficiency of on-site air-conditioning equipment varies widely depending on design and operating conditions but is generally half of that achievable with best commercially available technologies [3]. By contrast in DC systems (Figure 1b), cold production is centralized in a central chiller plant and delivered to end-users via a distribution network infrastructure and energy transfer stations (ETSs). The central chiller plant includes cooling equipment, pumps, heat-rejection equipment, a chemical treatment unit, controller, and other devices [10]. Indirect cold production by the central chiller can be supplemented by direct cooling provided by an available cold energy source. Other associated units include cold storage, pump stations and control systems. ETSs consist of heat exchangers and distribution/regulation valves [9].

DC systems can offer significant advantages over conventional standalone chiller plants installed in individual buildings, or industrial or commercial facilities. These advantages include (i) low energy requirements—for a given cooling demand, DC systems generally consume less energy than on-site cooling systems, mainly due to large-scale central water-cooled chiller plants being more efficient than on-site small-capacity air-cooled systems; (ii) efficient and flexible capacity use to fulfill load diversity and variability, as a result of DC system design and installation; (iii) peak-period saving potential; (iv) lower unit cost of cooling, due to lower energy-, maintenance- and construction costs; (v) reduced environmental impact—emissions are not only reduced but also more easily handled at a remote, centralized chiller plant than at individual building's air-conditioning systems; (vi) more reliable service (i.e., reliability in excess of 99.7%), because of high standard industrial equipment, backup chillers, and the availability of professional, ongoing operation and maintenance support, and longer life span (i.e., 25–30 years) than for conventional on-site air-conditioners (i.e., 10–15 years); (vii) space savings at the end-user site, since DC systems are remotely located [9–11]. The advantages of DC systems are most pronounced in dense districts exposed to hot climatic conditions throughout the year and characterized by rapid urbanization and building developments [9,12], as encountered in for example the GCC region.

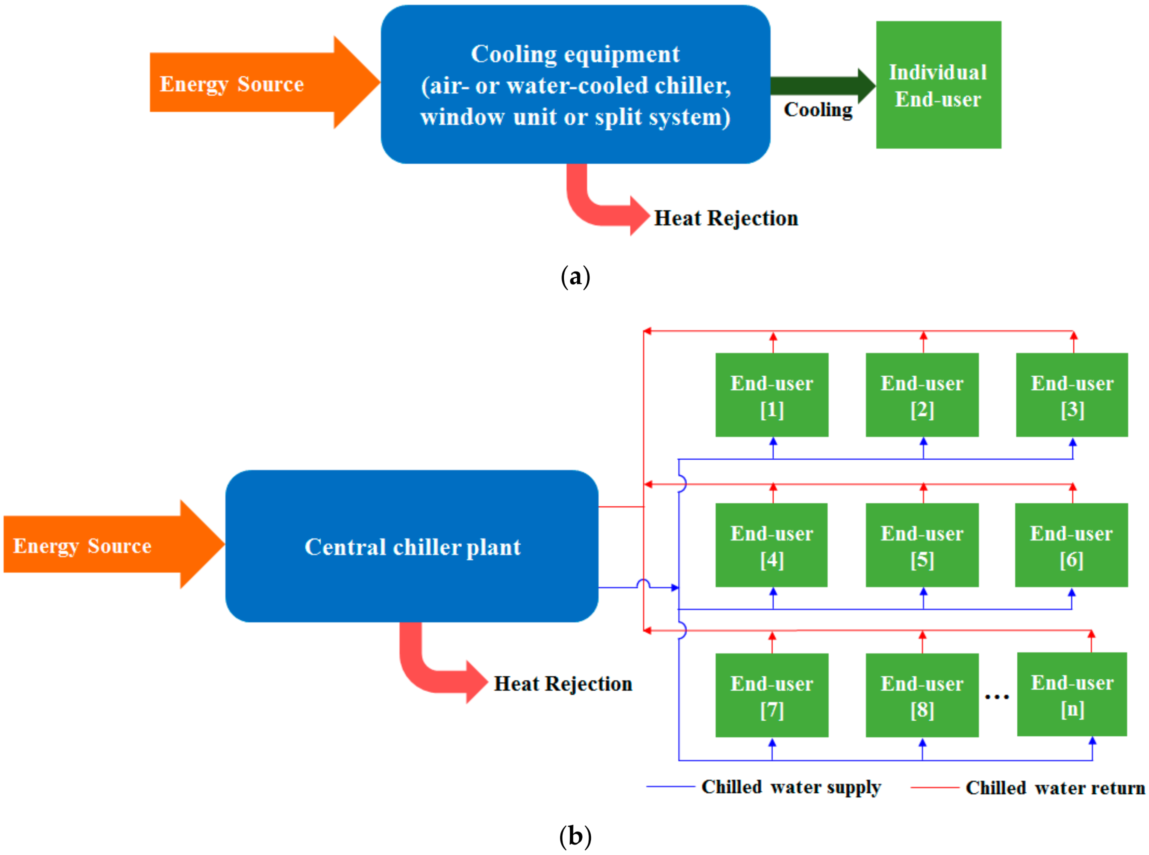

Figure 1. Building air-conditioning systems: (**a**) conventional on-site systems, (**b**) DC systems.

However, considering the substantial investments associated with double digit megawatt-cooling capacities and multi-kilometer distribution networks, DC systems should be carefully designed, evaluated, and optimized to permit a well-organized and cost-effective system to be ultimately deployed. Greater technology- and non-technology-related challenges exist for DC than district heating, with the former significantly less and later implemented than heating systems [8].

Historically, the United States of America (USA) were the main player in the early-stage implementation of contemporary commercial DC systems at district-scale (i.e., universities, airports, healthcare campuses, business districts) and then city-scale in the 1930′s, the deployment of which grew significantly in the mid to late 1990s [9,13]. DC implementation in Canada followed a similar timeline [9,14], but at limited deployment scale due to affordable hydroelectricity and fossil energy, and lack of large dense districts [12]. The implementation of DC in Europe began in France and Germany in the 1960′s and gradually spread to other European countries, mainly for summer air conditioning [15]. DC in Asia was introduced in Japan in 1970 where it expanded rapidly under government intervention towards higher efficiency and reduced environmental emissions [16]. After introducing DC in Beijing in 2004, China also actively deployed this technology [16]. Introduced in the GCC in 1999, DC implementation has since made significant progress, favored by rapid urbanization and building developments, particularly in the UAE [17]. Today, the Americas (led by the USA) hold 43% of the global installed DC capacity (i.e., 12.6 MRT or 44.3 GW_{th}), followed by the GCC (32%), Asia-Pacific and Africa (19%, led by Japan), and Europe (5%, led by Sweden and France) [14,17]. By 2019, the Middle East and North African (MENA) DC market is anticipated to overtake the American one and become the largest DC market [14].

To date, a limited number of reviews related to DC have been published [8,12,15,16,18–20]. Only Gang et al. [16] and Palm and Gustafsson [19] reviews were dedicated to DC, while [8,12,15,18,20] collectively considered district heating and cooling, with emphasis on heating. Gang et al. [16]

focused on the integration of renewable energy and combined cooling, heating, and power (CCHP) technologies, optimization, and projects in China. Palm and Gustafsson [19] analyzed technical, economic, environmental, and policy-related obstacles and enabling factors for the expansion of DC systems in Sweden. Rezaie and Rosen [12], Lake et al. [18] and Werner [15] reviewed district heating/cooling systems, in terms of technical, economic, environmental, and institutional/policy aspects. Werner [15] included some content specific to the DC market and cold sources, and highlighted the significantly smaller number of research publications and information on actual DC systems in comparison with district heating ones. Vandermeulen et al. [20] discussed control strategies for exploiting flexibility in district heating/cooling systems, to support increasing shares of fluctuating renewables in future energy systems. Pellegrini and Bianchini [8] defined the concept of cold district heating and cooling networks, that combine centralized energy distribution with minimized heat losses in supply, and their suitability for cold delivery.

The present article is intended to address the above gap through a review of DC design and analysis efforts that have aimed at improving the sustainability of cooling and dehumidification of buildings in cooling-dominated regions. These efforts are discussed in terms of DC cooling technologies and associated energy sources, cold energy distribution infrastructure, DC operation, analysis and optimization, economics, environmental impact, and challenges and opportunities.

This article is structured as follows. In Section 2, DC energy sources and associated cooling technologies, system configurations, cool thermal storage and cooling energy distribution network infrastructures are reviewed, with emphasis on heat-driven cooling technologies, and technologies suitable for high ambient temperature/humidity conditions. In Section 3, DC analysis, modeling and optimization methodologies are discussed. Considering the extreme and rising cooling demand of GCC countries, yet their limited exploitation of DC to date, Section 4 examines the current and future development of this technology specifically in the region, in terms of challenges, benefits, market, and potential solutions for improved sustainability. Based on the information compiled in Sections 2–4, collective research trends are identified in Section 5, leading to suggested future research themes in the design and analysis of sustainable DC systems for predominantly hot/humid climates. This article closes with concluding remarks in Section 6.

2. Sustainable District Cooling Systems

In the following sub-sections, DC cooling and thermal energy storage technologies, energy sources, distribution network infrastructure, operational aspects, and extension of DC end-uses to non-space cooling applications, are reviewed based on implemented DC technology information and published DC design and analysis research, focusing on the needs of cooling-dominated regions. In addition to space cooling technologies with present applicability to DC, alternative technologies in development are also discussed (Section 2.1.1). Renewable and waste/excess heat sources and their possible exploitations in DC systems are reviewed in Section 2.1.2. Natural and artificial cold energy sources and their potential applications are then contrasted in Section 2.1.3. Key aspects of cold energy storage and distribution, DC operation, and DC non-space cooling applications, are analyzed in Sections 2.2–2.5.

Published design and analysis DC studies are compiled in Table 1, in terms of geographical location, analysis timeline, energy sources (i.e., electrical, heat and cold), DC integration with other sectors, cooling and thermal energy storage technologies, cold energy distribution network, estimated energy savings and environmental benefits, and economics. This information is used in Sections 2.1–2.5 to analyze the potential of various energy sources and DC design/operational features to contribute to DC sustainability improvements, and to identify collective DC research trends and gaps in Section 5. The present emphasis is on analyses of DC systems with sustainable attributes and for cooling-dominated climates, complemented by DC studies considering other regions but with design/analysis features of value to hot climates. The studies in Table 1 are listed by chronological order of publication, to highlight developments in published DC research.

Table 1. Overview of published design and analysis studies of DC systems with sustainable energy attributes.

Source; Geographical Location; Analysis Timeline	Cross-Sectorial Integrations; Energy Sources	Cooling/Energy Storage Technologies and Capacities	Cold Energy Distribution Network Characteristics	Energy Savings and Environmental Benefits	Economic Benefits
Chan et al. (2006) [21]; Hong Kong (timeline N/R)	Integration: None (isolated DCS) Energy source: Grid electricity	Cooling: Seawater-cooled electrical vapor compression chillers (1 × 1500 RT and 7 × 5000 RT) with variable-speed seawater pumps Storage: Ice tanks, in either series storage-led, or series chiller-led arrangements with chillers	Primary (production) and secondary (distribution) loops with constant-speed/flow and variable-speed pumps, respectively	Energy savings: • DCS with ice storage and chiller-priority control consumes less electricity annually than for storage-priority control, regardless of storage fraction • Electricity consumption is minimum for ice storage with chiller-priority control at 40% partial storage Environmental benefits: N/R	Annual DCS electricity cost minimum for ice storage system with chiller-priority control at 60% partial storage under Guangdong Province Electricity Supply (GPES) tariff structure; however, prohibitive payback period
Chan et al. (2007) [22]; Hong Kong; (timeline N/R)	Integration: None (DCS distribution network only) Energy sources: N/R	N/R	Radial-shaped, tree-shaped, and mix of radial/tree-shaped networks	N/R	Piping network configuration optimization methodology developed to minimize piping investment and water distribution pumping energy cost
Trygg and Amiri (2007) [23]; Norrköping, Sweden (2004)	Integration: DCS, DHS and CHP Energy sources: • Waste-, biofuel-, rubber- and oil-fired CHP plant electricity and heat • Oil-fired boiler heat replaced by NG-fired CC heat for DHS • Free nearby river cooling water	Cooling: • Low-temperature absorption chillers (COP, 0.5–0.7) • Electrical vapor compression chillers (COP, 3–5) Storage: N/R	N/R	Energy savings: N/R Environmental benefits: Global CO_2 emissions reduced by up to 80% using absorption cooling only relative to compression cooling only	• Production cost of cooling (including investment and operating cost) reduced by 170% using absorption cooling only relative to compression cooling only • 302% reduction in system cost (i.e., capital, O & M, fuel, taxes, fees) due to electricity savings using absorption cooling only relative to compression cooling only
Söderman (2007) [24]; Finland (2006, 2020)	Integration: None (isolated DCS) Energy source: Unspecified electricity	Cooling: Electrical vapor compression chillers (COP, 3) • 2006: 1 centralized site, 8.3 MW_{th} • 2020: 2 centralized sites, 42.4 MW_{th} and 43.1 MW_{th}, and 6 distributed sites totaling 14 MW_{th} Storage: Cold water in above-ground steel tanks or underground basins (2006: 3525 kW, 3650 m^3); 2020: 37 MW, 37,750 m^3)	Chilled water transported to consumer from either distributed (i.e., local) chiller plant or cold storage tank via direct pipeline, or from central DC chiller plant or cold storage tank via DC mainlines	N/R	Annual DC investment and operating costs minimized to identify optimum cooling plants locations/capacities, storage media/capacities and distribution pipeline routing

Table 1. *Cont.*

Source; Geographical Location; Analysis Timeline	Cross-Sectorial Integrations; Energy Sources	Cooling/Energy Storage Technologies and Capacities	Cold Energy Distribution Network Characteristics	Energy Savings and Environmental Benefits	Economic Benefits
Feng and Long (2010) [25]; China (timeline N/R)	Integration: None (isolated DCS) Energy sources: • Unspecified electricity • Free river water cooling	Cooling: Electrical vapor compression chillers (COP, 5.1); design cooling load, 18,989 kW Storage: N/R	Pipe network with 42 nodes, 65 branches and 24 heat exchanger substations, with pipe diameters to be optimized	N/R	DCS annual cost (i.e., annualized investment, O & M, amortization) reduced by 4.2% through optimization of pipe diameter, relative to conventional recommended-velocity pipe sizing method
Svensson and Moshfegh (2011) [26]; Södertälje, Sweden (2007 onwards)	Integration: DCS and DHS Energy sources: • Heat from waste-fired, peat/biomass-fired, oil-fired, and electric boilers • Coal-, oil- and waste-fired CHP plant electricity and heat • Free lake cooling water	Cooling: • Absorption chillers (COP, 0.7) • Electrical vapor compression chillers (COP, 2–5) Storage: N/R	N/R	Energy savings: • Electricity consumption reduced by ~40% through use of absorption chillers to replace electrical chillers and increased lake water cooling • Electricity/heat production-induced CO_2 emissions reduced through investments in condensing power	Investments in new absorption chillers to replace electrical chillers and increased lake water cooling optimized through minimization of system costs (including new absorption chillers, pipelines, pumps, electricity/heat production-induced CO_2 emissions); Investments profitable
Udomsri et al. (2011) [27]; Bangkok, Thailand (2009)	Integration: DCS and MSW-fired co-generation plants Energy sources: Waste heat and electricity from MSW-fired power plants	Cooling: • Single-effect (COP, 0.7–0.73), double-effect (COP, 1.2–1.3) and low-temperature (COP, 0.7) H_2O/LiBr absorption chillers (centralized: 14 × 10 MW; decentralized: 257 × 300 kW) • Electrical vapor compression chillers (centralized: COP, 2–4, 14 × 10 MW; decentralized: COP, 2–4, 257 × 300 kW) Storage: N/R	N/R	Energy savings: Cooling energy consumption reduced by 1 $MW_{fuel}/MW_{cooling}$ compared with electrical chillers-based cooling Environmental benefits: Emissions reduced by 0.13 kg_{CO2}/kWh of cooling (i.e., by 60%) using MSW co-generation coupled with absorption cooling compared with electrical chillers-based cooling	• Total investment and annual O&M costs of MSW co-generation with 14 × 10 MW-absorption chillers: M$149.49 and M$28.6, respectively; 4.7 years payback period • Total investment and annual O&M costs of MSW co-generation and 14 × 10 MW-electrical chillers: M$139.44 and M$32.04, respectively; 4.9 years payback period
Al-Qattan et al. (2014) [6]; Kuwait (timeline N/R)	Integration: DCS and SOFC-GT co-generation plant Energy sources: • Waste heat from NG-fired SOFC-GT power plant • Electricity from NG-fired SOFC-GT power plant	Cooling: • Double-effect H_2O/LiBr absorption chillers (2620 RT; COP, 1.3) • Electrical vapor compression chillers (20,680 RT; rated efficiency, 0.61 kW/RT) Storage: Cold tanks (20,868 RT h)	N/R	Energy savings: Fuel energy consumption reduced by 54%, peak electrical power consumption reduced by 57%, and fuel-to-cooling efficiency improved by 346%, all relative to PACUs Environmental benefits: Annual CO_2 emissions reduced by 50% relative to PACUs	Cost of per ton-hour of cooling reduced by 53% relative to PACUs

Table 1. *Cont.*

Source; Geographical Location; Analysis Timeline	Cross-Sectorial Integrations; Energy Sources	Cooling/Energy Storage Technologies and Capacities	Cold Energy Distribution Network Characteristics	Energy Savings and Environmental Benefits	Economic Benefits
Ondeck et al. (2015) [28]; Austin, USA (2011)	Integration: DCS, NG-fired district-level island-mode CHP system, and DHS Energy sources: • Waste heat from NG-fired GT; heat from auxiliary NG-fired boiler • Electricity from NG-fired GT and rooftop PVs	Cooling (48,000 tons/hrs total chilled water capacity): • Steam-driven absorption chillers • Electrical vapor compression chillers Storage: Chilled water system (39,000 ton/hr capacity)	N/R	N/R	Profit from electricity sales to grid and neighborhood, cooling sales and some heating sales to neighborhood, maximized at $421,434 for selected analysis week (i.e., July 1–7) via scheduling optimization; Profit halved without PV integration
Erdem et al. (2015) [29]; Turkey (timeline N/R)	Integration: DCS, DHS and coal-fired power plants Energy sources: Steam extracted from inlet stage of LP turbine in eight existing coal-fired power plants	Cooling: • Single-stage absorption chillers (COP, capacity N/R) • Two-stage absorption chillers (COP, 1.0) Storage: N/R	N/R	Energy savings: Cooling energy consumption reduced (not quantified); Use of 30% LP steam extraction from coal power plant for absorption cooling improves the modified first-law efficiency for co-generation of electrical power and cooling by ~3–5.5% Environmental benefits: emissions reduced (not quantified)	N/R
Marugán-Cruz et al. (2015) [30]; Spain (2012)	Integration: DCS and solar CSP tower Energy sources: • Excess heat from solar heliostats • Auxiliary heat from NG-fired burner	Cooling: Steam-driven double-effect H_2O/LiBr absorption chillers (8 × 11.63 MW; COP, 1.4) Storage: Chilled water tank	Rectangular grid-type district network including 10 km primary and 46.4 km secondary networks	Energy savings: N/R Environmental benefits: Annual CO_2 emissions reduced by 19,870 Tm/year due to use of excess solar heat for cooling instead of fossil-fuel-derived electricity	Total annual net earnings and net present value (TNPV) of €106 million and €38 million, respectively, for assumed economic parameters, due to substitution of fossil-fuel-derived electricity by excess solar heat; up to 75% savings on consumer electricity bills
Perdichizzi et al. (2015) [31]; Abu Dhabi, UAE (timeline N/R)	Integration: DCS, solar thermal PTC field and CC Energy sources: • Heat from CC (i.e., steam extracted from ST LP turbine) fed to absorption chillers • Heat from solar PTC fed to CC HRSG • Electricity from CC	Cooling: • Steam-driven double-effect H_2O/LiBr absorption chillers (4 × 20.7 MW; COP, 1.31) • Electrical vapor compression chillers (COP, 2.2–4.0) Storage: N/R	None	Energy savings: • Fossil-fuel savings of 26% and 33% in winter and summer days, relative to fossil-fueled electricity compression cooling only • Peak electricity demand reduced by ~8 MW (20%) and ~25 MW (31%) in winter and summer days, respectively, relative to fossil-fueled electricity compression cooling only Environmental benefits: N/R	Non-quantified economic savings associated with reduced electricity consumption, reduced peak demand charges, and reduced CC investment cost

Table 1. *Cont.*

Source; Geographical Location; Analysis Timeline	Cross-Sectorial Integrations; Energy Sources	Cooling/Energy Storage Technologies and Capacities	Cold Energy Distribution Network Characteristics	Energy Savings and Environmental Benefits	Economic Benefits
Khir and Haouari (2015) [32]; Qatar (timeline N/R)	N/R	Cooling: Unspecified, generic chiller technology and capacity Storage: Chilled water tank	Tree-type piping network with size and layout to be optimized	N/R	Optimization methodology developed to minimize DCS investment and operating cost through optimization of chiller/storage tank capacities, piping network size/layout, and hourly cooling energy production and storage fraction
Karlsson and Nilsson (2015) [33]; Sweden (timeline N/R)	Integration: DCS, biomass-based CHP and DHS Energy sources: Excess heat from CHP heat-driven flash pyrolysis process oil condenser with sequential vapor condensation	Cooling: Single-stage H_2O/LiBr absorption chillers (COP, 0.78) Storage: N/R	N/R	Energy savings Annual CHP and pyrolysis efficiency improved by 1.3% and 6%, respectively; annual CHP electrical power production increased by 8.6–18.7% Environmental benefits: N/R	N/R
Gang et al. (2016) [34]; Hong Kong (timeline N/R)	Integration: None (isolated DCS) Energy source: Grid electricity	Cooling: Electrical vapor compression chillers (Configuration-1: 5 × 17,500 kW and 2 × 8750 kW; Configuration-2: 7 × 15,000 kW) Storage: Ice system	Chiller (primary) and cooling water system (secondary) pumps with 40 m and 20 m heads, respectively	Energy savings: DCS energy consumption has 80% probability of being overestimated using conventional design method that does not account for uncertainties in outdoor/indoor conditions and building design/construction Environmental benefits: N/R	Annual operating cost of DCS with ice storage, optimized using uncertainty-based method (i.e., uncertainties in outdoor weather, indoor conditions and building design/construction), has 80% probability of being lower than that of DCS optimized using conventional method
Gang et al. (2016) [35]; Hong Kong (timeline N/R)	Integration: Isolated DCS Energy source: Grid electricity	Cooling: Electrical vapor compression chillers (either 7 chillers of equal capacities with 105 MW total capacity; or 6 chillers of equal capacities and 1 chiller with 50% smaller capacity) Storage: N/R	Chiller (primary) constant-speed pumps	Energy savings: Using an uncertainty-and reliability-based design method, the use of chillers of different capacities has little and less impact on DCS than ICS energy savings Environmental benefits: N/R	The impacts of uncertainties in outdoor weather, indoor conditions and building design/construction and reliability on the design optimization, hence total annual capital, operating and availability risk cost, is smaller for DCS than ICSs
Ameri and Besharati (2016) [36]; Tehran, Iran (timeline N/R)	Integration: DCS/DHS/CCHP and DCS/DHS/CCHP/PV (i.e., energy scenarios 3 and 4, respectively) Energy sources: • NG-fired GT electricity and waste heat • Heat from NG-fired auxiliary boiler • Grid electricity • Solar PV electricity (scenario 4)	Cooling: • Absorption chillers (3 × 1725 kW, 1 × 5332 kW; COP 0.8) • Electrical vapor compression chillers (1 × 637 kW, 1 × 2426 kW, 1 × 3025 kW, 3 × 3159 kW, 1 × 3635 kW; COP 4.0) Storage: N/R	Four distribution pipelines with optimized heat transfer capacities	Energy savings: PES of 17.1–38.7% for scenarios 3–4, respectively, compared to conventional system (scenario 1) Environmental benefits: CO_2 emissions reduced by 35.8–52.6% for scenarios 3–4, respectively, compared to conventional system (scenario 1)	• Energy supply system initial and operating costs minimized to identify optimum CCHP equipment capacities and operational strategies • Energy costs reduced by 29.4–40.8% for scenarios 3–4, respectively, compared to conventional supply system (i.e., scenario 1 with grid electricity, NG-fired boilers heating, individual electrical chillers), with payback periods of 4.8–9.7 years

Table 1. *Cont.*

Source; Geographical Location; Analysis Timeline	Cross-Sectorial Integrations; Energy Sources	Cooling/Energy Storage Technologies and Capacities	Cold Energy Distribution Network Characteristics	Energy Savings and Environmental Benefits	Economic Benefits
Kang et al. (2017) [37]; Hong Kong (2015)	Integration: DCS and DGs Energy sources: • Electricity from distributed electric generators (i.e., gas engines) • Waste heat from distributed electric generators • Grid electricity	Cooling: • Absorption chillers (6 × 2054 kW; COP, 1.2) • Electrical vapor compression chillers (6 × 3980 kW; annual average COP, 5.36) Storage: N/R	Star-shaped chilled water distribution network	Energy savings: DGs-DCS primary energy savings of 9.6% relative to CES Environmental benefits: N/R	• DGs-DCS capacity optimized through minimization of payback period. DGs-DCS capital and annual operation cost of M$20.7 and M$9.2, respectively • CES capital and annual operation cost of M$7.2 and M$16.6, respectively • DGs-DCS additional capital payback period (relative to CES) of 1.9 years
Yan et al. (2017) [38]; Hong Kong (year N/R)	Integration: None (isolated DCS) Energy sources: N/R	N/R	• Buildings groups formed based on a newly defined grouping coefficient, to minimize secondary network variable-speed pumps' energy consumption • Lorenz curve and Gini coefficient applied to quantify (i) spatial/temporal inequality in normalized DCS buildings' load distribution (normalized to buildings' rated loads), and (ii) deviation in chillers' load from full load	Energy savings: • Low grouping coefficients (i.e., even buildings' hydraulic pressure requirements) lead to higher annual secondary pumps energy savings (up to 50%) and higher DCS energy savings (up to 4%) relative to ICSs • Low Gini coefficients (i.e., even distribution in buildings cooling loads) correlate with higher annual DCS energy efficiency, and higher annual chiller plant COP, and tend to lead to higher annual DCS energy savings relative to ICSs • Annual DCS energy savings of up to 14% when both the grouping coefficient and Gini coefficients are low, essentially due to grouping coefficient (i.e., chilled water distribution) rather than Gini coefficient (i.e., building cooling loads) Environmental benefits: N/R	N/R

Table 1. *Cont.*

Source; Geographical Location; Analysis Timeline	Cross-Sectorial Integrations; Energy Sources	Cooling/Energy Storage Technologies and Capacities	Cold Energy Distribution Network Characteristics	Energy Savings and Environmental Benefits	Economic Benefits
Coz et al. (2017) [39]; Slovenia (year N/R)	Integration: None (DCS network only) Energy sources: N/R	N/R	Network with either (i) polyurethane pre-insulated steel pipes or (ii) non-insulated polyethylene pipes	N/R	• Exergoeconomic optimal pipe diameters and insulation thicknesses determined to minimize the cost of cold (i.e., exergoeconomic product) for cooling capacities of 50–1500 kW • For the assumed economic parameters, pre-insulated steel pipes have higher exergy efficiency and lower exergoeconomic cost of cold than non-insulated polyethylene pipes
Dominković et al. (2018) [40]; South-west and Northern parts (Woodlands) of Singapore (2014, 2050)	Integration: DCS, GT/PV power plant and LNG regasification terminal Energy sources: • Waste heat from waste incineration plants and NG/LNG-fired GT power plants • Cold energy from LNG regasification plants (0.23 kWh of cold/kg of LNG) • PV electricity	Cooling: • Single-effect H_2O/LiBr absorption chillers (COP, 0.7) • Electrical vapor compression chillers Storage: Ice (7.7 GWh_{cold}; 90,536 m^3)	54 and 61 transmission and distribution pipe sections, respectively, for Singapore south-west part 4 and 5 transmission and distribution sections for Singapore Northern part (Woodlands)	Energy savings: Annual PES of 7.3–19.5% in 2050 DC and DC-PV energy scenarios, respectively, compared to business-as-usual (BAU) scenario without DC Environmental benefits: Annual 2050 energy system CO_2 emissions reduced by 19.7% and 41.5% in 2050 DC and DC-PV scenarios, compared to BAU scenario without DC	Singapore 2050 energy system DC grid investment cost (M$339) offset by annual socio-economic savings of 32.7% and 38.4% in DC and DC-PV scenarios, respectively, compared to BAU scenario
Gao et al. (2018) [41]; Hong Kong (2015)	Integration: DCS and DES Energy sources: • Electricity from distributed electric generators • Waste heat from distributed electric generators • Grid electricity	Cooling: • Double-effect absorption chillers (4 × 4000 kW; COP, 1.1) • Electrical chillers (4 × 4000 kW; COP, 5.5) Storage: N/R	Constant- and variable-speed pumps for primary and secondary chilled water networks, respectively	Energy savings: Monthly PES of 10–19% with DCS-DES depending on control strategy, compared with grid-powered DCS plus grid-powered individual cooling systems; Environmental benefits: N/R	• DCS-DES payback period of 6.4–10.4 years, depending on control strategy

Table 1. *Cont.*

Source; Geographical Location; Analysis Timeline	Cross-Sectorial Integrations; Energy Sources	Cooling/Energy Storage Technologies and Capacities	Cold Energy Distribution Network Characteristics	Energy Savings and Environmental Benefits	Economic Benefits
Franchini et al. (2018) [42]; Riyadh, Saudi Arabia (timeline N/R)	Integration: DCS and solar thermal PTC/ETC field integration; Energy sources: Thermal energy from solar PTCs and ETCs	Cooling: • PTC heat-driven double-effect H_2O/LiBr absorption chillers (2315 kW; COP, 1.39) • ETC heat-driven single-effect H_2O/LiBr absorption chillers (3250 kW; COP, 0.723) Storage: • Pressurized and non-pressurized hot water storage tanks for double- and single-effect absorption chillers, respectively • Cold tank (200 m^3)	District piping network with insulated pipelines and 16.8 km overall length; design	Annual primary energy and electricity consumptions, and CO_2 emissions reduced by ~500 toe (i.e., 70%) and 1400 tons per year relative to DCS with centralized electrical compression chiller cooling plant	• System components' sizes optimized by minimization of primary cost of solar field, storage tank and chillers • Overall cost of DCS with PTC-driven double-effect absorption chillers 30% lower than that of DCS with ETC-driven single-effect absorption chillers
Ravelli et al. (2018) [43]; Riyadh, Saudi Arabia (timeline N/R)	Integration: DCS and solar PTC/CRS co-generation plant; Energy sources: • Thermal energy from either North-south or East-west oriented PTCs, or CRS heliostats • Electricity and heat from PTC/CRS solar field-driven SRC, with steam extracted from SRC LP turbine to drive thermal chillers	Cooling: • Double-effect H_2O/LiBr absorption chillers (4 × 20.7 MW; COP, 1.31) • Electrical vapor compression chillers (50 MW; COP, 2.5–5.0) Storage: Two-tank molten salt	N/R	Energy savings of the three solar field configurations, the CRS system requires the lowest amount of solar energy and produces the least excess heat Environmental benefits: N/R	• Investment cost of solar and storage systems minimized through optimization of solar field aperture area and storage tank volume • Of the three solar field configurations, the CRS system leads to the lowest investment cost

Note: CES—centralized power plant and individual cooling systems. CC—combined cycle. CHP—combined heat and power. CCHP—combined cooling, heating, and power. CRS—central receiver system. CSP—concentrated solar power. DES—distributed energy system. DCS—district cooling system. DG—distributed generators. DHS—district heating system. ETC—evacuated-tube collector. GT—gas turbine. HP—high pressure. HRSG—heat recovery steam generator. ICS—individual cooling system. LNG—liquefied natural gas. NG—natural gas. LP—low pressure. MSW—municipal solid waste. N/R—not reported. O&M—operation and maintenance. PES—primary energy savings. PACU—packaged air-conditioning unit. PTC—parabolic trough collector. PV—photovoltaic or present value. RT—ton of refrigeration. SRC—steam Rankine cycle. SOFC—solid oxide fuel cell.

2.1. Cooling Technologies and Associated Energy Sources

Grid electricity, generally predominantly produced using fossil fuels, is currently the main energy source to produce cold using vapor compression chillers in DC systems. Figure 2 provides an overview of alternative sustainable energy sources and heat-activated cooling technology options, some of which have either been practically implemented in DC systems, previously evaluated in the DC literature, or are envisaged here. Sustainable energy sources include low-carbon (i.e., renewable, low-emission, waste/excess) electricity and heat to drive compression chillers and heat-activated chillers, respectively, as well as natural and artificial (e.g., cryogenic) cold for direct cooling. Key characteristics of sustainable heat-activated air-conditioning technologies presently applicable to DC central chiller plants, namely vapor compression and absorption refrigeration, are discussed in Section 2.1.1. Alternative refrigeration cycle options having features suitable for renewable/waste heat use and/or operation in high ambient temperature/humidity conditions are also identified, and their potential advantages and shortcomings discussed (Section 2.1.1). Sustainable heat sources for thermally activated cooling and cold sources, and their exploitations in published DC studies, are then reviewed in Sections 2.1.2 and 2.1.3, respectively.

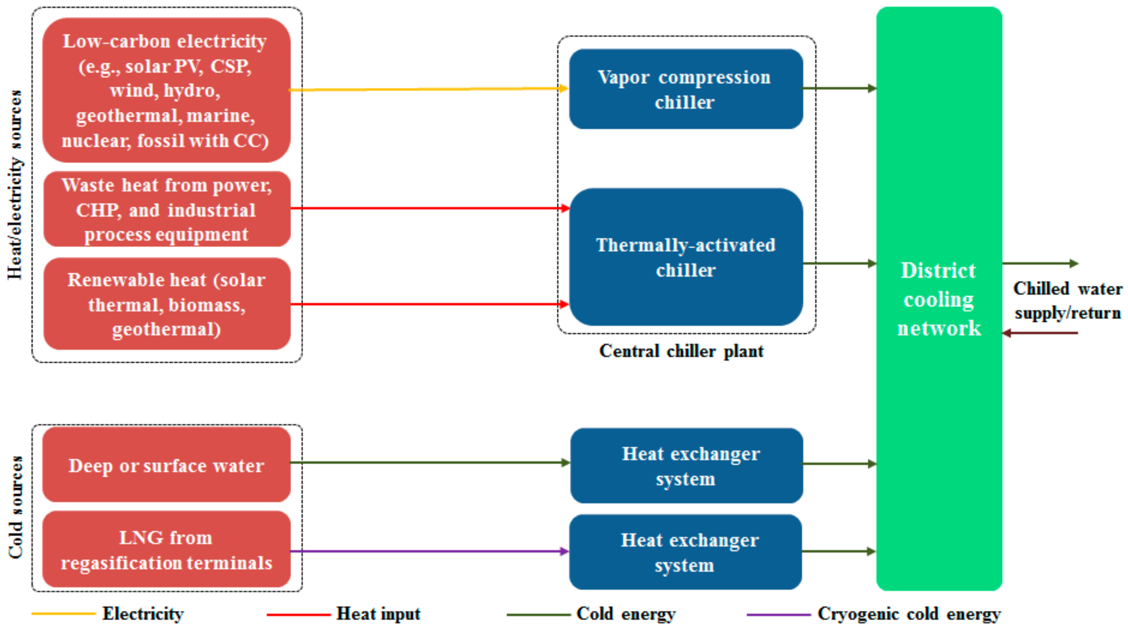

Figure 2. Sustainable cold production options for DC systems.

2.1.1. Cooling Technologies

Either a single or multiple cooling technologies may be incorporated in a DC central chiller plant, depending on available electrical/thermal energy sources and their production and demand profiles, and environmental and cost considerations. Technologies either implemented or evaluated in DC design/analysis studies mainly consist of vapor compression and single-/double-effect absorption refrigeration. This essentially reflects technology maturity and reliability, equipment availability at MW-scale capacity, and affordability. Among these technologies, electrical centrifugal water-cooled chillers are currently the most widely employed chillers in installed DC systems, because of their higher performance (COP > 7.0 10]) relative to their air-cooled counterparts [10], and reliable operation. Given the technology maturity of vapor compression refrigeration, the following sub-sections focus on thermally activated cooling technologies, which can be driven by renewable/waste heat and reduce the energy consumption of vapor compression chillers in a DC system and consequently peak electrical loads. In addition, some of the thermally activated cooling concepts discussed here have potential for hybridization with vapor compression refrigeration for performance/sustainability enhancement. Additional approaches of enhancing the performance of vapor compression refrigeration through condenser cooling and/or operational control in DC are also discussed in subsequent sections. Concepts currently investigated to enhance the performance of vapor compression refrigeration are outlined in more detail in [44].

Key characteristics (i.e., working fluids, driving heat source temperature ranges, typical COP values) of heat-driven air-conditioning and refrigeration technologies (i.e., sorption- and ejector-based) are listed in Table 2. Although sorption cooling is widely employed in small- to large-scale air-conditioning and refrigeration applications [45–47], single/double-effect lithium bromide-water absorption is essentially the only type of sorption technology either integrated in installed DC central chiller plants or reported in DC research studies to date. Thus, most sustainable DC system analyses in Table 1 have incorporated a combination of both vapor compression and either single-effect [23,26–28,36,40] or double-effect absorption cooling [6,31,37,41,43]. DC investigations in which vapor compression was the sole cooling technology [21,24,25,34,35] are generally earlier efforts [21,24,25], while DC studies focusing on absorption cooling are recent efforts [29,30,33,42].

Table 2. Typical characteristics of heat-driven cooling technologies [46,48–51].

Cooling Technology	Working Pair	Chilled Fluid Temperature (°C)	Heat Source Temperature (°C)	COP (-)	DC Analysis
SE absorption chiller	H_2O/LiBr	5–10	80–120	0.5–0.8	[26,27,29,33,36,40,42]
	NH_3/H_2O	<0	80–200	~0.5	—
DE absorption chiller	H_2O/LiBr	5–10	120–170	1.1–1.51	[6,27,29–31,37,41–43]
	NH_3/H_2O		170–220	0.8–1.2	—
TE absorption chiller	H_2O/LiBr	5–10	200–250	1.4–1.8	—
GAX chiller	NH_3/H_2O	<0	160–200	0.7–0.9	—
HE absorption chiller	H_2O/LiBr	5–10	50–70	0.3–0.35	—
Adsorption chiller	H_2O/Silica gel	7–15	60–85	0.3–0.7	—
	Methanol/activated carbon	<0	80–120	0.1–0.4	
Liquid desiccant cooler	N/A	Dehumidified cold air 18–26	Hot water 60–90, hot air 80–110	0.5–1.2	—
Solid desiccant cooler	N/A	Dehumidified cold air 18–26	60–150	0.3–1.0	—
Ejector cooler	H_2O	5–15	60–140	<0.8	[52]

Note: SE—single-effect; DE—double-effect; HE—half effect; TE—triple-effect; GAX—generator absorber heat eXchange. —cooling technology not applied in the published DC literature to date.

Absorption-based and alternative developing air-conditioning technologies with potential for renewable or waste heat use, and/or operation in high ambient temperature/humidity conditions, are identified and discussed in the following paragraphs.

Absorption-Based Cooling

Absorption chillers are a mature and well-established sorption cooling technology employed since the 1960′s in various air-conditioning and refrigeration applications [53,54]. Single-effect water-lithium bromide-absorption chillers are suitable for low-grade heat use (e.g., non-concentrating solar collector, geothermal, or waste heat), whereas double-effect water-lithium bromide-absorption chillers could be driven by higher-temperature sources (e.g., medium-concentration solar collectors, higher-temperature geothermal or waste heat). Triple-effect chillers would permit higher grade sustainable heat sources to be exploited for DC cooling, such as from concentrated solar power (CSP) plants as envisaged by [30], with improved COPs compared with lower-effect chillers [55]. However, the availability of triple-effect chillers at medium–large capacity is currently limited and would lead to higher investment cost than for lower-effect chillers [30,55]. An up-to-date list of commercially available, medium–large capacity, single- and higher-effect absorption chillers applicable in DC central chiller plants is compiled in Table A1, along with their key characteristics. (Absorption chiller capacities between 100 to 1000 kW and those exceeding 1000 kW are considered here medium- and large-scale capacities, respectively.) Alternative advanced absorption cycle configurations with potential for low-grade renewable/waste heat use, low energy consumption, and air-conditioning in cooling-dominated climates are identified below. These include bifunctional absorption, generator absorber heat exchange (GAX)-based absorption, and hybrid absorption-compression (also referred to as compression-assisted absorption).

Basic absorption cycles with insufficient external driving heat may be modified in their operation with internal recycling of absorber and condenser heat rejection to supplement the external heat input, as proposed by Arabkhoosar and Andresen [56]. The authors numerically evaluated this concept for evacuated-tube solar collector driven single-effect water-lithium bromide-absorption chillers to provide DC in summer in moderate/cool climates. The heat recuperated from the absorber and condenser served to compensate for the lack of excess heat diverted from a district heating system, which is generally insufficient in the hot season to cover absorption chillers' heat demand. The heat recuperated could also be employed for heating during other periods of the year. This absorption chiller configuration could be extended to cooling-dominated regions when insufficient low-carbon heat is available to drive absorption chillers.

GAX-based absorption and hybrid absorption-compression are currently attracting significant research attention and have technical features with potential for sustainable air-conditioning in cooling-dominated climates. GAX cycles make internal use of part of absorber heat rejection to supply heat to the desorber [57–59], while absorption-compression cycles incorporate a compression booster (i.e., mechanical compressor or ejector) [53,57]. Both types of cycles can achieve higher COPs than basic absorption cycles, and allow operation at higher ambient temperatures [53,55,57,58]. Hybrid absorption-compression systems can also operate at lower driving heat source temperatures than basic absorption cycles, which may be useful for the exploitation of low-grade renewable/waste heat [53,57]. Compression-assisted absorption is however considered more complex to operate than basic absorption [53]. GAX-based chillers are already applied to air-conditioning, but the capacities of commercially available systems [46] are presently insufficient for DC central chiller plant applications. Therefore, although the above advanced absorption cycle concepts hold potential for energy savings and performance improvements in hot climates, they require further development.

Alternative Thermally Activated Cooling

Additional heat-activated cooling technologies amenable to low-grade renewable/waste heat use, and/or operation in high ambient temperature/humidity conditions include adsorption refrigeration [60–62], desiccant-based sorption cooling [46,63–65] and ejector-based refrigeration [49,66]. Adsorption chillers are employed in for example industrial and data server air-conditioning applications, driven by on-site low-grade waste heat such as the server cooling fluid stream [62,67]. Solid desiccants can offer significant energy savings through separate air dehumidification via adsorption in high ambient air humidity conditions and can operate either as standalone or coupled with other air-conditioning technologies (e.g., compression refrigeration) [46,63–65]. Although of value for sustainable air-conditioning, the capacities of either adsorption chillers or desiccant systems are presently insufficient for DC applications, with both types of technologies currently undergoing further developments. Thus, their capacity limitations would restrain their potential application to air-conditioning at end-user sites' where a low-cost heat source may be available, thereby eliminating thermal energy distribution losses. If economically viable, such an approach could contribute to reduce the load of a DC central chiller in the district buildings considered.

Ejector-based refrigeration systems became widely applied in the air-conditioning of large buildings and railroad cars after the introduction of a vapor ejector-based refrigeration cycle in 1910, facilitated by the abundant availability of steam at the time [68,69]. The use of ejector-based air-conditioning systems ceased to expand with the introduction of higher performance, chlorofluorocarbon (CFC) refrigerant-based vapor compression chillers in the 1930's. However, ejector-based refrigeration systems are presently receiving considerable attention for space cooling due to their construction simplicity with no moving parts or seals, low maintenance requirements, low-grade renewable/waste heat use and energy consumption reduction potential, and compatibility with environmentally friendly working fluids [48,66,69,70]. Ejectors have been rarely applied in either existing DC systems (e.g., [52,71]) or researched DC systems to date. Although implementable at multi-MW scale, their main current limitations are the low performance (i.e., COP) and limited operational flexibility of the basic cycle with respect to generator (i.e., driving heat source) temperature and backpressure (which is related to ambient temperature). An actual DC system using a central chiller plant incorporating a 0.6 MW capacity steam jet ejector chiller and 0.6 MW compression chiller has however been in operation since 1998 in Gera, Germany [52,71]. The DC system uses both electricity and waste heat from a district heating network and CHP plants as energy sources to produce driving hot water for the steam ejector chiller. A two-stage triple ejector cycle configuration and steam pressure regulator are employed to provide flexibility in terms of cooling capacity and stability with respect to external conditions. The use of ejector refrigeration was estimated to reduce operating costs by up to 30% relative to an absorption chiller, due to reduced driving heat requirements [52,71]. Multi-ejector and hybrid ejector cycles (e.g., absorption-ejector, compression-ejector) are currently being researched for improved operating flexibility and performance (e.g., COP), as well as combined ejector-power cycles for co/tri-generation, in conjunction with control and storage systems [49,59,66].

In summary, multi-effect, GAX-based, and compression-assisted absorption, as well as desiccant-based sorption and ejector-based cooling, have promising technical features for sustainable air-conditioning, including in cooling-dominated regions. Of these technologies, ejector-based cooling has been occasionally implemented in DC, while multi-effect absorption may be realistically implementable in DC systems in the near future. Therefore, based on the current technical and commercial availability/capacity limitations of the above-listed technologies, the remainder of this article focuses on DC based on vapor compression and single/double-effect absorption refrigeration.

2.1.2. Heat Sources for Thermally Activated Cooling

DC system studies incorporating waste heat- and renewable heat-driven chillers are reviewed in in this section, in terms of system configuration, central chiller cooling technology, operating conditions, and key findings.

Heat Sources from Fossil-Fuel Conversion Systems

CHP technology has been widely used in district systems in heating-dominated regions [12]. Ondeck et al. [28] also highlighted that tri-generation plants driven by both fossil and renewable energy sources could also be a suitable choice to supply integrated utilities (i.e., cooling, heating, and electricity) to future districts in hot-climate regions. Their proposed tri-generation system (Figure 3), intended for application at the University of Texas, Austin, USA, included a natural gas-fueled CHP unit driving absorption chillers, while compression chillers were driven by a solar PV plant. In the CHP unit, superheated steam was generated from GT exhaust gas waste heat in a HRSG. When GT exhaust waste heat was not sufficient to produce the required amount of steam at a sufficient steam temperature, supplemental NG was fired in an in-duct burner to supply extra heat for steam production. Using utilities demand data obtained from a residential neighborhood in Austin, an optimum operating strategy was determined for the integrated CHP/PV system, with the effect of PV generation on system operation and operating profit evaluated. The 137 MW capacity plant could produce 581,505 kg/h of steam, 48,000 tons of chilled water, with a thermal storage capacity of 39,000 ton-hours of chilled water. Running in island mode (i.e., in isolation from the local/national electricity distribution network), the system could provide all the university's electricity, heat, and cooling requirements throughout the year, at an energy efficiency of over 80%.

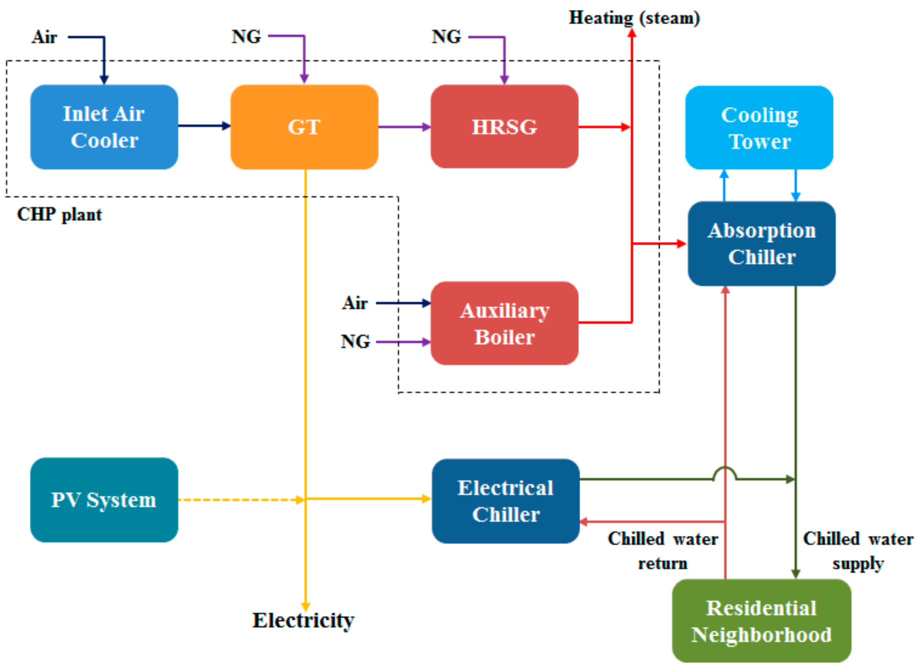

Figure 3. NG- and solar PV-powered tri-generation system proposed by Ondeck et al. for future residential neighborhoods in hot-climate regions, adapted from [28]. Note: CHP—combined heat and power; GT—gas turbine; HRSG—heat recovery steam generator; NG—natural gas; PV—photovoltaic.

Al-Qattan et al. [6] evaluated the performance of a modeled natural gas-fueled hybrid pressurized solid oxide fuel cell (SOFC)-gas turbine (GT) power plant integrated with a DC system (Figure 4) in Kuwait climatic conditions. Providing an estimated total cooling load of 96 MW, the cooling system included absorption chillers driven by GT exhaust heat, and electrical compression chillers driven by SOFC and GT electricity. Surplus SOFC-GT electricity was exported to the grid during periods of low cooling demand. A thermal cooling water storage tank was used to reduce system capacity. The combined system was operated at relatively high cooling tower inlet/outlet temperatures (i.e., 40 °C/35 °C) representative of the GCC's climatic conditions. To reduce the chilled water pumping power consumption, the temperature differential between the chilled water supply and return temperatures (i.e., 6.1 °C and 12.8 °C, respectively) was set marginally higher than typical values. The system was estimated to both improve the fuel-based efficiency of chilled water production by 346% and decrease annual fuel consumption by 750 TJ (54%) and peak power requirement by 24 MW (57%), relative to conventional packed air-conditioning units (PACs), which are commonly used for cooling homes. The DC system was estimated to contribute 53% reduction in capital and operating costs per ton-hour of cooling over PAC units.

As part of projected sustainable energy scenarios for Singapore in year 2050, Dominković et al. [40] identified waste heat sources from NG-fired and waste incineration power plants to supply absorption cooling to a future DC system, as well as waste cold from an LNG regasification terminal. Given its inclusion of renewable waste heat and cold energy use for DC, as well as renewable power generation, this work is discussed in more detail in sub-sections "Renewable Heat Sources" and "Artificial Cold".

Other studies in heating-dominated regions have also investigated the performance of cooling production at district level (together with heating production), by using waste heat from either existing thermal power plants (e.g., coal-fired power plants [29]) or coal-/oil-fired co-generation plants or boilers [23,26] during the hot season. Finally, Colmenar-Santos et al. [72] assessed the cost of converting European thermal electricity production plants to co-generation plants for electricity/heat-driven district heating and cooling. Their analysis demonstrated the cost and environmental benefits of using district heating networks for absorption cooling.

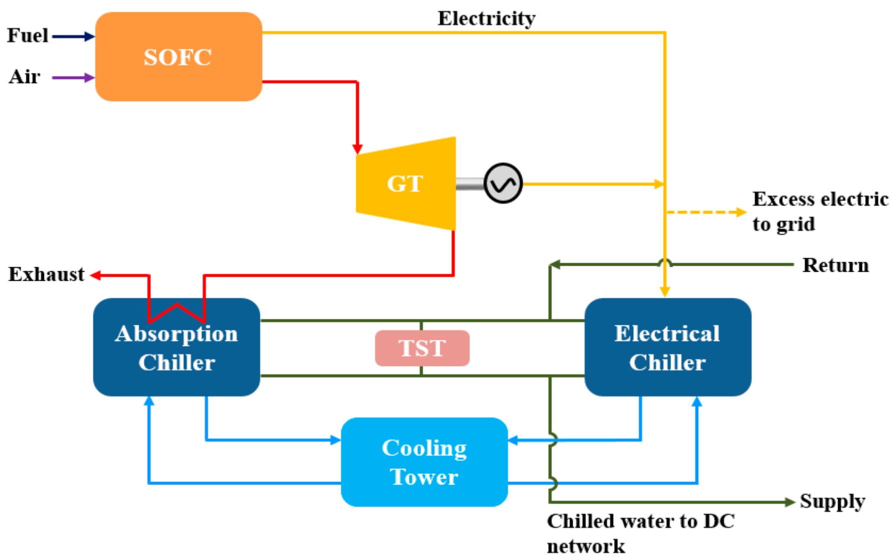

Figure 4. Integrated SOFC-GT and DC system proposed by Al-Qattan et al. for a new city in Kuwait, adapted from [6]. Note: GT—gas turbine; SOFC—solid oxide fuel cell; TST—thermal storage tank.

Renewable Heat Sources

Renewable thermal energy (e.g., solar, geothermal, biomass waste) can be transformed into cooling energy using heat-driven chillers, or into electrical/mechanical energy using thermal power plants to drive vapor compression chillers. DC systems based on renewable-heat-driven central chiller plants are discussed in this section, focusing on cooling-dominated regions.

Marugán-Cruz et al. [30] examined the technical and economic feasibility of using excess heat generated by the heliostats of a solar power tower for DC. Such heliostats require to be defocused from the central tower receiver placed when the maximum allowed thermal power is reached [30]. As proposed in Figure 5, the exceeding heliostats would be focused to an additional thermal power steam receiver located below the primary molten salt receiver. The steam produced from excess heat was used to drive double-effect H_2O/LiBr absorption chillers. Cooling water at inlet/outlet temperatures of 30 °C/37 °C was used as a heat sink for these absorption chillers. The system could supply chilled water at 7 °C to cover 47% of the cooling demand of 30,027 Spanish dwellings. The system was also equipped with backup natural gas burners activated when solar cooling was not sufficient to meet the cooling demand. This hybrid system was found to be cost-effective, with end-users estimated to save approximately 75% of their electricity bills. The steam was available at a temperature sufficient to activate triple-effect absorption chiller technologies (i.e., >250 °C, Table 2), suggesting that system performance could be further improved. However, no commercially available indirect-fired triple-effect chillers were found at the time of the study [30].

Perdichizzi et al. [31] proposed and simulated a solar combined cooling and power (SCCP) plant (Figure 6) for latitude and weather conditions similar to those of Abu Dhabi, UAE, representing an isolated location (i.e., island) in a hot-climate region. The SCCP plant comprised a combined gas turbine-steam turbine cycle, parabolic trough solar collectors (PTCs), and steam-driven double-effect H_2O/LiBr absorption chillers. Saturated steam extracted upstream of the low-pressure steam turbine was fed to the absorption chillers. Two alternative solutions to address peak power demand were evaluated: (i) the integration of CSP with the combined cycle to match the peak power demand of the electric grid; and (ii) the implementation of a DC system incorporating absorption chillers rather than mechanical chillers to reduce peak electricity demand and thus smoothen the electricity load profile. The performance of the proposed SCCP plant was compared with that of a conventional combined cycle driving mechanical chillers to meet similar power and cooling loads. The SCCP plant was found to offer the following benefits compared to the conventional fossil-fuel-based combined cycle: smaller gas turbine capacity, higher total energy efficiency, and 26% to 33% fossil-fuel savings in winter and summer, respectively. These significant fuel savings were mainly attributable to the integration of solar power and the use of absorption chillers.

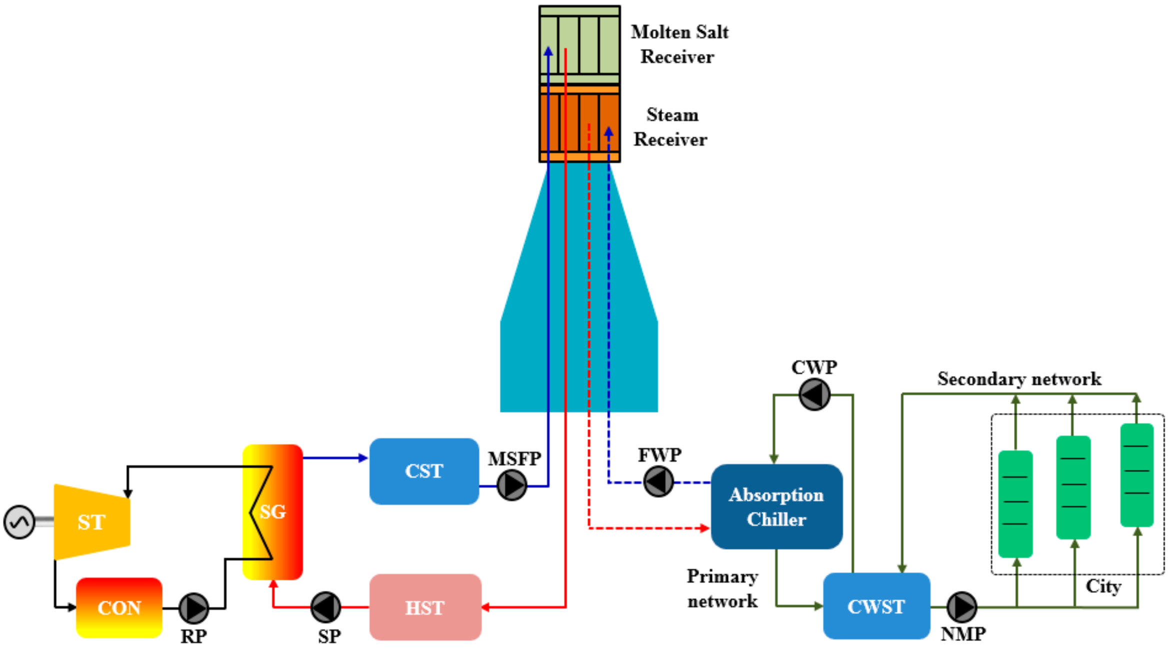

Figure 5. Solar power tower and DC system proposed by Marugán-Cruz et al., adapted from [30]. Note: CON—condenser; CST—cold storage tank; CWP—chilled water pump; CWST—chilled water storage tank; FWP—feed water pump; HST—hot storage tank; MSFP—molten salt feed pump; NMP—network main pump; RP—Rankine pump; SG—steam generator; SP—storage pump; ST—steam turbine.

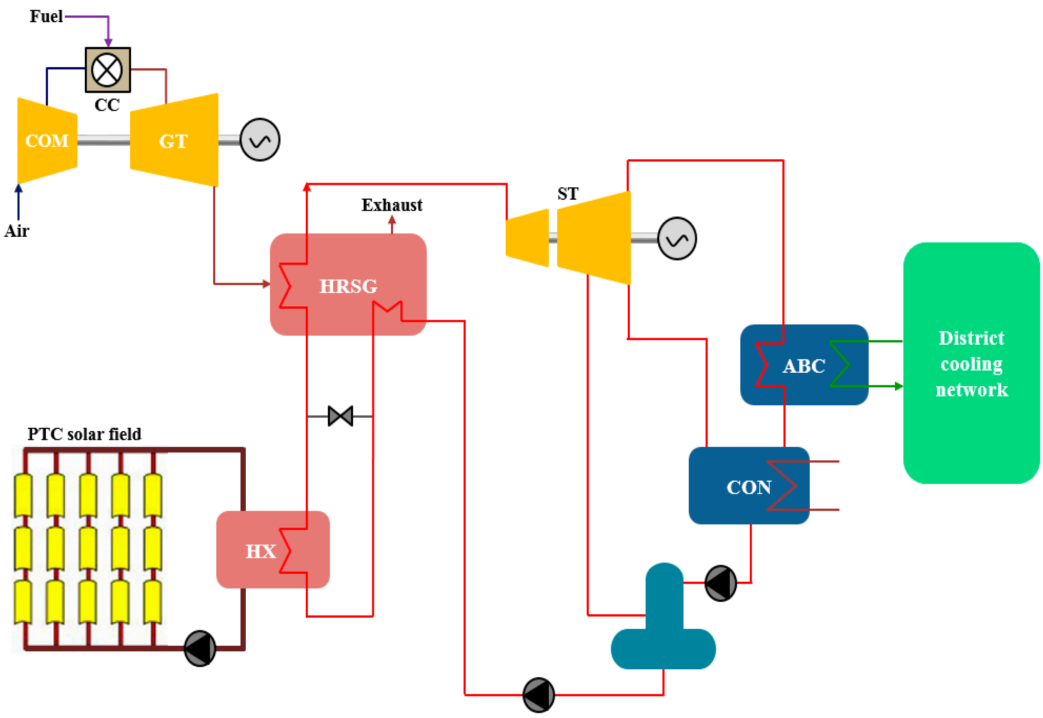

Figure 6. Solar combined cooling and power (SCCP) plant proposed by Perdichizzi et al., adapted from [31]. Note: ABC—absorption chiller; CC—combustion chamber; COM—compressor; CON—condenser; GT—gas turbine; HRSG—heat recovery steam generator; HX—heat exchanger, PTC—parabolic trough solar collector; ST—steam turbine.

Ravelli et al. [43] also proposed a CSP plant for the co-production of power and cooling to serve a Saudi Arabian community. The CSP plant included two different solar fields (i.e., PTCs, and central receiver system (CRS) with heliostats). The power unit consisted of a steam Rankine cycle including low- and high-pressure turbines. The CSP plant also included a thermal energy storage system that permitted to dispatch electricity in periods of low or no solar irradiation. Double-effect absorption chillers driven by steam extracted from the low-pressure steam turbine served to produce chilled water for distribution through a DC network. Supplemental electric chillers were required to meet peak summer cooling loads. The absorption chillers reduced DC electricity consumption by up to 5 MW and 30 MW in winter and summer, respectively, and contributed to peak shaving in summer.

Franchini et al. [42] investigated a solar DC system (i.e., solar field, central chiller plant, DC network and building load) incorporating two different central chiller plant technologies, consisting of a double-effect H_2O/LiBr chiller driven by a PTC, and a single-effect H_2O/LiBr chiller driven by evacuated-tube collectors (ETCs). The cooling load of a residential compound was simulated in the climatic conditions of Riyadh, Saudi Arabia. The sizes of all main DC system components were optimized by minimizing cost and maintaining an annual solar faction of 0.7. Annual transient simulations of the system configurations under variable operating conditions were undertaken to assess the annual energy performance of the solar DC system with a higher level of accuracy than for steady-state analysis-only. The solar DC system based on PTCs and double-effect H_2O/LiBr chillers was found to be more cost-effective than with single-effect H_2O/LiBr absorption chilling and led to ~30% reduction in primary costs including those of the DC network infrastructure. This was attributed to the high efficiency of the double-effect absorption chillers and the high level of local direct normal irradiation available. In comparison with conventional DC systems based on compression chillers, the solar DC system was anticipated to allow approximately 70% reduction in both annual primary energy consumption and CO_2 emissions.

Karlsson and Nilsson [33] investigated the benefits of using waste heat rejected by pyrolysis oil condensers in a biomass-based CHP plant to drive a DC system based on single-effect absorption cooling. Although for a heating-dominated region, the proposed DC concept based on the use of renewable-heat-driven thermal chillers is of interest to sustainable DC supply in cooling-dominated regions. The use of a single-effect absorption chiller driven by excess heat for DC cooling was investigated for three cooling demand scenarios, differing in both the magnitude and time duration of cold production. In a scenario maximizing pyrolysis oil output, 5 MW of DC could be provided using 6.4 MW of condenser heat rejected between June and August. The overall energy efficiency of the biomass CHP plant and DC system improved by 1.3%, and the efficiency of the pyrolysis process increased by 6%. In addition, mostly during summer months, the amount of electricity generated increased by approximately 9% to 19% depending on the cooling scenario considered.

Dominković et al. [40] investigated four different 2050 energy scenarios for Singapore (inclusive of electricity, heating, and transport), in terms of primary energy consumption, CO_2 emissions, and socio-economic expenses (i.e., capital and operating). The scenarios were based on either business-as-usual energy practices, the development of a DC system, increased share of solar PV generation as a replacement of natural gas power, or a combination of DC and solar PV deployment. In the two DC-based energy scenarios, waste heat was recovered from natural gas-fired and waste incineration power plants to supply absorption cooling to the DC system. In addition, cold energy was extracted from an LNG regasification terminal, and ice storage incorporated. Conventional electric chillers were used to provide cooling in periods of low waste heat availability, which overlapped high PV production periods, and served to absorb excess fluctuating PV electricity. In parallel, fossil transport fuels were partly displaced with electrically powered mobility that also contributed to reduce surplus electricity. Projected energy efficiency measures in the residential, industrial, and power sectors were accounted for. In comparison with the business-as-usual scenario, the best scenario (i.e., DC and 70.6% share of PV electricity generation) reduced primary energy consumption by 19.5%, CO_2 emissions by 41.5%, and socio-economic expenses by 38.4%, despite the significant capital investment incurred with DC. This study exemplifies a combination of waste heat (both from fossil and renewable waste sources) and waste cold recovery for DC, and synergy between DC and power generation for minimization of primary energy consumption, environmental emissions and excess electricity that could otherwise destabilize the electrical grid.

2.1.3. Cold Energy Sources

Cold sources that can be used by DC systems to increase heat rejection, hence overall cooling capacity and efficiency, may be categorized as either natural renewable sources or synthetic/artificial sources.

Natural Cold

Natural cold sources can be used for direct cooling either alone or in combination with active cooling technologies (e.g., mechanical compression and heat-driven technologies) to reduce active cooling energy consumption. Cold sources in actual DC systems include deep-seawater (e.g., [73] in China, [74] in Sweden), deep-lake water (e.g., [75], N.Y., USA and [76] in Toronto, Canada), aquifer (ground) water (e.g., [77] in London, UK), and lagoon and river water. A water temperature below either 5 °C (for 100% natural cooling) or 10 °C (for partial natural cooling) is typically required to achieve a DC supply temperature of 6–7 °C. After water filtration, the cold water is pumped to a heat exchanger station, where heat from a closed loop DC system is transferred to the cold water. Physical and chemical natural water properties (including harness, salt/contaminant concentrations) require monitoring to avoid damaging network components [8]. Discharge of the network water into natural water systems also requires temperature control to avoid undesired chemical/biological processes [8].

Given the lack of natural cold sinks in hot-climate regions, the use of natural cold sources in DC research studies [23,25,26] has been mainly for cooling in the summer season in heating-dominated regions. Svensson and Moshfegh [26] used deep-lake water for direct cooling in parallel with absorption chillers driven by heat from biomass-fired boilers and CHP units, to partly substitute vapor compression chillers and reduce electricity consumption in a Swedish DC system. Trygg and Amiri [23] supplied approximately 8% of their DC load using river water in Sweden, without the need for a cooling tower. Feng and Long [25] used river water at 6 °C to supply direct DC in summer in China.

A variant approach of using natural cold water is found in the cold district heating and cooling network concept defined by Pellegrini and Bianchini [8], which combines centralized energy supply with minimized heat losses in delivery. In this concept, low-temperature water (i.e., 10–25 °C, from e.g., surface, deep aquifer, sea, waste, and aqueduct water) is delivered to the network and serves as cooling fluid for either direct or active cooling when required. The supplied low-temperature water is chilled or heated by decentralized chillers/pumps for district cooling/heating, which reduces the thermal distribution losses and insulation costs that would arise in centralized water chilling/heating. The use of low-temperature water can also enable the use of renewable energy conversion technologies (e.g., solar, geothermal heat pumps) for heating, and facilitate the integration of district heating and cooling networks. Cold district heating/cooling networks can offer reductions in primary energy consumption through renewable energy use and reduced thermal losses, depending on the temperature-dependent COP of cooling equipment.

Artificial Cold

Given the lack of natural cold sinks in cooling-dominated regions, artificial cold from cryogens such as liquefied natural gas (LNG) for direct DC is a potential option that may take greater importance than in moderate climates. The cold exergy that can be practically recovered during LNG regasification at import terminals before gas distribution is of approximately 350–370 kJ/kg/s of LNG [78,79]. (Thermal exergy recovery, assuming an initial LNG state at ~70–80 bar for NG distribution and (−160)–(−165) °C.) With a global trade of 293 Mt in 2017, LNG currently represents 9.8% of the global gas supply [80]. LNG supply volumes are anticipated to double through 2016–2040, overtaking inter-regional pipeline supplies in the early 2020′s [2]. The current global LNG regasification capacity (i.e., 851 Mt/annum (MPTA)) is distributed between 39 countries and 121 terminals, including in several hot-climate regions in Asia, the Middle East, and South Europe [80]. A further 87.7 MTPA is under construction including in China and hot-climate regions (i.e., India, Turkey, Bahrain, Kuwait, Bangladesh, Panama, Philippines, Brazil). Among the GCC countries that face domestic gas shortages (i.e., Bahrain, Kuwait, UAE), the UAE was the first to build an LNG receiving terminal.

The majority of LNG importing terminals however reject their cold energy to the environment (i.e., air or seawater) in either open rack, submerged combustion, or ambient air vaporizers, without cold energy recovery [78]. This is attributable to the following technical and non-technical barriers: (i) communities and cold applications being generally remotely located from regasification terminals, for safety and practical reasons [81], coupled with the lack of suitable fluid carriers for cold transportation; (ii) a lack of perceived incentives for regasification facilities to diversify their products beyond NG distribution, combined with a reluctance to cooperate with potential cold users (e.g., district energy companies), and unsuitable business models; (iii) end-user variable cooling demands and/or resistance to new cold provision technologies [81–83].

Regarding technical barrier (i), a suitable, secondary cold carrier fluid is required to transport cold energy recovered from LNG over long distances for off-site DC [81]. Water/glycol mixtures have been proposed but require large mass flows and exhibit high viscosities at very low temperatures, resulting in elevated pumping power. Nanofluids and ice slurries have also been considered but are not suitable for long distance transportation due to high pumping power consumption compared with conventional secondary fluids [81]. Liquid CO_2 has lower viscosity than water/glycol, is non-flammable and considered environmentally benign and low cost [83,84]. CO_2 has been suggested to transport cold energy from LNG regasification terminals [81,83,84] to end-users (e.g., agro-food industries, supermarkets, hypermarkets located 2 km away from an LNG regasification terminal [81,84]).

As a consequence of the above barriers, the implementation of LNG cold energy recovery technologies has been limited to a few countries to date, including Japan and Spain [78]. When recovered, LNG cold energy is mainly exploited to either enhance the efficiency of on-site thermal power generation plants (generally, Rankine and direct expansion-based cycles), and less frequently, for on-site direct cooling applications (e.g., cryogenic air separation for oxyfuel combustion, GT inlet air cooling) rather than off-site uses (e.g., air-conditioning in supermarkets and agro-food processing facilities) [78,81]. However, in support of its GHG emissions reduction goals, the EU Commission now recommends the exploitation of LNG cold energy and waste cold in general to reduce building energy demand [82].

The use of LNG cold energy for DC has hardly been considered in the literature, except in [40,83,85]. Jo et al. [85] investigated a Type 2 absorption system using an ammonia-water solution as working fluid to transport LNG cold energy over long distances. The maximum ammonia-water transportation distance in a 15 cm diameter pipe was estimated at 270 km. In Dominković et al. [40], the envisaged transportation of cold energy extracted from regasified LNG for DC was limited to 20 km within Singapore area. Based in Spain, Atienza-Márquez et al. [83] proposed the cascaded co-generation of DC and Rankine/direct expansion cycle-based power augmentation using cold energy recovered from LNG regasification. LNG cold energy was transported using CO_2. DC was provided at three different temperature levels, for low- and medium-temperature food refrigeration, and building air-conditioning. It was recommended to maintain LNG at a relatively low pressure (~8 MPa) for DC application, due to LNG's heat capacity reduction with increasing pressure. Electricity savings, and seawater savings for regasification, were estimated at 81 kWh/ton_{LNG} and 68% respectively, relative to the standard power and cooling systems with no waste cold use.

Based on the existing and future LNG regasification capacity in cooling-dominated regions, LNG cold energy holds significant potential for DC, as well as for enhancing the efficiency of power generation and refrigeration cycles (e.g., compressor inlet air cooling in gas turbine power plants, heat sinking for heat-driven cooling and power generation technologies). The cold energy from LNG regasification terminals could be used for on-site space air conditioning or process-cooling applications, as well as space cooling in nearby buildings and industrial complexes.

2.2. Thermal Energy Storage

The concept of cool thermal energy storage (CTS) for DC applications was introduced in the early 1980s in the USA. Approximately 2000 CTS systems were installed in the USA by the 1990s, most of them (i.e., 80–85%) consisting of ice thermal storage (in the form of either crystals or slurries), then chilled water storage (i.e., 10–15%) and eutectic salt systems (i.e., 5%) [86,87]. CTS phase change materials (PCMs) include inorganic salt hydrates, organic chemicals (e.g., paraffins) and eutectic salt mixtures. Desirable CTS characteristics include low thermal losses during storage, high release efficiency of stored cold energy, low environmental impact, commercial availability, and cost effectiveness [10]. The characteristics of typical CTS systems are summarized in Table A2. Water has a high specific heat capacity, high availability, is non-toxic and low cost. Chilled water thermal storage is compatible with the evaporation temperature range of conventional chillers, while ice storage is more compact due to its higher volumetric energy density [87].

Centralized chiller plants facilitate the efficient and reliable integration of thermal energy storage, compared to conventional individual cooling systems [88]. The integration of CTS in building air-conditioning and DC has the following benefits [87,89–91]: improved cooling load management; increased cooling generation capacity by shifting operation from peak (i.e., daytime) to off-peak (i.e., nighttime) periods; reduced energy consumption and cost through load shifting for both the DC supplier and consumer; reduced installed cooling capacity, investment and operating cost; improved renewable (e.g., solar energy) integration by reducing energy production-demand mismatch, such as through excess solar energy storage for cooling production in non-sunshine periods; improved chiller efficiency by avoiding part load operation and transient/intermittent operation; and improved system reliability by using CTS as a backup [21,90]. To capitalize these benefits, the local electricity demand profiles and tariffs, and country's energy policy, are the most critical factors and should guide the selection of an operational configuration (e.g., series versus parallel CTS-chiller arrangement) and strategy (e.g., full versus partial storage) [21,90]. CTS is particularly beneficial with large day-night outdoor temperature swings [86,90], such as in for example the GCC. Hasnain [86] studied applications of CTS systems, including building air-conditioning and GT inlet air cooling, and their economic effects in hot-climate regions including the Kingdom of Saudi Arabia (KSA), at daily ambient temperature variations of ~18 °C. The use of CTS was found to reduce peak cooling and peak electrical demands in commercial buildings by approximately 30–40% and 10–20%, respectively. However, certain economies in cooling-dominated regions such as the GCC apply energy subsidies and flat-like tariff profiles that do not enable the potential of CTS to be fully exploited. Few DC design and analysis studies have reported details of CTS selection, design and/or operation/control (Table 1). Chan et al. [21] compared the energy savings achieved for different ice storage operational strategies, namely chiller-priority and storage-priority control, as a function of storage fraction in a Hong Kong-based DC system. The energy/economic savings were found to be highly dependent upon the local cooling demand profile, CTS capital cost and electricity tariff rates, with a prohibitive CTS payback period for application in Hong Kong at the time, and further research in these above areas was recommended. For another DC system in Malaysia, the electricity cost reductions obtained with ice thermal storage were also found to be marginal for the prevailing electricity tariff and limited day-night outdoor temperature variation (i.e., 8 °C) [90].

2.3. Distribution Network Infrastructure

A DC network infrastructure consists of pumping systems and distribution pipelines through which the cooling energy carrier is transferred and distributed from the central chiller plant (or cold energy source) to end-users via ETSs. The cooling energy carrier (i.e., cooling medium), could be chilled water, ice-water, ice slurry, water/glycol mixture or other secondary fluids. The DC network infrastructure requires careful design and optimum operation, as it often represents the largest initial investment in a DC system (i.e., typically 50–75% of total investment) [9].

The pumping system includes pumps operating at either variable or constant flow, that are located at the central chiller plant, within the distribution network infrastructure, and/or end-user substations. In practice, one of three types of pumping arrangements are employed in DC distribution networks: centralized (primary) pumping, primary–secondary pumping, and distributed pumping [92]. In the centralized pumping scheme, a single pumping system is employed to deliver chilled water to the entire system using two-way control valves for controlling the flow of chilled water supply to each end-user. In the case of a primary–secondary pumping arrangement, two separate pumping loops are involved: one at the central chiller plant, and one at the distribution network or circuit, which incorporates secondary variable-speed pumps. In distributed pumping, a distribution pump system is used at each distribution branch [92].

The pipe network structure and configuration are significant design aspects of DC distribution networks, as they directly relate to their operational and structural features. Three types of pipeline network layouts are encountered in DC systems, namely tree-shaped, radial, and looped networks [93]. These layouts are either used separately or more commonly, in combination within the same DC system. The selection of a piping material depends on both material cost and compatibility with the cooling medium being transported [94]. The most commonly used piping materials are welded steel, soldered copper, ductile iron, cement pipe, fiberglass-reinforced plastic, polyvinylchloride (PVC) and polyethylene (HDPE) [10,94]. Similarly to hot water distribution in district heating networks, chilled water distribution in DC networks also requires pipeline insulation, particularly in hot climates, to avoid heat gains that would adversely impact on overall system performance and translate into an economic loss. In addition, occurrences of high heat gains generally coincide with peak space cooling load periods, leading to additional plant capacity requirement. As the supply/return temperature difference in DC systems (i.e., ~10 °C) is lower than in district heating networks (i.e., ~40–50 °C), larger pipe dimensions are required, which tends to increase network cost relative to district heating networks [24]. However, unlike in district heating systems, no high-temperature resistant materials are required for DC pipelines, heat exchangers, valves, and instrumentation, and instead low-cost materials such as plastics can be employed [8]. Above-ground pipe networks are more easily accessible for maintenance, but are more prone to damage and heat gain, and should be protected from vapor condensation on their surface. Hence, buried insulated distribution pipeline networks are usually preferred in hot-climate regions.

2.4. Operational Conditions and Strategies

Key aspects related to the impact of DC operation and flexibility on performance and sustainability are discussed in this section.

The main factors affecting the operation of DC systems are the operating conditions of the sub-systems (i.e., central chiller plant, distribution network, CTS), usage and environmental conditions and economic factors. End-user behavior can vary significantly depending on user and time, strongly affects DC operating conditions and is a major aspect in determining operational strategies. Such strategies should aim at efficient chiller plant operation and cold distribution, reduction control of GHG emissions, and water conservation. The feasibility of operating the DC system at a high efficiency depends on the feasibility of operating the central chiller plant at optimum efficiency and maintaining the design chilled water temperature difference between the supply and return pipelines. Improvements in the efficiency of cold production lead to annual reductions in GHG emissions.

Typically, the central chiller plant and the cooling sub-systems located in end-user buildings are operated separately, which is the consequence of separate management. However, the coordinated operation of central and end-use site systems is of advantage to both the end-user and DC provider. The typical approach of designing DC systems is to size the system to meet the maximum peak cooling demand; however, the period of peak cooling load is significantly shorter than that of the base load. Consequently, this design approach contributes to large capital investments, energy losses, and distribution costs. Alternative DC design and operation approaches involve intelligent control and communication, such as through innovative demand-response management. Rifai [95] presented an example of DC demand-response model. The model involved forecasting the schedules of energy production and consumption, and resource planning to balance supply and demand. Energy demand can be forecasted based on historical and climatic data.

DC system flexibility is defined by Vandermeulen et al. [20] as an ability to adjust the rate of energy addition/removal to or from the system, respectively. The authors [20] identified thermal energy storage, the DC network, and buildings as flexibility providers. They highlighted the need for improved control strategies to enhance the distribution of DC thermal energy, operate efficiently and stabilize energy systems. Advanced hybrid control strategies combining attributes of centralized and distributed control were proposed as a future research direction.

Flexibility within energy systems, including through synergies between districts and other sectors, is advocated by the EU Commission to facilitate the use of waste heat/cold energy in buildings towards reduced GHG emissions [82]. DC system flexibility is of critical importance not only to the efficient operation of the DC system itself, but also in supporting a renewable-based energy system in which the DC system is integrated. Energy systems with high fluctuating renewable electricity/heat generation shares are prone to destabilization and inefficient use of resources unless excess electricity/heat could be absorbed or stored, or other system stabilization measures are applied [96]. DC systems can be used to absorb excess/waste electricity and thermal energy from other sectors to provide space cooling.

Gao et al. [41] analyzed the energetic performance of modeled integrated distributed energy systems and DC systems in subtropical conditions in Hong Kong, in comparison with standalone DC systems and individual cooling systems (ICSs) that only depended on the electrical network. The impact of four different control approaches on the performance of the coupled distributed energy and DC systems was assessed seasonally. These four control strategies were classified as following either the electric load, the cooling load, or the higher or smaller consuming load of primary energy (i.e., electric or cooling load). The analysis was performed using historical 2015 hourly cooling and electricity load data for Hong Kong Polytechnic University campus. The cooling provided by the coupled DC and distributed energy systems was found to be highly sensitive to the control strategy. The interaction between the DC system and the electrical network was also analyzed in terms of the amount of imported or exported electricity to the network. Integration of the DC and distributed energy systems was found to lead to 10–19% reduction in energy consumption relative to a DC system solely dependent on the grid. Under cooling load control or higher consumer load control, the coupled DC and distributed energy systems could fulfill 81.6% and 82.9% of the annual cooling loads, respectively, compared with only 64.1% and 62.6% for the electrical load or lower consumer load controls, respectively. Thus, under a regulation allowing surplus electricity to be exported to the grid, the control strategy following the higher primary energy consuming load led to the lowest energy consumption, was more self-sufficient in terms of electrical grid independence, and supported the electrical network in meeting peak demands. If surplus electricity cannot be exported to the grid, then the electric load following control strategy, which is presently advised in Hong Kong, would be preferable. The payback time of the coupled DC and distributed energy systems was estimated to range from 6.4 to 10.4 years, depending on the control strategy. The cooling load-based and higher consumer load-based control approaches had payback periods of less than 6.6 years.

The extension of DC to non-space cooling applications is another form of flexibility option discussed in Section 2.5.

2.5. Extension of DC to Non-Space Cooling End-Uses

Extensions of DC to non-space cooling end-uses could enable sharing of capital and energy/material resources with other systems/applications towards smart energy systems, leading to thermodynamically more efficient systems and improved sustainability. Conceivable extensions of DC to non-space cooling end-uses of interest to cooling-dominated regions include electrical power augmentation, hot water production [10,12] and water desalination/treatment [12,97].

Regarding power augmentation, although not previously reported in the DC literature but proposed here, the efficiency of GT power plants in high ambient temperatures could be improved through either direct or indirect compressor inlet air cooling provided by the DC system. Compressor inlet air cooling using waste heat-driven absorption refrigeration has been shown to yield significant enhancements in GT power generation and efficiency in harsh climatic conditions in for example the GCC [98], where traditional evaporative coolers perform poorly in high ambient humidity and consume large deionized water volumes that is not recycled. The GT plant could be located remotely from the DC central chiller plant, as long as the cooling energy distribution system has sufficient capacity.

DC central chiller heat rejection, which is at a temperature (~45 °C) insufficient for direct exploitation in most potential non-DC heat use applications, could be recycled for either hot water generation or (sea)water thermal desalination/treatment (e.g., multi-stage flash (MSF), multi-effect distillation (MED)) after upgrading the heat rejected to a suitable temperature (~70–110 °C). This could be achieved by incorporating additional units such as absorption heat transformers, the application of which to desalination and other uses is reported in [99,100]. This could contribute to reduce the energy consumption of thermal desalination/treatment, which is energy-intensive and is a major mean of fresh water provision in hot-climate regions such as the GCC [101]. Hugues at al. [97] found that the cumulative capital and operating cost of MED driven by DC waste heat would break even with that of reverse osmosis (RO) desalination after 4 to 6.5 years of operation in the UAE (depending on utility prices), mainly due to a 25% reduction in MED annual operating cost relative to RO.

Applications of DC to GT power augmentation and recycling of DC chiller heat rejection are scarce or lacking in DC design/analysis studies to date, leaving opportunities for future investigations.

3. Analysis, Modeling and Optimization

Although DC systems can offer higher energy efficiency, and economic and environmental benefits over on-site cooling systems, they represent substantial capital investment and operational costs. Consequently, the performance evaluation and optimization of DC systems at the planning and design stages are key to capitalize their potential benefits. This section firstly reviews district-level cooling load evaluation and analysis methodologies, which is a critical input for DC system design/analysis (Section 3.1), followed by DC thermodynamic performance, economic and environmental impact evaluation methodologies (Section 3.2) and optimization (Section 3.3).

3.1. Cooling Load Estimation and Analysis

DC systems can provide both space cooling, and as discussed in Section 2.5, could also support non-space cooling applications of interest to cooling-dominated regions, such as power augmentation, hot water generation and water desalination/treatment.

With regard to space cooling and dehumidification, the cooling capacities and usage patterns of different end-users (i.e., residential, commercial, institutional, transport, and industrial buildings) can differ significantly and require detailed analysis, as cooling load is often considered the most critical input for the design, performance, and economic viability analysis of DC systems. For example, commercial buildings (e.g., office type, shopping malls, supermarkets) have high cooling loads for regular air-conditioning on weekdays but also to cool server rooms. On the other hand, shopping malls require a significant cooling energy throughout the week, with peak loads during weekends and evenings. Industrial complexes have high cooling demands for both air-conditioning and process applications.

DC systems can be most effectively used in districts where the cooling loads and number of full-load operating hours are high. A high cooling load density is required to recover the distribution network infrastructure investment cost, which represents approximately 60% of the total overall system capital cost [10]. This makes DC systems most attractive in densely populated urban areas and high-density building groups requiring high cooling loads. New urban developments, either at the planning or design stages, are good candidate DC applications, as they allow building owners to make maximum use of building footprint by placing most of the cooling and heat-rejection equipment off-site. Since DC systems are capital intensive, the equivalent full-load hours of cooling (i.e., annual cooling energy demand in MWh per installed capacity in MW) are important to maximize benefits.

Cooling loads need be quantified at an early stage of the DC design and analysis process. Three types of cooling loads are typically sought in standard DC design/analysis practices: (i) peak cooling load data for system capacity sizing, (ii) annual average hourly cooling load data for economic (i.e., cost-benefit) analysis, and (iii) hourly daily cooling demand data for operational and control design/analysis [10]. The most straightforward district-level cooling load estimation approach uses cooling load density data per unit area (m^2/kW) from engineering standards such as ASHRAE [10]. These data are applicable with caution at the preliminary DC planning stage, given their accuracy limitations.

A limited number of research studies have discussed more advanced cooling load estimation [6,21,22,30,31,34,36] and analysis [38] methodologies at district level. This is in contrast with individual buildings, for which significant attention has been devoted to cooling load analysis and simulation [102–104]. District loads are however the largest source of uncertainty in DC system design [34]. District-level cooling load calculation/analysis approaches employed or developed in DC research studies may be categorized under the following six types (i)–(vi), described below. Their applications to DC design/analysis is also summarized in Table 3, with emphasis on studies for cooling-dominated regions, in terms of input data, DC system characteristics, modeling software, output data and key findings as applicable.

In the first approach (i), applied in for example [6,31,105], actual measured end-user data for existing buildings is employed, such as chilled water flow rate combined with the temperature difference between the supply and return chilled water [105], electricity demand data [31], historical and present district cooling load data [6], energy metering data from an energy monitoring system, utility bills, and installed equipment capacities [10]. However, end-user data are often incomplete or not available [10].

In the second approach (ii), the cooling load a standard building is approximated using the overall heat transfer conductance (UA) for the building envelope (accounting for both external and internal loads), and an indoor-outdoor dry bulb air temperature difference derived from measured meteorological data, with dynamic heat transfer effects neglected [30]. Alternatively, the cooling load temperature difference (CLTD)/solar cooling load factors (SCLs)/cooling load factors (CLFs) method may be applied to account for dynamic effects, in conjunction with hourly weather data for a typical day in the cooling period of the year considered [106]. The cooling load of the standard building is multiplied by the number of buildings in the district. This approach is applicable to districts made of buildings with similar heat transfer characteristics.

In the third approach (iii), presented in for example [34,35], the cooling load of each building in the district is calculated using either commercially available or proprietary dynamic building simulation software, a review of which is provided in [104], in conjunction with building construction data and measured weather data. The detailed simulation of each building to derive individual building cooling loads is however unlikely to be practically feasible in large districts, with reduced-order models employed in [34,35].

Gang et al. [34] extended approach (iii) by quantifying uncertainties in district cooling loads due to uncertainties in weather data, indoor data and building design/construction data. Historical weather data for three decades were employed to estimate uncertainties in outdoor conditions, rather than typical metrological year (TMY) data. For other sources of cooling uncertainty, normal and uniform distributions were assumed. DC system size was identified based on the peak cooling load distribution, while DC performance distribution was evaluated based on the annual cooling load for several alternative DC configurations/technologies. For a planned DC system in Hong Kong, uncertainties in indoor conditions (i.e., occupant density, lighting density, plug-in load density, and particularly ventilation rate) were found to have the largest impact on cooling load estimation, whereas uncertainties in building construction/design had the smallest impact. The DC system annual average and peak cooling loads were found to have 80% and 90% chance, respectively, of being lower than those estimated using a conventional design method (i.e., without uncertainties), which would tend to overestimate such loads and lead to oversized DC system capacity, particularly when a safety margin is applied. The impacts of uncertainties on DC system technology selection, configuration, sizing, and performance prediction were examined using sensitivity analyses. In an accompanying optimization study [35] (discussed in terms of optimization aspects in Section 3.3), DC system design and total annual cost were found to be less sensitive to uncertainties in cooling loads compared with individual cooling systems.

The fourth approach (iv), adopted in [21,22,92,107,108] extends approach (iii) through the development of a database of space cooling loads per unit floor area (i.e., cooling load intensity, in W/m^2, which represents the peak cooling load of a building normalized by its total gross floor area (GFA).) for each type of building in the district. This approach may particularly be applicable to large districts, either existing or future ones, during their planning and design phase. The approach involves categorizing end-user buildings into groups according to their type of operation and energy consumption patterns/magnitude [107]. Typical categories include office buildings, dwelling houses, hotels, and retail buildings. Representative buildings are then selected from each building category, with their detailed description and characteristics (e.g., floor plan, construction materials, occupancy, operating schedule, lighting, and equipment specifications). The total GFA that requires air-conditioning in each building category is then established. The cooling load intensity for each building category is determined using local building energy codes, local weather data, and dynamic building simulation software. From the cooling load data obtained from simulation of each building category, the total district peak load, and total district hourly, monthly, and yearly cooling loads, can be estimated. This method avoids the detailed modeling of all individual buildings in an entire district, which would be practically infeasible for large districts. However, although energy simulation tools have the potential to provide more accurate cooling load data than cooling load density data from engineering standards, numerical prediction of cooling loads is prone to errors in absence of model validation using reference data, particularly in large districts.

Focusing on district cooling loads spatial/temporal distribution, Yan et al. [38] proposed a new methodology (referred to as approach v) to analyze the effects of (i) discrepancies in buildings' hydraulic pressure requirements within a given group of buildings on secondary network variable-speed pumps' energy consumption and overall DC system energy consumption, (ii) spatial/temporal inequalities in normalized DC system buildings' load distribution (i.e., normalized to buildings' rated loads), and deviations in chillers' load from full load, on both DC chiller plant energy consumption and overall DC system efficiency savings relative to an ICS. Discrepancies in buildings' hydraulic pressure requirements were quantified using a newly introduced grouping coefficient. This grouping coefficient was used to identify buildings groups than can be served by a common branch of the DC water network, to minimize secondary pump energy consumption. Lorenz curve and the Gini coefficient were proposed as criteria to capture spatial/temporal differences in district building cooling load distribution and deviation in chillers' load from full load. These metrics were applied to evaluate the energy performance analysis of a modeled DC system under different cooling load profiles in a developing area of Hong Kong. Using the grouping coefficient to optimize the layout of secondary chilled water pumps, secondary pumping power and total DC energy consumption could be reduced by up to 50% and 4%, respectively. A low Gini coefficient, reflective of a more homogenous cooling load distribution, was found to correlate with higher annual chiller plant COP and higher annual DC system energy efficiency, and to generally lead to higher annual DC system energy savings relative to an ICS. The grouping coefficient had a more significant influence on energy consumption than the Gini coefficient, suggesting the greater importance of the chilled water network in terms of DC energy performance, than building cooling loads. At low grouping and Gini coefficients, overall DC annual energy consumption could be reduced by up to 14%.

Table 3. Overview of district-level cooling load evaluation and analysis methodologies in DC design/analysis studies.

Source	Approach Type and Implementation Specifics	Simulation Tool	End-User Type and Location	Remarks
Perdichizzi et al. (2015) [31]	Type (i), with hourly electrical consumption of compression chillers on a typical summer day and winter day estimated from total electricity demand	N/A	Mid-size community (~50,000 inhabitants) assumed in Abu Dhabi (UAE)	• Total peak electricity demands of 83 MW_e and 42 MW_e in summer and winter, respectively • Daily total electricity demand varies by 40% and 50% between day and night in winter and summer, respectively • Electric chillers represent 15–20% and 45% of total electricity demand in winter and summer, respectively
Al-Qattan et al. (2014) [6]	Type (i), with DC hourly cooling load profiles for a selected April day and August day predicted based on historical and present weather data	Unspecified numerical solver	Block of 805 residential villas (each with 800 m^2 air-conditioned space area), 4 schools, 2 community shopping centers and 4 houses of worship in a district of a new city in Kuwait	• Peak DC load in summer estimated at 96 MW • Chilled water supply/return temperature of 6.1/12.8 °C
Marugán-Cruz et al. (2015) [30]	Type (ii), with standard building (UA) value taken as 0.38 kW/ °C, outdoor dry bulb air temperature estimated using local weather station temperature data, and assumed indoor dry bulb temperature (i.e., 25 °C) based on the Spanish Regulation on Thermal Facilities in Buildings, and external and internal loads	N/A	30,027 dwellings in Ciudad Real (Spain)	• Daily cooling demand profile of an average dwelling from mid-May to early October 2012 and hourly cooling data profile for the hottest day (August 10) reported
Ameri and Besharati (2016) [36]	Type (iii), with building energy simulation based on building architectural drawings and data for complete DC project	Dynamic building simulation software EnergyPlus	137 buildings in residential complex (~500,000 m^2) in Eastern Tehran (Iran)	• Hourly building cooling loads for a set of typical days used to derive reported annual hourly cooling demand profile • Weather data and indoor conditions data N/R
Gang et al. (2016) [34,35]	Type (iii), using historical weather data, both sample building design/construction data, and sample indoor conditions for each building, with uncertainties in these three input data types accounted for	Reduced-order building energy model implemented in EPC software	Planned district in Hong Kong, including 37 buildings (i.e., office, government, hospitals, hotels, metro stations, etc.)	• Uncertainties in DC loads estimated at the DC system design stage for each building, based on three sources of uncertainties, namely outdoor weather data, indoor conditions and building design/construction • Uncertainties in indoor conditions (particularly ventilation rate) found to have the largest impact on cooling loads • DC system annual average and peak cooling loads found to have 80% and 90% chance, respectively, of being lower than those estimated using a conventional design method, which would overestimate such loads; Uncertainties have less impact on district- than individual cooling systems' loads

Table 3. *Cont.*

Source	Approach Type and Implementation Specifics	Simulation Tool	End-User Type and Location	Remarks
Chow et al. (2004) [107]	Type (iv), with cooling load profile of each building category for 12 months represented by 2016 h (i.e., a typical week in each month)	Dynamic building simulation software DOE-2	Five building categories in Hong Kong, including offices/residential buildings, shopping mall, hotel, and mass-transit railway station	• Cooling load profile of each building category reported for 12 months • Daily cooling load profiles reported for three types of days (i.e., weekday, Saturday, Sunday)in a summer month
Chan et al. (2006) [21]	Type (iv), with typical weather year data for Hong Kong used as input	Dynamic building simulation software DOE-2	Planned building mix in West side of Hong Kong City, including offices, hotels, retails, government depots, schools, indoor recreational centers, and magistracy	• District annual hourly cooling demand profile determined (peak load, 116 MW and minimum load, 1 MW)
Chan et al. (2007) [22]	Type (iv), with hourly weather data of a typical metrological year (TMY) for Hong Kong developed in [109] used as input	Dynamic building simulation software EnergyPlus	Hypothetical site in Hong Kong with different building mixes, including offices, hotels, retails, schools, hospitals, and mass-transit railway station	• Annual hourly cooling load and hourly chilled water demand for each building category determined (data N/R)
Yan et al. (2017) [38]	Type (v), with Lorenz curve and Gini coefficient employed to quantitatively describe building cooling load characteristics and their effects on DC system energetic performance	TRNSYS software applied to predict DC system energy consumption	Three planned development areas including different type of buildings (office, hotel, commercial mall, residential, school and hospital) with a total GFA of 80,000 m^2	• Impact of building load characteristics on DC system energy performance quantitatively evaluated
Gros et al. (2016) [110]	Type (vi), with 2008 meteorological data, and indoor setpoints of 19 °C and 26 °C in non-occupation and occupation periods, respectively	• Outdoor direct and diffuse solar irradiance calculated using SOLENE software • Outdoor reflected solar irradiance and longwave interchanges calculated using EnviBatE software • Outdoor wind fields computed using QUIC software • Building heat transfer modeling software N/R	• 10 nine story building blocks (70,000 m^2) in Buire district, Part-Dieu, Lyon (France) • Mix of historical and 1960′s 7-storey buildings, plus one 51 m and one planned 153 m high towers (60,000 m^2), in Money district, Part-Dieu, Lyon (France)	• District cooling energy demand (MWh/yr) reported for several alternative urban plans (green versus albedo) in summer period (i.e., May 1–September 30) • DC load reduced by 3%, 35% and 76% with tree growth, green roofs, and increased used of surface albedo

Note: Cooling load evaluation/analysis approaches (i)–(v) described in the text body of Section 3.1. EPC—Engineering, Procurement & Construction (EPC). N/A—not applicable. N/R—not reported.

In approach (vi), presented in [110], district-level cooling loads are evaluated using coupled building energy and outdoor microclimatic simulations. Microclimatic simulations of hourly atmospheric flow and temperature fields around buildings are employed to yield more detailed outdoor environmental data than single-site, urban-level data from a near weather station. Such simulations can capture heat island effects on district outdoor air temperatures, district cooling loads and pollutant concentrations in dense urban areas, and enable the evaluation of alternative urban plans (e.g., landscaping, vegetation, surface albedo) to reduce such effects. The additional computational expense associated with atmospheric modeling would depend on the fluid flow and heat/mass transport calculation methods used, and may currently restrain the application of this method to a selected annual period.

Combinations of the above approaches (e.g., accounting for the effects of both uncertainties and district microclimate on cooling loads) could potentially yield further accuracy improvements in cooling load prediction, at the expense of increased analysis complexity and time.

3.2. Performance Evaluation

Energy performance, and economic and environmental impact evaluation methodologies employed in published DC system analyses are reviewed in this section.

3.2.1. Energy Performance

The DC system design and analysis studies in Table 1 have focused on energy analyses, except for Coz et al. [39], who evaluated DC system performance based on exergy and exergoeconomic analyses. Although still limited in number, exergy-based analyses of combined district heating and cooling systems in heating-dominated regions have received more attention [39,111]. Energy-related DC operating and performance parameters typically include annual cooling energy supplied, maximum cooling load supplied over the operational life consumed, central chiller plant COP, annual energy consumption, chilled water supply temperature, design chilled water temperature difference, average chilled water temperature difference achieved, and distribution system makeup water rate (% of circulation) [10]. Based on the studies in Table 1, the annual energy savings achieved using a DC system relative to a conventional cooling system is the most widely employed energy consumption-related metric.

In addition to the above widely used performance metrics, Yan et al. [38] proposed a water transport factor (WTF),

$$WTF = \frac{Q_c}{E_d} \quad (1)$$

where Q_c is the cooling energy produced by the central chiller plant, and E_d is the energy expended by the chilled water distribution system. An accompanying system coefficient of performance (SCOP) was also proposed [38]:

$$SCOP = \frac{Q_{DC}}{E_c + E_d} \quad (2)$$

where Q_{DC} is the effective cooling energy delivered to end-users after subtracting distribution losses, and E_c is the energy consumed by the central chiller plant. Distribution losses were assumed to represent approximately 80% of chilled water pump energy consumption [38].

In addition, the non-renewable primary energy factor (PEF) may be useful in comparing the fuel use of different sustainable DC design options or technologies. The non-renewable PEF measures the combined effects of efficiency and use of renewable and waste energy sources. The lower the PEF value, the more fossil energy is being saved. The non-renewable PEF accounts for the process of extraction, processing/refining, storage, and transportation of the fuel considered [112,113]. The non-renewable PEF for DC applications is a dimensionless variable defined as [112,113]:

$$PEF_{DC} = \frac{\sum_{i=1}^{n} E_{F(i)} \cdot f_{F(i)}}{\sum_{j=1}^{n} Q_{DC(j)}} \quad (3)$$

where PEF_{DC} is the non-renewable PEF for delivered cooling by a DC system to the end-user within a considered period (in kWh/kWh), $E_{F(i)}$ is the net energy content of fuel (i) (in kWh) delivered to the system where it is finally converted to cooling within the considered period, $f_{F(i)}$ is the non-renewable PEF factor for fuel i (values of which are provided in Table A3), and $Q_{DC(j)}$ is the cooling energy (in kWh) delivered to end-user substation (j) within the considered period.

Gros et al. [110] proposed an energy performance index (EPI) to compare the effects of alternative urban modeling strategies (e.g., landscaping, vegetation, surface albedo) on district cooling energy consumption:

$$EPI_i = \frac{E_{ref} - E_{coolstrat(i)}}{E_{ref} - E_{ideal}} \quad (4)$$

where E_{ref}, $E_{coolstrat(i)}$ and E_{ideal} designate the district cooling energy consumption for the reference uncooled district, district cooling strategy (i) under evaluation, and ideal cooling strategy. In the latter strategy the district topology is unchanged, but the albedo and emittance of all opaque and non-vegetated surfaces are increased to 0.8 and 0.9, respectively. The EPI was applied by Gros et al. [110] to analyze the outputs of coupled building energy and microclimatic models in terms of the effects of alternative urban designs on district cooling energy consumption.

3.2.2. Environmental Impact

The higher efficiency of DC systems relative to on-site cooling, in conjunction with the use of low-carbon energy sources can contribute to significantly reduce environmental emissions. Emissions from biomass and waste in district heating/cooling systems have however prompted concerns [12,18].

Environmental impact assessments of DC systems are generally based on the operational phase CO_2 equivalent emissions avoided through the introduction of both centralized versus individual cooling systems, and sustainability enhancement options discussed in Section 2. Environmental impact can also be quantified using the amount of CO_2 emissions released relative to the amount of energy delivered to the end-user [112], which is a useful performance parameter to compare the fuel use of different DC design options (or technologies):

$$K_{DC} = \frac{\sum_{i=1}^{n} E_{F(i)} \cdot K_{F(i)}}{\sum_{j=1}^{n} Q_{DC(j)}} \quad (5)$$

where K_{DC} is the CO_2 factor for supplied cooling to the end-user (in kg of CO_2/MWh of cooling), $E_{F(i)}$ is the net energy content of fuel (i) delivered to the system where it is finally converted to cooling within the considered period, $K_{F(i)}$ is the specific CO_2 emission factor for energy source (i) (in kg of CO_2/MWh_{fuel}, Table A3), and $Q_{DC(j)}$ is the cooling energy delivered to end-user substation (j) within the considered period.

As an alternative CO_2 emission-related metric, the CO_2 payback time (CPT) (Equation (6)) was applied in [114] to quantify the environmental benefits obtained through replacement of air-source heat pumps by ground-source ones for a district heating and cooling system in Tokyo (Japan). The CPT can be a useful concept to evaluate and interpret net CO_2 emissions, and assess systems from a life-cycle CO_2 emissions point of view:

$$CPT = \frac{CO_2 \text{ emissions during the construction phase}}{\text{annual } CO_2 \text{ emission reduction by the introduction of new systems}} \quad (6)$$

Genchi et al. [114] found that 87% of life-cycle emissions resulted from the ground-source heat pumps digging process. Their district heating and cooling system contributed annual CO_2 emission reductions of 54%, with a CPT at 1.7 years.

Gros et al. [110] proposed an ambient temperature mitigation index (ATMI) to compare the effects of alternative urban modeling strategies (e.g., landscaping, vegetation, surface albedo) on outdoor temperature:

$$ATMI_i = \frac{DH_{ref} - DH_{coolstrat(i)}}{DH_{ref} - DH_{ideal}} \quad (7)$$

where DH_{ref}, $DH_{coolstrat(i)}$ and DH_{ideal} are the number of degree-hours higher than the cooling temperature setpoint in the district under analysis (e.g., 26 °C in French regulation [110]) for the reference uncooled district, district cooling strategy (*i*) under evaluation, and ideal cooling strategy. In the latter strategy the district topology is unchanged, but the albedo and emittance of all opaque and non-vegetated surfaces are increased to 0.8 and 0.9, respectively. The ATMI was employed by Gros et al. [110] in conjunction with the EPI (Equation (4)) to analyze the outputs of coupled building energy and microclimatic models.

Although not suggested in [110], district outdoor air quality indicators could also be employed, since atmospheric modeling software can yield predictions of pollutant concentrations.

The ozone depletion potentials (ODPs) and global warming potentials (GWPs) of commonly used refrigerants in both conventional air-conditioning and DC systems are compiled in Table A4. Widely employed refrigerants in compression refrigeration cycles include hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), ammonia, CO_2, sulfur dioxide and hydrocarbons, as alternatives to highly ozone-depleting chlorofluorocarbons (CFCs) [115]. HCFC-22 is used in most air-cooled chillers in buildings in developing countries, and although less ozone-depleting than CFCs, unrepaired refrigerant leaks have an adverse impact on the environment as well as on chiller efficiency [116]. Certain DC systems in developing regions including the GCC still use CFC-11 and CFC-12 refrigerants [117]. DC systems can facilitate the phase-out of ozone-depleting refrigerants through the use of HFCs and ammonia, which are not restricted by international protocols (e.g., Montreal Protocol) [118]. DC systems also offer opportunities to use cooling technologies with near-zero ozone depletion and global warming, such as $H_2O/LiBr$ and NH_3/H_2O absorption chillers.

Another environmental benefit of DC systems is that they are less likely to cause adverse noise and vibration in a densely populated urban environment, than conventional on-site air-conditioning systems. The latter systems generate approximately 74 dB sound level, which is equivalent to heavy traffic.

3.2.3. Economics

The total investment cost of a DC system comprises the costs of the central chiller plant, distribution network infrastructure, ETSs, and project development costs.

The investment and production costs of cooling energy using the central chiller plant depend on several factors, including plant size, type and characteristics of energy sources, system diversity factor (i.e., required cooling capacity divided by total market demand), ambient air conditions, supply/return temperatures, local legislation (e.g., for refrigerants) and other conditions [119]. The operation and maintenance costs include the administrative cost for operating and maintenance staffs, maintenance contracts, and materials for preventive maintenance. The space savings associated with replacement of on-site cooling equipment by an off-site, centralized DC chiller plant should also be taken into consideration in an economic analysis, as this space becomes available for other purposes at the end-user site. This can result in economic benefits over the system lifetime.

The cost of the distribution network infrastructure generally represents 50–75% of the initial investment [9]. This cost is influenced by several factors including pipeline density, which is defined as cooling energy or cooling capacity provided by the DC system per unit length of pipeline network [119]. A pipeline cooling energy density greater than 4 MWh/m and cooling capacity greater than 3 kW/m indicate that the cost of the distribution network infrastructure is within a reasonable range [119].

The capital cost of end-user equipment (e.g., heat exchangers, distribution/regulation valves) is considered the least significant [9]. Standardized prefabricated ETSs have relatively well known and stable capital cost. ETS installation cost in end-user buildings depends mainly on local labor costs.

Operational costs (i.e., utilities, service, maintenance) are influenced by the types of energy sources and their pricing, and the efficiency of cold production and delivery, which are affected by chiller/storage efficiency, system layout and control strategy, chilled water supply/return temperatures, thermal energy, and pumping losses, hence district density [12]. The overall cost of DC can be significantly influenced by regulations (e.g., utility pricing, carbon taxes/benefits, customer connection costs) [12].

The DC system economic assessment metrics employed in the studies in Table 1 include investment cost [26], annual operating cost [34], annual fuel/electricity cost savings [3,21], total production cost of cooling (including investment and operation costs) [23–25,27,32,36], specific production cost of cooling (i.e., per unit cooling energy) [6], profit from cooling and electricity sales [28] or annual net earnings [30], total net present value (TNPV) [30], payback period [37,41], and reduction in peak energy demand charges [31]. The impact of uncertainties and availability risk (i.e., reliability) were included as part of total annual cost in [35]. Rezaie et al. [12] presented a generic district enviro-economic function to extend investment and operating costs to business environmental costs, including carbon tax and carbon benefits. The exergoeconomic cost of cooling was only evaluated in one study [39].

Short-term district regulation models generally do not permit long-term technical, economic, and environmental sustainability goals to be attained [12]. A life-cycle cost analysis (LCCA) and the use of TNPVs are recommended to reach rational decisions on engineering projects involving district energy systems and are useful to compare DC systems with on-site cooling production [10]. Such analyses should include not only quantitative (quantifiable) but also qualitative (non-quantifiable) life-cycle economic parameters [120]. Quantifiable parameters include the capital costs of the central chiller plant and distribution network infrastructure, energy and utility costs, and operational and maintenance costs. Non-quantifiable parameters include: re-use of space for other valuable purposes (rentable area and roof garden); visible architectural and environmental impacts; lower GHGs emission; cost stability; reliable service; freeing up maintenance staff; makeup water; only pay for the energy used; refrigerant storage and management; and others.

3.3. Optimization

In general, the mathematical optimization of district heating and/or cooling systems has been less investigated and is thus less advanced than at building-scale [121], particularly in regions where district energy systems are not well developed, and/or where energy conservation incentives are limited. However, district systems are spatially and temporally large-scale systems with complex characteristics and that require dedicated optimization methodologies [32,111,121], including in terms of objectives and constraints. Their optimizations involve both continuous and discrete variables (e.g., existence of a power generator, chiller, pump, pipe or other network element, pipe insulation material and thickness), non-linear performance parameters, and a larger design space than at building-scale [121].

An overview of DC system optimizations [22,24,25,32,35,37,39,121,122], with emphasis on studies for cooling-dominated regions, is presented in Table 4. Most of these studies [22,24,25,32,122] have focused on the optimization of the DC distribution network infrastructure, which represents substantial investment, to investigate possible distribution pipeline designs and network configuration alternatives that would reduce piping capital and installation costs, and pumping energy cost. Coz et al. [39] extended these efforts to exergetic and exergoeconomic optimizations of a DC distribution pipeline network.

Table 4. Overview of DC system optimization studies.

Source (Country)	Item Optimized	Model	Optimization Objective(s)	Optimization Decision Variable(s)	Optimization Constraint(s)	Optimization Algorithm(s)
Chow et al. (2004) [107] (Hong Kong)	Mix of overall GFA of building types in a district	N/A	Minimize central chiller plant cooling load fluctuations	Percentage shares of GFA of each building types to the total GFA served by the DC system	Sum of percentage share of GFA of each building type equal to 100%	GA
Chan et al. (2007) [22] (Hong Kong and UK)	Configuration of distribution piping network	Graphical-based, with undirected links and integer string representation in encoding method	Minimize piping cost and pumping energy cost	Combination of piping configurations to connect central chiller plant and end-users	Structural	GA with local and looped local search methods; stochastic uniform selection function
Söderman (2007) [24] (Finland)	Central cold production unit, distribution pipe lines, cold medium storage	MILP	Minimize overall DCS annualized investment and operating costs	Operational and structural variables	Material and energy balances; components' existence	IBM CPLEX 9.0 solver
Feng and Long (2008) [122] (location-generic)	Pipe network layout design	Mathematical, with constrained conditions	Minimize network annual equivalent cost, consisting of total investment, annual operating, maintenance and amortization cost, and annual cooling loss costs	Discrete standard pipe diameters	Flow equilibrium [(1)]; water velocity ($V \leq V_{max} = 3.5$ m/s); pipe diameter ($d_{min} \leq d \leq d_{max}$) where d_{min} is DN15 and d_{max} is DN1400	Single-parent GA (SPGA)
Feng and Long (2010) [25] (China)	Pipe network layout design	Mathematical, with constrained conditions	Minimize network total annual cost, including initial investment, and operation, depreciation, and maintenance costs	Discrete standard pipe diameters	Pipe diameter; flow equilibrium; pressure equilibrium [(2)]; users' flow requirements; water velocity; DCS hydraulic stability	GA
Khir and Haouari (2015) [32] (Qatar)	Capacity of central chiller plant; storage tank capacity; layout and size of main distribution piping network	MILP	Minimize DCS total investment and operational costs	Temperature and pressure of supplied chilled water; chilled water flow rate and stock level in storage tank at the end of each period; existence of sub-systems (central chiller, storage, type, and layout of pipe)	Structural, chilled fluid temperature and pressure	IBM ILOG CPLEX 12.5 solver
Gang et al. (2016) [35] (Hong Kong)	DCS central chiller	Cooling loads calculated as in [34]; Cooling load uncertainties propagated using Monte Carlo approach; Sub-system reliability modeled using Markov method	Minimize DCS total annual capital (i.e., DCS chiller), operation (i.e., electricity) and availability risk cost (i.e., non-fulfilled cooling demand)	DCS central chiller plant capacity	Chiller capacity identified by restricting non-fulfilled hours to < 35 h with 100% probability	N/R
Kang et al. (2017) [37] (Hong Kong)	Sizes of distributed power generators, and both DCS absorption and electric chillers	N/R	Minimize payback time of distributed power generators and DCS, i.e., ratio of additional capital cost to annual operating cost savings relative to centralized power plant and individual cooling systems	Capacities of distributed power generators and DC chiller	• Electricity and cooling outputs ≤ equipment capacities • Primary energy consumption savings maximized in each annual hour	N/R

Table 4. *Cont.*

Source (Country)	Item Optimized	Model	Optimization Objective(s)	Optimization Decision Variable(s)	Optimization Constraint(s)	Optimization Algorithm(s)
Coz et al. (2017) [39] (Slovenia)	Pipe network material, diameter, insulation thickness	Exergetic and exergoeconomic	• Maximize exergy efficiency of cold exergy transportation, or • Minimize total exergoeconomic product (i.e., cold) cost	Pipe diameter, insulation thickness	N/R	N/R
Al Noaimi (2018) [88] (hypothetical site with operational and economic parameters representative of Qatar DC systems)	Tree-like network configuration, including chiller plants' technology, locations and sizes, pipe network layout, distribution strategy	MILP	Minimize DCS total annual capital and operating cost for electricity and cold production, storage, and distribution	Chiller/storage system location and capacity, pipe location, chiller water production/delivery flow, chilled water temperature/pressure	• Chiller output cannot exceed chiller capacity • Network edges should route chilled water to all end-users simultaneously • No redundant network edges • Maximum chilled water temperature rise in network connection • Maximum pressure drop	IBM ILOG CPLEX 12.6.1.0 solver
Perez et al. (2018) [121] (France)	Building materials, energy (heating, cooling, hot water) production and distribution systems	Energy, economic and environmental	• Energy-based: minimize total annual primary energy consumption (electricity/gas for heating, cooling, hot water, lighting, auxiliaries, electrical equipment) • Economic-based: minimize total investment (building structural/insulation materials, fenestrations, heating/cooling/hot water production systems), installation, maintenance, and energy (electricity, gas) costs • Environmental-based: minimize district life-cycle equivalent CO_2 emissions	• Building (structural, insulation, window) material type, insulation location and thickness • Building configuration • Energy production (boilers, CHP, heat pumps, electric/solar heaters, solar PV roof area coverage), ventilation and storage (hot water tank) systems • Energy distribution network	• Building energy demand < 45 kWh/m^2/year • Total primary energy consumption for electricity and gas < 120 kWh/m^2/year • Solar irradiation (for selection of roof surfaces for solar PV installation) > 900 kWh/m^2/year	GA; brute force search; shortest path (Dijkstra)

Note: DCS—district cooling system; GA—genetic algorithm; GFA—gross floor area; MILP—mixed integer linear programing; MTR—mass-transit railway; (1) Algebraic sum of water flow of all branches connected to one nodal point is zero; (2) denotes that algebraic sum of the pressure differences of all branches included in any circuit of pipe network is zero. N/A—not applicable. N/R—not reported.

By contrast Chow et al. [107] focused on identifying an optimal mix of DC end-user building categories and cooling load patterns to minimize fluctuations in cooling demand, which can improve DC chiller use and reduce payback time. Al Noaimi et al. [88] optimized chiller plant/storage system parameters (chiller technology selection, location, size), network pipe layout, chiller water flow, and temperature/pressure, to minimize investment and operating cost. Kang et al. [37] determined the optimum size of distributed power generators, absorption, and electric chillers to minimize the payback time of an energy system including distributed power generators and DC, relative to centralized power generators and individual cooling systems. Gang et al. [35] presented a DC cost minimization methodology focusing on central chiller sizing, by accounting for the impact of both uncertainties in cooling loads and availability risk (i.e., reliability). Their work extends the cooling load uncertainty-based DC design methodology of Gang et al. [34], which was discussed in Section 3.1, and is examined here in terms of optimization aspects.

Unlike for building-scale optimizations, most DC optimizations [22,24,25,32,35,37,122] have been single-objective. The above optimization efforts are reviewed in this section, focusing on cooling-dominated regions. Additional region-generic district heating/cooling optimization studies are summarized in [88].

Chan et al. [22] used a modified version of the genetic algorithm (GA) to find optimum or near-optimum piping network configurations for a DC system in a hypothetical site in Hong Kong. A modified GA method using a local search and looped local search techniques was employed to improve performance in the search of a near-optimal piping network configuration. The optimization objectives were to minimize both the investment (i.e., capital) and operational (i.e., pumping energy consumption) costs associated with the piping configuration. Flexible pipe connection options were applied using different types of network layouts (e.g., radial, tree-shaped or combinations of both). Accordingly, structural constraints were applied to include restrictions on the number of links in relation to a given number of nodes (e.g., n nodes must have n-1 links), and to prevent flow recirculation (i.e., cycles between nodes). Using a series of parametric simulations, the mathematical model developed was tested for two cases, namely eight and 16 consumer buildings, with different GA population sizes and mutation rates investigated. Incorporating local search led to improved search performance (i.e., reduced convergence time) and better optima (i.e., improved objective functions values).

For a new urban area requiring a DC system, or either the expansion or retrofitting of existing DC systems, Söderman [24] employed a mixed integer linear programming (MILP) model to optimize both DC structural and operational aspects. The model was tested using actual 2006 cooling demand data for an existing DC system, as well as using predicted demand data for the year 2020, representing an expansion of the existing 2006 DC system. The single optimization objective was to minimize total annual cost, which included annualized investment cost and running costs of the central chiller plants with auxiliary units and main distribution pipelines. The optimization solution would assist in decision-making on how the existing DC system should be expanded in the future, in terms of the number, capacity and spatial arrangement of DC sub-systems (i.e., central chiller plants, storage tanks, and pipeline networks). Furthermore, the optimization solution contained information on how the DC system should be operated over different time periods, for example in terms of the chilled water flow rates in different sections of the pipeline network during different periods of the year (day, night, seasons), and the charging/discharging of storage tanks, and operation of the chiller plants. The author considered constraints related to supply and demand, enthalpy flow balance with heat gains/losses, and power consumption constraints. Technical hydraulic and temperature constraints were however omitted in the model.

Feng and Long [122] developed a mathematical model to optimize the pipe network layout of a DC system by minimizing the system's total annual cost. The total cost comprised annualized overall investment, operating, maintenance and amortization costs, as well as the cost of piping energy losses. An improved form of GA (i.e., single-parent GA (SPGA)), was applied. The optimization problem was constrained by flow equilibrium constraints at each nodal point, an upper bound chilled water flow velocity (i.e., 3.5 m/s), and limits on the pipe diameter range, which is considered to be an important DC system design factor. The solution obtained using the SPGA was compared with Dijkstra's algorithm, and the results showed that SPGA was useful in network piping scheme assessment and decision-making. It was also useful to select the optimal location of the central chiller plant(s). According to the authors, SPGA demonstrated high search efficiency, rapid convergence, and stability. It was also suggested that road and building distribution in the district should be considered before a final optimum DC design is selected.

Feng and Long [25] subsequently applied a standard GA to the optimization of a pipe network layout in the same DC system as in [122], with additional optimization constraints to obtain a more realistic model than in [122]. The additional constraints related to pressure balance (equilibrium), hydraulic stability, and end-user cooling demand. The objective function incorporated initial investment, operational, depreciation and maintenance costs.

The above optimizations [22,24,25,122] focused on economic objectives, by imposing structural optimization constraints, without temperature and pressure constraints. Khir and Haouari [32] considered pressure and temperature-related technical constraints, which are critical for DC system functionality and integration with both the central chiller plant and end-user ETS. Such constraints were used to minimize the sum of the fixed costs of a building chiller plant and storage tank, the variable production and storage costs, and the fixed costs related to the purchase and installation of the distribution pipelines. A MILP model of the DC network was constructed using a reformulation-linearization technique (RTL). All relevant data (i.e., cooling demand, costs, capacities, and other parameters) were collected from appropriate sources (i.e., market, services) and prescribed as inputs to the MILP model. Optimal and near-optimal solutions could be obtained within a reasonable computational time for a distribution network up to 60 nodes.

Coz et al. [39] performed an exergoeconomic optimization of a DC distribution pipeline network, by modeling exergy transfer due to heat gains and viscous (pumping) losses (i.e., pressure drop) associated with cold distribution in the network. The optimization sought to minimize the cost of cold (i.e., final product) for the main consumer, and the exergetic efficiency of cold transportation, through determination of the optimum pipe diameter and pipe insulation thickness. This optimization was performed for polyurethane-pre-insulated steel pipes and non-insulated polyethylene pipes, at cooling capacities of 50 to 1500 kW. Slovenian unit electricity and input heat prices were applied. Higher cooling capacities were found to reduce the exergetic cost of cold (i.e., full cost of cold production). In addition, polyethylene pipes had smaller exergetically optimum diameters than pre-insulated steel ones, due to the lower surface roughness of the former material, hence lower frictional losses and flow rate requirement to carry the same quantity of cold. However, polyethylene pipes exhibited lower exergetic efficiency than insulated steel pipes due to larger parasitic heat gains. By contrast the exergoeconomically optimum polyethylene pipes were found to be larger in diameter than those of the insulated steel pipes. The minimized cost of transporting cold was lower for insulated steel than polyethylene pipes. For steel pipes, the price of the inlet cold exergy was found to have the largest impact on the total exergoeconomic product (i.e., cold) cost, when compared with the impacts of the specific costs of insulated steel pipes and construction, and electricity price to drive pumping. For steel pipes, higher polyurethane insulation thicknesses improved exergetic efficiency because of reduced heat gains, while increasing pipe diameters resulted in lower frictional losses but higher heat gains. Consequently, an exergoeconomically optimal pipe diameter existed at which the total product cost was minimum. In summary, pre-insulated steel pipes were somewhat advantageous in terms of exergy efficiency and exergoeconomic product cost of cold. Such results however depend on the input electricity and inlet heat prices. The analysis methodology could be extended in future work to a complete DC system and undertaken for several cooling technologies.

The existence of a large variety of end-user buildings and different cooling load profiles in a DC system can result in a relatively steady cooling demand profile [107]. Thus, a design approach could seek to identify and select the optimum mix of end-user building categories and cooling load patterns that could minimize the cooling energy production cost to maximize effective system use and ultimately lead to a shorter payback period. Chow et al. [107] proposed an approach to determine the optimal mix of building types using a GA. The buildings mix was described by the percentage share of the overall GFA of the different types of end-user buildings that are served by the DC system. The optimization and cooling load estimation approaches were illustrated for three case studies in Hong Kong and reported to be effective to produce optimal or near-optimal solutions. In the first case study, five building types were considered which included hotels, residences, offices, shops, and mass-transit railway (MTR) station. The optimum GFA shares of the building types were found to be 67.0%, 13.8%, 14.1%, 3.4% and 1.6%, respectively. As the MTR station had the least effect, it was disregarded in the second case study, leading to an optimized end-user building mix shares of 81.4%, 12.0%, 5.1% and 1.5% for the hotels, residence, office, and shops, respectively. In practice, it would be difficult to implement a high share of hotel buildings (such as 81.4% as in the second case study) within a district [107]. Therefore, in the third case study, the GFA share of the hotel category was set to a constant 5% value, with the shares of the remaining three other end-user building types optimized. This case led to more stable solutions than the other two case studies and the fitness function converged to two close specific fitness values (i.e., cooling demand fluctuation index of 0.60415 and 0.60425). The slightly better fitness was obtained for an office GFA share of 2% to 7.5%, residential building share of 30% and 40%, and shop share of 40% to 80%.

Kang et al. [37] investigated the energetic performance and economics of a modeled distributed energy system comprising distributed power generators (i.e., gas engines), DC chillers (i.e., absorption and electrical), electrical and chilled water distribution networks, and end-users in a group of 12 buildings in Hong Kong Polytechnic University campus. The power generators provided both electricity and waste heat to the electrical and absorption chillers respectively, for district cooling. The optimum size of the distributed generators, absorption and electric chillers were determined to minimize the payback time of the overall energy system, destined to substitute a centralized energy system, in which cooling was provided by individual water-cooled centrifugal chillers powered by the grid (i.e., coal-fired centralized power plant). The absorption chillers provided most of the cold supply in winter, but the opposite occurred in summer. From April to November, the DC system chillers achieved a higher COP than those of the centralized cooling system. Electricity consumption from the grid was reduced through the substitution of grid power by distributed generators and of electric chillers by absorption systems, and effectively shaved peak electrical loads. Such loads were reduced by up to 72% in summer. The distributed energy system led to 9.6% reduction in primary energy consumption relative to the centralized energy system, at the expense of three times the capital cost, but 45% lower operating expenditure. The payback time of the distributed energy system investment was estimated at 1.9 years.

Gang et al. [35] extended their cooling load uncertainty-based DC design approach [34] (Section 3.1) to a cost minimization methodology, by accounting for the economic impact of uncertainties in both DC cooling loads and operational reliability (i.e., DC sub-system availability risk). The DC system total annual cost included capital cost (which depended on DC chiller capacity), operational cost (i.e., electricity cost, which depended on both cooling loads and DC chiller capacity), and availability risk cost (i.e., costs associated with non-fulfilled cooling demand due to underestimation of DC system capacity, and/or DC sub-system performance loss or malfunction; such costs depended on both cooling loads and DC chiller capacity). Uncertainties in cooling loads were propagated using a Monte Carlo approach, while sub-system reliability was quantified using Markov method. The impact of incorporating uncertainties on DC chiller sizing and annual cost were evaluated relative to standard DC capacity sizing (i.e., without uncertainties and with a safety margin). The optimal DC chiller capacity obtained by accounting for all uncertainties (i.e., in cooling loads and operational reliability) was lower than that obtained using either standard capacity sizing or by only accounting for operational risk, but higher than by only accounting for uncertainties in cooling loads. The minimized total annual cost of a DC system sized by including either all uncertainties or using a standard approach were similar (as the contribution of DC chiller capital cost to total annual cost was not significant), but significantly lower than by accounting for operational risk only, particularly at assumed high availability risk prices. Finally, uncertainties in both DC cooling loads and operational reliability were found to have larger impacts on the design of individual on-site cooling systems than on the design of DC systems.

Perez et al. [121] highlighted the need for multi-objective optimizations of district heating/cooling systems, as single-objective optimizations generally do not effectively incorporate holistic sustainability criteria. The authors presented a five-level, multi-objective (energy-, environmental- and economic-based) district heating and cooling system optimization procedure. Although the methodology was demonstrated for a heating-dominated region, it would be applicable to cooling-dominated environments and is of interest in terms of handing building to district-scale features and incorporating multiple sustainability-related performance criteria. The optimization procedure steps involved concurrent building envelope optimization and rooftop solar PV exploitation potential evaluation, followed by distribution networks optimization, then complete building optimization and identification of optimal combinations of complete building configurations in the district (at local decentralized branch heat, cold or hot water production scale), with in parallel combinations of building envelope configurations and complete district optimization (at centralized production scale). The procedure closed with an aggregation of all results at local (branch) and central (urban) production scales. Several optimum search methods were employed including the non-dominated sorting GA. The number of possible solutions could be effectively reduced using sustainable energy-related constraints. The optimization procedure was applied to a future industrial estate planned in Grenoble (France) for the year 2030, including 48 residential, office, and retail buildings and parking lots, combined in 12 urban islands. Cooling was delivered to retail and office buildings using absorption heat pumps in summer. Comparing the results obtained in Grenoble (France) and Stockholm (Sweden) climatic conditions, it was found that for the hotter climate, the optimization led to solutions that focused on reducing solar-induced overheating, whereas in the colder climate, insulation from the outdoor environment was emphasized. This methodology has potential for DC systems in cooling-dominated climates.

4. GCC Regional Air-Conditioning Challenges, DC Status and Future Opportunities

A considerable potential exists for DC in the Middle East, in particular in the GCC, due to its harsh climatic conditions that make air-conditioning a necessity almost all year round, high-pace and dense urbanization, and popular building architectures with extensive glass exteriors. In this section, space cooling challenges specific to the GCC region are summarized, before providing an overview of the current and forecasted development of the DC market in the region, including economic and environmental opportunities. Potential technical and policy-related solutions to address regional space cooling challenges are then identified.

4.1. Air-Conditioning Challenges

Air-conditioning in the GCC faces the following challenges: a lack of natural cold sinks (i.e., air, water) for either direct cooling or heat rejection from air-conditioning systems; natural water scarcity; a growing cooling energy demand driven by population and economic developments; elevated energy use per capita and high reliance on fossil fuels including for cooling production with an associated environmental impact; high utility tariff subsidies paid by governments; and a lack of air-conditioning and urbanization legislation [123,124]. These aspects are developed in this section.

General population, economic, energy, water and CO_2-equivalent GHG emissions indicators for GCC countries are tabulated in Table 5 and compared with the world average and other major energy users. From approximately 52.7 M inhabitants in 2015, the region's population will grow to 66.5 M (+26%) and 76.7 M (+46%) by 2030 and 2050, respectively, at annual growth rates above the world average through most of the 2015–2050 period [4]. As highlighted by the data in Table 5, GCC countries have had among the highest annual energy, electric power consumption, and CO_2 emission rates per capita in the world. Natural gas and oil are the dominant primary energy resources used in the region. The UAE, Qatar and Oman cover above 60% of their total domestic energy needs, particularly electricity production, using natural gas. Bahrain, KSA, and Kuwait mostly use oil, which fulfills 53.8%, 71.2%, and 77.9% of their total energy demands, respectively, and a substantial portion of their electricity generation.

Table 5. General population, economic, energy, water, and emissions indicators for GCC countries, compared with the World average and other major energy users [4,125,126].

	Population [a]	GDP [b]	Energy Use [c]	Electricity Use [d]	Energy Intensity [e]	Renewable Water [f]	Water Consumption [g]	CO_2 Emissions [h]
Bahrain	1.4 (2.01%)	23.7	10,158	18,415	244	84.2	348 (2003)	22.7
Kuwait	3.9 (5.44%)	35.4	10,093	15,689	134	5.1	447.2 (2002)	28.2
Oman	4.2 (6.45%)	17.8	6502	6097	153	311.7	509.3 (2003)	16.3
Qatar	2.5 (4.93%)	72.9	17,221	14,960	138	26.0	376.6 (2005)	41.9
Saudi Arabia	31.6 (6.65%)	22.2	6663	8556	137	76.1	907.5 (2006)	18.7
UAE	9.2 (2.03%)	41.2	7619	10,899	127	16.4	665.2 (2005)	20.1
World	7383.0 (1.19%)	10.5	1890	3050	132	6064	506 (2002)	4.9
USA	319.9 (0.72%)	56.2	6983	13,116	138	9538	1864 (2005) 1543 (2010)	16.7
EU	508.2 (0.10%)	34.1	3251	6108	94	2961	593 (2002)	6.9
China	1397 (0.54%)	8.0	2129	3483	192	2018	435.2 (2007) 425 (2015)	7.3
India	1309 (1.23%)	1.7	597	0.727	123	1458	559.9 (2000) 602.3 (2010)	1.6
Japan	127.975 (−0.09%)	38.1	3615	8100	99	3397	652.1 (2007) 640.6 (2009)	9.5

[a] 2015 population in millions, with percentage annual average rate of population change (2010–2015) in parentheses () [4]. [b] Annual GDP per capita (2013–2017), in current kUSD/capita [125]. [c] Annual energy use per capita (2010–2014), in kgoe/capita [125]. [d] Annual electricity use per capita (2010–2014), in kWh/capita [125]. [e] Annual energy intensity (2010–2014), in kgoe per USD 1000 [125]. [f] Total renewable water (internal and external surface/groundwater) availability, in m^3/capita/year. Data for the year 2014, except for world average and EU (both for the year 2012) [126]. [g] Water consumption (year), in m^3/capita/year [126]. [h] Annual equivalent CO_2 emissions per capita (2010–2014), in Mt/capita [125].

Space cooling in the GCC is essentially provided using fossil electricity-driven window units, split systems, central air-cooled or water-cooled chillers, and to a limited extent by DC systems (i.e., ~5% of space cooling capacity) [5]. Whereas 10% of electricity consumption is expended globally for space cooling, in the GCC this application represents approximately 50% of total electricity use [5] and up to 70% of peak-period electricity use in the UAE and Kuwait [3,6]. This is contributed by climatic conditions, high living standards with insufficient emphasis on energy conservation, including in the use of low-efficiency air-conditioning systems and building designs/constructions [123]. The annual energy use per capita for space cooling is of approximately 590 kWh in the Middle East (which extends beyond the GCC), compared with the following figures in other regions, including in predominantly hot climates: 35 kWh in Africa, 60 kWh in India, 70 kWh in Indonesia, 320 kWh in the EU and China, 760 kWh in Japan and above 1800 kWh in the USA [3]. By 2050 these figures will more than double in the Middle East and China, and be multiplied by over 12 in India and Indonesia, with significantly less pronounced rises in the EU, USA, and Japan [3]. The GCC is known for its significant variations in building cooling loads both on a daily basis between day and night (i.e., 40% and 50% in winter and summer, respectively, in for example the UAE [31]), and on a seasonal basis between winter and summer, with peak winter loads of order 50% lower than summer loads in the UAE [31]. Peak cooling demand periods (i.e., afternoon/evening) also coincide with peak ambient temperatures and humidity, during which the efficiency of thermal power generation significantly decreases [3]. The resulting electricity demand fluctuations for vapor compression cooling adversely impact power plant efficiency as they operate at off-design conditions for a major part of the year and induce stress on electrical networks [31]. In for example the UAE, the minimum total annual electricity demand (i.e., in a winter night) is approximately 40% lower than the annual peak demand (i.e., in a winter day) [127].

The GCC peak cooling demand is expected to triple between 2010 and 2030 (Figure 7) as a consequence of population growth, rapid urbanization and the sought for improved comfort. KSA and the UAE will continue to have the highest peak cooling demands among the GCC members at 19–52 MRT (2010–2030) and 8–21 MRT (2010–2030), respectively. It has been estimated that if GCC countries were to continue using conventional air-conditioning technology and keep their cooling energy consumption patterns, based on projected population and economic developments, it would cost approximately $100 billion to acquire the projected new cooling hardware by 2030, and over $120 billion to provide the associated power supply capacity [5].

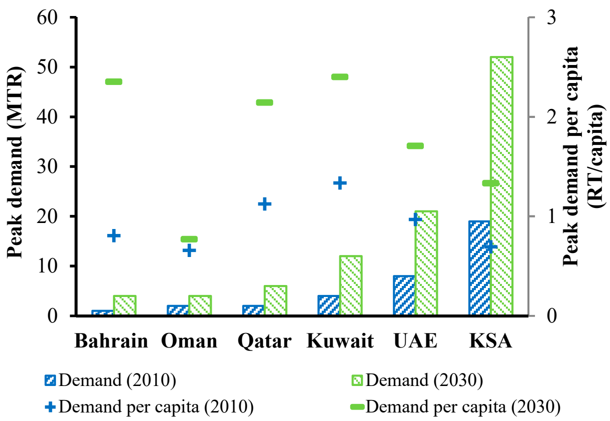

Figure 7. Peak cooling demand (2010–2030) of GCC countries, based on [4,5,128].

Both electricity generation for space cooling (currently essentially thermal, with increasing shares of solar PV and CSP generation in the future [127]), and the operation of cooling towers in air-conditioning systems require water [129,130]. Water requirements for power generation vary widely depending on technology and climate, and increase in arid and semi-arid (i.e., desert) conditions such as in the GCC [129]. Solar electricity installations require regular surface cleaning in dusty (e.g., sandy) environments [129]. Air-conditioning cooling towers require makeup water to compensate for water losses through evaporation or blow-down effect (to maintain water quality, within specified limits) [131]. Due to a lack of rainfall and groundwater, the available renewable water volume in the GCC ranges from 5 to 312 m^3/capita (in Kuwait and Oman, respectively), with an average at approximately 77 m^3/capita, which is far below the global water scarcity limit (i.e., 1000 m^3/capita) [129]. Conversely GCC regional average water consumption (i.e., 760 m^3/capita [123]) significantly exceeds the corresponding worldwide average (i.e., 506 m^3/capita [126]). The resulting water stress indexes in the region range from 106.2% in Oman to 2610% in Kuwait, compared with a European average of 8% (with values of less 70% in any European country) and world average of 13% [126]. (SDG 6.4.2 water stress, defined as 100* (total freshwater consumption)/(total renewable water resources-environmental flow requirements) [126]. Kuwait, Saudi Arabia, and the UAE have three of the top four highest water stress levels in the world [132].) Water scarcity in the GCC is accompanied by a degradation in water quality and extensive reliance on seawater desalination [129,133]. The GCC desalination sector accounts for approximately 40% of the global desalination capacity, with approximately two thirds of the GCC's capacity met by thermal desalination (essentially MSF), which is energy-intensive [123]. In addition, 66% of surface water in Arab countries is from outside the region, which has been and remains a potential target and source of political instabilities [129]. Finally, space requirements for the installation of cooling towers make it increasingly difficult for individual end-users in densely populated areas to install individual water-cooled chiller technologies [116].

Despite the abundance and affordability of fossil fuels in the GCC, the above context and need to grow regional fossil-fuel exports rather than consume fuel production domestically, will require local energy/water conservation and efficiency improvement efforts, and increased penetration of low-carbon energy resources. The deployment of more sustainable air-conditioning is a key opportunity in the GCC to improve the efficiency of energy use and address climate change.

4.2. Existing and Developing District Cooling Market

Interest in DC in the GCC began in the late 1990s, prompted by its higher efficiency and lower environmental impact than conventional on-site cooling systems. The first commercially successful DC system in the region was introduced in 1999 at Zayed Military City in Abu Dhabi [134]. This plant was a significant technical success which led to further progress in the design and implementation of DC systems in the GCC. DC systems in the GCC range from small-scale (i.e., capacity < 10,000 RT) to large-scale (i.e., capacity > 10,000 RT) and are operated by several private and government-owned DC companies. In 2010, the largest DC system in the world was built at The Pearl Island in Qatar, with a capacity of 130,000 Ton of Refrigeration (RT) [134]. Other large-scale DC systems deployed or under construction in the GCC are listed in Table A5.

As of 2014, the GCC DC market (4.1 MRT or 44.3 GW_{th}, with 10,000 km distribution network) represented 32% of the worldwide installed DC capacity (i.e., 12.6 MRT), with a market size of approximately 5.5 billion USD [17,135]. 65% of the current GCC DC capacity is installed in the UAE, followed by 22% in KSA and 7% in Qatar [17]. DC end-users in the GCC are mostly residential (56.2%), followed by commercial (39.1%) and industrial (3%) users [17].

Figure 8 contrasts the breakdown of installed GCC DC capacity by country in 2014, with its forecasted potential by 2019 and 2030. Despite progress in DC implementation in the region, the current penetration of DC in the GCC cooling market remains limited to approximately 5% (i.e., 4.1 MRT) of total space cooling capacity, with the largest share in the UAE (i.e., 11%) [5]), highlighting significant potential for further growth. In addition, the currently installed GCC DC capacity is estimated to be used at only 50% of its capacity [135]. 60% of the DC capacity is powered by DC utilities, and the rest by government- and large single-owned utility companies [135]. The GCC DC market is forecasted to rise at an average 16% cumulative annual growth rate through 2014–2019 [17]. These forecasts are based on large-scale development projects in real estate and the commercial sectors, population growth, and increased awareness of and governmental focus on energy saving measures. KSA is estimated to be the fastest growing user of DC systems in the GCC, with a projected growth rate of 34% between 2014 and 2019, followed by Qatar at 18% growth rate over the same period [17]. DC growth in Qatar is mainly associated with increased construction activity driven by the 2022 FIFA World Cup, and government initiatives for the promotion of DC systems. In Bahrain and Oman, real estate developments are the key drivers for the growth of DC capacity, whereas in Kuwait, infrastructure and industrial development are the main drivers. From cooling market shares of <1% and 11% in KSA and the UAE in 2014, by 2030, the share potential of DC in these countries is estimated at 26% and 50% of national cooling capacity in KSA and the UAE, respectively (Figure 8).

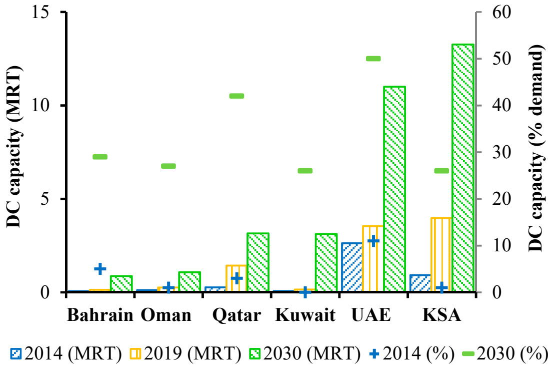

Figure 8. Installed (2014) and projected (2019, 2030) DC capacity potential in GCC countries, based on [5,17]. Percentage DC capacity is relative to total cooling requirement.

Average energy savings of 0.78 kWh (46%) per ton-hour of cooling are reported by a leading DC provider for 43 monitored actual water-cooled DC systems implemented in the GCC [116] relative to real-world data for monitored air-cooled building chillers. Based on data for approximately 72 existing regional DC plants (63 of which are located in the UAE) operated by the same provider (i.e., TABREED [136]) and its associate companies and joint ventures, and delivering approximately 1.1 MRT of combined cooling annually, these plants are estimated to reduce the electricity consumption of the region by approximately 1.53 TWh annually, with an accompanying 768,000 tons of avoided CO_2 emissions annually.

4.3. Future Opportunities and Directions

The forecasted energy, economic and environmental benefits anticipated through the expansion of DC capacity and space cooling share in the GCC, assuming continued use of existing DC technologies, are summarized in Section 4.3.1. Further technical and policy-related opportunities that remain to be tackled and potential solutions to fully exploit DC to reduce the energy, economic and environmental impact of space cooling in the region, are identified in Sections 4.3.2 and 4.3.3, respectively.

4.3.1. Forecasted Energy, Economic and Environmental Benefits

Based on the existing and forecasted 2012–2019 GCC DC capacity (i.e., 3.2–8.7 kTR [14,17]), and annual average specific energy consumptions for monitored DC systems and on-site air-cooled chillers in the UAE (i.e., 0.92 and 1.7 kWh/ton-hour, respectively [10,116]) and other sources, GCC regional space cooling electricity savings of approximately 46% could be achieved annually between 2012 and 2019 using DC instead of conventional on-site air-cooled chillers. The corresponding annual CO_2 equivalent emissions avoided, based on 2008 annual average specific GHGs (i.e., CO_2, CH_4 and N_2O) electricity emission factors in the GCC [137], assuming a reliability of 99.96% for the DC system [17], would be in the range of 19.2–51.3 Mt per annum between 2012 and 2019. These energy and emissions savings would even be more substantial considering that the installed capacity of existing DC systems is typically 15% lower than that of conventional on-site cooling systems. Energy and emissions savings estimated by comparison of DC with window/split air-conditioning units, which have annual average specific energy consumptions of approximately 2.0 kWh/ton-hour [116], rather than air-cooled chillers, would also be more significant.

By 2030, it has been estimated that the regular use of DC in the GCC region could result in 20 GW reduction of in new power capacity requirements, thereby saving USD 120 billion in power capital expenditure, and the equivalent of 200,000 oil barrels per day in fuel consumption [5]. The avoided CO_2 emissions in for example the UAE are estimated at 31 Mt/year [5].

The above energy, economic and environmental estimates are based on existing current DC system design and operational practices in the GCC. Potential technical and non-technical solutions to improve the sustainability of DC systems in the region are outlined in Sections 4.3.1 and 4.3.2, that could enable higher energy, economic and environmental benefits.

4.3.2. Technical Opportunities

Due to a history of abundant and low-cost fossil fuels, compounded by the lack of natural cooling potential in the region, current GCC energy systems, including DC systems, rely almost solely on fossil primary energy supplies. DC systems in the GCC typically use fossil electricity-powered, water-cooled fixed-speed compression chillers [138], that are more efficient than their air-cooled counterparts [10]. Forced-draft cooling towers are employed to reject heat from chiller condensers [5,131,138]. Elevated ambient temperatures in the region have an adverse impact on both chiller and cooling tower efficiencies. Cooling tower efficiency also degrades at elevated inlet air humidity, depending on geographical location and daily/seasonal period [138]. DC capacity sizing and distribution planning, operational strategies, and performance evaluation methodologies (e.g., without life-cycle considerations) also require improvements [138]. Technical opportunities and potential solutions to improve DC system sustainability in the region are identified below in terms of DC energy sources, cooling/storage technologies, operation, and performance evaluation.

A diversification of the energy mix (e.g., including renewable and nuclear energy) and energy efficiency improvements, including through the replacement of conventional cooling with DC, and use of renewable and waste energy sources, is feasible and already under way in the region to reduce fossil-fuel consumption and its environmental impact, with the additional benefit of more diversified economies. Such a shift is expected to increase the availability of crude oil for export for KSA and Kuwait, and reduce the dependence on costly natural gas imports for Bahrain, Kuwait, and the UAE. Considering electricity generation, renewable shares of up to approximately 15%, 20–25%, 25% and 30% are envisaged in Kuwait, the UAE, Saudi Arabia, and Qatar by year 2030, with emphasis on solar power [127]. In addition, Saudi Arabia aims at 30% renewable electricity by 2040, while the UAE targets 44% and 75% renewable and clean electricity generation (including nuclear and clean coal power), respectively, by 2050 [127]. Progress in more sustainable electricity generation will be complemented by solar thermal energy use, less energy-intensive water desalination/treatment and conservation, and developments in other sectors [124]. Therefore, there is scope to prepare for a shift from fossil-dominated space cooling to more sustainable cooling in the region. However, the appropriate mix of solar electrical and thermal power conversion technologies (in particular PV and CSP) should be carefully planned in the region to provide both electricity and cold in future GCC energy systems.

Potential pathways of sustainable DC production to assist in meeting the significant year-round cooling demands of the GCC region using locally available energy sources include indirect cooling via low-carbon electricity-driven and low-carbon heat-driven chiller technologies, direct cooling using waste cold energy recovered from LNG regasification terminals, as well as optimized use of thermal storage systems [138].

Based on future energy plans in the regions, low-carbon electricity for vapor compression chilling could be provided by solar PV/CSP, and to some extent by wind installations, the economic potential of which is less evident than that of solar energy in the region, as well as waste-to-energy, and nuclear power in the UAE's case [127]. As daily periods of high cooling demand coincide with sunshine hours, electrically driven space cooling could also contribute to reduce future excess electricity levels at growing solar/wind power shares in future GCC energy systems [127] and its adverse effects on grid stability and the efficiency of resource use. In parallel, heat-driven chillers could reduce electricity demand in non-sunshine (i.e., night time) periods. The efficiencies of solar PV and CSP technologies will however be affected by high ambient air temperature and humidity, respectively, in afternoon/evening peak cooling demand periods [127]. The cooling demand-provision match could be improved using short-term weather forecast in conjunction with historical energy demand data, as well as smart energy monitoring and storage management [138].

Sustainable energy sources for heat-driven cooling include waste heat from regional energy-intensive industrial facilities (e.g., aluminum, cement, and hydrocarbon production facilities), and thermal energy from solar and biomass waste plants. In addition to single/double-effect absorption chillers, triple-effect chillers, subject to increased commercial availability at large capacity, could be considered to exploit higher-temperature CSP/industrial heat with improved efficiency, as well as reversible heat pumps/chillers, as recently envisaged in [138]. In parallel, the deployment of tri-generation, waste heat recovery technologies and a thermal grid and heat trading system have also been recognized as potential solutions to reduce the energy consumption of GCC DC systems [138]. Gas engine CHP systems could provide both electricity to vapor compression chillers and heat to absorption chillers for both space and non-space cooling applications, as well as heat to other applications (e.g., hot water generation). Flows of hot/cold thermal energy (including waste heat/cold) from a variety of sources between the DC and other systems would be enabled by an intelligent thermal network, with reduced energy distribution losses.

The extension of DC end-uses to non-space cooling applications, including augmentation of power generation, recycling of DC chiller heat rejection for either hot water production or water treatment/desalination, are also envisageable.

Improving the efficiency of electricity/heat-driven DC central chiller and cooling towers in the regions' harsh climatic conditions requires customized technical solutions. For example, in moderate climates, the heat source and chilled water inlet temperatures of single-effect H_2O/LiBr absorption chillers may typically be set at 100 °C and 10 °C, respectively [139]. However, the COP of a basic H_2O/LiBr absorption chiller reduces from 0.75 to 0.65 when the heat-rejection medium temperature of the absorber and condenser, connected in parallel, increases from 15 °C to 35 °C, while its cooling capacity drops by 55% [139]. Potential concepts that could be investigated to improve chiller efficiency would involve reducing the heat-rejection temperature of the DC chiller plant, and could include:

- Incorporation of innovative thermodynamic cycles with operational flexibility (e.g., hybrid absorption-compression cycles and combined power-refrigeration absorption cycles) to improve chiller thermodynamic performance by extending the operating conditions of its absorber and/or condenser (e.g., operating the absorber at a relatively higher pressure for the same heat rejection, chilled water, and heat source temperatures). Such cycles could provide flexibility to cope with both seasonal and daily fluctuations in ambient conditions and thus cooling loads.
- Exploitation of artificial cold sources, such as LNG from regasification terminals, as a heat sink for the condenser (and/or absorber) of the chiller plant, to reduce its heat-rejection temperature. Among the GCC countries that face domestic gas shortages (i.e., Bahrain, Kuwait, UAE), the UAE was the first to build an LNG receiving terminal in Dubai. Kuwait and the UAE (in Abu Dhabi and Dubai) currently have 5.8 and 9.8 MTPA regasification capacities, respectively [80]. Kuwait and Bahrain will have additional 11.3 and 6 MTPA regasification capacities by 2021 and 2019, respectively [80]. Even if partly exploited, the above regasification capacities could enhance the thermodynamic, economic, and environmental performance of DC and other direct cooling applications, and power generation in the region, subject to adequate cold transportation. CO_2 has been proposed as a potential cold transportation medium, which could offer additional opportunities of CO_2 sinking and valorization, which in the GCC, have essentially been limited to CO_2 injection into hydrocarbon reservoirs for enhanced recovery to date.

Customized solutions to improve cooling tower efficiency could involve development and integration of innovative dehumidification technologies to reduce the moisture content of cooling tower inlet air, as suggested in [138]. Approaches to improve the sustainability of water provision/use for DC should also be pursued. The water required by cooling towers is either scarce or difficult to access in the region and requires treatment before being used. Although seawater can be employed in cooling towers, it requires more costly corrosion- and fouling-resistant equipment, with higher maintenance costs. Similarly, alternative low-quality water, such as treated sewage effluent (TSE), brackish groundwater and partially desalinated water [131], could be used but also with increased capital and maintenance costs. TSE is used as makeup water in for example the cooling tower of Sheikh Zayed Road DC plant in Dubai [131]. Challenges are encountered with the use of TSE in DC systems, including fluctuating availability (i.e., quantity, quality, pressure) which may not match demand, and management of discharge products. Alternatively, seawater, TSE [138] or other water sources could be employed directly as heat-rejection medium–cool chiller condensers, rather than as working fluids for a cooling tower. This approach has been employed in a DC system in Bahrain [140].

In parallel, cold distribution losses from the DC piping network and pumping stations, which are significant in hot-climate regions, should also be addressed. As the chilled water temperature supplied to end-users increases, cooling capacity reduces. To compensate for increased water supply temperature, larger chilled water volumes need to be supplied to meet the demand, that require additional pumping energy. Alternatively, additional cooling energy needs to be supplied to maintain the desired system temperatures, resulting in increased primary energy consumption. Therefore, the distribution network pipe materials and their geometry, and their installation environment, along with external factors that affect cold distribution losses, should be carefully designed/planned. The need for novel pipe designs with special insulation materials to reduce cold distribution losses, and their life-cycle assessment in GCC DC plants, has been recently suggested [138].

The need for improved engineering models, operational strategies, and life-cycle assessments to reduce the energy consumption, capital/operational cost, and environmental impact of DC systems in the GCC has also been raised [138]. Suggested development areas towards more efficient DC design and operation include (i) identification and prioritization of energy saving opportunities; (ii) improved modeling of electric centrifugal compressors, accounting for equipment environment- and operating condition-dependent performance; (iii) improved control strategies, including variable-speed rather than fixed-speed operation for electric centrifugal compressors, thermal energy storage and water conservation/recycling. Predictive chiller/storage control and management strategies with the use of short-term weather forecast, historical and real-time energy consumption monitoring should optimize cooling production, storage, and consumption. Ultimately, holistic life-cycle DC performance and impact assessment approaches will be required to evaluate the sustainability of DC systems more meaningfully.

Finally, urban outdoor ambient air temperatures and pollutant concentration, and DC cooling energy consumption can be reduced through thermal design of urban areas (e.g., building construction/design, landscaping, vegetation, surface albedo), which can be optimized using dedicated simulation methodologies, such as through coupled building-atmospheric flow, heat, and mass transport models.

4.3.3. Policy-Related Opportunities

The importance of regulations in enabling technically, economically, and environmentally efficient district heating/cooling systems was outlined in [12,18]. Despite initiating an energy transition, GCC economies still have indulgent energy and environmental regulations that do not effectively support the introduction of energy/water conservation measures, clean energy sources, efficient energy conversion technologies, and GHG emissions reduction actions [141]. It is widely recognized that GCC governments need to bring energy and environmental policy reforms and regulations [124,141]. Regarding air-conditioning, its supply is not considered by most GCC governments as a utility service that requires public policy and planning, which has resulted in an unregulated environment in the deployment and operation of DC systems, which are sub-optimal from energy use, environmental and economic perspectives. Based on critical observations relating to the implementation of DC in the GCC and international DC guidelines [5,10,138], five key policy-related areas that need to be tackled are identified below in terms of challenges and potential solutions, namely reforming of utility tariffs, support of DC front-load investments, integration of planning/decision-making between building, DC and urban development stakeholders, improvement of DC cost recovery practices, and establishment of local DC service standards and technical codes.

Low, subsidized electricity and water tariffs in GCC countries, rather than tariffs based on real costs, mask the true economic advantages of DC systems over conventional on-site cooling systems. This is compounded by flat tariffs rates (i.e., with no or limited peak hour tariffs), that reduce the economic gains that could be realized with CTS systems, and the application of different tariff rates between regions of the same country (e.g., UAE emirates). Electricity and water tariffs require conservation-driven reforms across the region to stimulate sustainability improvements in space cooling provision and use.

Rapid large-scale urbanization developments and their subsequent deceleration in the GCC have revealed the risks associated with real estate investments. DC systems, particularly their cold distribution network infrastructure, require substantial early front-load investment. Although chiller plants are more suited to modular investment than distribution infrastructure, they still involve some degree of front-load investment. These front-load investments have been exaggeratedly high due to overestimation of cooling load intensities at the design stage, and under-realization of DC development goals due to excess capacity. Government backing for front-loaded distribution network infrastructure investments can mitigate DC system investment risks and improve DC competitiveness relative to conventional space cooling.

Building development and associated engineering decisions are made independently. Hence, different decision makers and timelines are involved as well as different design practices. Therefore, developers mostly follow non-aggregated development decisions, that form an easier, quicker, and cheaper process, rather than aligning plans with other developers. Instead, the implementation of DC systems requires integrated planning and design practices to achieve optimal energy use. Governments can assist in such planning including the designation of appropriate zones for DC deployment as part of future urban development.

The cost recovery models typically employed by DC providers are complex, diverse, and inappropriate, resulting in discrepancies in the distribution of costs (i.e., connection, capacity, use) among involved stakeholders (i.e., DC developers, owners, tenants) from project to project and buildings to building. In general, developers include the capital and fixed operating costs of conventional on-site air-conditioning systems in the purchase price or building rent. By contrast, DC providers typically require a fixed charge to recover capital costs. In addition, the operating costs of conventional on-site air-conditioning systems are also often hidden. For instance, in buildings with central chilled water supply, there is generally no metering for in-building cooling systems—instead, the usage costs are recovered indirectly via tenant rent or management fees. Greater consistency should be adopted in the allocation of DC costs between projects and between buildings [5].

As with other utilities (e.g., electricity), DC could be better benefited from using a proper regulatory framework to protect all involved stakeholders (e.g., developers, providers, and end-users). Guidelines should be set to define areas for DC implementation where cooling load density is appropriate. Guidelines should also include integration of DC planning with urban and infrastructure planning, including power and water. Governments can support the DC market by establishing appropriate national tariff frameworks for DC. They should also define the minimum level of requirements for DC providers for reliability and performance. Such requirements should be accompanied by technical codes to ensure quality in design, installation, and operation of DC systems.

In summary, the GCC DC market requires regulation to address the above issues, to better benefit from the economic advantages of DC systems, ensure end-user protection regarding pricing and service quality, and increase energy and water use efficiency [5]. GCC governments can play a key role in developing and enforcing such regulations. Even if the form of government intervention varies from country to country, it should be focused on the above five areas. Finally, as for any energy/water system in the GCC, the development of sustainable DC systems will be highly dependent on the future availability and affordability of local fossil and renewable resources, economic market forces, energy-environmental policies/legislation, social acceptance, and education.

5. Research Trends and Future Outlook

Sustainable DC technologies, operational aspects, and analysis, modeling, and optimization methodologies, were reviewed based on published DC design and analysis studies in Sections 2 and 3, focusing on the needs of cooling-dominated regions. The status and challenges of DC implementation in the GCC region were examined in Section 4, with potential solutions and opportunities identified. In this section, key collective research trends are compiled from the works reviewed, leading to suggested future research directions that could facilitate the performance improvement, and wider deployment of sustainable DC in cooling-dominated regions. DC trends and future opportunities are categorized in this section under the following thematic areas:

- Geographical deployment location
- Sustainable energy sources and cross-sectorial DC integrations
- Sustainable cooling and storage technologies
- Thermodynamic, environmental, and economic analysis and optimization methodologies

- Energy, environmental and economic benefits findings.

5.1. Geographical Deployment Location

In terms of DC geographical deployment location, the largest single group of DC studies in cooling-dominated regions has focused on South Asian regions, followed by another group of studies for the Persian Gulf. Most of DC systems analyzed in South Asia were based in Hong Kong. These works are complemented by studies in non-cooling-dominated regions, essentially in Europe including in Scandinavia. Despite the size of the existing DC market in the USA, published research focusing on DC appears to be limited. There has been little if no published DC research activity to date in the MENA other than in the Persian Gulf. These observations suggest that there is significant scope for extending sustainable DC research and deployment to other cooling-dominated regions, including in the Americas, Australia, Malaysia, and MENA.

Despite progress in DC deployment in the GCC, only a limited fraction of regional cooling loads is yet fulfilled by this technology. Based on this and considering the regions' extreme climatic conditions, natural cooling water scarcity, dense and expanding urbanization, renewable resource potential, and availability of industrial waste heat and waste cold, the GCC therefore represents a major opportunity for further DC research and implementation. The energy demand and cost of space cooling in the region is currently compounded by elevated energy intensity- and emissions per capita, domestic natural gas shortages, volatile revenues from hydrocarbon production, and indulgent energy and environmental regulations. GCC-specific technical and non-technical solutions identified to improve the sustainability of DC cooling while addressing harsh climatic conditions and renewable water scarcity were discussed in Sections 4.3.2 and 4.3.3. If effectively implemented, DC could play a key role in advancing sustainable space cooling in the GCC residential, commercial, and industrial sectors, and contribute to decarbonizing this historically fossil-fuel-reliant region. Such progress could serve as model to DC development in other cooling-dominated regions.

5.2. Sustainable Energy Sources and Cross-Sectorial DC Integrations

Renewable energy sources pursued in DC research studies to date have essentially consisted of solar thermal power (as reported in Saudi Arabia, Spain, and the UAE) to drive thermally activated cooling, solar electricity (as reported in Iran, Singapore, and USA) to drive compression chillers, and biomass electricity/heat (i.e., waste/biofuels, as reported in Singapore, Sweden, and Thailand). In comparison with district heating studies, the use of CHP technology for DC in cooling-dominated regions has been less common, partly due to a lack of heating demand in the residential sector. Most investigations have focused on a single renewable energy conversion technology, with few studies comparing the performance of alternatives, such as different CSP options. Mixes of renewable energy conversion technologies, and 100% renewable energy-driven DCs (such as in a Saudi Arabian investigation) were rarely envisaged. Non-solar low-carbon energy sources, such as wind, hydroelectricity, geothermal, marine, and nuclear power, have rarely or not been reported in DC systems for cooling-dominated climates to date, suggesting further opportunities to integrate renewables in DC applications. Low- to ultra-low-grade renewable heat such as produced by solar collectors, or extracted from geothermal or sea water, as well as ultra-low-grade waste heat sources, have received little attention. Their potential upgrade and exploitation to drive sorption chillers could be investigated in future work. Although integrating DC with intermittent renewable utilities (e.g., solar, wind) could provide means of absorbing excess electricity in future energy systems, this aspect has been rarely discussed, unlike for district heating. This may be related to less progress being achieved in the integration of high shares of fluctuating renewables in energy systems in cooling-dominated regions, compared with for example European regions.

Low–medium-grade heat use from fossil-fired utility production installations (i.e., gas-fired combined cycles, gas engines, coal-fired plants, coal/oil-fired CHP plants, hybrid solid oxide fuel cell-gas turbine plants) to drive thermally activated cooling was considered in both hydrocarbon producing regions (Iran, Kuwait, USA) and others (Hong Kong, Singapore, Sweden, Turkey).

The use of free cold sources (i.e., river water in China/Sweden, lake water in Sweden) and artificial cold sources (i.e., LNG in Singapore) has been limited in DC studies to date, reflecting a lack of natural cold sinks in hot climates, and lack of cryogenic cold energy recovery implementation. LNG cold energy was only considered in two instances for direct district cooling including in parallel with power augmentation, while its use for enhancing the efficiency of thermodynamic cooling cycles has not been reported in previous DC studies. Therefore, given the projected growth of the LNG market, the exploitation of cryogenic cold for either direct cooling provision or enhancing the efficiency of thermodynamic power/cooling cycles serving DC applications deserves greater attention, in conjunction with cold transportation. Potential cold transportation media require further investigation, such as CO_2, which could offer opportunities of CO_2 sinking/valorization.

In terms of cross-sectorial DC integrations, which can enable material/energy recycling, hence efficient capital use, energy conservation and flexibility, the following synergies between DC systems and energy-intensive industrial heating and power production processes, have been considered. DC systems analyzed in Sweden, USA, Turkey, and Iran were integrated with district heating and CHP units, understandably because of climatic conditions. In such regions, excess waste heat generated from thermal power, co-generation/CHP, or biomass-fired power plants during the hot season, was exploited for cooling production at district level in the hot season. In cooling-dominated regions, cross-sectorial integrations have essentially been limited to centralized or distributed fossil/renewable-fueled power generators, and in one instance, an LNG regasification terminal. Few studies have analyzed DC systems as part of broad or complete energy systems, which may have limited the consideration of cross-sectorial integration options in the literature. Examples of potential DC cross-sectional integrations of interest to cooling-dominated regions and that have not yet been considered include conventional thermal power augmentation, fresh water production and synthetic gas production from fluctuating excess electricity/heat in future renewable-based energy systems. Thus, hot-climate regions generally experience significant losses in gas turbine power generation capacity and efficiency, and suffer from a scarcity of natural water sources, resulting in an extensive reliance on seawater desalination. Two possible concepts of DC cross-sectorial integration or extension of DC to non-space cooling end-uses in such regions would be the supply of (i) compressor inlet air cooling by the DC system to maintain power generation performance in yearly elevated high ambient temperature conditions, as well as (ii) recycling DC chiller plant waste heat to reduce the energy consumption of thermal desalination technologies, which currently dominate the desalination market in for example the GCC, as well as waste water treatment. In future renewable-based energy systems with excess electricity, the recovery of power-to-gas parasitic heat losses from either electrolysis or catalytic methanation, which has already been proposed in the power-to-gas literature for district heating, could also potentially serve to drive thermally activated DC cooling.

To conclude, based on published DC analyses to date, there is scope for the more systematic identification and exploitation of a broader mix of sustainable electricity/heat sources and natural/artificial cold sources available locally, to drive DC systems based on an optimized combination of electrical and thermally activated chillers. In hot-climate, densely populated regions that are also geo-politically sensitive, the exploitation of local energy/material sources rather than imported ones to drive DC systems would play a strategic role towards energy self-sufficiency. The integration of DC systems in future 100% renewable energy scenarios, and their role in absorbing excess fluctuating electricity/heat to facilitate renewable penetration, hence contribute to energy security and climate change mitigation, are also suggested areas of further research.

5.3. Sustainable Cooling and Storage Technologies

Based on published DC research studies to date, DC design/operation sustainability improvement approaches in cooling-dominated regions have involved one or more of the following approaches: (i) replacement of fossil electricity-driven compression cooling with either renewable electricity-driven compression cooling, and/or with waste/renewable-heat-driven absorption cooling, in conjunction with capacity optimization; (ii) introduction of cold thermal energy storage; (iii) artificial cold energy recovery; (iv) reducing DC distribution energy consumption (i.e., pumping power, thermal energy losses); (v) improved chiller/storage control strategies; and (vi) improved modeling/optimization approaches. However, when considered individually, DC studies have generally exploited a restricted range of technology alternatives in a given application environment.

The focus on renewably powered electrical compression cooling and low-carbon heat-driven absorption cooling is mainly attributable to technology maturity, availability at MW-scale equipment capacity, and affordability. Thus, at present, commercially available thermally activated cooling technologies with sufficient capacity and reliability for DC applications are essentially limited to single/double-effect water-lithium bromide-absorption refrigeration.

In the future, triple-effect absorption chillers, subject to commercial availability at sufficient capacity, may potentially be integrated in DC chiller plants to exploit sustainable heat sources with higher temperatures, such as from high concentration solar power plants or industry, with improved COPs compared with lower-effect chillers, albeit at higher equipment cost. Based on an existing DC plant incorporating an ejector chiller, with further technology developments, ejector-assisted refrigeration could also potentially become an option in parallel with other chiller technologies, with benefits including ejector construction simplicity, amenability to low-grade renewable/waste heat conversion, low energy consumption, and low maintenance requirements, providing that sufficient performance and operational flexibility can be achieved through ejector cycle enhancements (e.g., layout, controls, storage). Other identified sustainable air-conditioning technologies having promising technical features for cooling-dominated regions include GAX-based absorption, compression-assisted absorption, and desiccant-based cooling. However, these concepts are presently not available in commercial systems with sufficient capacity and require further developments. In addition, the need for innovative dehumidification technologies for DC cooling tower inlet air has been suggested to improve tower efficiency in high ambient humidity conditions. Potential future research topics also include hybrid refrigeration cycle concepts.

Technical concepts that could be investigated to enhance heat rejection from DC central chiller plants in high ambient temperature conditions include the use of cold energy as heat-rejection medium if available (e.g., LNG from regasification terminals), in conjunction with suitable cold energy transportation options, as well as incorporation of innovative thermodynamic concepts in the design of the central chiller plant, as mentioned above.

Regarding cold thermal energy storage, chilled water thermal storage is compatible with the evaporation temperature range of conventional chillers, while ice storage can offer compactness in dense districts. Local ambient conditions, combined with consumer and renewable generation profiles, result in unique electrical/thermal load and energy supply profiles. The potential of cold thermal energy storage to reduce cooling energy consumption is known to be more significant where large daily ambient temperature variations exist between day and night, such as in arid regions. However, based on the present review, the incorporation of thermal energy storage technologies in DC systems or the specific storage technology employed are however frequently not reported in DC design/analysis studies. When reported, chilled water and ice storage received similar levels of attention. Either hot water or molten salts were employed for concentrated solar thermal energy storage. However, the justification for selecting a given storage technology and consideration of alternative storage options is generally lacking, with limited efforts devoted to storage design and optimization. This suggests that greater attention could be given to the design and evaluation of thermal storage in DC research studies for cooling-dominated regions. In parallel, electricity demand profiles and tariffs, and local energy policies, may require adjustments or reforms in certain regions, as these are critical factors in the selection of a storage technology and in capitalizing its benefits.

5.4. Thermodynamic, Environmental and Economic Analysis and Optimization Methodologies

Cooling loads (i.e., peak loads—typically for system capacity sizing, and annual hourly cooling loads—for operational, control and economic analyses) are an essential if not the most essential input data to the design, simulation, and optimization of DC systems. Therefore, a high-priority research task should be the collection and analysis of measured cold deliveries in existing DC systems. Such data could not only directly guide potential DC design retrofits and/or operational improvements, but also provide supporting reference information for the development and validation of predictive district cooling load and performance models. Among published DC-level cooling load estimation procedures, a trade-off between analysis accuracy and computational expense/time may be achieved using the combined use of local building energy codes, local weather data, and dynamic building simulation applied to identified building categories in the district, to develop a database of space cooling loads per unit floor area for each building category in a given district. Such a procedure should however be combined with uncertainties in district cooling loads (as well as sub-systems reliability/availability risk), which have been rarely incorporated in DC systems design and analysis studies to date. Based on numerical investigations, uncertainties in cooling loads have been found to essentially arise from indoor conditions (i.e., mainly ventilation rate, but also occupant, lighting, and plug-in load densities), rather than outdoor weather or building design/construction. These uncertainties have been shown to likely significantly impact technology selection, capacity sizing and performance evaluation. Incorporating these uncertainties in DC system design could avoid under- or over-designs, and more accurately estimate performance, cost, and environmental impact, with quantified confidence levels. The evaluation of district cooling loads could be refined further using coupled building energy and microclimatic simulations to capture heat island effects on outdoor temperatures and district cooling energy consumption, and evaluate alternative urban designs for planned districts.

Most DC performance evaluations in cooling-dominated environments to date have been steady-state, energy analysis-based, and have focused on the operational phase. In addition to common performance criteria generically applicable to space cooling systems, the non-renewable PEF, EPI, CO_2 factor for supplied cooling to the end-user (in kg of CO_2/MWh of cooling), CO_2 payback time (CPT), and ATMI have been proposed as additional DC system sustainability-related metrics. However, the application of such criteria to DC systems has been limited to date. Similarly, holistic sustainability metrics have rarely been employed, with hardly any exergy, exergoeconomic and life-cycle analyses of DC systems reported. Collectively, analyses of combined district heating and cooling systems in heating-dominated regions appear to be more advanced from these perspectives.

In terms of DC system optimization, published works tend to focus on the optimization of the distribution pipeline network layout design and end-user's facilities (e.g., mix of buildings, cooling load patterns), rather than either the central chiller plant or complete DC system including demand and supply sides. This is related to the significant investment cost of the distribution network, as well as prohibitive optimization complexity and computational cost. Most optimizations have been single-objective, focusing on an economic criterion, typically the sum of annualized investment and operational costs. In terms of software tools, mixed integer linear programing and genetic algorithms have been the most commonly applied.

Based on these observations, there is scope to further extend the range of DC performance metrics and analysis approaches to (i) dynamic analyses incorporating dynamic system operation characteristics (e.g., capacity-, load-, and temperature-dependent COPs of cooling equipment), and dynamic utility prices, with sensitivity assessments to projected fuel prices (i.e., fossil, biomass, synthetic); (ii) design methods that incorporate uncertainties in cooling loads and sub-system reliability; (iii) design methods that account for the effects of outdoor microclimate on district outdoor temperature and cooling loads; (iv) more comprehensive environmental impact assessments, rather than solely operational CO_2 emissions-based; (v) concurrent demand- and supply-side optimizations, with linkage with other sectors; (vi) use of holistic sustainability metrics and their incorporation in multi-objective optimizations, including exergy, exergoeconomic, and reliability-based criteria, with account made of DC energy/material recycling (e.g., waste heat/cold sources, waste water, emissions), as well as quantitative and qualitative (non-quantifiable) life-cycle economic parameters. Regarding item (vi), additional sustainability criteria proposed for districts but not previously reported in DC studies, could include for example exergy-based COPs for DC chiller plants, primary exergy ratios, compound CO_2 emissions, composite rationality indicators [142] and emergy-based indicators [143] to contribute to the analysis of district metabolism, including in terms of energy, waste, and material (e.g., waste/fresh water, emissions) flows (i.e., including production, use and re-use/recycling), intensity and efficiency. Aspects (i)–(vi) could contribute to the better design and life-cycle management of DC systems as parts of smart energy hubs.

5.5. Energy, Environmental and Economic Benefits Findings

The energy savings contributed by implemented DC systems compared with on-sight cooling systems are in large part due to the higher efficiency of large-scale central water-cooled chiller plants compared with on-site small-capacity cooling systems. In addition, the use of a CTS system shifts electricity/thermal energy consumption from peak to off-peak periods, which can significantly contribute to more effective energy use. As a relevant example, average energy savings of 0.78 kWh (46%) per ton-hour of cooling have been reported by a leading DC provider for several conventional water-cooled DC systems implemented in the GCC relative to air-cooled building chillers. Such DC systems were based on fossil electricity vapor compression cooling and standard design/operational practices, rather than energy conversation-driven, state-of-the-art designs/operation.

The studies reviewed in this article highlight further energy savings that could be contributed by the use of sustainable energy sources and cooling, storage, and cold distribution technologies, in conjunction with appropriate control strategies. The energy benefits associated with a given type of sustainability enhancement are generally not isolated in published studies when several sustainability enhancement options (discussed in Sections 5.2 and 5.3) are applied in the same DC system. However overall, the replacement of fossil electricity-driven compression cooling with either renewable electricity-driven compression cooling, and/or with waste/renewable-heat-driven absorption cooling, which have been the most widely investigated options, have led to reported reductions in DC system energy consumption spanning a wide range (i.e., 10–70%), depending on DC system design/operating characteristics and modeling methodologies. As part of such enhancement options, DC system cross-sectional integration can enable the exploitation of low-cost, low-emission excess electrical/thermal energy generated in the power and industrial sectors, to drive DC. Benefits are also obtained for the excess energy provider, in terms of avoided electricity curtailment and/or thermal energy losses, which may be sold at low cost to the DC system operator to generate revenues.

The benefits of cold thermal storage are known to be more significant in regions with large daily ambient temperature variations between day and night, such as in for example the GCC climate. The benefits of thermal energy storage include shifting cooling operation from peak to off-peak demand periods, which can (a) reduce peak electricity demand; (b) reduce energy cost for both the cooling supplier and consumer; (c) enable the more efficient use of solar thermal energy through absorption of excess heat/electricity generated during sunshine hours, the use of which is shifted to non-sunshine demand periods; (d) reduce installed cooling capacity requirements; and (e) improve system reliability by using stored thermal energy as a backup. However, the energy, environmental and economic benefits of a given thermal energy storage technology strongly depend on electricity demand profiles and tariffs, and local energy policies. In conjunction with technical sustainability improvement efforts, DC-related energy policies require greater attention in cooling-dominated regions, with examples of thematic regulatory areas outlined in this article for the case of the GCC region.

Published DC system analysis studies indicate that annual CO_2 emissions in sustainable DC systems can be reduced in relative magnitudes comparable to those of energy consumption reductions (i.e., up to 80%), relative to conventional cooling systems. Heat-activated sorption cooling can also contribute to reduce not only fossil energy consumption, but also the use of conventional ozone-depleting and/or global warming refrigerants, as well as cooling equipment noise and vibration.

In terms of economic benefits, implemented DC systems have been shown to offer several cost reduction advantages over conventional on-site cooling systems including lower energy-, maintenance- and construction costs, with payback periods of a few to ten years. In addition, the expected life of DC systems is at least 25–30 years, compared with 10–15 years for conventional on-site air-conditioners. The findings from the reviewed DC literature are consistent with those from larger energy system studies (i.e., including but not limited to districts) [144], that increased investment costs associated with sustainable energy technologies are often offset by reduced operating costs (i.e., including fuel costs, maintenance/operating costs, peak energy demand charges). However, the estimated economic benefits are also sensitive to the economic assumptions and modeling/optimization methodology applied. In particular, future commodity price projections, constant versus variable cooling equipment performance parameters, (non)incorporation of the impacts of uncertainties (particularly in indoor conditions) or reliability (i.e., availability risk), and analyzing the DC system as part of a broader energy system rather than in isolation or with limited cross-sectorial interactions, can have significant impacts on the estimated economic benefits. Economic benefits are also obtained for excess energy providers, in terms of avoided electricity curtailment and/or thermal energy losses, which may be sold at low cost to the DC system operator to generate revenues.

6. Concluding Remarks

Due to economic and population growth driving energy demand in hot/humid climate regions, compounded by climate change and its effect on cooling loads, sustainable district cooling (DC) systems will gain increasing importance over the coming decades. Most previous publications related to district energy systems have focused on the needs of heating-dominated regions, thereby lacking specificity to cooling-dominated regions. In the present article, available and developing sustainable space cooling technologies driven by low-carbon energy sources and with present or potential future applicability to DC were reviewed, as well as DC analysis, modeling, and optimization methodologies. The challenges, status and future energy, environmental and economic potential of DC specifically in the GCC region were discussed, with opportunities for DC technology customization and market regulation highlighted.

Based on the present review, the potential of DC systems to contribute significantly to energy conservation, improvements in operational cooling capability, efficiency, flexibility, and reliability, as well as reductions in the environmental impact and cost of building air-conditioning has been well established. However, based on the collective research trends identified in this article, several research gaps remain to be addressed to enable the potential of this technology to be more effectively exploited in cooling-dominated regions. Key directions proposed include increased DC cross-sectorial integrations and synergies to enable exploitation of sustainable and low-cost energy/material flows (including recycled waste/excess flows), more systematic exploitation of locally available renewable electricity/heat supply options and natural/artificial cold sources for direct cooling, and application of more holistic thermodynamic, environmental and economic performance evaluation methods, under an appropriate regulatory framework.

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Appendix A

Table A1. Medium–large-capacity, commercially available absorption chillers from leading manufacturers and suitable for DC applications.

Manufacturer (Country)	Capacity (kW)	Working Fluid Pair	Technology
AGO (Germany) [145]	50–1000	NH_3/H_2O	SE (Indirect-fired)
Broad (China) [146]	105–5272	H_2O/LiBr	SE (Indirect-fired) DE (Direct/Indirect-fired)
Carrier (USA) [147]	387–3516 359–5803	H_2O/LiBr	SE (Indirect-fired) DE (Direct/Indirect-fired)
Hitachi (Japan) [148]	106–19,690	H_2O/LiBr	DE (Direct/Indirect-fired)
Kawasaki (Japan) [149]	281–1758 281–3517 563–1196	H_2O/LiBr	SE (Indirect-fired) DE (Direct/Indirect-fired) TE (Direct-fired)
LG (South Korea) [150]	98–3587 176–5275 258–3427	H_2O/LiBr	SE (Indirect-fired) DE (Direct/Indirect-fired) DE Double-lift (Indirect-fired)
Sakura (Japan) [151]	105–5274 176–5274 264–4571	H_2O/LiBr	SE (Indirect-fired) DE (Direct/Indirect-fired) SE Double-lift (Indirect-fired)
Shuangliang (China) [152]	2901–1630	H_2O/LiBr	SE, DE (Direct/Indirect-fired)
Thermax (India) [153]	175–35,001 35–140,001 350–3500	H_2O/LiBr	SE (Indirect-fired) SE, DE (Direct/Indirect-fired) TE (Indirect-fired)
Trane Company (USA) [154]	392–4725 350–5775	H_2O/LiBr	SE (Indirect-fired) DE (Direct/Indirect-fired)
Johnson Controls (USA) [155]	420–4850 700–2460	H_2O/LiBr	SE (Indirect-fired) DE (Direct/Indirect-fired)
Fischer Eco Solutions (Germany) [156]	15–5000	H_2O/LiBr Methanol/LiBr	SE (Indirect-fired)

Table A2. Characteristics of typical CTS systems suitable for building air-conditioning [10,86,87].

Characteristic	Chilled Water System	Ice Thermal Storage System	Eutectic Salt
Chiller fluid	Standard water	Low-temperature secondary fluid	Standard water
Latent heat of fusion (kJ/kg)	N/A	334	80–250
Specific heat (kJ/kg·K)	4.19	2.04	N/R
Tank volume (m^3/kWh)	0.089–0.169	0.019–0.023	0.048
Charging temperature (°C)	4–6	(−6)–(−3)	4–6
Discharge temperature (°C)	1–4 (above charging temperature)	1–3	9–10
Chiller charging (kW/ton)	0.6–0.7	0.85–1.4	0.6–0.7 (PCM)
Chiller charging efficiency (COP)	5.0–5.9	2.9–4.1	5.0–5.9
Footprint (plant area/ton-h)	Fair	Good	Good
Modularity	Poor	Excellent	Good
Ease of retrofit	Excellent	Fair	Good
Simplicity and reliability	Excellent	Fair	Good
Economy-of-scale	Excellent	Poor	Good
Dual-use as fire protection	Excellent	Poor	Poor

Note: N/A = not applicable; N/R = not reported.

Table A3. Non-renewable PEF and CO_2 emission factors for fuels/energy carriers [113].

Fuel/Energy Carrier	Non-Renewable PEF, $f_{F(i)}$ (-)	CO_2 Emission Factor, $K_{F(i)}$ (kg CO_2/MWh_{fuel})
Lignite	1.02	369
Hard coal	1.19	369
Heavy fuel oil	1.35	296
Light fuel oil	1.35	283
Natural gas	1.36	222
Peat	1.02	417
Bioenergy (primary)	0.1	7
Bioenergy (refined)	0.2	12
Bioenergy (secondary)	0.06	3
Residual fuel	0.05	88
Waste as fuel	0	94
Electricity (input and output)	2.6	420
Industrial waste heat	0	0
Geothermal heat	0	0
Solar heat	0	0

Table A4. GWP and ODP values of commonly used refrigerants in conventional air-conditioning and DC systems.

Refrigerant	Application	GWP [1]	ODP [2] (-)
HCFC-123	DC system/Conventional	77	0.06
HCFC-22	Conventional	1810	0.055
HFC-134a	DC system/Conventional	1430	0
HFC-245fa	Conventional	1030	0
Propane (R-290)	Conventional	3	0
HFO-1234yf	Conventional	4	0
Ammonia (R-717)	DC system/Conventional	0	0

[1] GWP (100 year), GWP for CO_2 = 1 [157]. [2] ODP, CFC-11 = 1 [158].

Table A5. Large-scale (i.e., capacity > 10,000 RT) DC projects in operation or under development in the GCC [17,136,159–162].

Project Name (Country)	Company	Capacity (TR)	Chiller Technology	Starting Year	End-Users
West Bay (Qatar)	Qatar Cool	Plant 1: 25,000 and 25,000 RT-hour CTS Tank	10 Mechanical chillers	2006	Residential and commercial buildings
		Plant 2: 32,000 and 20,000 RT-hour CTS Tank	12 Mechanical chillers	2009	
		Plant 3: 35,000 and 25,000 RT-hour CTS Tank	14 Mechanical chillers	2016 (third quarter)	
The Pearl Qatar (Qatar)	Qatar Cool	130,000	52 Mechanical chillers	2010	Residential accommodations and mixed-use developments
Barwa City (Qatar)	Marafeq Qatar	37,000	Multiple mechanical chiller plants	2014	6000 apartments, schools, nurseries, shopping centers, a bank, health club, mosques, and restaurants
Lusail City (Qatar)	Marafeq Qatar	Up to 500,000	Multiple mechanical chiller plants	Under construction	Residential and commercial buildings, schools, mosques, medical facilities, sport, entertainment, and shopping centers.
Dubai Motor City (UAE)	Emicool	80,000 and 77,600 RT-hour CTS Tank	Two mechanical chiller plants (each 40,000 RT)	2010	Residential buildings, business towers, motor-sports complexes, retail, and theme park
				2012	
Dubai Investment Park (UAE)	Emicool	Plant 3: 60,000 and 15,000 RT-hour CTS Tank	Centrifugal water-cooled chillers	2012	Residential buildings, commercial towers, motor-sports facilities, shops, and theme park
		Plant 4: 20,000 and 5000 RT-hour CTS Tank		2007	
		Plant 6: 30,000 and 30,000 RT-hour CTS Tank		2010	
Dubai Metro (UAE)	Tabreed	Total: 36,400 Al Rigga (10,000); Al Barsha (7500); Jumeirah Island (7000); Jebel Ali Industrial (4400); Al Rashidiya (7500)	Multiple mechanical chiller plants	2010	Dubai metro stations (47 stations)
Business Bay Executive Towers Dubai (UAE)	Empower	35,200	16 Centrifugal chillers (each 2200 RT)	2009	Mixed-use community development within Business Bay
Saudi Aramco Dhahran complex (KSA)	Saudi Tabreed	Total: 32,000 (20,000 RT and 7000 RT-hour CTS Tank)	8 York Centrifugal chillers (each 2500 RT)	2013	Office complex, communities, hospital, and data centers
King Abdullah Financial District (KSA)	Saudi Tabreed	100,000 (two phases each 50,000 RT) and 15,000 RT-hour CTS Tank	Multiple mechanical chiller plants	2013	Office towers
Jabal Omar Development Project (Makkah, KSA)	Saudi Tabreed	55,000	Multiple mechanical chiller plants	2014	13 twin towers catering for hotels, malls, commercial outlets, and residential buildings
Knowledge Oasis Muscat (Oman)	Tabreed Oman SAOC	Total: 25,000 (planned)	Multiple mechanical chiller plants	2010	Technology park
		5000 (cooling load)			
Bahrain Financial Harbor (Bahrain)	Tabreed Bahrain	22,000	Mechanical chiller plant using sea water as a heat-rejection medium	2009	Offices, luxury residential accommodation, shopping complex housing, retail outlets, and hotels
Reef Island (Bahrain)	Tabreed Bahrain			2010	
Bahrain World Trade Center (Bahrain)	Tabreed Bahrain			2006	

References

1. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Edenhofer, O.R., Pichs-Madruga, Y., Sokona, E., Farahani, S., Kadner, K., Seyboth, A., Adler, I., Baum, S., Brunner, P., Eickemeier, B., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2014.
2. BP. BP Energy Outlook. 2018 Edition. Available online: https://www.bp.com (accessed on 25 November 2018).
3. International Energy Agency (IEA). The Future of Cooling. Opportunities for Efficient Air Conditioning. 2018. Available online: https://www.iea.org/publications/freepublications/publication/The_Future_of_Cooling.pdf (accessed on 25 November 2018).
4. Strategy. Unlocking the Potential of District Cooling: The Need for GCC Governments to Take Action. 2012. Available online: https://www.strategyand.pwc.com/media/file/Unlocking-the-potential-of-district-cooling.pdf (accessed on 25 November 2018).
5. Al-Qattan, A.; Elsherbini, A.; Al-Ajmi, K. Solid oxide fuel cell application in district cooling. *J. Power Sources* **2014**, *257*, 21–26. [CrossRef]
6. United Nations. Population Division. Department of Economic and Social Affairs (DESA). Available online: https://population.un.org/wpp/Download/Standard/Population/ (accessed on 25 November 2018).
7. Liew, P.Y.; Walmsley, T.G.; Wan Alwi, S.R.; Abdul Manan, Z.; Klemeš, J.J.; Varbanov, P.S. Integrating district cooling systems in Locally Integrated Energy Sectors through Total Site Heat Integration. *Appl. Energy* **2016**, *184*, 1350–1363. [CrossRef]
8. Pellegrini, M.; Bianchini, A. The Innovative Concept of Cold District Heating Networks: A Literature Review. *Energies* **2018**, *11*, 236. [CrossRef]
9. Dinçer, İ.; Zamfirescu, C. *Sustainable Energy Systems and Applications*; Springer International Publishing: New York, NY, USA, 2011; ISBN 9780387958606.
10. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). *ASHRAE District Cooling Guide*; ASHRAE: Atlanta, GA, USA, 2013; ISBN 9781936504428.
11. International District Energy Association (IDEA). *District Cooling Best Practices Guide*; IDEA: Westborough, MA, USA, 2008; ISBN 10 0615250718.
12. Rezaie, B.; Rosen, M.A. District heating and cooling: Review of technology and potential enhancements. *Appl. Energy* **2012**, *93*, 2–10. [CrossRef]
13. Seeley, R.S. District cooling gets hot. *Mech. Eng.* **1996**, *118*, 82–84.
14. MarketsandMarkets. District Cooling Market. Global Trend & Forecast to 2012–1019. 2014. Available online: https://www.marketresearch.com/product/sample-8361266.pdf (accessed on 25 November 2018).
15. Werner, S. International review of district heating and cooling. *Energy* **2017**, *137*, 617–631. [CrossRef]
16. Gang, W.; Wang, S.; Xiao, F.; Gao, D.C. District cooling systems: Technology integration, system optimization, challenges and opportunities for applications. *Renew. Sustain. Energy Rev.* **2016**, *53*, 253–264. [CrossRef]
17. Marafeq Qatar. District cooling GCC and Qatar. In Proceedings of the 37th Euroheat & Power Congress, Tallin, Estonia, 27–28 April 2015. Available online: http://www.ehpcongress.org/archive-2015/wp-content/uploads/2015/04/62_Eric_LINDSTR%C3%96M.pdf (accessed on 25 November 2018).
18. Lake, A.; Rezaie, B.; Beyerlein, S. Review of district heating and cooling systems for a sustainable future. *Renew. Sustain. Energy Rev.* **2017**, *67*, 417–425. [CrossRef]
19. Palm, J.; Gustafsson, S. Barriers to and enablers of district cooling expansion in Sweden. *J. Clean. Prod.* **2018**, *172*, 39–45. [CrossRef]
20. Vandermeulen, A.; van der Heijde, B.; Helsen, L. Controlling district heating and cooling networks to unlock flexibility: A review. *Energy* **2018**, *151*, 103–115. [CrossRef]
21. Chan, A.L.S.; Chow, T.T.; Fong, S.K.F.; Lin, J.Z. Performance evaluation of district cooling plant with ice storage. *Energy* **2006**, *31*, 2414–2426. [CrossRef]
22. Chan, A.L.S.; Hanby, V.I.; Chow, T.T. Optimization of distribution piping network in district cooling system using genetic algorithm with local search. *Energy Convers. Manag.* **2007**, *48*, 2622–2629. [CrossRef]
23. Trygg, L.; Amiri, S. European perspective on absorption cooling in a combined heat and power system—A case study of energy utility and industries in Sweden. *Appl. Energy* **2007**, *84*, 1319–1337. [CrossRef]
24. Söderman, J. Optimisation of structure and operation of district cooling networks in urban regions. *Appl. Therm. Eng.* **2007**, *27*, 2665–2676. [CrossRef]

25. Feng, X.; Long, W. Optimal design of pipe network of district cooling system based on genetic algorithm. In Proceedings of the 2010 6th International Conference on Natural Computation, Yantai, China, 10–12 August 2010; Volume 5, pp. 2415–2418. [CrossRef]
26. Svensson, I.L.; Moshfegh, B. System analysis in a European perspective of new industrial cooling supply in a CHP system. *Appl. Energy* **2011**, *88*, 5164–5172. [CrossRef]
27. Udomsri, S.; Martin, A.R.; Martin, V. Thermally driven cooling coupled with municipal solid waste-fired power plant: Application of combined heat, cooling and power in tropical urban areas. *Appl. Energy* **2011**, *88*, 1532–1542. [CrossRef]
28. Ondeck, A.D.; Edgar, T.F.; Baldea, M. Optimal operation of a residential district-level combined photovoltaic/natural gas power and cooling system. *Appl. Energy* **2015**, *156*, 1–14. [CrossRef]
29. Erdem, H.H.; Akkaya, A.V.; Dagdas, A.; Sevilgen, S.H.; Cetin, B.; Sahin, B.; Teke, I.; Gungor, C.; Atas, S.; Basak, M.Z. Renovating thermal power plant to trigeneration system for district heating/cooling: Evaluation of performance variation. *Appl. Therm. Eng.* **2015**, *86*, 35–42. [CrossRef]
30. Marugán-Cruz, C.; Sánchez-Delgado, S.; Rodríguez-Sánchez, M.R.; Venegas, M.; Santana, D. District cooling network connected to a solar power tower. *Appl. Therm. Eng.* **2015**, *79*, 174–183. [CrossRef]
31. Perdichizzi, A.; Barigozzi, G.; Franchini, G.; Ravelli, S. Peak shaving strategy through a solar combined cooling and power system in remote hot climate areas. *Appl. Energy* **2015**, *143*, 154–163. [CrossRef]
32. Khir, R.; Haouari, M. Optimization models for a single-plant District Cooling System. *Eur. J. Oper. Res.* **2015**, *247*, 648–658. [CrossRef]
33. Karlsson, V.; Nilsson, L. Co-production of pyrolysis oil and district cooling in biomass-based CHP plants: Utilizing sequential vapour condensation heat as driving force in an absorption cooling machine. *Appl. Therm. Eng.* **2015**, *79*, 9–16. [CrossRef]
34. Gang, W.; Augenbroe, G.; Wang, S.; Fan, C.; Xiao, F. An uncertainty-based design optimization method for district cooling systems. *Energy* **2016**, *102*, 516–527. [CrossRef]
35. Gang, W.; Wang, S.; Augenbroe, G.; Xiao, F. Robust optimal design of district cooling systems and the impacts of uncertainty and reliability. *Energy Build.* **2016**, *122*, 11–22. [CrossRef]
36. Ameri, M.; Besharati, Z. Optimal design and operation of district heating and cooling networks with CCHP systems in a residential complex. *Energy Build.* **2016**, *110*, 135–148. [CrossRef]
37. Kang, J.; Wang, S.; Gang, W. Performance and Benefits of Distributed Energy Systems in Cooling Dominated Regions: A Case Study. *Energy Procedia* **2017**, *142*, 1991–1996. [CrossRef]
38. Yan, C.; Gang, W.; Niu, X.; Peng, X.; Wang, S. Quantitative evaluation of the impact of building load characteristics on energy performance of district cooling systems. *Appl. Energy* **2017**, *205*, 635–643. [CrossRef]
39. Coz, T.D.; Kitanovski, A.; Poredo, A. Exergoeconomic optimization of a district cooling network. *Energy* **2017**, *135*, 342–351. [CrossRef]
40. Dominković, D.F.; Rashid, K.A.; Romagnoli, A.; Pedersen, A.S.; Leong, K.C.; Kraja, G.; Dui, N. Potential of district cooling in hot and humid climates. *Appl. Energy* **2017**, *208*, 49–61. [CrossRef]
41. Gao, J.; Kang, J.; Zhang, C.; Gang, W. Energy Performance and Operation Characteristics of Distributed Energy Systems with District Cooling Systems in Subtropical Areas Under Different Control Strategies. *Energy* **2018**, *153*, 849–860. [CrossRef]
42. Franchini, G.; Brumana, G.; Perdichizzi, A. Performance prediction of a solar district cooling system in Riyadh, Saudi Arabia—A case study. *Energy Convers. Manag.* **2018**, *166*, 372–384. [CrossRef]
43. Ravelli, S.; Franchini, G.; Perdichizzi, A. Comparison of different CSP technologies for combined power and cooling production. *Renew. Energy* **2018**, *121*, 712–721. [CrossRef]
44. Shea, X.; Cong, L.; Nie, B.; Leng, G.; Peng, H.; Chen, Y.; Zhang, X.; Wen, T.; Yang, H.; Luo, Y. Energy-efficient and -economic technologies for air conditioning with vapor compression refrigeration: A comprehensive review. *Appl. Energy* **2018**, *232*, 157–186. [CrossRef]
45. Ziegler, F. State of the art in sorption heat pumping and cooling technologies. *Int. J. Refrig.* **2002**, *25*, 450–459. [CrossRef]
46. Deng, J.; Wang, R.Z.; Han, G.Y. A review of thermally activated cooling technologies for combined cooling, heating and power systems. *Prog. Energy Combust. Sci.* **2011**, *37*, 172–203. [CrossRef]
47. Best, R.; Rivera, W. A review of thermal cooling systems. *Appl. Therm. Eng.* **2015**, *75*, 1162–1175. [CrossRef]
48. Jradi, M.; Riffat, S. Tri-generation systems: Energy policies, prime movers, cooling technologies, configurations and operation strategies. *Renew. Sustain. Energy Rev.* **2014**, *32*, 396–415. [CrossRef]

49. Besagni, G.; Mereu, R.; Inzoli, F. Ejector refrigeration: A comprehensive review. *Renew. Sustain. Energy Rev.* **2016**, *53*, 373–407. [CrossRef]
50. Thermax Global Triple Effect Absorption Chiller. Available online: http://www.thermaxglobal.com/thermax-absorption-cooling-systems/vapour-absorption-machines/triple-effect-chillers/ (accessed on 25 November 2018).
51. Kawasaki Thermal Engineering. Direct-Fired Double-Effect Absorption Chiller. Available online: http://www.khi.co.jp/corp/kte/EN/product/df-chiller1.html (accessed on 25 November 2018).
52. Schwerdt, P. Activities in Thermal Driven Cooling at Fraunhofer Umsicht. In Chapter 4: Thermally Driven Heat Pumps for Cooling. Available online: https://depositonce.tu-berlin.de/bitstream/11303/5164/1/117_schwerdt.pdf (accessed on 25 November 2018).
53. Srikhirin, P.; Aphornratana, S.; Chungpaibulpatana, S. A review of absorption refrigeration technologies. *Renew. Sustain. Energy Rev.* **2001**, *5*, 343–372. [CrossRef]
54. Wu, W.; Wang, B.; Shi, W.; Li, X. An overview of ammonia-based absorption chillers and heat pumps. *Renew. Sustain. Energy Rev.* **2014**, *31*, 681–707. [CrossRef]
55. Abed, A.M.; Alghoul, M.A.; Sopian, K.; Majdi, H.S.; Al-shamani, A.N.; Muftah, A.F. Enhancement aspects of single stage absorption cooling cycle: A detailed review. *Renew. Sustain. Energy Rev.* **2017**, *77*, 1010–1045. [CrossRef]
56. Arabkoohsar, A.; Andresen, G.B. Supporting district heating and cooling networks with a bifunctional solar assisted absorption chiller. *Energy Convers. Manag.* **2017**, *148*, 184–196. [CrossRef]
57. Alefeld, G.; Radermacher, R. *Heat Conversion Systems*; CRC Press, Inc.: Boca Raton, FL, USA, 1994; ISBN 9780849389283.
58. Jawahar, C.P.; Saravanan, R. Generator absorber heat exchange based absorption cycle—A review. *Renew. Sustain. Energy Rev.* **2010**, *14*, 2372–2382. [CrossRef]
59. Xu, Z.Y.; Wang, R.Z. Absorption refrigeration cycles: Categorized based on the cycle construction. *Int. J. Refrig.* **2016**, *62*, 114–136. [CrossRef]
60. Wang, L.W.; Wang, R.Z.; Oliveira, R.G. A review on adsorption working pairs for refrigeration. *Renew. Sustain. Energy Rev.* **2009**, *13*, 518–534. [CrossRef]
61. Shmroukh, A.N.; Ali, A.H.H.; Ookawara, S. Adsorption working pairs for adsorption cooling chillers: A review based on adsorption capacity and environmental impact. Renew. Sustain. *Energy Rev.* **2015**, *50*, 445–456. [CrossRef]
62. Goyal, P.; Baredar, P.; Mittal, A.; Siddiqui, A.R. Adsorption refrigeration technology—An overview of theory and its solar energy applications. *Renew. Sustain. Energy Rev.* **2016**, *53*, 1389–1410. [CrossRef]
63. Sahlot, M.; Riffat, S.B. Desiccant cooling systems: A review. *Int. J. Low-Carbon Technol.* **2016**, *11*, 489–505. [CrossRef]
64. Enteria, N.; Mizutani, K. The role of the thermally activated desiccant cooling technologies in the issue of energy and environment. *Renew. Sustain. Energy Rev.* **2011**, *15*, 2095–2122. [CrossRef]
65. Liu, X.H.; Yi, X.Q.; Jiang, Y. Mass transfer performance comparison of two commonly used liquid desiccants: LiBr and LiCl aqueous solutions. *Energy Convers. Manag.* **2011**, *52*, 180–190. [CrossRef]
66. Chen, J.; Jarall, S.; Havtun, H.; Palm, B. A review on versatile ejector applications in refrigeration systems. *Renew. Sustain. Energy Rev.* **2015**, *49*, 67–90. [CrossRef]
67. Ruch, P.; Saliba, S.; Ong, C.L.; Al-Shehri, Y.; Al-Rihaili, A.; Al-Mogbel, A.; Michel, B. Heat-driven adsorption chiller for sustainable cooling applications. In Proceedings of the 11th IEA Heat Pump Conference 2014, Montréal, QC, Canada, 12–16 May 2014. Available online: https://pdfs.semanticscholar.org/7db6/bc0436cd1db75103f7bffaf24a0fabc17e66.pdf (accessed on 25 November 2018).
68. Elbel, S. Historical and present developments of ejector refrigeration systems with emphasis on transcritical carbon dioxide air-conditioning. *Int. J. Refrig.* **2011**, *34*, 1545–1561. [CrossRef]
69. Chen, J.; Havtun, H.; Palm, B. Screening of working fluids for the ejector refrigeration system. *Int. J. Refrig.* **2014**, *47*, 1–14. [CrossRef]
70. Saleh, B. Performance analysis and working fluid selection for ejector refrigeration cycle. *Appl. Therm. Eng.* **2016**, *107*, 114–124. [CrossRef]
71. Energieversorgung Gera GmbH District Cooling System in Gera Cold Supply with Steam Jet Ejector Chilling Technology. Available online: http://dampfstrahlkaelte.de/links/downloads/fernkaelteversorgung_gera_e.pdf (accessed on 25 November 2018).

72. Colmenar-Santos, A.; Rosales-Asensio, E.; Borge-Diez, D.; Collado-Fernández, E. Evaluation of the cost of using power plant reject heat in low-temperature district heating and cooling networks. *Appl. Energy* **2016**, *162*, 892–907. [CrossRef]
73. Zhen, L.; Lin, D.M.; Shu, H.W.; Jiang, S.; Zhu, Y.X. District cooling and heating with seawater as heat source and sink in Dalian, China. *Renew. Energy* **2007**, *32*, 2603–2616. [CrossRef]
74. Lind, L.; Mroczek, S.; Bell, J. Seawater used for district cooling in Stockholm. GNS Science, 2014. Available online: https://www.yumpu.com/en/document/view/9050455/seawater-used-for-district-cooling-in-stockholm-gns-science (accessed on 25 November 2018).
75. Peer, T.; (Lanny) Joyce, W.S. Lake-Source Cooling. *ASHRAE J.* **2002**, *44*, 37–39.
76. Tredinnick, S.; Phetteplace, G. District cooling, current status and future trends. In *Advanced District Heating and Cooling (DHC) Systems*; Wiltshire, R., Ed.; Woodhead Publishing (Elsevier): Cambridge, UK, 2016; pp. 167–188.
77. Ampofo, F.; Maidment, G.G.; Missenden, J.F. Review of groundwater cooling systems in London. *Appl. Therm. Eng.* **2006**, *26*, 2055–2062. [CrossRef]
78. Gómez, M.R.; Garcia, R.F.; Gómez, J.R.; Carril, J.C. Review of thermal cycles exploiting the exergy of liquefied natural gas in the regasification process. *Renew. Sustain. Energy Rev.* **2014**, *38*, 781–795. [CrossRef]
79. Invernizzi, C.M.; Iora, P. The exploitation of the physical exergy of liquid natural gas by closed power thermodynamic cycles. An overview. *Energy* **2016**, *105*, 2–15. [CrossRef]
80. International Gas Union (IGU). 2018 IGU World LNG Report, 2018 Edition. 27th World Gas Conference & Exhibition Edition. Available online: https://www.igu.org/sites/default/files/node-document-field_file/IGU_LNG_2018_0.pdf (accessed on 25 November 2018).
81. La Rocca, V. Cold recovery during regasification of LNG part one: Cold utilization far from the regasification facility. *Energy* **2010**, *35*, 2049–2058. [CrossRef]
82. European Commission. An EU Strategy on Heating and Cooling, COM(2016) 51 Final, Brussels, 16.2.2016. Available online: http://ec.europa.eu/energy/sites/ener/files/documents/1_EN_ACT_part1_v14.pdf (accessed on 7 January 2019).
83. Atienza-Márquez, A.; Bruno, J.C.; Coronas, A. Cold recovery from LNG-regasification for polygeneration applications. *Appl. Therm. Eng.* **2018**, *132*, 463–478. [CrossRef]
84. La Rocca, V. Cold recovery during regasification of LNG part two: Applications in an Agro Food Industry and a Hypermarket. *Energy* **2011**, *36*, 4897–4908. [CrossRef]
85. Jo, Y.K.; Kim, J.K.; Lee, S.G.; Kang, Y.T. Development of type 2 solution transportation absorption system for utilizing LNG cold energy. *Int. J. Refrig.* **2007**, *30*, 978–985. [CrossRef]
86. Hasnain, S.M. Review on sustainable thermal energy storage technologies, Part II: Cool thermal storage. *Energy Convers. Manag.* **1998**, *39*, 1139–1153. [CrossRef]
87. Yau, Y.H.; Rismanchi, B. A review on cool thermal storage technologies and operating strategies. *Renew. Sustain. Energy Rev.* **2012**, *16*, 787–797. [CrossRef]
88. Al-Noaimi, F.; Khir, R.; Haouari, M. Optimal design of a district cooling grid: Structure. *Eng. Optim.* **2019**, *51*, 160–183. [CrossRef]
89. Oró, E.; de Gracia, A.; Castell, A.; Farid, M.M.; Cabeza, L.F. Review on phase change materials (PCMs) for cold thermal energy storage applications. *Appl. Energy* **2012**, *99*, 513–533. [CrossRef]
90. Abdullah, M.O.; Yii, L.P.; Junaidi, E.; Tambi, G.; Mustapha, M.A. Electricity cost saving comparison due to tariff change and ice thermal storage (ITS) usage based on a hybrid centrifugal-ITS system for buildings: A university district cooling perspective. *Energy Build.* **2013**, *67*, 70–78. [CrossRef]
91. Lizana, J.; Chacartegui, R.; Barrios-Padura, A.; Ortiz, O. Advanced low-carbon energy measures based on thermal energy storage in buildings: A review. *Renew. Sustain. Energy Rev.* **2018**, *82*, 3705–3749. [CrossRef]
92. Chow, T.T.; Au, W.H.; Yau, R.; Cheng, V.; Chan, A.; Fong, K.F. Applying district-cooling technology in Hong Kong. *Appl. Energy* **2004**, *79*, 275–289. [CrossRef]
93. Chow, T.T.; Fong, K.F.; Chan, A.L.S.; Yau, R.; Au, W.H.; Cheng, V. Energy modelling of district cooling system for new urban development. *Energy Build.* **2004**, *36*, 1153–1162. [CrossRef]
94. Skagestad, B.; Mildenstein, P. *District Heating and Cooling Connection Handbook—Programme of Research, Development and Demonstration on District Heating and Cooling*; International Energy Agency—IEA District Heating and Cooling: Paris, France, 2002; ISBN 9057480298.

95. Rifai, S.M.M. Demand-Response Management of a District Cooling Plant of a Mixed Use City Development. Master's Thesis, KTH—Royal Institute of Technology, Stockholm, Sweden, 2012.
96. Eveloy, V.; Gebreegziabher, T. A Review of Projected Power-to-gas Deployment Scenarios. *Energies* **2018**, *11*, 1824. [CrossRef]
97. Hughes, B.R.; Rezazadeh, F.; Chaudhry, H.N. Economic viability of incorporating multi-effect distillation with district cooling systems in the United Arab Emirates. Sustain. *Cities Soc.* **2013**, *7*, 37–43. [CrossRef]
98. Eveloy, V.; Rodgers, P.; Popli, S. Trigeneration scheme for a natural gas liquids extraction plant in the Middle East. *Energy Convers. Manag.* **2014**, *78*, 204–218. [CrossRef]
99. Parham, K.; Khamooshi, M.; Tematio, D.B.K.; Yari, M.; Atikol, U. Absorption heat transformers—A comprehensive review. *Renew. Sustain. Energy Rev.* **2014**, *34*, 430–452. [CrossRef]
100. Rivera, W.; Best, R.; Cardoso, M.J.; Romero, R.J. A review of absorption heat transformers. *Appl. Therm. Eng.* **2015**, *91*, 654–670. [CrossRef]
101. Eveloy, V.; Rodgers, P.; Qiu, L. Hybrid gas turbine-organic Rankine cycle for seawater desalination by reverse osmosis in a hydrocarbon production facility. *Energy Convers. Manag.* **2015**, *106*, 1134–1148. [CrossRef]
102. Harish, V.S.K.V.; Kumar, A. A review on modeling and simulation of building energy systems. *Renew. Sustain. Energy Rev.* **2016**, *56*, 1272–1292. [CrossRef]
103. Shi, X.; Tian, Z.; Chen, W.; Si, B.; Jin, X. A review on building energy efficient design optimization from the perspective of architects. *Renew. Sustain. Energy Rev.* **2016**, *65*, 872–884. [CrossRef]
104. Wang, H.; Zhai, Z.J. Advances in Building Simulation and Computational Techniques: A Review between 1987 and 2014. *Energy Build.* **2016**, *128*, 319–335. [CrossRef]
105. Shimoda, Y.; Nagota, T.; Isayama, N.; Mizuno, M. Verification of energy efficiency of district heating and cooling system by simulation considering design and operation parameters. *Build. Environ.* **2008**, *43*, 569–577. [CrossRef]
106. Jing, Z.X.; Jiang, X.S.; Wu, Q.H.; Tang, W.H.; Hua, B. Modelling and optimal operation of a small-scale integrated energy based district heating and cooling system. *Energy* **2014**, *73*, 399–415. [CrossRef]
107. Chow, T.T.; Chan, A.L.S.; Song, C.L. Building-mix optimization in district-cooling system implementation. *Appl. Energy* **2004**, *77*, 1–13. [CrossRef]
108. Gang, W.; Wang, S.; Gao, D.; Xiao, F. Performance assessment of district cooling systems for a new development district at planning stage. *Appl. Energy* **2015**, *140*, 33–43. [CrossRef]
109. Chan, A.L.S.; Chow, T.T.; Fong, S.K.F.; Lin, J.Z. Generation of a typical meteorological year for Hong Kong. *Energy Convers. Manag.* **2006**, *47*, 87–96. [CrossRef]
110. Gros, A.; Bozonnet, E.; Inard, C.; Musy, M. A New Performance Indicator to Assess Building and District Cooling Strategies. *Procedia Eng.* **2016**, *169*, 117–124. [CrossRef]
111. Sameti, M.; Haghighat, F. Optimization approaches in district heating and cooling thermal network. *Energy Build.* **2017**, *140*, 121–130. [CrossRef]
112. Renewable Smart Cooling for Urban Europe (RESCUE). Cool Conclusions How to Implement District Cooling in Europe. 2015. Available online: http://www.rescue-project.eu/fileadmin/user_files/FinalReport/Rescue_Cool_Conclusions_Final_Report_A4_EN_RZ.pdf (accessed on 25 November 2018).
113. Ecoheat4cities. Guidelines for Technical Assessment of District Heating Systems. Available online: https://www.euroheat.org/wp-content/uploads/2016/04/Ecoheat4cities_3.1_Labelling_Guidelines.pdf (accessed on 25 November 2018).
114. Genchi, Y.; Kikegawa, Y.; Inaba, A. CO_2 payback-time assessment of a regional-scale heating and cooling system using a ground source heat-pump in a high energy-consumption area in Tokyo. *Appl. Energy* **2002**, *71*, 147–160. [CrossRef]
115. Calm, J.M. The next generation of refrigerants—Historical review, considerations, and outlook. *Int. J. Refrig.* **2008**, *31*, 1123–1133. [CrossRef]
116. Kassim, J. Efficiency Gains and Emissions Reductions Achieved Through District Cooling. In Proceedings of the International District Energy Association Annual Conference & Trade Show 2014 (IDEA 2014), Seattle, WA, USA, 8–11 June 2014. Available online: https://www.districtenergy.org/HigherLogic/System/DownloadDocumentFile.ashx?DocumentFileKey=e8e778c9-452c-8b50-eccb-8850764965e8 (accessed on 25 November 2018).

117. Montreal Protocol on Substances that Deplete the Ozone Layer. Available online: http://conf.montreal-protocol.org/meeting/mop/mop-27/presession/Background%20Documents%20are%20available%20in%20English%20only/RTOC-Assessment-Report-2014.pdf (accessed on 25 November 2018).
118. Bolaji, B.O.; Huan, Z. Ozone depletion and global warming: Case for the use of natural refrigerant—A review. *Renew. Sustain. Energy Rev.* **2013**, *18*, 49–54. [CrossRef]
119. Swedblom, M.; Peter, M.; Anders, T.; Frohm, H.; Rubenhag, A. District Cooling and the Customers' Alternative Cost (Renewable Smart Cooling for Urban Europe (RESCUE) WP2. 2014. Available online: http://www.rescue-project.eu/index.php?id=2 (accessed on 25 November 2018).
120. Tredinnick, S. Benefits of Economic Analyses (Part 2): Real World Examples. District Energy. 2011. International District Energy Association. pp. 66–69. Available online: https://www.eesi.org/files/districtenergy2011Q3-dl.pdf (accessed on 25 November 2018).
121. Perez, N.; Riederer, P.; Inard, C. Development of a multiobjective optimization procedure dedicated to the design of district energy concept. *Energy Build.* **2018**, *178*, 11–25. [CrossRef]
122. Feng, X.; Long, W. Applying single parent genetic algorithm to optimize piping network layout of district cooling system. In Proceedings of the 4th International Conference on Natural Computation (ICNC 2008), Jinan, China, 18–20 October 2008; Volume 1, pp. 176–180. [CrossRef]
123. Amulla, Y. Gulf Cooperation Council (GCC) Countries 2040 Energy Scenario for Electricity Generation and Water Desalination. Master's Thesis, School of Industrial Engineering and Management, KTH Royal Institute of Technology in Stockholm, Stockholm, Sweden, 2014. Available online: https://www.diva-portal.org/smash/get/diva2:839740/FULLTEXT01.pdf (accessed on 25 November 2018).
124. International Renewable Energy Agency (IRENA). Pan-Arab Renewable Energy Strategy 2030. 2014. Available online: https://www.irena.org/DocumentDownloads/Publications/IRENA_Pan-Arab_Strategy_June%202014.pdf (accessed on 25 November 2018).
125. World Bank. Available online: http://databank.worldbank.org/data/indicator/ (accessed on 25 November 2018).
126. Aquastat. Food and Agriculture Organization of the United Nations. 2014. Data. Available online: http://www.fao.org/nr/water/aquastat/data/query/results.html (accessed on 25 November 2018).
127. Eveloy, V.; Gebreegziabher, T. Excess electricity and power-to-gas storage potential in the future renewable-based power generation sector in the United Arab Emirates. *Energy* **2018**, *166*, 426–450. [CrossRef]
128. Malit, F.; Naufral, G. Labour Migration, Skills Development and the Future of Work in the Gulf Cooperation Council (GCC) Countries. Working Paper, International Labour Organization (ILO), October 2017. Available online: https://www.ilo.org/newdelhi/whatwedo/publications/WCMS_634982/lang--en/index.htm (accessed on 25 November 2018).
129. United Nations-Water. Managing Water Report under Uncertainty and Risk. The United Nations World Water Development Report 4. 2012, Volume 1. Available online: http://www.unesco.org/new/fileadmin/MULTIMEDIA/HQ/SC/pdf/WWDR4%20Volume%201-Managing%20Water%20under%20Uncertainty%20and%20Risk.pdf (accessed on 25 November 2018).
130. Pirouz, B.; Maiolo, M. The Role of Power Consumption and Type of Air Conditioner in Direct and Indirect Water Consumption. *J. Sustain. Dev. Energy Water Environ. Syst.* **2018**, *6*, 665–673. [CrossRef]
131. Spurr, M. Cooling, power, water and waste. Why Middle East governments should integrate utility planning. *First Quart. 2007 Dist. Energy Mag. Permis. IDEA* **2007**, *93*, 56–57.
132. United Nations. Food and Agriculture of the United Nations. 6 Clean Water and Sanitation. Progress on Level of Water Stress. Global Baseline for SDG Indicator 6.4.2. 2018. Available online: http://www.unwater.org/app/uploads/2018/10/SDG6_Indicator_Report_642-progress-on-level-of-water-stress-2018.pdf (accessed on 25 November 2018).
133. United Nations-Water. United Nations Development Programme. Water Governance in the Arab Region—UNDP. Arab Water Government Report. Water in the Arab Region: Availability, Status and Threats. Chapter 1. Available online: http://www.bh.undp.org/content/dam/rbas/doc/Energy%20and%20Environment/Arab_Water_Gov_Report/Arab_Water_Report_AWR_Chapter%201.pdf (accessed on 25 November 2018).
134. TABREED. Company Overview. Available online: http://www.tabreed.ae/uploads/documents/Tabreed%20Media%20Kit%20English%20and%20final%20%20last%20update%2022%2011%202012.pdf (accessed on 25 November 2018).

135. Younan, F. How will district cooling evolve in the GCC. In Proceedings of the District Cooling 2016 a Climate Solution, Dubai, UAE, 13–15 November 2016.
136. National Central Cooling Company PJSC (DFM: TABREED). Investor Presentation. May 2018. Available online: https://www.tabreed.ae/wp-content/uploads/2018/05/Tabreed-Corporate-Presentation-May-2018.pdf (accessed on 7 January 2019).
137. Brander, M.; Sood, A.; Wylie, C.; Haughton, A.; Lovell, J. *Technical Paper. Electricity-Specific Emission Factors for Grid Electricity*; Ecometrica: Edinburgh, UK, 2011; pp. 1–22.
138. Hassan, J. Next Generation District Cooling Network—A High-Level Overview. Clean Cooling. In Proceedings of the New "Frontier Market" for UAE & GCC Region, Dubai, UAE, 9–10 April 2018. Available online: https://www.eugcc-cleanergy.net/sites/default/files/events/20180410_dubai/clean_cooling_workshop_dubai_09.04.2018_session_3_hassan_javed_aateco.pdf (accessed on 25 November 2018).
139. Herold, K.E.; Radermacher, R.; Klein, S.A. *Absorption Chillers and Heat Pumps*, 2nd ed.; CRC Press, Inc.: Boca Raton, FL, USA, 2016; Volume 1, ISBN 9788578110796.
140. TABREED. 2016 H1 Results Presentation National Central Cooling Company PJSC. 26 July 2016. Available online: https://www.tabreed.ae/uploads/documents/H1%202016%20Analyst%20presentation.pdf (accessed on 25 November 2018).
141. Bhutto, A.W.; Bazmi, A.A.; Zahedi, G.; Klemes, J.J. A review of progress in renewable energy implementation in the Gulf Cooperation Council countries. *J. Clean. Prod.* **2014**, *71*, 168–180. [CrossRef]
142. Kilkis, B.; Kilkis, S. Hydrogen economy model for nearly net-zero cities with exergy rationale and energy-water nexus. *Energies* **2018**, *11*, 1226. [CrossRef]
143. Kilkis, S. A nearly net-zero exergy district as a model for smarter energy systems in the context of urban metabolism. *J. Sustain. Dev. Energy Water Environ. Syst.* **2017**, *5*, 101–126. [CrossRef]
144. Connolly, D.; Lund, H.; Mathiesen, B.V. Smart energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. *Renew. Sustain. Energy Rev.* **2016**, *60*, 1634–1653. [CrossRef]
145. AGO. Available online: http://www.ago.ag (accessed on 25 November 2018).
146. BROAD Group. Available online: http://en.broad.com/ (accessed on 30 September 2018).
147. Carrier Corporation. Available online: https://www.carrier.com/carrier/en/us/products-and-services/commercial-refrigeration/ (accessed on 25 November 2018).
148. Hitachi. Large-Tonnage Chiller. Available online: https://www.jci-hitachi.com/products/chillers/ (accessed on 25 November 2018).
149. Kawasaki Thermal Engineering. Available online: http://www.khi.co.jp/corp/kte/EN/index.html (accessed on 25 November 2018).
150. LG Catalogue Absorption Chillers. Available online: http://www.lg.com/global/business/download/resources/sac/Catalogue_Absorption%20Chillers_ENG_F.pdf (accessed on 25 November 2018).
151. SAKURA. Available online: http://www.sakura-aircon.com/Products/commercial/SAKURA_Absorption_Chiller_2015.html (accessed on 25 November 2018).
152. SHUANGLIANG ECO-ENERGY. Available online: http://sl-ecoenergy.com/products/0/163310/ (accessed on 25 November 2018).
153. THERMAX. Available online: http://www.thermaxglobal.com/thermax-absorption-cooling-systems/ (accessed on 25 November 2018).
154. TRANE. Available online: http://www.trane.com/commercial/north-america/us/en/products-systems/equipment/chillers/absorption-liquid-chillers.html (accessed on 25 November 2018).
155. Johnson Controls. Available online: http://www.johnsoncontrols.com/buildings/hvac-equipment/chillers (accessed on 25 November 2018).
156. Fischer Eco Solutions. Available online: www.fischer-group.com (accessed on 25 November 2018).
157. IPCC Fourth Assessment Report: Climate Change 2007. Climate Change 2007: Working Group I. The Physical Science Basis. Direct Global Warming Potentials. Available online: https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html (accessed on 25 November 2018).
158. United Nations Environment Programme (UNEP). *Ozone Depletion Potential*; UNEP Ozone Secretariat: Nairobi, Kenya, 2006.
159. TABREED. Landmark Projects. Available online: https://www.tabreed.ae/landmark-projects/ (accessed on 25 November 2018).

160. Emicool Emirates District Cooling LLC Pre-Qualification Documents. Available online: https://www.emicool.net/en/Downloads/Pre_Qualification_Emicool.pdf (accessed on 25 November 2018).
161. Marafeq Qatar. Lusail Development. Available online: http://www.marafeq.com.qa/main.php?content=Projects&link=48&type=content (accessed on November 2018).
162. Qatar Cool West Bay and the Pearl Qatar. Available online: http://www.qatarcool.com/our-districts/ (accessed on 25 November 2018).