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Flexible Demand Management Using District Cooling Systems for Smart Grid Optimization in Saudi Arabia

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Abstract-** District cooling systems (DCSs) are often considered efficient alternatives to individually installed air-conditioning, however, their importance for providing flexibility to power systems has not been sufficiently addressed in the planning of hot climates. This review looks at how chilled water and ice storage, predictive control, digital sensing, variable cooling prices, the thermal inertia of buildings and coordination with renewable energy can make DCSs dispatchable demand-side resources for smart-grid optimization in Saudi Arabia. A structured integrative review of 30 peer-reviewed publications published from 2020 to 2025 was conducted, covering technical, economic, environmental, comfort and implementation aspects. Statistical pooling was not carried out as the system scopes and performance indicators vary widely across the studies. The literature shows that operational rescheduling, storage dispatch, model predictive control, and demand-response coordination can both reduce peak electrical demand and lower operating costs while at the same time improving the use of renewable energy. Saudi-specific studies also indicate that cooling demand is very sensitive to the properties of the building envelope, the climate zone, the accuracy of the forecasts, and the indoor set-point policy. The review suggests a layered flexibility architecture that connects buildings, thermal networks, plant equipment, cold storage, digital frameworks, and grid signals. It concludes that when deploying district cooling in Saudi Arabia the priority should be given to interoperable telemetry, dispatch based on forecasts, explicit comfort constraints, time varying incentives, and field validation during periods of extreme heat. District cooling should therefore be regarded not only as an efficient infrastructure but also as a controllable thermal battery capable of helping to balance the grid and assisting with urban decarbonisation.

I. INTRODUCTION

A key problem for power systems in hot regions is that peak cooling demand coincides with periods when commercial activity, high outside temperatures, and reduced thermal equipment efficiency already stress power networks. Saudi Arabia is particularly relevant because air conditioning affects summer electricity demand patterns, required investment, and the level of operation utilities must maintain. Evidence from residential areas indicates that buildings account for a large share of the country's total electricity consumption and that improved building-envelope design can reduce requirements (Alaboud and Gadi, 2022). Results from Saudi Arabia show thatHVAC demand varies across climate zones because of differences in thermal properties, solar radiation, and building construction methods, and building construction methods (Farouk et al., 2022; Alqahtani et al., 2024). The smart grid challenge is therefore not to produce more electricity, but to shift when electricity for cooling is consumed.

District cooling delivers a promising link among thermal comfort and electrical flexibility. Rather than each building reacting separately to changes in weather and occupancy, a central plant can combine the various cooling requirements, run high-efficiency chillers, optimize pumping and temperatures, and store cooling for later use. Thermal energy storage (TES) alters the relationship over time between electricity consumption and the provision of cooling. A chiller can make chilled water or ice during a period when electricity prices are low or when renewable energy is abundant, and then the network can supply the buildings from storage when a subsequent peak occurs on the grid. This separation turns cooling from a load that is mostly simultaneous with electricity use into a resource that can be partly dispatched. Case studies have demonstrated that storage scheduling alone can be a major driver of energy consumption, cost and emissions, without the need to replace any major equipment (Anderson et al., 2021), while techno-economic studies have shown that optimal sizing and dispatch of storage can impact the plant capacity, as well as provide extended asset value (Mazzoni et al., 2021).

The review framework was informed by the demand-side-management architecture proposed by Saleem et al. (2023) Saleem and others (2023) describe smart energy management as an integration problem that includes immediate monitoring, communication, optimization, and load control. As a proof of concept for a controllable load they use air-conditioning and show the practical significance of closing the loop between sensing and action. In the case of district cooling the same approach can be applied to go from individual devices up to an urban thermal network: the meters and sensors keep track of demand, the forecasts estimate the cooling needs in the near term, an optimisation stage co-ordinates the chillers, the pumps and the storage, and the control commands alter the behaviour of the plant or of the building. This review changes its aim from focusing on control at the device level to assessing DCSs as grid-interactive flexibility assets for Saudi Arabia.

Recent research is strong but disparate. The behavior of the thermocline, sensible and latent cold storage, and commercial operating conditions for physical storage were studied (Abd Majid et al., 2020; Shao et al., 2020). The solar-assisted design, plant topology, chiller configuration and network connection and joint design-operation decisions were optimized (Alghool et al., 2020; Neri et al., 2022; He et al., 2023). Digital control studies integrated forecasting, physics-based models, machine learning and model predictive control (Jia et al., 2022; Kim et al., 2022; Tang et al., 2023). The cooling demand response was studied as an economic and operational resource, including price-mediated user response and explicit extreme-heat resilience (Zhu et al., 2024; Wang et al., 2025). No synthesis has linked these areas in Saudi Arabia with comfort and climate constraints.

The study looks at that gap. Flexible demand management is defined as the coordinated adjustment of electrical input, cold production, stored cooling, hydraulic operation, building pre-cooling, and acceptable set-point variation in response to signals from the grid, relating to price, renewables, weather, and occupancy. The key question is not whether district cooling is efficient on its own, but rather under what technical and institutional conditions it can offer measurable flexibility to the Saudi power system. The review thus assesses the evidence using five areas of focus: load shifting, renewable alignment, economic dispatch, occupant comfort, and functional resilience. The synthesis of the findings helps to guide research projects, pilot schemes, and policy decisions.

II. AIM, OBJECTIVES AND REVIEW QUESTIONS

The purpose of this review is to carry out a critical evaluation of the way in which district cooling can function as a flexible resource on the demand side for the optimisation of smart grids in Saudi Arabia. The review is guided by five objectives: the first is to identify the physical and digital mechanisms which give rise to cooling flexibility; the second consists in comparing the various optimisation and control methods that are appropriate for use in hot-arid conditions; the third involves looking at how the characteristics of buildings and the climate in Saudi Arabia affect the range of available flexibility; the fourth is to synthesise the evidence regarding the trade-offs involving cost, peak demand, carbon emissions and comfort; and the fifth is to put forward a practical architecture together with a research programme for the deployment of grid-interactive district cooling systems. The review seeks to find out which of the flexibility mechanisms are technically mature, which of the performance indicators are most relevant to decision-making, and which of the existing knowledge gaps need to be addressed before system operators can count on district cooling as a reliable grid service.

III. REVIEW METHODOLOGY

An integrative review based on a formal approach was chosen since the subject area involves various fields such as thermal engineering, building science, power-system demand response, controls, optimization, and urban energy planning. A traditional meta-analysis would not be suitable because the studies cited differ in regard to plant capacity, storage media, climate, tariff structures, objective functions, assumptions about comfort, and the reference baselines used. The method instead involves a clear process of evidence synthesis in which each paper is looked at in terms of its system boundary, the decision variables, the control method, the measured or simulated outcome, and its transferability to the conditions in Saudi Arabia. This

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is similar to the comparative gap analysis in the attached paper but has been adapted for the purpose of a review rather than an experimental application (Saleem et al., 2023).

The search was limited to journals published between 2020 and 2025. The studies under consideration were found by means of scholarly indexing and by checking the publisher's records, using combinations of the terms "district cooling", "thermal energy storage", "cold storage", "demand response", "cooling flexibility", "model predictive control", "smart grid", "optimization", "Saudi Arabia", "hot arid", and "cooling load prediction". In order to be included a study had to make a peer-reviewed contribution and have to provide direct evidence relating to at least one of the four areas: DCS design or operation, cooling-side demand response, digital energy management, or Saudi/arid-climate cooling behaviour. Exclusion from the study took place if the cooling was only incidental, if the controllable demand was not dealt with, or if the metadata could not be verified. The final set of publications includes 30 articles that have either a verified DOI or publisher metadata. All the sources listed in the reference section are within the 2020 to 2025 period requested.

The studies were qualitatively assessed according to six analytical categories: flexibility mechanism, temporal horizon, optimization technique, grid-facing objective, user/comfort constraint, and evidence type. The flexibility mechanisms covered chilled-water or ice thermal energy storage, chiller sequencing, variable pumping, adjustment of the supply temperature, pre-cooling, the use of building thermal mass, dynamic pricing, and coordination with renewable energy sources. The temporal horizons extended from seconds-to-minutes supervisory control through day-ahead scheduling to long-term design optimization. Evidence was divided into field demonstration, experimental testing, calibrated simulation, numerical optimization, or review and synthesis. This approach assures that high-performing simulation results are not regarded as equivalent to genuinely operationally proven grid services.

Triangulation was used instead of simple ranking. In the first place, the direction of the effect was compared between the studies to see if a given strategy decreased peak load, total electricity consumption, operating costs, emissions, or discomfort. In the second place, the numerical results were kept along with their original setting and were not combined across cases that were not compatible. Third, Saudi relevance was evaluated by referring to local evidence concerning building envelopes, climate zones, the prediction of cooling loads, and the performance of residential systems (Alayed et al., 2022; Irshad et al., 2022; Al-Abduljabbar et al., 2023). Fourth, the most recent studies on DCS-demand response examined whether the proposed architecture remained credible when faced with variation from clean energy sources and extreme heat (Huang et al., 2025; Wang et al., 2025). Thus, the method attains a balance between engineering specificity and reasonable prudence regarding generalization over different contexts.

IV. SAUDI COOLING DEMAND AS A FLEXIBILITY RESOURCE

The flexibility in cooling in Saudi Arabia starts with the thermal characteristics of the buildings, not with the chiller plant. A DCS is able to shift electricity only when both the buildings and the storage system can accommodate a separation between the production and the delivery of cold. Studies carried out locally show that this range of flexibility differs significantly according to the type of construction and the climate. Alayed et al. (2022) show that thermal mass can either improve or deteriorate energy performance depending on the control and boundary conditions, which cautions against the assumption that more substantial construction always results in useful storage. Alqahtani et al. (2024) reach a similar conclusion by identifying climate-zone-specific relationships among thermal diffusivity and cooling energy, meaning that one demand-response model should not be used for Riyadh, Jeddah, Abha, and Tabuk. Pre-cooling windows and the rebound risk must therefore be adjusted locally.

Envelope efficiency and flexible operation should be seen as complementary rather than opposing strategies. Alaboud and Gadi (2022) find a great deal of capacity for reducing cooling load by improving the thermal design of residential buildings, and Al-Abduljabbar et al. (2023) show that roofs, columns, and slabs can make major contributions to the cooling load as well as indicating that insulation considerations should not be limited to the external walls. When the baseline load is lower, the capacity of the plant is reduced and the period during which stored cold or thermal inertia can maintain comfort is lengthened. On the other hand, an inefficient envelope may result in a large nominal "flexible load" which vanishes quickly since the indoor temperature rises rapidly when active cooling is stopped. Flexible demand must therefore be measured as sustainable shiftable load within comfort limits, not simply as the electrical demand before control is applied.

The need for forecasting is also specific to Saudi conditions. In hot-arid climates, the demand for cooling is greatly influenced by the outdoor temperature, solar radiation, humidity in coastal regions, occupancy, and the building's thermal profile. Irshad et al. (2022) demonstrate that model-based approaches are able to achieve good performance when predicting both heating and cooling loads for the case study in Dhahran. It is important to have accurate forecasts since decisions regarding storage and chiller operation have to be taken before the full load is known. Over-forecasting may result in unnecessary charging and losses in storage; under-forecasting might leave insufficient cold stored and could cause chillers to operate during the period of high electricity demand. Forecast-error margins and a reserve policy should therefore be included in every flexibility service rather than depend on a single deterministic load profile.

Thermal comfort sets a strict limit on flexibility. Souayfane et al. (2022) show that, in a subtropical desert environment, weather-clustered optimisation can lower cooling costs at the same time as managing thermal discomfort. Farouk et al. (2022) also prove that phase-change materials can reduce HVAC power demand in various climate areas of Saudi Arabia, indicating that passive and distributed thermal storage might increase the duration of flexibility available to a DCS. The pertinent operational principle is regulated thermal buffering: it involves pre-cooling when low-carbon or low-cost electricity is available, permitting the temperature to vary within an acceptable range for a limited period, and avoiding a simultaneous rebound when the normal set-points are resumed. Thus, comfort becomes a state variable in grid optimisation, and not just a check carried out after the fact.

The Saudi deployment also have to take into account the increasing cooling stress and the carbon intensity of marginal generation. Khourchid et al. (2023) find that climate change can have a significant effect on cooling demand in building situations in arid areas, whereas solar power can greatly cut down the emissions associated with cooling in their life-cycle analysis. Krarti et al. (2023) estimate that there will be very large national savings in electricity and carbon as a result of using more efficient hybrid cooling technologies throughout the Saudi residential sector. Although these studies do not directly assess DCS demand response, they do show why flexible cooling is strategically important: future planning should at the same time limit peak capacity, improve end-use efficiency, and ensure that electrical consumption matches cleaner generation. DCSs can make a contribution to all three aspects provided that control is based on grid conditions rather than on plant efficiency alone.

V. FLEXIBILITY MECHANISMS IN DISTRICT COOLING

The simplest method of separating cooling service from electrical demand is cold thermal storage; chilled-water tanks provide simple storage when the basic operating conditions are met. Although ice and other phase-change systems can store more energy in a smaller amount of space, they are more difficult to manage and may reduce chiller efficiency when they are being charged. Abd Majid et al. (2020) note that the quality of the thermocline and the charging performance influence the amount of usable cooling that a large tank can provide. Shao et al. (2020) discover that the selection of the storage medium and the flow conditions can considerably affect the energy capacity in commercial situations. In the case of smart-grid applications, the rated storage capacity is not sufficient; the usable capacity has to take into account stratification, state of charge, efficiency, discharge limits, and supply temperature.

Storage becomes significant for the grid when its operation is aligned with the existing electricity conditions. Anderson et al. (2021) discovered that by

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adjusting the schedules of the cold storage, chillers, and cooling towers within a campus DCS, electricity consumption was reduced by 38% in their study, together with lower costs and less emissions. Mazzoni et al. (2021) demonstrate that improving latent storage can influence chiller sizing and economic operation, indicating that flexibility has an effect on both daily operations and long-term planning. Tang et al. (2023) apply load prediction, a physical system model, and model predictive control to an ice-storage DCS, and report an 8% reduction in operating costs over a two-month period when compared with standard methods. The studies mentioned indicate that storage provides flexibility and that forecasting and optimization are necessary in order to convert such flexibility into actual grid value.

Even if the amount of storage is limited, improvements in cooling and hydraulic aspects can allow greater flexibility. Hinkelman and others (2022) created a model of an actual district system and discovered annual reductions in energy use, cost, and carbon emissions by adjusting the set-points, selecting the equipment, and improving the pump controls. He and colleagues (2023) applied multi-objective optimization to demonstrate that the plant's configuration and its operating objectives should be addressed together, rather than based on fixed assumptions about the equipment. Neri and co-authors (2022) found that the network design, the sizing of the pipes, and the choice of connections can be enhanced by means of mixed-integer and heuristic procedures. A Saudi plant is going to have to be controllable and efficient when operating at part load if it is to be flexible; otherwise, shifting the demand simply shifts the inefficient operation from one time to another.

Predictive and learning-based control methods provide an extra degree of flexibility. Jia and colleagues in 2022 combined deep learning with physics-based models in order to optimize ice storage and thus obtained an 11.2% improvement in cost savings. Kim and co-authors in 2022 demonstrated in real-world applications that the use of model predictive control on a large chiller plant equipped with thermal energy storage led to a reduction in peak demand and greenhouse-gas emissions of approximately 10%, and decreased excess photovoltaic generation by about 25%. The key benefit of model predictive control is that it adjusts its decisions as the forecasts, the level of storage, the weather conditions, and the state of the grid change, rather than following a fixed daily schedule. For systems in Saudi Arabia, this method is superior to static night charging since both solar generation and peak periods vary with the season. The ability to respond additionally extends the flexibility beyond the limits of the plant. Zhu and others in 2024 developed a model of a District Cooling System incorporating ice storage with the aim of achieving demand response and found that operating costs were reduced by 11.17% while at the same time improving computing performance via a per-unit formulation. Wang and co-workers in 2025 directly coordinated the supply from the District Cooling System with user demand during periods of extreme heat by means of time-varying cooling prices and taking into account the thermal inertia of the buildings. In their case study they achieved a 12.1% reduction in peak cooling load and an 8.57% reduction in the users' cooling costs while still preserving comfort at a specified baseline. This is a key conceptual point: a District Cooling System is not restricted to deciding when the chillers should operate; it is also able to influence when customers request cooling, provided that price signals, automation, and comfort safeguards are all designed in conjunction with one another.

Coordinating renewable energy brings in an extra element of flexibility. Alghool et al. (2020) demonstrate that solar-assisted district cooling, storage, and the sizing of equipment can all be optimized simultaneously. Huang et al. (2023) integrate ice storage with demand response in a grid-free district cooling system and discover additional primary-energy benefits from coordinating demand. Huang et al. (2025) go further by including renewable energy, storage, smart demand response, and decarbonization in their model, which shows significant carbon reductions and a 6.1% decrease in cooling load when demand response is implemented. In Saudi Arabia, where both solar power generation and the demand for cooling are high during the day, it might be more advantageous to carry out midday 'solar soaking' rather than charging only at night. The control strategy should be based on the actual value to the grid, not simply on the assumption that off-peak electricity always occurs after midnight.

VI. A SMART-GRID OPTIMIZATION ARCHITECTURE FOR SAUDI DCS

A five-layer structure can be employed by a Saudi grid-interactive District Cooling System The first layer consists of the building interface, and this includes smart thermal meters, indoor temperature sensors, data on occupancy or schedule, controllable valves, and building-management systems. The second layer is the thermal network, in which the manner in which cooling is delivered is determined by differential pressure, the supply and return temperatures of the chilled water, the flow rates, and the network limits. The third layer is the plant, and it comprises chillers, pumps, cooling towers, heat exchangers, and thermal energy storage. The fourth layer involves digital intelligence and this covers forecasting, system estimation, optimization, anomaly detection, and cybersecurity. The fifth layer is the grid market, and it offers information on tariffs, renewable energy availability, peak alerts, and flexibility requests. Figure 1 depicts these layers as part of a closed feedback system, not as a one-way energy chain.

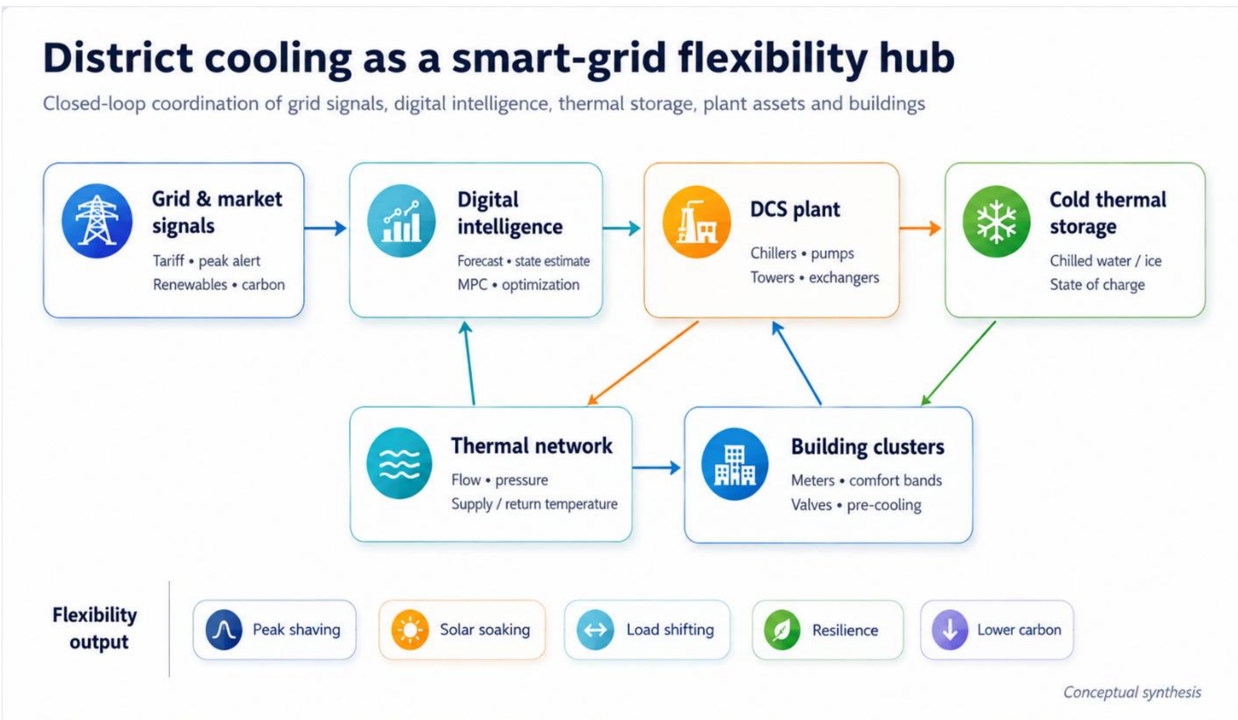

Figure 1. District cooling as a smart grid flexibility hub

This approach applies to the district level the principle of real-time sensing and control developed by Saleem et al. (2023). The smart energy management system proposed by them draws attention to the requirement for two-way communication, cloud-based processing, analytics, and device control. In a DCS, these functions must make use of industrial-grade controls and contain robust local backup facilities. The fast protective loops and important plant sequencing should remain at the edge, whereas more complicated day-ahead forecasting and economic optimisation can be carried out in supervisory or cloud systems. This arrangement guarantees that cooling remains safe during a loss of connectivity and enables coordination at the system level.

Forecasting must provide probabilistic inputs rather than just single-point estimates. Forecasts of weather, occupancy, the thermal state, and price are used to create a rolling plan which estimates cooling demand, the availability of renewable energy, and the risk of grid constraints. The optimizer then determines the chiller's output, whether to charge or discharge the thermal energy storage, the pump set-points, the supply temperature, and any optional building pre-cooling. The goal is to reduce the cost, peak demand, carbon intensity, equipment wear, and discomfort. The constraints involve the chiller's capacity as well as efficiency, the limits on the state of charge of the TES, network hydraulics, minimum supply temperatures, the indoor comfort ranges, and the requirement for reserves. The relative importance of each objective should vary according to the operating mode, for example normal dispatch, renewable absorption, peak emergency, or extreme-heat resilience.

Treat thermal storage and buildings as separate yet co-ordinated sources of flexibility. The central TES has a measurable state of charge and a fairly predictable ability to discharge. The thermal inertia of buildings is less straightforward, as it depends on the occupants and is affected by the climate, although it can reduce the amount of storage required during a peak event. The system should determine two ranges of flexibility: a guaranteed plant-side flexibility and a conditional demand-side flexibility. The first one supports firm commitments to the grid, while the second can be put into use when the forecasts for comfort, occupancy, and rebound permit. This helps to prevent making excessive promises regarding cooling reductions when severe weather occurs. This is not an information-technology add-on. Meter drift, the absence of temperature sensors, poor valve authority, inaccurate plant curves, or delayed communications can cause an optimizer's decisions to be invalid. Commissioning therefore needs to set up a data dictionary, achieve timestamp synchronisation, define measurement uncertainty, carry out sensor health checks, and establish automated fallback rules. Zaw et al. (2023) show that real-time operational optimisation can achieve real efficiency gains in a commercial DCS, but such optimisation assumes that trustworthy live data and actionable set-points are available. For the Saudi pilots, a "measure-control-verify" loop should compare the forecast demand, the commanded flexibility, the delivered cooling, the electrical response, the comfort outcomes, and the post-event rebound after each activation.

Security and interoperability are just as important since grid-interactive cooling connects the utility signals to the major building services. The interfaces must make use of secure communication, provide for access based on roles, employ encrypted channels, and keep the optimization services separate from the safety controls. It is better to use open data models than proprietary ones when there are many building owners, DCS operators, aggregators, and utilities concerned. Interoperability also has an impact on scalability; a pilot that works only with manual engineering at a single plant cannot support flexibility on a city-wide basis. The digital layer should display standard signals such as available upward or downward electrical flexibility, the duration, response time, confidence, thermal state, and recovery requirements.

Figure 2 illustrates the way the system operates over a typical day. Prior to the expected grid peak, the plant can pre-charge the TES and pre-cool certain buildings. When there is a lot of solar power available, the chillers may be operated more in order to use electricity that would otherwise be wasted or which has a low carbon impact. In the evening or at system peak, use of the storage takes place, chiller operation is restricted, and the buildings allow their set-points to relax within the agreed limits. After the event, the recovery is carried out over a longer period to prevent a rebound spike. It should be noted that the figure is conceptual and not based on an actual Saudi load curve, and it is intended to help explain the control steps.

VII. EVIDENCE SYNTHESIS: BENEFITS, TRADE-OFFS AND PERFORMANCE METRICS

The study indicates that a single metric is not sufficient for assessing the flexible operation of a DCS. It is possible for energy efficiency to increase while peak demand rises, and a strategy which reduces costs under a given tariff might not add to a reduction in carbon emissions if it shifts usage to periods of high emissions. Conversely, operating in accordance with renewable energy sources may result in a slight increase in the electricity used by the chillers but will reduce emissions and curtailment. Kim et al. (2022) illustrate the importance of using multiple metrics by providing data on the peak, photovoltaic, and greenhouse-gas effects from MPC, whereas Hinkelman et al. (2022) show the energy, cost, and carbon benefits resulting from improved controls. A evaluation carried out in Saudi Arabia should include information on peak reduction, shifted energy, total electricity, plant efficiency, TES effectiveness, cost, carbon, comfort deviation, response time, forecast error, and rebound.

The economic outcomes are very much influenced by tariffs. As Tang et al. (2023) point out, the value of ice storage varies depending on the time-of-use pricing structure, meaning that a system designed for one kind of tariff may lose its advantages if the price difference between off-peak and on-peak periods decreases. Neri et al. (2024a) indicate that it is notably beneficial to optimise both the design and the operation of a system when the cooling demand extends over a long period, whereas Neri et al. (2024b) show that in certain cases omitting thermal storage can cause the total system cost to increase considerably. Saudi decision-makers should take into account not only plant economics but also tariffs, capacity charges and flexibility payments. Flexibility will, however, be restricted if operators are paid only for the kilowatt-hours of cooling and are not rewarded for avoiding system peaks or for using renewable energy.

The environmental effects will vary according to the type of electricity supply and the technology employed. Kadam et al. (2022) find that hybrid vapor-compression and absorption systems are able to reduce both costs and warming effects as compared with conventional arrangements, thus showing how important it is to select the appropriate supply technology. Khourchid et al. (2023) demonstrate that the energy transition has a major influence on emissions associated with cooling in arid climates. These results support the main point that DCS optimisation should make use of time-varying carbon or renewable signals where possible; it is only beneficial to the environment to shift a megawatt-hour from one hour to another if the power mix changes in a positive way.

Comfort and toughness must stay a clear focus. Marszal-Pomianowska et al. (2024) note that demand response in district heating and cooling is moving toward practical trials. However, business models, rules, customer participation, and operational barriers are still big barriers. Extreme heat makes these problems worse because cooling is needed for health and service continuity. Wang et al. (2025) show that a well-designed comfort penalty can keep indoor conditions acceptable while cutting peak cooling. Saudi programs should set event-specific limits for temperature drift, maximum duration, vulnerable sites, override rights, and post-event recovery. Hospitals, data centers, hotels, homes, and offices should not all have the same flexibility contract.

Table 1 compares key studies by mechanism and lesson, while Table 2 turns the findings into a Saudi implementation roadmap. The best evidence supports a step-by-step approach: first, optimize existing controls; second, add or improve TES; then, bring in forecast-driven grid services and customer-side response. New DCS projects can go further by co-optimizing network layout, storage size, plant capacity, and digital controls from the start. Flexibility should be seen as a measurable service with clear rules for baseline, activation, verification, and settlement.

Table 1. Representative evidence on district-cooling flexibility and transferability to Saudi smart-grid operation.

Study	System / method	Flexibility mechanism	Reported evidence	Transferable Saudi lesson
Anderson et al. (2021)	Campus DCS; exergy + TRNSYS	TES and equipment rescheduling	38% electricity reduction; cost and CO_2 savings in case study	Operational schedules can unlock value before major retrofit
Mazzoni et al. (2021)	DCS microgrid; MIQP	Latent cold TES	Peak shaving affects chiller sizing and NPV	Co-optimize storage footprint, capacity and dispatch
Hinkelman et al. (2022)	Real DCS; Modelica	Set-points, pumps, economizer	Annual energy, cost and carbon savings	Calibrated plant/network models improve control credibility
Kim et al. (2022)	Large chiller plant + TES; MPC	Forecast-driven TES dispatch	~10% peak reduction; ~25% excess PV reduction	Use grid and renewable signals, not fixed night charging
Jia et al. (2022)	Ice TES; deep learning + physics	Predictive optimization	11.2% additional cost saving	Hybrid models can balance prediction speed and physics
He et al. (2023)	DCS; multi-objective optimization	Configuration + operation	Lower cost and electricity in modeled case	Use multi-objective KPIs rather than cost only
Tang et al. (2023)	Ice-storage DCS; MPC	Load prediction + ToU dispatch	~8% operating-cost reduction	Tariff design strongly affects storage value
Zaw et al. (2023)	Live commercial DCS	Real-time holistic optimization	~10% efficiency improvement; multi-year validation	Field telemetry and actionable control are essential
Zhu et al. (2024)	DCS + ice storage; DR optimization	Grid-responsive storage dispatch	11.17% operating-cost reduction	Computational tractability matters for large plants
Wang et al. (2025)	DCS under extreme heat; game-based DR	Price + building thermal inertia	12.1% peak cooling reduction; 8.57% user cost reduction	Comfort-constrained customer response can complement TES

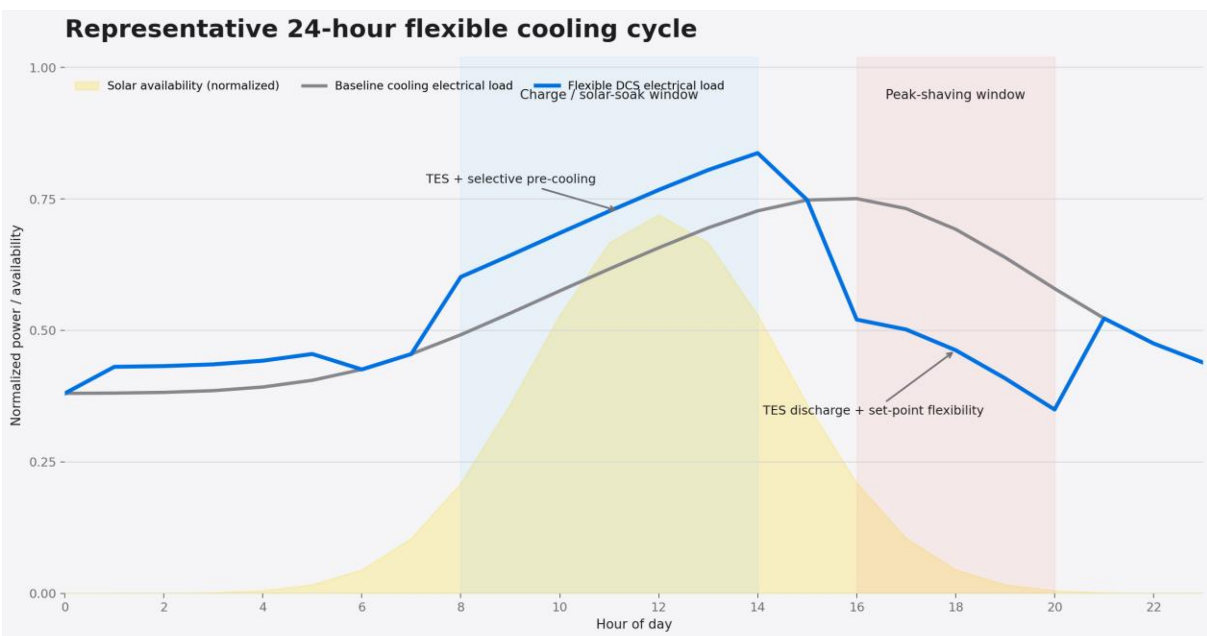

Figure 2. Representative 24-hour flexible cooling cycle.

VIII. RESEARCH GAPS AND SAUDI IMPLEMENTATION ROADMAP

There are four evidence gaps that are decisive. First, there is a lack of field data from Saudi Arabia at the district level regarding demand response. Although studies of individual buildings are useful, they cannot take the place of actual measured electrical responses from the demand control system, the state of the storage, the network temperatures, comfort levels, and the rebound that occurs during real grid events. Second, most of the optimization studies assume that the models are accurate and that the assets are controllable; future pilot projects should assess performance under conditions involving sensor errors, communication failures, forecast bias, fouling, and changing occupancy. Third, the grid value is generally deduced from tariff information rather than being tested against specific signals from the Saudi power system. The pilots should compare dispatch based on prices with dispatch following renewable energy, dispatch aimed at avoiding capacity shortages, and dispatch aimed at meeting emergency peak demands. Fourth, customer behaviour and the governance arrangements are not well defined, especially in the case where a demand control system caters to multiple owners who have different comfort and operating priorities.

There are three stages in a practical roadmap. In the first stage observability is set up by means of high-quality metering, calibrated plant curves, short-term load forecasting, and a verified baseline model. In the second stage controllability is established through automated chiller sequencing, pump and temperature optimization, TES condition estimation, and safe supervisory control. In the third stage grid interaction is achieved by making day-ahead flexibility offers, activating in response to events, carrying out customer-side pre-cooling, verifying performance, and handling settlement. The order of the stages is important since taking part in the market before the system is operationally ready may result in unreliable commitments. Each stage must be assessed over at least one complete cooling season and should include extreme-heat days, not just mild commissioning periods.

Research should also make a distinction between energy flexibility and capacity adequacy. Although a plant may be able to shift several megawatt-hours it may still be impossible to promise a particular megawatt reduction over a two-hour period if the storage is only partly depleted or if the buildings are already close to their comfort limit. Saudi studies in the future therefore ought to publish flexibility curves which show the available power reduction as a function of duration, the initial state of the thermal energy storage, the forecast temperature, the building class, and the recovery requirement. These curves would then enable grid planners to compare the flexibility of DCS with that of batteries, generators, or other demand-response resources in a consistent manner.

Regulations and control systems should be designed together. If incentives only reward cooling sales, if customers cannot join automated replies, or if data rights are unclear, then technical solutions alone will not provide reliable flexibility. Demonstration projects should include clear contracts, comfort guarantees, cybersecurity requirements, transparent measurement and verification, and rules for sharing grid-service revenue. The aim is not to maximize curtailment, but to ensure flexibility that is repeatable, auditable, and keeps cooling as the main priority.

Table 2. Saudi implementation roadmap for grid-interactive district cooling.

Domain	Priority action	Core KPI	Primary risk	Mitigation / evidence need
Observability	Calibrate thermal/electrical meters, plant curves and TES state	Data completeness; forecast RMSE	Bad data drives wrong dispatch	Sensor health checks; timestamp alignment; commissioning tests
Plant control	Automate chiller sequencing, pumps and supply temperature	kW/RT; COP; response time	Efficiency loss at part load	Validated component maps and safe fallback logic
Thermal storage	Estimate usable, not nameplate, flexibility	MW × duration; state of charge	Stratification / charging losses	State estimation and periodic capacity tests
Building response	Pre-cool and relax set-points within contract	Peak kW; °C-hours discomfort	Occupant dissatisfaction; rebound	Building-class comfort bands and staggered recovery
Grid interface	Receive tariff, carbon, renewable or peak signals	Delivered MW vs committed MW	Unclear dispatch value	Pilot multiple signal types and settlement methods
Cybersecurity	Separate safety control from external optimization	Availability; authenticated events	Remote-control vulnerability	Role-based access, encryption, local fallback
Verification	Baseline, activate, measure and settle every event	Baseline error; persistence; rebound	Overstated flexibility	Independent M&V protocol across full cooling season

IX. CONCLUSION

District cooling can contribute to the optimisation of Saudi Arabia's smart grid by linking large and climate-sensitive electricity demand with thermal storage, centralised controls, and a group of buildings. The evidence examined between 2020 and 2025 indicates that significant flexibility can be achieved through storage dispatch, plant optimisation, model predictive control, the thermal inertia of buildings, dynamic cooling prices, and coordination with renewable energy sources. Yet the technical potential should not be taken to mean that there is reliable grid capacity. Useful flexibility is limited by the state of the storage, forecast errors, network hydraulics, equipment efficiency, indoor comfort, and rebound effects. Saudi Arabia's approach to deploying district cooling therefore needs to shift from one that focuses only on efficiency to adopting a framework based on measured flexibility which includes local forecasting, interoperable telemetry, resilient control, clear comfort limits, and verification following each event. The most realistic short-term route is to optimise the existing DCS assets, determine the extent of their flexibility, and then integrate them with grid or market signals via a series of pilot projects. Using this method, district cooling can act as a controllable thermal battery: taking in electricity when it is in abundance or low in carbon emissions, reducing demand when the grid is under pressure, and continuing to provide cooling services under the increasingly severe hot weather conditions.

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