

GLOBAL EVOLUTION OF DISTRICT COOLING SYSTEMS: COMPARATIVE REGIONAL PATTERNS, ARCHETYPES AND IMPLICATIONS FOR SOLAR-BASED URBAN COOLING

Summary

This study presents a comparative global assessment of district cooling systems based on a structured dataset of 32 documented case studies across six regions. The analysis evaluates temporal diffusion patterns, ownership and operational models, and cooling production technology configurations to identify regional deployment characteristics and institutional differences. Results indicate strong post-2000 expansion, clear regional variation in governance structures, and climate-dependent technology selection, particularly regarding natural cooling integration. The findings highlight district cooling as a structurally promising infrastructure for solar-based urban decarbonization, with integration pathways dependent on governance context and climatic conditions. The study provides a transferable comparative framework supporting solar-driven district cooling deployment strategies.

Keywords: District cooling, solar cooling, urban energy systems, cooling production technology, ownership and operational models, renewable integration, thermal energy storage, decarbonization

Field of application for the findings: Urban energy planning, solar-integrated district cooling systems, renewable energy integration strategies, district energy system design, climate-responsive cooling infrastructure development

Addressed audience: Researchers in solar and district energy systems, urban energy planners, policy makers, infrastructure developers and stakeholders involved in sustainable urban cooling solutions

1. Introduction

Space cooling demand is rapidly increasing in urban areas due to rising ambient temperatures, expanding building floor area, urban heat island effects, and growing expectations for thermal comfort. In many regions, cooling demand contributes significantly to peak electricity loads, placing stress on power systems during periods of high demand. These peak loads often coincide with periods of strong solar photovoltaic (PV) generation, creating opportunities for solar-aligned cooling strategies that combine renewable electricity with thermal storage and demand flexibility. District cooling systems (DCS) are increasingly recognized as an effective approach to improve cooling efficiency through centralized production, enable large-scale thermal energy storage, and integrate low-carbon cooling sources such as seawater, deep lake water, free cooling, waste heat-driven absorption cooling, and renewable electricity. By aggregating cooling demand and optimizing system operation, district cooling can significantly reduce electricity consumption and improve system reliability in dense urban environments. Despite growing interest in district cooling technologies, the existing evidence base remains fragmented. Most studies focus on individual case studies or specific technological solutions, while systematic cross-regional comparisons of deployment timing, governance models, and technology configurations remain limited. This lack of comparative analysis constrains the transferability of lessons for cities and utilities seeking to implement large-scale cooling infrastructure. This study addresses this gap by developing a comparative global framework for analyzing district cooling systems. Using a dataset-driven approach, the research evaluates regional deployment patterns, institutional delivery models, and technology configurations to identify pathways for integrating solar-based cooling within urban energy systems. The study addresses the following research questions:

- How do adoption timelines for DCS differ across globe (early adoption vs rapid scaling)?
- What do these patterns imply for solar-based cooling integration (PV-coupled cooling, solar thermal cooling, and storage-enabled load shifting)?

2. Methodology

The analysis is based on a structured dataset comprising 32 district cooling systems distributed across six regions: Asia, Europe, the Middle East, North America, Oceania, and Africa (Fig. 1). Case studies were selected based on the availability of publicly documented operational systems with accessible technical and institutional information. Data sources included operator reports, utility documentation, infrastructure descriptions, and technical summaries. For each system, key variables were recorded, including geographical location, system operator, year of commissioning, and descriptive information on system design and operational characteristics. The systems analyzed span commissioning years from the early 1970s to the early 2020s, enabling the evaluation of long-term diffusion trends. To enable systematic comparison, a three-dimensional analytical framework was developed focusing on: (i) temporal diffusion, (ii) ownership and operational models, and (iii) cooling production technology configuration.



Fig 1: Global distribution of district cooling systems included in the presented study (Red dots indicate country-level locations of the DCS)

Temporal diffusion was assessed using the earliest identifiable commissioning year for each system. Where phased development or subsequent upgrades were reported, the first operational phase was used to ensure comparability across regions. A cumulative diffusion curve was constructed to identify adoption waves and periods of accelerated deployment. Regional diffusion characteristics were further examined using the first-adoption year and median establishment year as indicative metrics of market maturity and deployment dynamics. Ownership and operational models were categorized according to the institutional entity responsible for system development and operation. Four principal categories were identified: utility-led systems (municipal or integrated district energy utilities), private concession-based systems (specialized cooling providers operating under long-term service agreements), public-sector operated systems (government-led infrastructure), and institutional systems, such as university or campus-based cooling networks. Cooling production technologies were classified according to the primary cooling source and heat rejection mechanism. The classification includes seawater cooling, lake or river water-source cooling, free cooling operation, underground distribution network configurations, and documented integration of thermal energy storage. The dataset was analyzed using descriptive statistics and categorical comparison to identify regional archetypes in governance structures and cooling production technologies, enabling the comparative assessment of district cooling deployment patterns across different climatic and institutional contexts. This framework enables the identification of regional deployment archetypes and provides a basis for assessing the implications of institutional structures and technology configurations for solar-integrated district cooling development.

3. Results

The cumulative diffusion analysis indicates that district cooling deployment has expanded significantly since 2000. Although a limited number of systems were established in the 1970s and 1980s, the majority of systems in the dataset were commissioned after 2000, with particularly strong growth between 2005 and 2015. This trend suggests a transition of district cooling from a niche infrastructure concept toward a mainstream urban cooling solution. Regional comparisons reveal distinct diffusion trajectories. Asia includes some of the earliest documented systems, with installations dating back to the early 1970s. However, the median commissioning year lies in the late 2000s, reflecting both early pioneers and more recent development associated with large-scale urban districts. In Europe, district cooling deployment has expanded steadily since the 1990s, often as an extension of established district heating infrastructure. In contrast, the Middle East demonstrates rapid expansion

beginning in the early 2000s, driven by large-scale urban development and high cooling demand in hot-arid climates.

Ownership and operational models also show clear regional differences. European systems are predominantly utility-led, reflecting strong involvement of municipal or integrated district energy utilities and long-standing traditions of coordinated urban infrastructure planning. In the Middle East, district cooling systems are commonly developed and operated by private concession-based providers within master-planned developments. Asia shows a diverse mix of private, utility-led, and public-sector operated systems, reflecting variations in national regulatory frameworks and urban planning strategies. North American systems often combine municipal utilities with institutional or campus-based networks. Cooling production technologies also differ significantly between regions. European systems frequently employ water-source cooling technologies using lakes, rivers, or fjords, enabling seasonal free cooling and reduced electricity consumption. Similar configurations are observed in some North American municipal systems. Coastal developments in Europe and Asia sometimes integrate seawater cooling. In contrast, systems in the Middle East more commonly rely on large-scale electrically driven chilled-water production. While natural cooling opportunities are limited by climatic conditions, the scale and centralized architecture of these systems provide opportunities for efficiency improvements and integration of renewable electricity and thermal energy storage. Overall, the results demonstrate that technology selection is strongly influenced by climatic conditions, geographic context, and institutional planning traditions. Temperate regions tend to favor natural cooling pathways, whereas hot-arid regions emphasize large centralized production capacity.

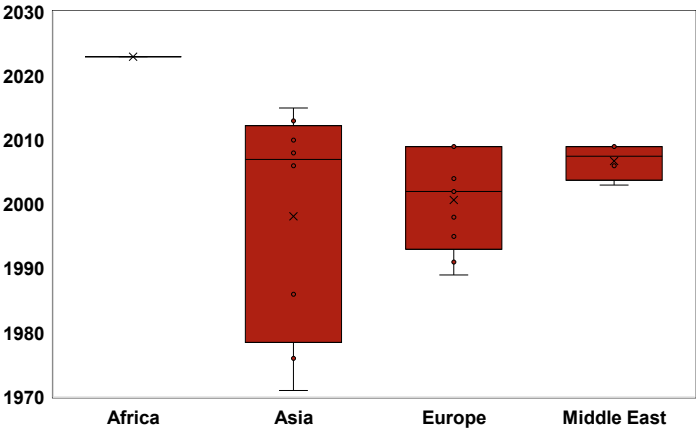


Fig. 3: Regional distribution of district cooling system commissioning years based on the analyzed case studies (n = 32).

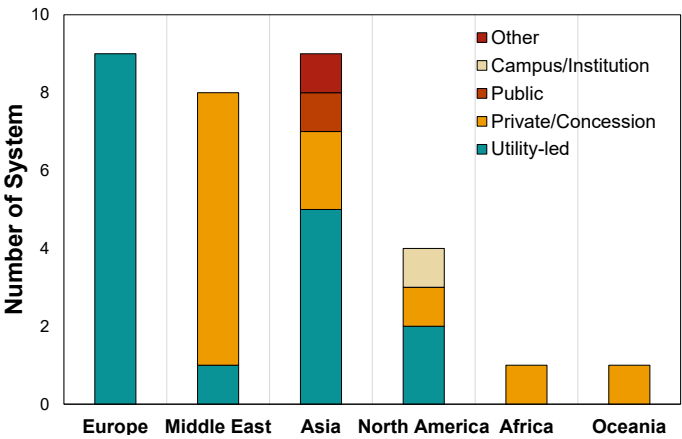


Fig. 2: Ownership and Operational Model by Region

4. Implications for Solar-Integrated Urban Cooling

The findings have important implications for solar-integrated cooling strategies. Cooling demand typically coincides with periods of strong solar PV generation, creating favorable conditions for integrating renewable electricity into district cooling systems. Centralized cooling plants also enable the deployment of chilled-water or ice-based thermal storage systems that decouple cooling production from demand and allow flexible system operation. Utility-led district cooling systems, common in Europe, may facilitate coordination between cooling networks and electricity grids, supporting renewable energy integration and demand-side flexibility. In concession-based systems, typical in the Middle East, regulatory frameworks and tariff structures may play a critical role in incentivizing renewable integration and flexible operation. Overall, district cooling systems represent a promising infrastructure platform for solar-based urban decarbonization. However, the pathways for integration depend strongly on regional governance structures, climatic conditions, and technological configurations. This study contributes a comparative global dataset and analytical framework that supports urban planners and energy system designers in identifying regionally appropriate strategies for deploying solar-integrated district cooling systems.