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Design of heat-resilient housing in hot-arid regions

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ABSTRACT

Extreme heat events in urban areas increasingly challenge the capacity of electrical distribution systems to serve building cooling equipment under peak loads and, when power is interrupted, the thermal response of buildings that can delay the onset of dangerously high indoor temperatures. The design of new buildings and their operation can mitigate the risks of intense heatwaves, but architects and planners face a myriad of choices about what measures to select, and how best to estimate their individual and collective performance. To aid the design and operation of heat-resilient buildings, this paper takes a multidisciplinary approach that is novel in two key aspects. First, it evaluates the individual and aggregated impact of factors associated with architectural and urban design, equipment technologies, and human behavior. Second, its valuation metrics include the magnitude of peak electrical load, appropriate for assessing active measures aimed at reducing peak power, and the time after a power outage for indoor temperatures to reach levels associated with heat stress, an indication of the efficacy of passive (no power) measures. The application of the method in the Middle East North Africa (MENA) region, where growing populations and demand for space cooling make it particularly relevant, relies on knowledge of building codes and local construction practice. Single-factor testing shows that pre-cooling produces the largest reduction in peak electrical load during a simulated four-day heatwave, followed by building adjacency, maximum temperature set point and equipment loads. A combination of all considered factors reduces peak power by 70% and shifts the reduced peak to a later hour. In response to a power outage, the incorporation of architectural factors (roof, wall and window thermal resistance above code minima, increased thermal mass, reduced glazing solar heat gain coefficient and window shading) reduces the time above a Heat Index of 28 °C (caution) in a week-long test period in which the power failure occurs at hour 40 from 119 to 53 h. The presented methodology applies broadly to other building types and to regions affected by very hot weather.

1. Introduction

1.1. The urgent and unique challenge of resilience to heatwaves

Heat waves have caused more deaths globally than any other hazard over the last 100 years [1]. According to the Intergovernmental Panel on Climate Change (IPCC), "warming trends" and "extreme heat" factor into 80 % of key climate-change risks for North Africa and the Middle East region (MENA) [2]. The MENA region, which this research uses as a case study, will be home to 750 million people by 2050, with the tropics holding half the world's population by 2030 [3,4]. Scientists predict heat waves will become relatively longer, more frequent, and more intense due to climate change [5]. More troubling, heat waves in Africa, the Middle East, and the Indian Subcontinent will begin breaking through the 35 °C wet-bulb temperature threshold above which humans can no longer regulate body temperatures [6]. As a result, heat-stress mortality risk is estimated to increase in Africa by 3–7 times between 2040–2070 under a greenhouse gas (GHG) concentration pathway that stabilizes radiative forcing at no more than 4.5 W/m^2 (RCP4.5) [7]. As is the case with other disasters, risk from heat stress is expected to disproportionally hit poorer nations and lower resource households the hardest due to a lack of air-conditioning and other resources used to mitigate heat strain [8] and requires attention from the perspectives of both public health and urban planning [9].

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Fig. 1 shows projections of dry-bulb temperatures and Heat Index for Kuwait City. Each plot includes a typical meteorological year (TMY) that is synthesized from recorded data over a 15-year period (chapter 5.3 in [10]) and four projections for 2050 and four for 2080 derived from Shared Socioeconomic Pathways (SSPs) defined in the IPCC Sixth Assessment Report's Synthesis Report [11] and Physical Science Basis [12]. Also included are six years of historic data, spanning decades back to 1975. Heat Index, used is this paper to quantify heat stress, is a "feels like" temperature index that accounts for both dry-bulb temperature and relative humidity [13]; the equivalent temperature concept can be extended to consider the impact of wind speed, radiation and barometric pressure [14].

Heatwaves are a unique form of climate hazard. Unlike hurricanes, fires, and many other disasters, heatwaves are difficult to avoid in advance due to their vast spatial scale (regional or continental) and their short prediction times. Heatwaves can create complex cascading multi-hazards across entire cities due to increased cooling demand and decreased electrical power production and distribution efficiency as temperatures increase [15]. This often leads to grid failures through brownouts (reduced power), rolling blackouts (selective power outages), or even total blackouts (widespread power outage) [16]. Reduced power availability during heatwaves translates to partial or total cooling capacity losses and can rapidly shift residents from a state of relative safety to impending heat stress [17]. As a result, resilience to extreme heat requires two sets of strategies, one to maintain grid stability whenever possible – what we will refer to as active resilience – and one to maintain safe indoor conditions if a grid failure occurs – what we refer to as passive resilience. Some adaptations benefit both active and passive resilience while others benefit one while harming the other. Likewise, it has already been shown that climate-change mitigation strategies aimed at reducing total yearly energy use can decrease resilience [18].

Power grid stability and resilience across a city are highly interdependent [19]. Households and businesses that can reduce power consumption during heat waves (often high-income households) benefit entire communities, including the most vulnerable, because demand is aggregated and power supplies are ultimately shared by all customers in a service territory. This interdependency is less so the case in flooding or

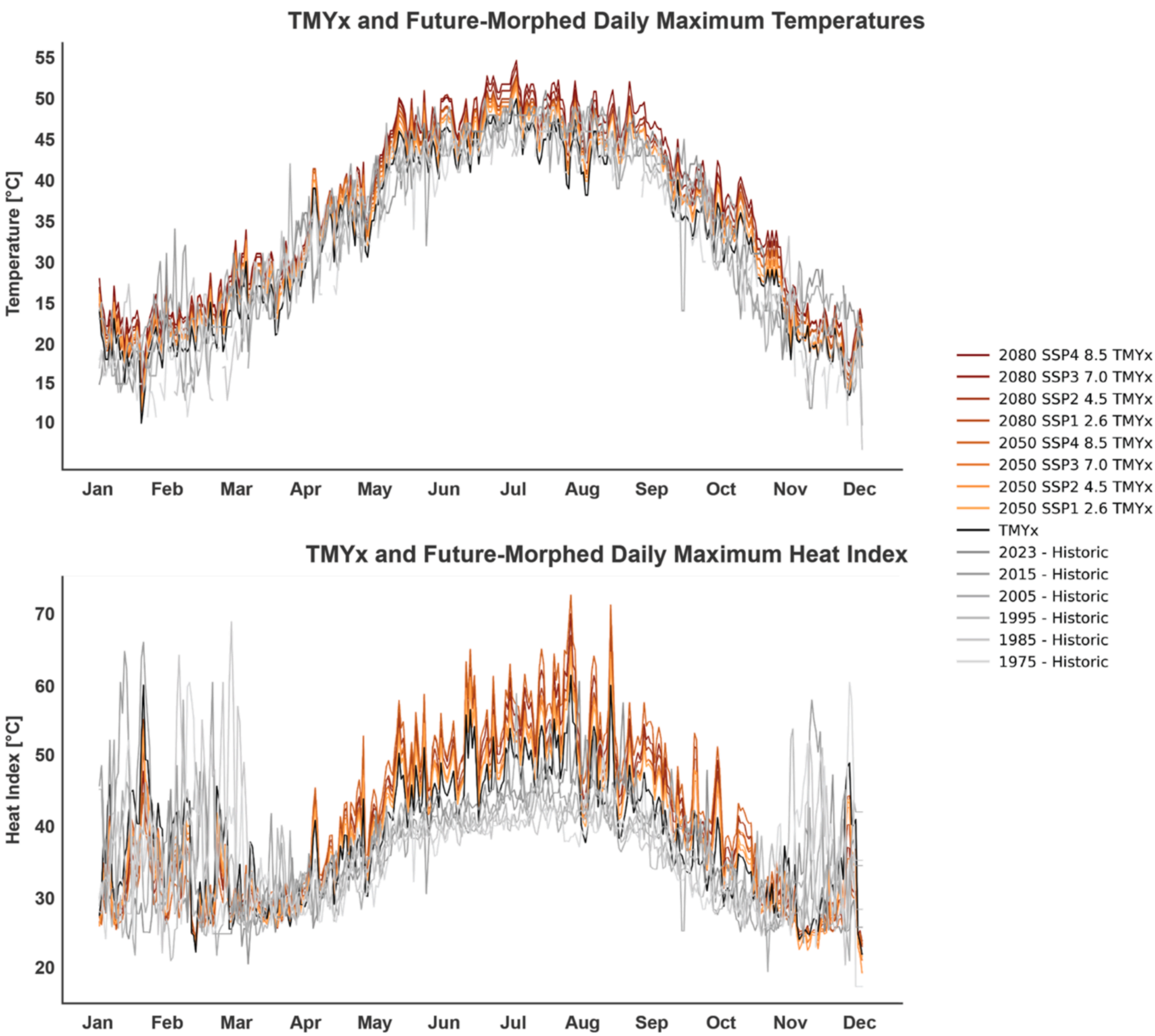

Fig. 1. Projections of future dry-bulb temperature and Heat Index in Kuwait City. Shown are projections for GHG concentration pathways, for both 2050 and 2080, based on a current typical meteorological year. Heat Index projections are based on temperature and relative humidity. Also shown are historic data at decadal intervals, which reveal spikes in Heat Index during days of extreme heat and humidity.

hurricanes, where less exposed households have no direct way to help protect those in more exposed areas from being harmed. The characteristics of heatwaves, therefore, bring both unique challenges *and* unique opportunities for mitigation, which requires rigorous research to dissect and understand.

1.2. Overview of current research and contribution

The study of urban- and architectural-scale heat resilience is relatively new as a discipline and undergoing active development. A broadly agreed upon definition of heat resilience is yet to be established [20]. However, recent scholarship identifies common definitions for heat resilience across the literature and proposes a definition and framework for cooling resilience criteria [21]. Published research in this nascent field understandably focuses on in-depth consideration of one or two specific areas of heat resilience, among them:

Active heat resilience to protect grid operation, focused on residential [22] and commercial [23] buildings.
Passive heat resilience to maintain safe indoor conditions during a power outage ([15], previously described; and [24,25,26,27,28] which, in order, assess domestic indoor overheating through the lens of public health, focus on high-rise residential buildings, rank a set of interventions in U.K. dwellings, assess the performance of older housing in two U.S. cities, and distinguish vulnerable and non-vulnerable households).
Urban scale **microclimate mitigation** ([29], a review of the state of the art in urban-heat-island reduction; [30], a case study in a European city; [31]; and [32] urban-planning strategies for microclimate mitigation and adaptation).
Metrics for measuring heat resilience [33].

While a comprehensive study that addresses all of these topics simultaneously is not feasible, this paper addresses the following key

Table 1
Parameter baseline and tested value.

			Baseline Scenario		Tested Value		
Category	*#*	*Parameters*	*Value*	*Notes*	*Value*	*Notes*	*Units*
Urban	1	Floor-to-floor height	3.25	1, 6	2.75	9	m
	2	Number of building stories	3	1, 6	1	9	number
	3	Basement (lowest level below ground level)	None	1, 5, 6	Yes	7	_
	4	Tree shading	None	2	EW	7	_
	5	Footprint shape and building orientation	1:1.5; North-South	1, 6	1:1	7	ratio, axis
	6	Neighboring buildings to each side and behind	None	2	Yes, SEW 2 m	7	m_
	7	Street depth (house front to house front)	20	2	15	7	m
	8	Shared party walls on two sides	None	2, 6	E, W	7	_
Architectural	9	Roof Insulation (U-value)	0.18	3	0.12	8	W/m^2C
	10	Wall Insulation (U-value)	0.39	3	0.15	8	W/m^2C
	11	Internal thermal mass (inboard of insulation)	285	3	380	7, 9	kJ/m^2C
	12	Window-to-wall ratio	15	3	10	10	%
	13	Window Insulation (U-value)	3.61	3	0.8	8	W/m^2C
	14	Window solar heat-gain coefficient (SHGC)	0.4	3	0.25	8	SHGC
	15	Fixed window shading	None	2	Border .5m	7	m
	16	Envelope air-tightness (infiltration rate)	0.00015	3	0.0001	8	$m^3/s/m^2$
	17	Roof and wall albedo	0.7	3	0.9	7	% reflectivity
Technological	18	Air conditioning coefficient of performance (COP)	4.5	3	6.5	7	COP
	19	Air conditioning set-point (constant)	23	1	26.5	7	C
	20	Ventilation heat-recovery system (latent + sensible)	None	2, 4	0.8, 0.8	8	%_
	21	Automated window shade (90% opacity)	None	2, 4	Yes		%_
	22	Lighting load (at full-occupancy)	5	3	3	7	W/m^2
	23	Equipment and plug load (at full-occupancy)	13.4	4	8	7	W/m^2
	24	Pre-cooling of house (variable set-point during day)	None	5	3 (+/-)	7	C
	25	Layered set-point (by floor level)	None	5	23, 26.5, 32	7	C/floor
Occupant + Human Comfort	26	Occupant density	0.013	4	0.002	7	$persons/m^2$
	27	Occupant schedule	7AM-3PM	1	All Day	7	hours
	28	Emergency ventilation schedule	Occupancy based (10l/s)	5	12 l/s at night, 0 l/s for 4 hours in afternoon	7	l/s
	29	Emergency equipment schedule	None	5	Lighting use does not exceed 50% of power density over the day	7	% W/m of max
	30	Emergency lighting schedule	None	5	Equipment use is 50% of typical between noon and 10 pm	7	% W/m of max

(1) Typical construction practice or occupant behavior as relayed by local experts (DAR) or evident from satellite imagery; (2) High variability in real-world, worst case tested to cover all cases; (3) MEW 2019 Regulations; (4) No regulations apply, author calculations with best available data supplied from DAR; (5) Novel strategy being tested and not regulated; (6) Conserves total window area; (7) Author calculations; (8) PHIUS standard or best practice; (9) Most peak-load-reducing, reasonable value in Kuwait; (10) Minimum value allowed under MEW 2018.

gaps: (1) the separation and thus incomparability of solutions within multiple domains including urban, architectural, technological, and behavioral; (2) the separation of active and passive resilience analysis when there are clearly competing factors, which is beginning to be addressed by researchers in policy recommendations [20] and measures for vulnerable and underserve communities [34]; and (3) the relative lack in innovation and testing of methods (either new or traditional) for improving active or passive resilience. We address these gaps by utilizing a multi-step simulation method to assess active and passive resilience through single and multi-factor sensitivity analysis. In total this study tests 30 individual parameters across urban, architectural, technological, behavioral, emergency, and climatic domains (Table 1). We measure resilience using simple, well established, and broadly applicable metrics that encourage reproducibility and further validation and refinement of our approach.

Because resilience is always contextual, baselines must be established before evaluating the costs and benefits of an adaptation [35]. This study considers the potential for both active and passive heat resilience improvement in a typical detached villa (single-family) housing typology in Kuwait. Using an extreme test case in one of the hottest regions of the world, we aim to provide broadly applicable findings pursuant to baseline comparisons and testing for local economic, cultural, and geographic appropriateness. While we focus on new construction, many of the identified measures to boost resilience also apply to building retrofits.

The authors conducted all simulations using EnergyPlus, a free, open-source, validated, cross-platform simulation building physics simulation engine [36]. Its development is funded by the U.S. Department of Energy's (DOE) Building Technologies Office (BTO). Along with OpenStudio, EnergyPlus is part of BTO's Building Energy Modeling Program portfolio [37]. EnergyPlus has been validated using ASHRAE Standard 140 tests [38], the IEA HVAC BESTEST E100-E200 test suite [39], and recently using Lawrence Berkeley National Laboratory's FLEXLAB, an empirical test facility where it was concluded that EnergyPlus does not produce "any significant difference" to the empirically measured thermal loads [40].

2. Materials and methods

2.1. Simulation

This study utilizes Ladybug Tools 1.6.0 [41] and OpenStudio [42] to prepare models for calculation in EnergyPlus, a validated energy simulation engine. Ladybug is a plugin toolset developed for Grasshopper, a visual scripting environment for Rhinoceros 3D, which is an industry standard 3D modeling program for architecture and urban design. Ladybug allows user control and input of 3D geometries representing buildings, building components (windows, etc.), trees, and other urban features along with setting controlling parameters that include HVAC systems, wall assemblies, and schedules. Simulations use a Kuwait Institute for Scientific Research (KISR) EPW weather file for climate data. EPW files are created by analyzing multiple years of real weather data to determine the most typical weather for each month [43]. An extreme heat week, August 8–14, was used for both active (three days, August 10–12, which includes the hottest day, August 11) and passive (seven days, August 8–14) resilience simulations, with highs over the week ranging from 43 to 49° C and night-time lows ranging from 26.5 to 34.1 °C.

2.2. Comprehensive, multi-domain strategy testing

The set of 30 distinct parameters tested in this study is the most we are aware of in a heat resilience study. The list of parameters uses as reference previous studies and reports on heat resilience: a ranking of interventions to reduce dwelling overheating [26], a comparison of overheating risk in near-zero energy dwellings [33], a study of precinct-scale retrofits in Australia [44], an analysis of optimal pre-cooling strategies in residential buildings [45], reviews of resilient-cooling strategies [46] and impacts of heat waves and corresponding [47]. The list also relies on our own expertise in thermodynamics, building technology, architecture, and urban design (see Table 1). A strategy we did not test due to limitations in scope was an earth tube or Canadian well to precool air before entering the dedicated outdoor air system (DOAS). The parameters tested cover all key domains including: 1) urban and architectural design, 2) building technology and systems, 3) occupant behavior, and 4) climate. Additionally, a set of under-investigated strategies specifically aimed at short-term emergency actions is tested (see 2.4 below for more information).

Baseline values for most parameters (insulation, thermal mass, etc.) are set using Kuwait City's most current building regulations set in 2018 by the Ministry of Electricity and Water Standards [48]. Unregulated parameters required for simulations are set using either a) typical values for Kuwait City (provided by research partners), b) calculations by the authors, c) ASHRAE Standards 62.2 – 2019, Ventilation and Acceptable Indoor Air Quality [49] and 90.1 – 2019, Energy Standard for Buildings Except Low-Rise Residential Buildings [50], or d) minimum standard values. Tested values were set to provide the greatest possible reduction in peak load or increase in safe interior conditions within reasonable bounds of typical best-practices and within MEW 2018 regulations. ASHRAE standards, the Passive House Institute US's (PHIUS) Passive Building Standard [51], best-available products (e.g. window SHGC) or technologies (AC coefficient of performance), and general rules of thumb for architectural and urban design were used to set these values.

The global climate crisis is prompting efforts to design or retrofit buildings to reduce energy consumption, cost and carbon emissions, ideally over a life cycle that accounts for building construction as well as operation. In general, a building optimized for life-cycle operation will have many features that promote resilience to extreme heat events, particularly thermal resistance of enclosure materials (walls, roof and windows), that reduce cooling loads in extreme heat and will moderate the increase in indoor temperature under power interruptions. In addition, efficient lighting and appliances as specified in advanced building standards codes and certifications, including those established by PHIUS and the international Passive House Institute (PHI) [52], promote both active and passive resilience. The ability to schedule space-conditioning equipment to reduce peak utility loads in important in heating-dominated climates and an important factor as well in active resilience in increasingly frequent extreme-heat events. Two notable exceptions to the often-aligned interests of annual performance and heat resilience are window shading and natural ventilation. In heating-dominated climates, solar heat gains through windows reduce heating loads. If windows are not properly shaded for summer, building cooling loads increase, active and passive resilience suffers, and warm-weather shading is essential. And if power is interrupted and sufficient passive measures are not in place, indoor temperatures can rise above the already-high ambient conditions. In this case, the building must be ventilated to bypass the highly insulated building enclosure.

2.3. Under-investigated strategies

To our knowledge, the following strategies are not regularly tested in the heat-resilience literature: (1) pre-cooling for load shedding, (2) using basements to couple the building to the earth's thermal mass, (3) using rooms with different set-points to create thermal gradients within the house, and (4) emergency-scheduling for lighting equipment, and ventilation rates.

Precooling as a strategy for peak load reduction in residential [45] and commercial [53] buildings is well established in the broader sustainability literature but is not yet widely tested in comparative heat resilience studies such as those focused on policy recommendations [20], simulation-based evaluation of thermal resilience in high-rise residential buildings [25], and the technology and occupant behavior associated with common adaptation measures [54]. Using basements and thermal gradients by floor or room is likewise not widely simulated in comparative studies, even though both methods have been used in traditional architecture [55]. To our knowledge, the use of emergency household schedules whereby lighting, equipment, and ventilation demands are heavily curtailed during a heatwave has not been tested. Emergency actions by cities and communities during heat waves focus on human health services [56], coordination with social services focused to help vulnerable populations access needed medical attention when at risk of heat strain [57], community involvement in heatwave planning [58], and impacts of heatwaves on critical infrastructure as well as human health [59].

2.4. Precooling

Pre-cooling methods reduce peak demands on electrical distribution systems while maintaining adequate thermal comfort of building occupants, typically by scheduling indoor temperature set points. As a complement to air-conditioning, ceiling-mounted or other fans can promote thermal comfort at elevated temperatures by increasing convective heat transfer at the skin of occupants. In this study, we jointly adjust fan speed and temperature set points through a method [60] that incorporates three key steps: (1) using EnergyPlus simulations to develop baseline models to predict electrical load and occupant thermal comfort; (2) applying linear regression to fit perturbation models that relate fan speed and temperature set point adjustments to perturbations in load and thermal comfort; and (3) employing a linear optimizer to efficiently determine the trade-off of peak load reduction and a decrease in thermal comfort. Drawing on an experimental study of ceiling fans [61], we set a baseline air speed of 0.35 m/s and an average power consumption of 0.48 W per square meter of floor area.

2.5. Single and multi-factor sensitivity analysis

This study utilizes both single and multi-factor sensitivity analysis. First, all 36 parameters were tested for active and passive resilience one-at-a-time while maintaining baseline values for all other parameters. Second, parameters were tested many-at-a-time for both active and passive resilience by natural category (e.g. urban, architecture, technology) (Table 2, columns A-E). It is important to note that some individual parameters are mutually exclusive. When competing parameters exist, we use the more effective parameter based on the one-at-a-time testing for many-at-a-time testing (Table 3). Third, parameters were tested many-at-a-time for both active and passive resilience by multiple categories together (e.g. urban and architectural, technology and behavior) (Table 2, columns F-H). Fourth, all strategies were tested together to estimate the maximum active resilience potential (Table 2, column I).

Finally, we use insights gleaned from single- and multiple-factor simulations A-I and design two scenarios that incorporate factors from all categories with the goals of: 1) producing a balanced, low-cost scenario for reduced peak power, and 2) producing a low-cost scenario that

Table 2
Multiple-factor testing setup.

			Grouping By Category					**Special Grouping**					
			A	B	C	D	E	F	G	H	I	J	K
Category	*#*	*Parameters*	*Urban*	*Arch.*	*Tech.*	*Behavior*	*Responsive*	*Passive Systems*	*Emergency*	*Non-Responsive*	*All*	*Active Resilience*	*Active/Passive Resilience*
Urban	1	Floor-to-floor height	X					X		X	X		X
	2	Building stories	X					X		X	X		X
	3	Basement	X					X		X	X	X	X
	4	Tree shading	X					X		X	X		
	5	Footprint and orientation	X					X		X	X	X	X
	6	Neighboring buildings	X					X		X	X	X	X
	7	Street depth	X									X	X
	8	Shared party walls	X					X		X	X	X	X
Arch.	9	Roof U-Value		X				X		X	X		X
	10	Wall U-Value		X				X		X	X		
	11	Internal Thermal Mass		X				X		X	X	X	
	12	WWR		X				X		X	X	X	X
	13	Window U-Value		X				X		X	X	X	
	14	Window SHGC		X				X		X	X	X	
	15	Fixed window shading		X				X		X	X		X
	16	Envelope air-tightness		X				X		X	X	X	
	17	Roof and wall albedo		X				X		X	X		X
Tech	18	AC – COP			X				X	X	X		
	19	Air conditioning set-point (constant)			X	X			X	X	X		
	20	Ventilation recovery			X				X	X	X	X	
	21	Auto window shade			X				X	X	X		
	22	Lighting loads			X				X	X	X	X	X
	23	Equipment loads			X				X	X	X	X	X
	24	Pre-cooling of house			X		X		X		X	X	
	25	Layered set-point											X
Behavior	26	Occupant density				X							
	27	Occupant schedule					X			X	X		
	28	Ventilation schedule				X	X		X		X	X	X
	29	Emergency equipment schedule					X				X	X	
	30	Emergency lighting schedule					X				X	X	

Table 3
Single-factor results for active and passive resilience.

			Active Resilience	Passive Resilience			
Category	*#*	*Parameter*	*% Reduction from Peak (negative % is improvement)*	*Time in hours to HI Caution (THIC)*	*% Change from Baseline (positive % is improvement)*	*Hours Above Caution (HAC)*	*% Change from Baseline (negative % is improvement)*
Urban	1	Floor-to-floor height	−5.4 %	41	−0.0 %	87	0 %
	2	Number of building stories	−3.0 %	42	2.4 %	86	−1.1 %
	3	Basement (lowest level below ground level)	−6.7 %	40	−2.4 %	88	1.1 %
	4	Tree shading	−5.1 %	44	7.3 %	81	−6.9 %
	5	Footprint shape and building orientation	−3.0 %	42	2.4 %	86	
	6	Building situated on street with neighbors	−4.8 %	43	4.8 %	80	−8.0 %
	7	Neighbors and street orientation	−7.9 %	**58**	**41.46 %**	**70**	**−19.5 %**
	8	Shared party walls on two sides	**−14.7 %**	**62**	**51.22 %**	**66**	**−24.1 %**
Architectural	9	Roof Insulation (U-value)	<1%	41	0.0 %	87	0.0 %
	10	Wall Insulation (U-value)	−4.0 %	43	4.8 %	80	−8.0 %
	11	Internal thermal mass (inboard of insulation)	<1%	41	0.0 %	86	−1.1 %
	12	Window-to-wall ratio (even distribution)	−5.9 %	**46**	**12.2 %**	**76**	**−12.6 %**
	13A	Window-to-wall ratio (uneven distribution)	−8.9 %	**58**	**41.5 %**	**70**	**−19.5 %**
	13B	Window Insulation (U-value)	−7.8 %	**56**	**36.6 %**	**76**	**−12.6 %**
	14	Window solar heat-gain coefficient (SHGC)	−7.8 %	**58**	**41.5 %**	**70**	**−19.5 %**
	15	Fixed window shading (top and sides)	−1.2 %	**58**	**41.5 %**	**70**	**−19.5 %**
	16	Envelope air-tightness (infiltration rate)	−8.7 %	41	0.0 %	82	−5.7 %
	17	Roof and wall albedo	−1.5 %	41	0.0 %	87	0.0 %
Technological	18	Air conditioning coefficient of performance (COP)	−2%	–	–	–	–
	19	Air conditioning set-point (constant)	−10 %	41	0.0 %	87	0/0%
	20	Automated window shade (90 % opacity)	−6%	–	–	–	–
	21	Ventilation cooling-recovery system (latent + sensible)	−4%	–	–	–	–
	22	Lighting load	−4%	–	–	–	–
	23	Equipment and plug load	**−14 %**	**–**	**–**	**–**	**–**
	24	Precooling (variable set-point during day)	**−23.8 %**	**4**	**−90.2 %**	**119**	**0.0 %**
	25	Layered set-point	**−11.3 %**	41	0.0 %	87	0.0 %
Behavior	26	Occupant Density	**−29.6 %***	41	0.0 %	87	0.0 %
	27	Occupant schedule	−4.3	–	–	–	–
	28	Ventilation schedule	−5.6 %	40	−2.4 %	88	1.1 %
	29	Emergency equipment schedule	**−24.2 %**	**–**		**–**	**–**
	30	Emergency ventilation schedule	−7.7 %	–		–	–

Note: **Bold** = >10 % reduction in peak load or percent change from baseline, * = Normalized to energy use per-person

balances active and passive resilience (Table 2, columns L and M).

2.6. Measuring active and passive resilience

Active resilience is defined as the percent reduction in peak load from the baseline scenario to the tested scenario. Peak load reduction is a well-established metric to measure active resilience because it calculates the reduced burden on the grid from a demand source (household, business, etc.,), as included in a review of measures to reduce the impact of heatwaves ([47], and as applied to residential buildings in Australia and New Zealand [62]). The primary goal of active resilience is improving the likelihood of grid stability throughout a heatwave such that all buildings can run cooling systems (air-conditioners, fans, dehumidifiers, etc.) [15]. Maintaining active cooling capacity inside all buildings remains the safest method for protecting a population against heat stress [63].

Passive resilience is broadly the capacity of a building to maintain a safe indoor environment without active cooling (air-conditioning, dehumidification, etc.) [64], as distinct from providing thermally comfortable conditions [65]. It is widely accepted to compare passive resilience strategies through calculating the hours of exposure to different heat stress levels [66]). However, a universal metric for measuring heat stress itself is not yet established, as concluded from studies of concepts and definitions of resilient cooling of buildings [21], ranked interventions to reduce dwelling overheating [26], evolving building energy codes [67], and the impact of regulations on overheating risk [68]). We chose the Heat Index (HI) scale to measure heat stress for several reasons: it includes the two most relevant interior climate parameters, humidity and temperature; it is easily obtained from EnergyPlus simulations; it is widely established in public health assessments (OSHA, etc.); and it is easily understood by all stakeholders. A limitation of the HI scale is that it does not account for wind or direct radiation. Assuming no wind or radiation striking individuals inside a building is not unreasonable in the context of this study. During a heatwave, individuals are very likely to close curtains or otherwise avoid direct sunlight. The assumption of still air inside a house (no fans present) provides a worst-case scenario because air flow over bodies improves the thermal experience [69]. (Note: Direct solar radiation is calculated in an EnergyPlus energy balance, so radiation through windows impacts the radiant exchanges between elements and ultimately the dry-bulb temperature). We use two metrics to measure passive resilience in our studies: 1) Time to HI Caution (THIC) and 2) Hours Above Caution (HAC) where, in both metrics, an HI of 28 °C is the Caution threshold. In these metrics a higher THIC and a lower HAC both indicate improvement.

3. Results and discussion

3.1. Single factor analysis

3.1.1. Active resilience

The single-factor sensitivity analysis results for active resilience are shown in Fig. 2 and Table 3; the latter includes results for passive resilience that will be presented in section 3.1.2. It is important to note that the results must be read in the context of Kuwait City's building code [48], which is already stringent in many areas and thus offers less room for improvement in those categories than might otherwise be expected in other regulatory contexts. There are several important findings:

There are **several pathways to improving active heat resilience** in Kuwait City. Each category (urban, architectural, etc.) has multiple parameters with greater than 5 % reduction in peak load and at least one parameter with a greater than 10 % reduction in peak load. This indicates broad potential for existing and new construction to reduce peak loads by at least 10 % or more with strategies that best fit their specific circumstances. In addition, **many effective strategies are affordable** and can be implemented with little to no additional financial cost for new construction (shared party walls, street orientation, window location), have secondary benefits that pay dividends in other areas (tree shading), or offer financial benefits due to lower overall energy use (AC COP, equipment energy efficiency, lighting efficiency).

Equipment and plug loads are an important aspect of overall peak-load reduction. These loads tend to peak during the afternoon cooling peak. The heat dissipated by these electrical loads boosts the cooling load that active systems must remove from the building and their power demand directly magnifies the peak electrical load. This also indicates that studies that only look at cooling loads will miss important interactions with other building energy demands.

The **novel emergency strategies** presented in this paper are highly effective, producing three of the six most impactful peak load reductions. Moreover, these strategies don't require any changes to the building or built form and thus can be implemented in all houses (new and existing) and with minimal effort. They focus on manipulating when and where cooling is used to selectively and more energy efficiently maintain a safe indoor environment in specific areas of the home.

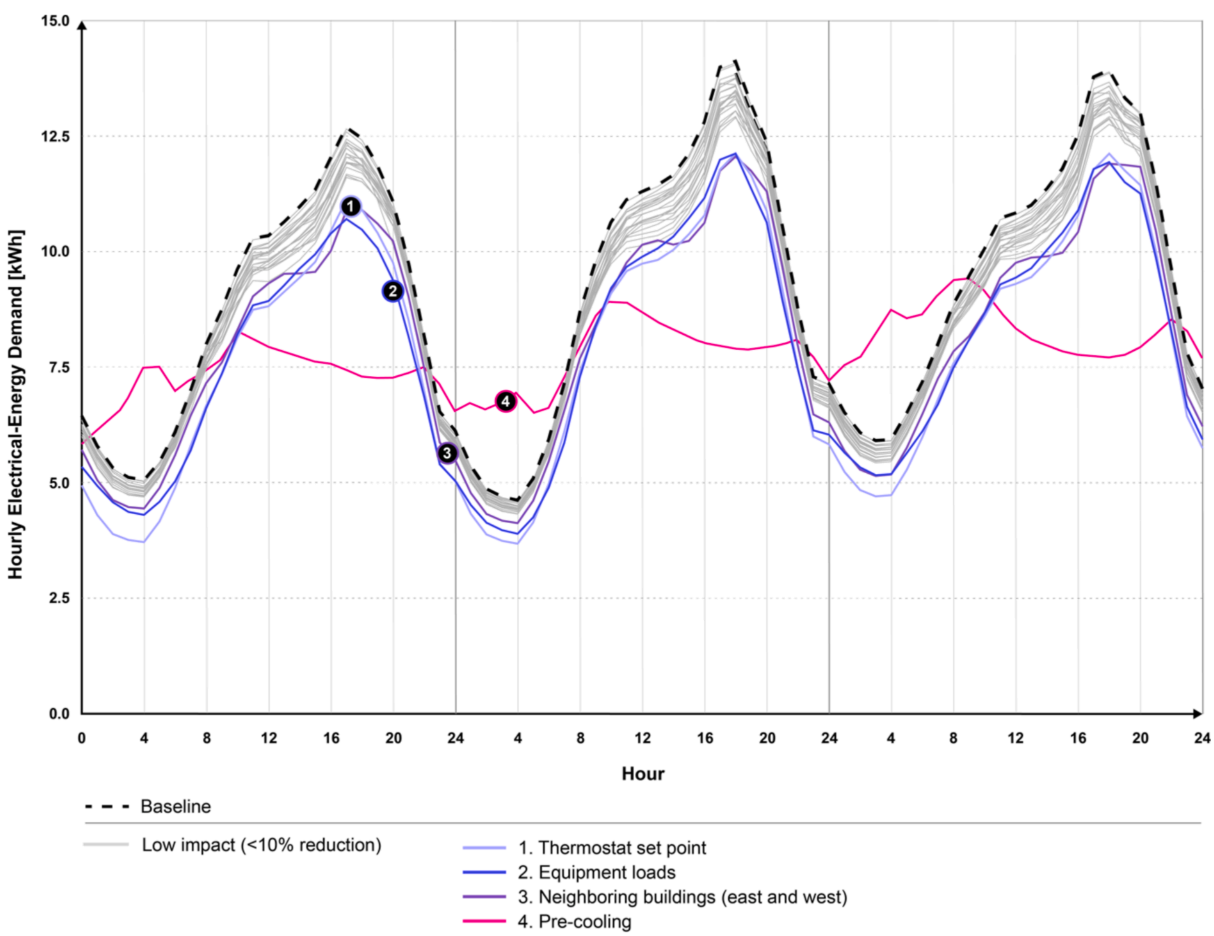

Fig. 2. Single-factor active resilience: hourly electrical-energy demand during a three-day heatwave in kWh.

Of the emergency strategies, **pre-cooling** is especially beneficial because it: a) maintains the useability of the entire house during a heat wave (not overly burdensome), b) is the third largest peak load reduction of all 30 tested strategies c) shifts the timing of peak load to times when grid operation is more efficient, c) can be implemented for free, d) gives users flexible control over the magnitude of pre-cooling to ensure safety for vulnerable populations, and e) interacts positively with many other strategies including basement construction, layered set-points, air-conditioning COP. Of course, relying on individual households to do their part also has drawbacks. Policy and potentially direct or automated control over thermostat setpoints should be investigated further but could readily lead to maladaptation or abuse by grid operators [70]. It is important to note, as well, that pre-cooling requires significant thermal mass to store cooling capacity during non-peak hours. Concrete construction is standard in Kuwait City, but in wood-based or other light-weight construction-based areas, additional thermal mass would be needed.

Reducing conditioned floor area per person is the **single most impactful strategy** for reducing peak load. This strategy must be taken in context, however, as the baseline peak energy demand would also be reduced equally by reducing floor area per person. What this indicates, therefore, is *not* that smaller houses are more heat resilient, but rather during heat waves, if families and friends are able to huddle together in one house as opposed to two or three houses, and if the non-occupied houses are able to be unconditioned during the heatwave, then combined peak load reductions will be significant. This strategy would be especially effective for singles or couples living in large houses and with close family nearby that they can safely reach during a heat wave. It would seem necessary for governments to find ways to incentivize this behavior, however, as it will be burdensome to all participants.

Further improved AC Equipment COP, building insulation and roof and wall albedo changes are the least effective strategies in this context because Kuwait City's building regulations already dictate highly insulated and reflective buildings with building systems.

3.1.2. *Passive resilience*

Single factor sensitivity analysis results are shown in Fig. 3 and in Table 3. The baseline building has a Time to HI Caution (THIC) of 41 h from the start of a power outage and 87 Hours Above Caution (HAC).

Urban and Architectural factors are the most effective in improving passive heat resilience. A building's material, form, and relationship to other buildings have the most impact on passive

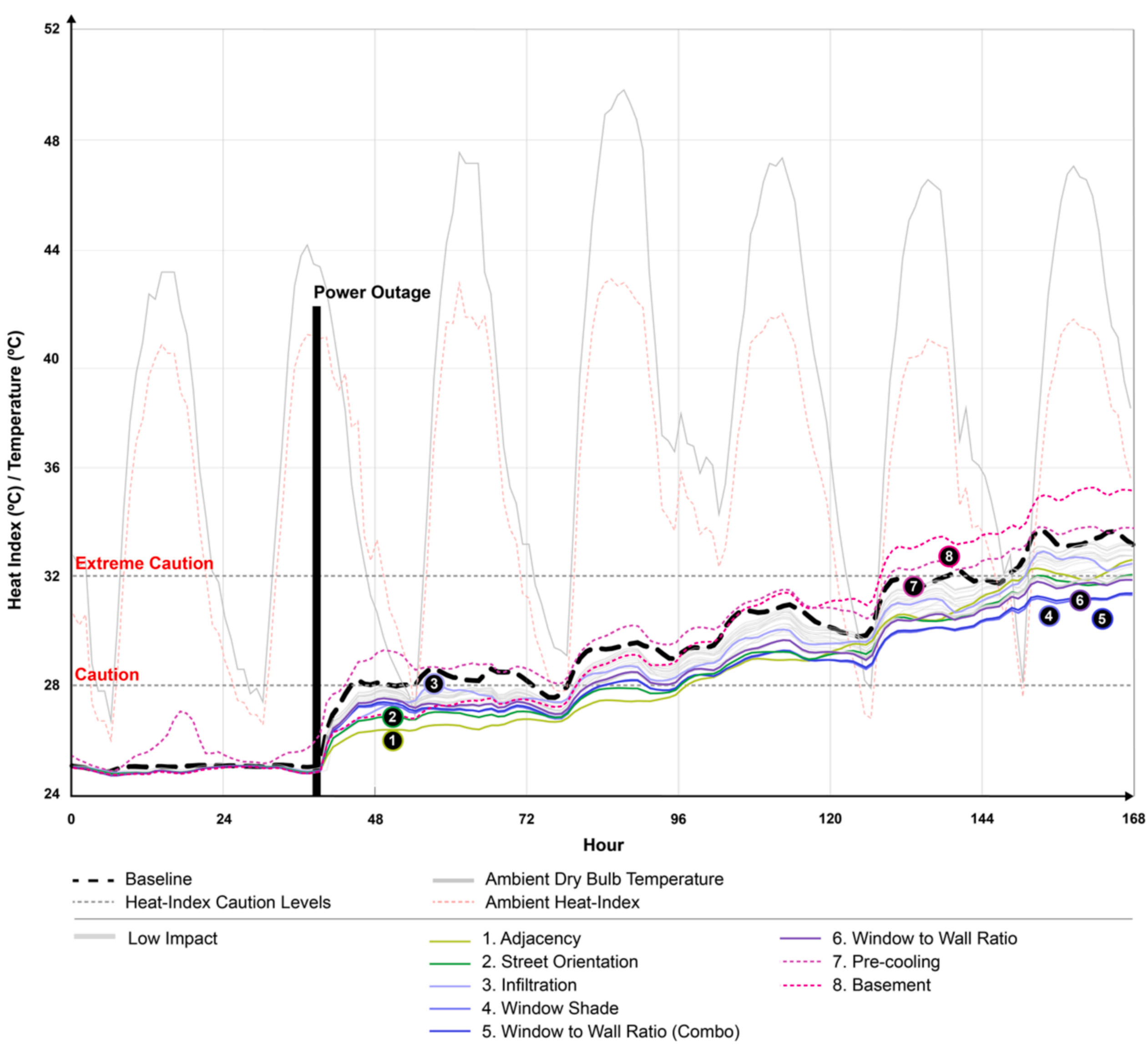

Fig. 3. Single-factor passive resilience: indoor Heat Index during a power outage.

resilience. With building adjacencies to both the east and west, the THIC is increased to 61 h, 20 h (51 %) over the baseline. Optimal building and street orientation renders an improvement of 17 h (~40 %) with a THIC of 58 h. Similarly, window SHGC, window shade, WWR, and street orientation all have a THIC of 58 h, an improvement of 17 h (41 %) from the baseline. Not included in this study, which was based on prevailing local architectural forms, basements can offer a cool shelter that enhances passive resilience (increase THIC) via coupling to the ground as a heat sink [71].

Window performance plays a key role in a building's passive survivability. Of the seven factors that reduce HAC by at least 10 % from the baseline, window characteristics account for five. Window-to-wall ratios (WWR) that are sensitive to building orientation and distribution, window shading, and SHGC improve the THIC by over 40 % and reduce the HAC by nearly ~ 19 %.

Many factors that improve active resilience decrease passive resilience. The most significant peak-power reduction, 23.8 % (Table 3), is made from using a pre-cooling schedule. However, this strategy is shown in Fig. 4 to have a negative effect on passive resilience, wherein the THIC is greatly reduced and HAC greatly increased. Pre-cooling intentionally cycles temperature set points to a higher value of 28 C, which leads to an internal Heat Index of ~ 27 C at its peak. A power outage is likely to occur during the latter and hottest part of the day, near the peak internal heat-index of the pre-cool schedule. The internal heat-index then rises rapidly, surpassing the cautionary heat-index hours after the power outage and quickly passing an extreme caution heat-index threshold. Scheduled pre-cooling set points can be adjusted to achieve the desired balance of impacts on active and passive resilience.

3.2. Multiple factor analysis

3.2.1. Active multiple factor resilience

The impacts of individual strategies within the single-factor analysis are not perfectly additive within the multi-factor analysis because many strategies are variations on one another (window location), or otherwise operate on the same underlying principle (e.g. reducing solar radiation exposure) (Table 4 and Fig. 4). Confirming point 1 in section 3.1.1, that there are multiple pathways to improving active heat resilience, each basic category in the multi-factor study, besides behavior, reduces peak demand by at least 25 %. Emergency strategies alone offer the largest combined peak-load reduction of any basic category at nearly 50 %. When multiple basic categories are combined, peak load reduction can reach up to 70 %. While most literature on heat resilience focuses on interventions to the built form (e.g. insulation, windows, etc.), in the context of this study, which includes our novel emergency strategies, it is technology, behavior, and emergency adaptations that together offer nearly 60 % reduction in peak load. This is an important finding because LED light bulbs, efficient appliances, higher COP air-conditioning systems, and dedicated outdoor air systems with heat exchangers can be easily retrofitted into older buildings and have natural replacement cycles of less than 20 years. Likewise, emergency schedules and behavioral adaptations are required for only a few weeks a year and otherwise do not disrupt normal everyday life.

The results from the active resilience portion of this study indicate that in cities with extremely hot temperatures and with well-developed building regulations similar to Kuwait City, the need to reduce peak loads will be best met by a combination of three approaches: first, new urban design regulations that reduce exposed surface area of houses

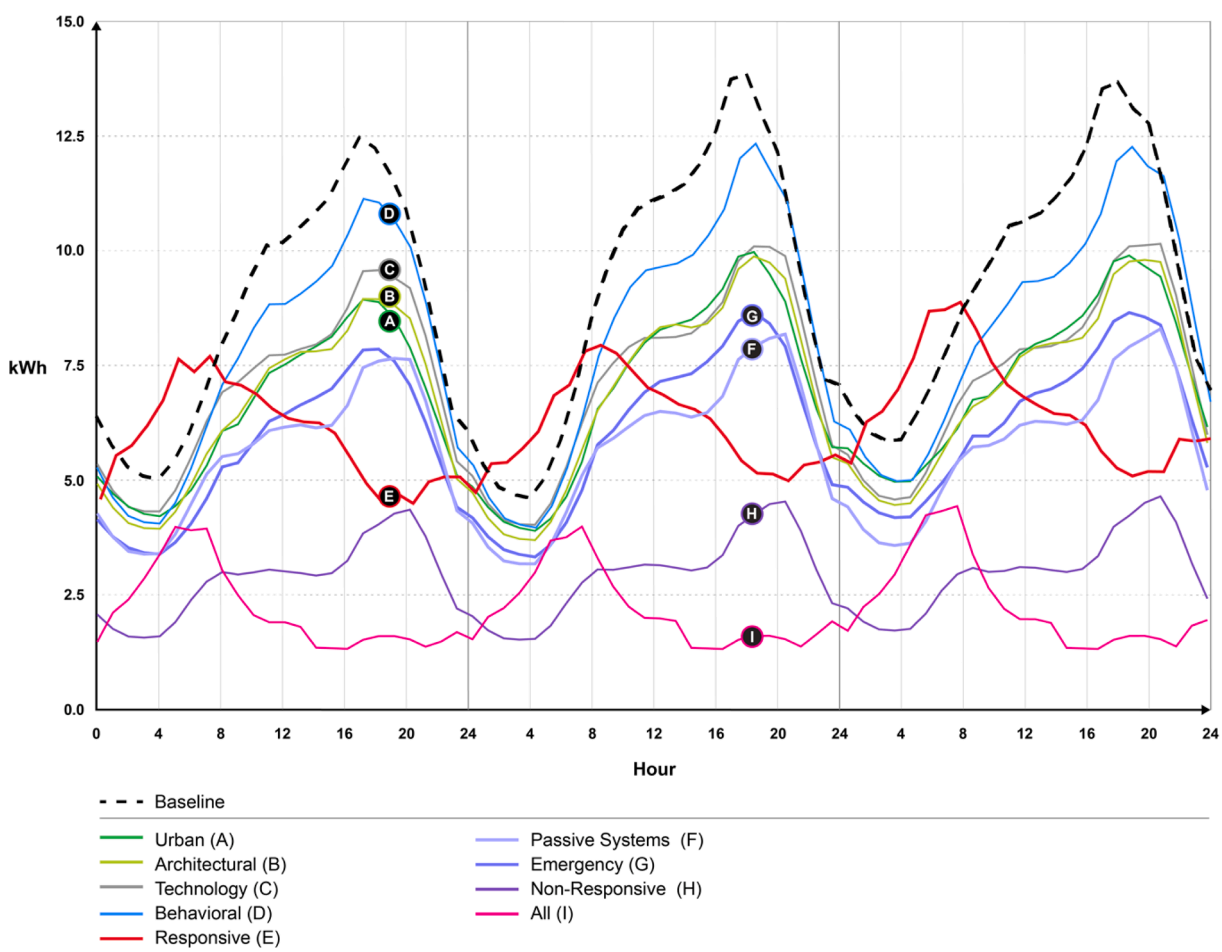

Fig. 4. Multiple-factor active resilience: hourly electrical-energy demand during a three-day heatwave in kWh

Table 4
Multiple factors – percent peak load reduction.

	Grouping By Basic Categories					Multiple Categories			
	A	B	C	D	E	F	G	H	I
	Urban	*Arch.*	*Tech.*	*Behavior*	*Responsive*	*Urb + Arch.*	*Tech. + Behavior*	*Urb, Arch., Tech.*	*All*
Baseline Peak Demand	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9
Multi factor Peak	10.9	10.2	10.0	12.1	7.3	9.3	8.7	5.7	4.2
% Reduction	**−21 %**	**−27 %**	**−28 %**	**−13 %**	**−48 %**	**-33 %**	**−38 %**	**−59 %**	**−70 %**

through the use of shared party walls and/or basements; second, regulations for replacing outdated and inefficient building technologies with more efficient systems; and third and most novel to this study, new policies to develop, test, and implement behavioral adaptations focused on short-term emergency actions that households can perform in situ to reduce peak demand. If a combination of these approaches can be implemented through new policies Kuwait City and similar cities in the MENA region (relatively wealthy with high air-conditioning penetration rates) should be able to counteract the threat that increasingly severe heatwaves pose to grid stability. It is important to note that this study only considers demand-side regulation. Supply systems (power plants, transformers, power lines) may fail regardless of peak load reduction due to extreme temperatures [16].

3.2.2. Passive multiple factor resilience

The capacity of buildings to maintain safe interior conditions when no air-conditioning is available presents a very different challenge than active resilience (Table 5 and Fig. 5). Technologies and emergency behaviors aimed at reducing peak load (active resilience) have no benefit for passive resilience during a power outage because there is no electricity demand to be attenuated. They influence passive resilience negatively, however, by increasing the interior Heat Index prior to a power outage. As a result, emergency heat responsiveness measures that are best performers for active resilience are the worst for passive resilience. On the other hand, architectural strategies which are only moderately effective at reducing peak load are best for passive resilience because they reduce convective, conductive, and radiative heat transfer into the house with no input of energy. Increased internal thermal mass (architectural) increases thermal inertia and dampens internal temperature extremes and daily temperature ramp, leading to an overall reduced temperature increase that can be observed in the baseline over the power outage period. Some urban strategies that are also moderately effective at peak load reduction make passive resilience worse. While internal operative temperatures are reduced and more stable, the internal humidity gain from occupants rises rapidly because of reduced infiltration and remains high because of the lack of mechanical ventilation during the power outage. Elevated internal humidity translates to an increased HI even though internal temperatures remain relatively low.

3.3. Recommendations

This study confirms what other studies have also revealed: strategies that improve active resilience can harm passive resilience [18]. **Going forward, there is a need to study active and passive resilience together as a coupled system and to set this as standard practice to avoid maladaptive design.** Due to complex multiple hazards and other unforeseen failures during heatwaves, grid operators cannot assume they will always be able to provide the rated capacity of their power plants. In addition, peak-load reduction strategies, while potentially very helpful for improving active resilience, may also ultimately fall short in preventing blackouts or brownouts. Therefore, it is critical that cities implement both active resilience measures to reduce the likelihood of blackouts while simultaneously planning for passive resilience if and when temporary power outages occur or are needed to protect the grid. Planning and regulatory approaches should therefore aim to lower peak loads while not increasing passive vulnerability.

It is not immediately obvious which combinations of building factors produce a balance between a building that is both highly power efficient and maintains a low internal Heat Index in the event of a power outage. The designed scenarios from Table 2, Columns J and K, give cost-motivated recommendations for balanced active strategies to reduce peak energy demand (J) and to strike a balance between active and passive resilience (K). Scenario J shows a peak power reduction of ~ 66 %, which is significant because it only differs by 3 % from scenario K that deploys all factors. Scenario K results show a ~ 40 % reduction in peak power (Table 6 and Fig. 6). These results are promising because they combine some of the more cost-efficient methods and yield highly effective results. Scenario K relies on architectural and urban characteristics, yet still performs better than scenario F, "Passive Systems." However, under power-outage conditions, scenario J performs very poorly and is among the worst scenarios for passive resilience. Scenario K performs much better under a power-outage condition; while not as effective as some of the most impactful multiple-factor scenarios like scenario F, "Passive Systems," it still reduces HAC from 87 to 41 h, a 52 % decrease. (Table 7 and Fig. 7).

These two recommended scenarios illustrate the challenges of building design for both passive and active resilience at the same time. While scenario J successfully reduces the peak load by a significant amount by deploying a range of factors, it simultaneously creates dangerous conditions in the case of power outage. This may be an appropriate approach to resilience if, for example, the major concern was reducing demand during heat waves, not the reliability of the grid. Scenario K may be an appropriate approach to resilience if the robustness of the electrical grid is in question, for example its ability to produce and transmit electricity during extreme heat.

Table 5
Multiple factors – passive resilience during power outage.

	Grouping By Basic Categories					Multiple Categories			
	A	B	C	D	E	F	G	H	I
	Urban	*Arch.*	*Tech.*	*Behavior*	*Emergency*	*Passive Systems.*	*Emergency*	*Non-Responsive*	*All*
Baseline Hours to Caution (HI 28)	5	5	5	5	5	5	5	5	5
Scenario Hours to Caution (HI 28)	18	90	0	0	0	65	1	0	5
Baseline Hours Above Caution	119	119	119	119	119	119	119	119	119
Scenario Hours Above Caution	103	38	128	128	128	55	128	128	128
% Hours Above Caution	**80%**	**29%**	**100%**	**100%**	**100%**	**42%**	**100%**	**100%**	**100%**
% Change from Baseline	**-13%**	**-69%**	**7%**	**7%**	**7%**	**-49%**	**7%**	**7%**	**7%**

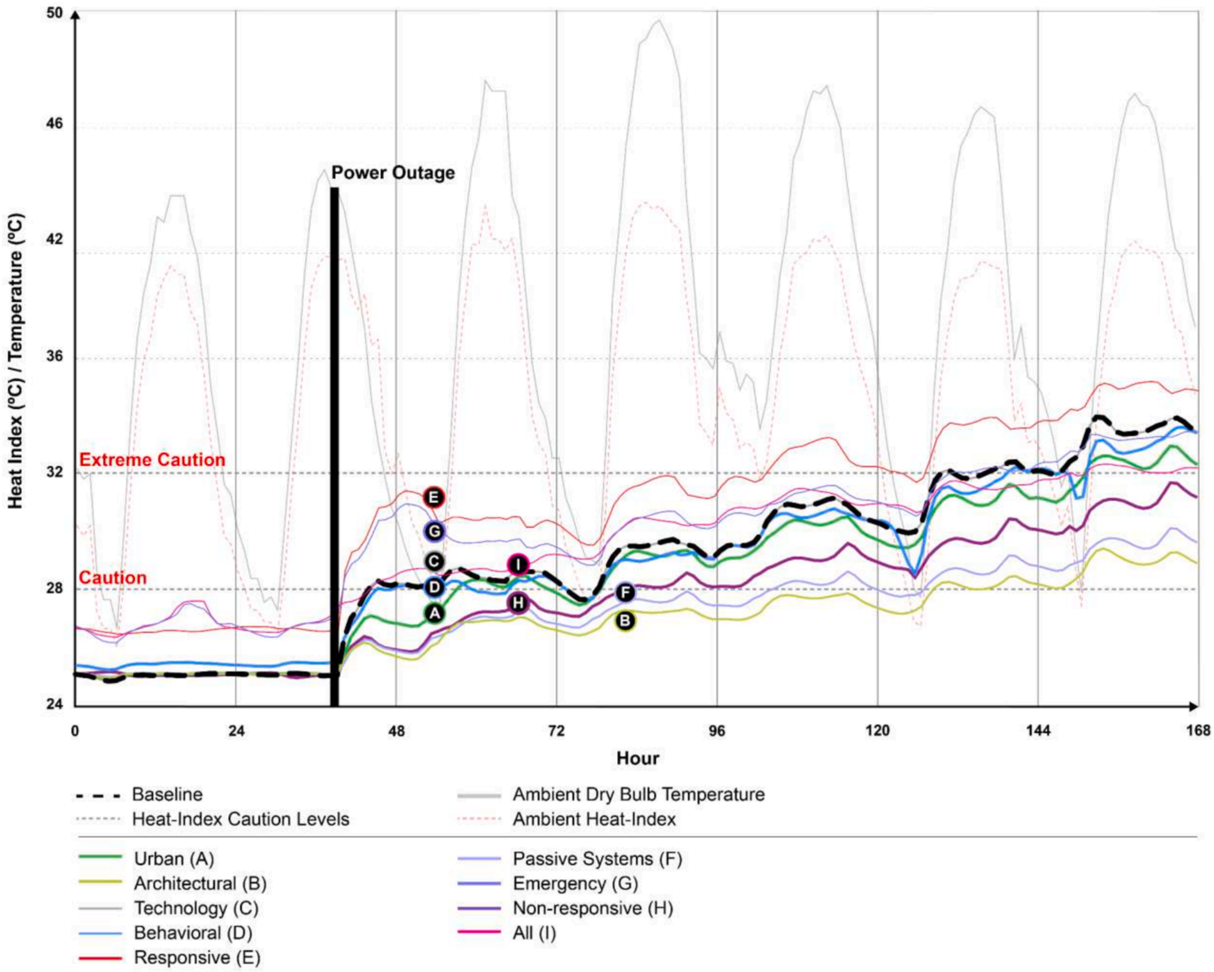

Fig. 5. Multiple-factor passive resilience: indoor Heat Index during a power outage.

Table 6
Designed scenarios for peak load reduction.

	J *Active Resilience*	K *Active/Passive Resilience*
Baseline Peak Demand	13.9	13.9
Multi factor Peak	4.60	8.18
% Reduction	**−66.7 %**	**−40.9 %**

More broadly, we recommend that researchers and practitioners follow a multi-factor approach to balance active and passive heat resilience in buildings of different types in different climates, considering both new construction and building retrofits. Such efforts will benefit from consideration of cost, which depends heavily on both materials and labor and is therefore highly dependent on temporal and locational variations in economic conditions. Here cost should be weighed comprehensively, accounting for the cost of material and construction, savings in building operation, savings to energy providers associated with meeting peak loads, and savings to communities associated with potential reductions in cost of cool shelters and health care costs associated with heat stress. Environmental costs associated with carbon emissions should be mapped to financial metrics via nationally accepted values for the cost per metric ton of emitted greenhouse gases. Government agencies today subsidize a range of actions intended to reduce the carbon emissions associated with buildings. Given that a lack of heat resilience has significant societal cost, it is conceivable that governments could support specified measures that have been shown to be effective.

Future efforts should also include experiments in constructed buildings that quantify the performance of selected strategies. The goal here is not exhaustive tests of many combinations of features, a task for which simulation is well suited and physical construction is not, but data sufficient to validate or improve simulations and enhance professional and public confidence in strategies to enhance the heat resilience of buildings. Physical tests could include experiments with small test cells at universities or government labs with limited control of features (window shades, internal loads, scheduled pre-cooling); tests of full-sized houses when unoccupied (at time construction finishes or occupants are away); and tests in occupied buildings, where occupants have some choice about adjusting shades or changing temperature set points. In each case, environmental conditions would be recorded, along with indoor temperature(s) and humidity and sub-metered building electrical power (to isolate equipment/lighting electricity from cooling/ventilation systems) over the duration of the test. Researchers will need sufficient information about construction to establish models but a citizen-science approach, in which experiences are recorded and shared, can boost interest at the community level in effective heat resilience.

Studies that report measured indoor conditions have value even if they lack data needed for physics-based simulations that require information about building construction and operation to inform heat-resilient building design and retrofits. A reported correlation of indoor temperature and humidity in a sample set of low- and middle-income housing in New York City with outdoor conditions and use of those correlations to establish indoor HI during recorded heat waves usefully spotlights exceedance of threshold HI values and motivates action [72]. A citizen-science approach, in which building occupants use inexpensive

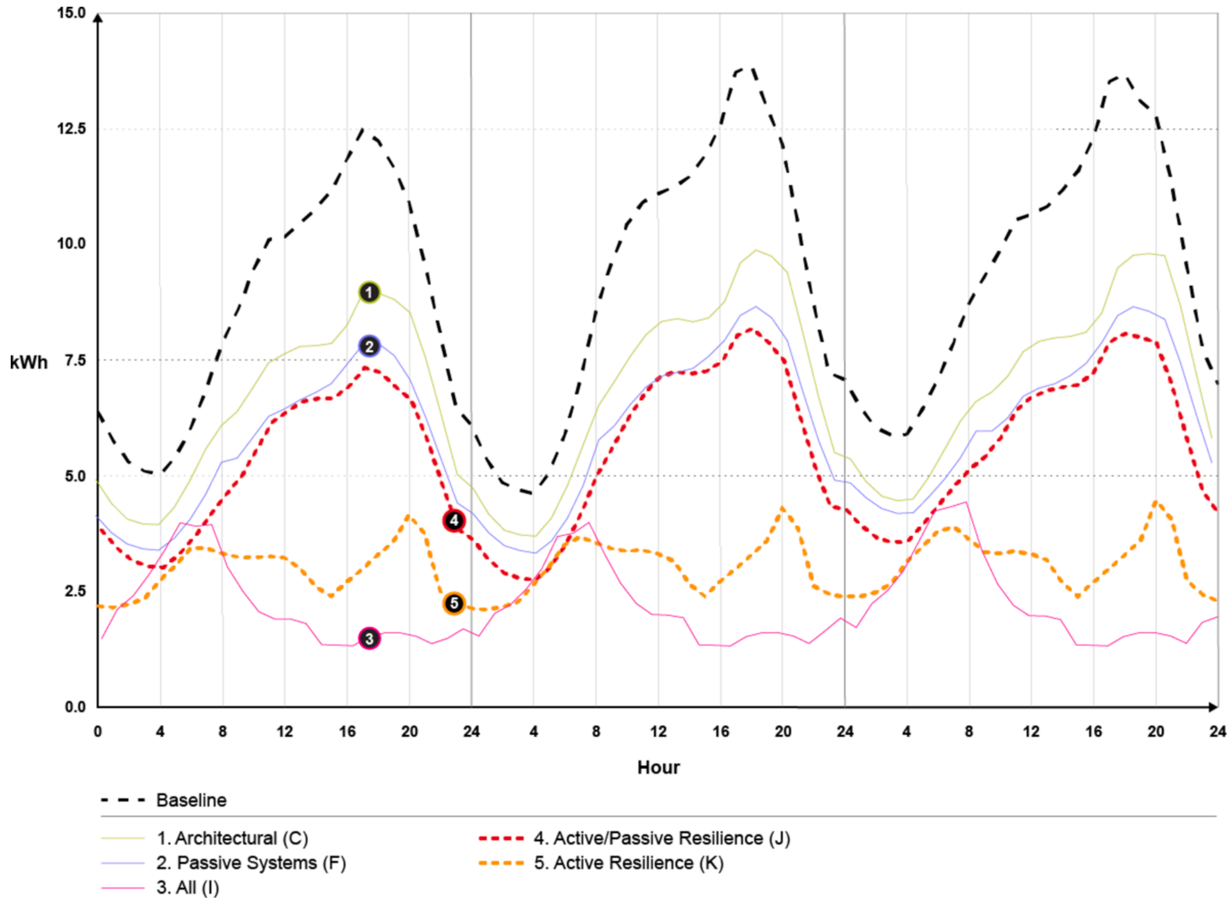

Fig. 6. Recommended factor combinations for peak power reduction.

Table 7
Designed scenarios for passive resilience.

	J	K
	Active Resilience	*Active/Passive Resilience*
Baseline Hours to Caution (HI 28)	5	5
Scenario Hours to Caution (HI 28)	5	63
Baseline Hours Above Caution	119	119
Scenario Hours Above Caution	123	65
% Hours Above Caution	**96%**	**50%**
% Change from Baseline	**3%**	**-45%**

temperature/humidity data loggers to document and share their experiences during heat waves, can boost interest at the community level in effective heat resilience and provide researchers with valuable information about occupant behavior.

4. Conclusion

This paper outlines a holistic simulation-based approach to modeling demand side active and passive heat resilience in Kuwait City. Using tools readily available to architects, designers, and planners, our new methodology contributes to global heat resilience studies in two ways: the breadth of the considered factors, spanning architecture, technology and occupant behavior; and their impact on both active (peak load reduction) and passive (power outage survivability) heat resilience. Our simulations show that a pre-cooling air conditioning schedule and an emergency equipment scheduling protocol offers substantial reduction in peak energy, yet both factors reduce passive resilience. Urban and architectural factors are predominant in enhancing passive survivability: building adjacencies, optimal street orientation, window shading, and window orientation are most successful.

Combinations of factors lead to significant reductions in peak load; however, we demonstrate that these combinations do not always translate to favorable results in terms of passive resilience. As such, we demonstrate the importance of a balanced approach to both active and passive resilience where most combinations of strategies that reduce energy peaks tend to worsen passive resilience, in some cases detrimentally.

Finally, the paper offers two multi-factor combinations that are motivated by cost and performance in both active and passive resilience. These scenarios demonstrate that there is a certain degree of flexibility in resilience measures and highlight the importance of goal setting early in the design process or in community resilience conversations. The scenarios additionally serve to establish possible outcomes of the methodology we propose, with the aim of illuminating the possible pathways to demand side resilience in Kuwait and other hot desert climates.

CRediT authorship contribution statement

David P. Birge: Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Jonathon Brearley:** Writing – original draft, Visualization, Validation, Software, Investigation, Formal analysis. **Zhujing Zhang:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis. **Leslie K. Norford:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization.

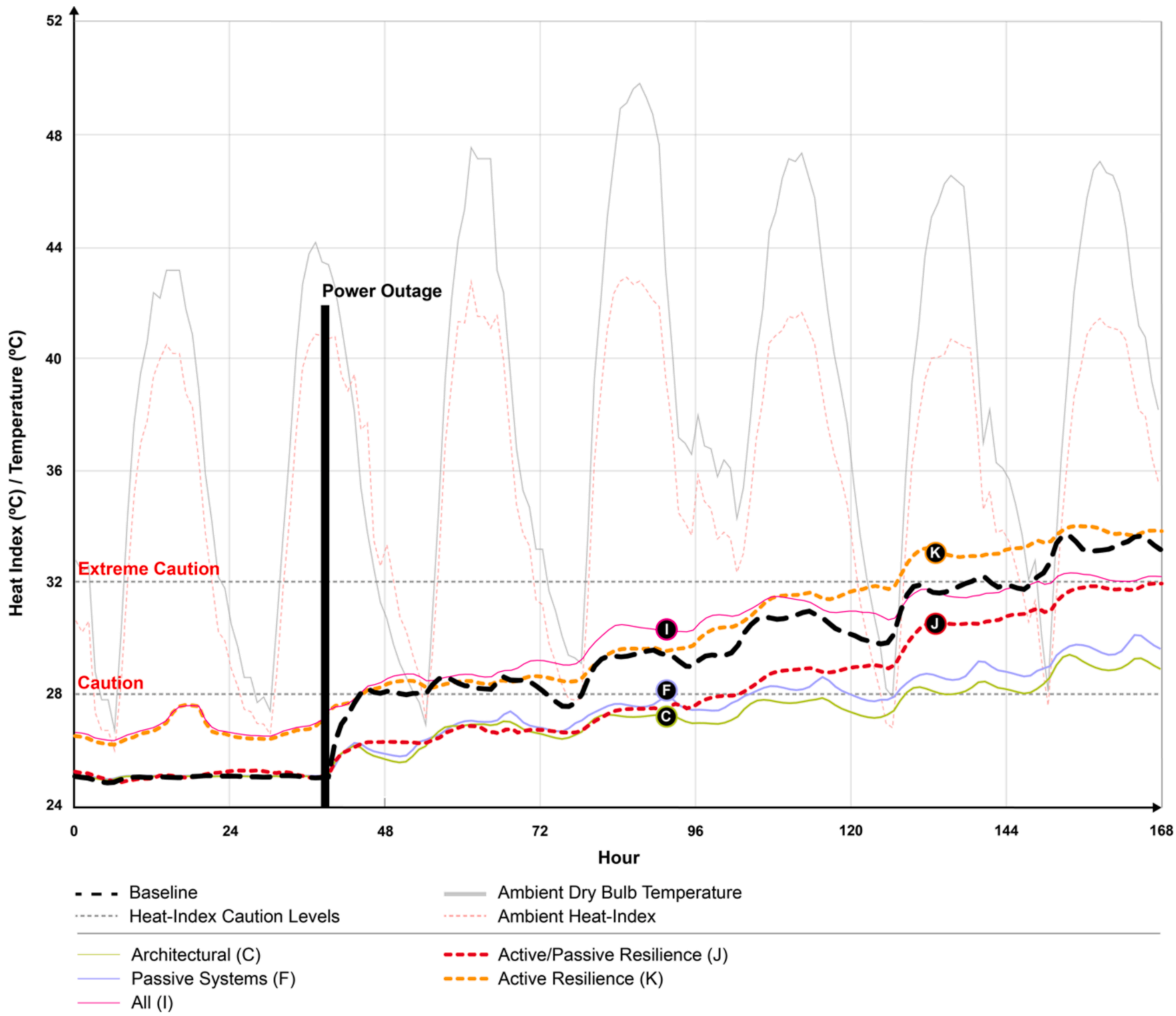

Fig. 7. Recommended factor combinations during power outage.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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