Empirical Evaluation of Technologies Enhancing Heatwave Resilience: Adap~~ta~~tive~~tion~~ ~~Capacity~~ and Vulnerability Reduction Capacities for Ex-Ante and Ex-Post Damage Mitigation

by

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Abstract

One of the major impacts of climate change is the increasing frequency and intensity of extreme weather events. Among these, heatwaves have become particularly severe, leading to rising economic losses, infrastructure malfunctions, and even human casualties. Although policies to enhance climate resilience have been widely recognized as essential ~~adaptation~~adaptive strategies, there remains a lack of empirical evaluation of effectiveness in resilience terms. This study aims to develop an empirical model capable of estimating the policy effects on heatwave-induced damage costs, thereby offering critical information to policymakers in selecting region- and time-specific interventions. We constructed a panel dataset by integrating regional heatwave disaster records, economic loss data, and climate ~~adaptation~~adaptive technologies across municipalities in South Korea. Using a structural equation modeling approach, we estimate how vulnerability reduction and ~~adaptation~~adaptive capacities affect ex-ante and ex-post damages. Preliminary results indicate that regions with stronger vulnerability reduction ~~capacity~~capacities tend to experience significantly lower damage, underscoring the effectiveness of resilience-oriented policies. Furthermore, proactive adaptation measures yield greater economic benefits and are more effective at reducing damage uncertainty compared to reactive post-disaster responses. By quantifying the reduce ~~avoide~~d losses attributed to climate resilience, this study provides empirical evidence to support the optimal targeting of disaster risk management strategies. Our approach contributes to the climate ~~adaptation~~adaptive literature by presenting a novel empirical model that incorporates both observable ex-post and latent ex-ante damage components. The findings highlight the importance of data-driven resilience strategies and offer practical implications for decision-makers addressing extreme heat events.

Keywords: ~~Adaptation~~Adaptive ~~Capacity~~Capacities, Vulnerability Reduction, Marginal Effec~~t~~ts,

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Ex-ante and Ex-post damage, Stochastic damage function

JEL Classification R11

1. Introduction

In recent decades, one of the most prominent effects of global climate change has been the increasing frequency, intensity, and duration of heatwaves. According to the WMO Global Climate Update (2025–2029), global temperatures are projected to rise by 1.2°C to 1.9°C above pre-industrial levels each year between 2025 and 2029. In South Korea, the summer of 2024 recorded the highest average temperature on record, surpassing that of 2018 (25.3°C), and the number of tropical nights between June and August reached 20.2 days, exceeding previous highs of 16.5 days in 2018 and 1994. These trends suggest that heatwaves are no longer short-lived anomaly~~ies~~ but represent recurring and ~~systemic~~ systematic climate risks.

Urban areas are particularly vulnerable to heatwaves due to the urban heat island effect (Lee, 2020). Cities with populations exceeding one million tend to be 1–3°C warmer than surrounding areas and suffer more than four times the heat-related damages. Heatwaves are not only associated with increased discomfort and heat-related illnesses but also cause serious threats to vulnerable populations such as the elderly and low-income households. In addition, they contribute to instability in energy supply, reduced labor productivity due to fatigue and lack of concentration, and disruptions to industrial activities (Lee & Cho, 2014; Park, 2023; Lee, 2020).

In response to these broad and intensifying societal impacts, the South Korean government has implemented various physical measures, including rooftop and wall greening projects, the installation of cooling fog systems and shade canopies, and support for cool roof adoption in both public and private sectors (Pyon, 2022; Lee & Cho, 2024). However, heatwave damage is not simply a result of rising temperatures, rather i~~. I~~t is determined by a complex interaction between exposure, vulnerability, and response ~~capacity, and~~capacities and thus cannot be adequately addressed through fragmented efforts by individual elements~~departments~~ (Yi et al., 2024).

Despite growing attention to the need for policy-level heatwave adaptation, much of the existing research remains limited to evaluating the effects of individual technologies at the micro level. In this study, we expand on a previous analysis, "A Regional Benefit-Cost Analysis of Heatwave Climate Resilience Technologies" (Bae et al., 2025), by evaluating the macro-level effectiveness of these technologies using a comprehensive panel dataset. While the earlier study focused on mean and variance effects of ~~physical~~ resilience in terms of physical infrastructure in relation to specific technologies, the current study differentiates climate resilience into two components: vulnerability reduction ~~capacity~~ and ~~adaptation~~adaptive capacit~~y~~ies.

Specifically, w~~W~~e ~~assess~~assesses whether individual technologies can (1) mitigate ex-ante

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damage~~s~~ by reducing vulnerability, and (2) reduce ex-post ~~damages~~damage by enhancing ~~adaptation~~adaptive ~~capacity~~capacities. Climate resilience, in this context, refers to the ~~capacity~~capacities of human, ecological, and infrastructural systems to absorb and recover from extreme weather events such as heatwaves and heavy rainfall (Baek et al., 2024). This ~~capacity~~ includes both pre-disaster vulnerability reduction and post-disaster response and recovery. Each of these policy capacities can be further disaggregated into economic, social, governance, physical, and demographic domains in the context of climate resilience.

This study links unit-level heatwave response technologies—such as cooling fog systems and green infrastructure—to these policy capacities and quantifies their damage-reduction effects in monetary terms. We define heatwave damage as the sum of direct costs (e.g., treatment of heat-related illnesses) and indirect costs (e.g., productivity losses~~), and~~) and define the benefit of a given technology as the extent to which it reduces these damage costs.

Furthermore, we investigate the temporal dimension of how heatwave response technologies operate to reduce damage. We argue that o~~O~~bserved damages represent ex-post outcomes already mitigated by both ~~adaptation~~adaptive ~~capacity~~ and vulnerability reduction capacities. These damages are the residual of a broader process in which latent ex-ante damages are first prevented through vulnerability reduction and subsequently absorbed through ~~adaptation~~adaptive ~~capacity~~capacities. Thus, instead of merely estimating the direct effects of technologies, we ~~clarify~~ identify the mechanisms through which they reduce heatwave-related economic losses focusing on ~~adaptation~~adaptive ~~capacity~~capacities and vulnerability reduction ~~capacity~~capacities.

By estimating both the benefits and the threshold cost of each technology (i.e., the cost required to generate one unit of benefit), this study contributes to more precise targeting of ~~adaptation~~adaptive investments. Using annual data from 2016 to 2022 across all ~~17 provinces and metropolitan cities~~229 municipalities in South Korea, we analyze both the average and variance effects of each policy capacity. These findings offer practical insights for optimizing regional resilience strategies and prioritizing heatwave ~~adaptation~~adaptive technologies under resource constraints.

2. Methods and Data

2.1. Data Construction

This study utilizes an extended panel dataset originally developed in ″A Regional Benefit-Cost Analysis of Heatwave Climate Resilience Technologies″ (Bae et al., 2025). The dependent variable—heatwave-related damage cost—is defined as the sum of medical expenses for heat-related illnesses and productivity losses due to reduced labor ~~capacity~~capacities, calculated for each municipality (Si-Gun-Gu) between 2016 and 2022. Productivity losses are derived using estimated WBGT (Wet Bulb Globe Temperature) values and industry-specific wage data to calculate lost labor output due to excessive heat.

The panel dataset integrates the full list of input variables and sources is summarized in Table 1 below.

Table 1. Input data lists and sources

Data	Sources	Items
Cost of care for febrile illnesses	Claimed data from Health Insurance Review and Assessment service (HIRA) ~~Claim data~~	City and district (Si-gun-gu), inpatient/outpatient classification, number of patients, claims, and total cost of care for T67 (heat and light effects)
Weather variables	Korea Meteorological Administration (KMA) Open MET Data Portal	Average temperature, maximum temperature, relative humidity
Wages, number of workers by city	Ministry of Employment and Labor (MOEL) Business labor force survey	Number of workers and wage by industry & city
Heatwave response technology installations	Open information portal of Korea	Heatwave response technologies installations by year
~~Note: All collection periods range from 2016 to 2022~~		

Note: All collection periods range from 2016 to 2022

The composite climate resilience index is decomposed into two policy-relevant components:

1. Vulnerability reduction ~~capacity~~capacities (a~~e~~ffecting in the ex-ante damage),
2. ~~Adaptation~~Adaptive ~~capacity~~capacities (a~~e~~ffecting in the ex-post damage).

Vulnerability is reduced when a system prevents damage before it occurs, while adaptation involves reducing observed damage after an event. To ~~operationalize~~operate this distinction, we categorized variables under each capacity based on domain-specific indicators, using publicly available datasets such as KOSIS (Korean Statistical Information Service), urban statistics, GIS

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data, and water infrastructure statistics.

To ensure comparability, vulnerability-related variables were reverse-coded such that a higher value indicates lower vulnerability level, and thus a higher "reduction ~~capacity~~capacities." The variables for each component are presented in Tables 2 and 3.

Table 2. Indicator configuration variables for ~~Adaptati~~Adaptive capacities~~on ability~~

Sectors	S~~s~~ub sectors	Sources	Variables
Economy	Economic Power	Korean Statistical Information Service (Referred to as KOSIS) Regional Income	Amount of local tax per capita, financial independence rate, GRDP
	Industry ~~Development~~development	Survey of R&D in Korea	R&D expenditures per capita, number of researchers
Social	Medical r~~R~~esponse c~~C~~apability	Emergency Medical Services Statistics	Number of ambulances,
		Korean Urban Statistics	Number of hospitals/health centers/ medical personnel/emergency medical centers, health insurance subscribers
		~~KOSIS~~ e-Regional Indicators of KOSIS	Number of hospital beds per 1,000 people
	Social ~~infrastructure~~infrastructure	Korean Water Supply Statistics	Daily water consumption per capita, water supply rate, revenue water ratio
	Energy	Korean Urban Statistics	Energy use of buildings
Physical Infra	Shelters of extreme heat	Korean Urban Statistics	Number of welfare facilities for the aged, the homeless, the disabled, and children
	Green i~~I~~nfra	Korean Urban Statistics	Park area, green area, orchard area, forest area, stream area
Governance	Budget	Local Finance Integrated Open System	Amount of welfare budget
		KOSIS	Natural disasters management fund
	Response personnel	Korean Urban Statistics	Population per 1 fire-fighting officer, number of officers (si-do)

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Table 3. Indicator configuration variables for vulnerability reduction capacities

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Sector	sub sector	Source	Variables
Economy	Industry development	Economically Active Population Survey from KOSIS~~KOSIS Economically Active Population Survey~~	Unemployment rate
Social	Medical r~~R~~esponse c~~C~~apability	e-Regional Indicators from KOSIS~~KOSIS e-Regional Indicators~~	Unmet healthcare ratio
	Social ~~infrastructu~~ infrastructure~~re~~	Korean Water Supply Statistics	Number of people under unmet water supply
Human	Vulnerable populations	Population Statistics Based on Resident registration of KOSIS ~~Population Statistics Based on Resident registration~~	Population under 5 years of age, population of over 65 years of age, number of the disabled
		Korean Urban Statistics	Number of beneficiaries of national basic livelihood
		Local Area Labor Force Survey	Number of construction workers, number of skilled agricultural, forest, and fishery workers, number of grunt workers/temporary workers
	Underlying disease	Medical Service Usage Statistics by Region	Number of people with hypertension, number of people with diabetes
	Population density	KOSIS	Population density
Physical Infra	Vulnerable facilities	Geospatial Information Platform	Number of old buildings (20-24y/25-29y/30-34y/over 35y), road area, railroad area
	Shelters of extreme heat	Korean Urban Statistics	Number of welfare facilities for the aged, the homeless, the disabled, and children

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	Green i~~I~~nfra	Korean Urban Statistics	~~Unexecuted park~~Unexecuted Park area, paddy area, greenhouse area, upland field area
	Density of buildings	Geospatial Information Platform	Number of buildings, average height of buildings, average building coverage ratio, average building volume ratio

2.2. Analytical Approach

2.2.1. Step 1: ~~1 –~~Estimating Effects of Technologies on Policy Capacities

We begin by estimating the impact of each unit technology on physical ~~adaptat~~adaptive capacities~~ion~~ and vulnerability reduction capacities using the following log-linear ~~regressio~~regression models~~ns~~ as follows:

$$\log(X1_{Physical\text{-}\ i,t}) = \delta_1 clfog_{i,t} + \delta_2 clroof_{i,t} + \delta_3 grroof_{i,t} + \delta_4 shades_{i,t} + u_{i,t} \quad (1)$$

$$\log(X2_{Physical\ \text{-}i,t}) = \gamma_1 clfog_{i,t} + \gamma_2 clroof_{i,t} + \gamma_3 grroof_{i,t} + \gamma_4 shades_{i,t} + u_{i,t} \quad (2)$$

w~~W~~here,

- $X1_{physical\ i,t}$ = physical ~~adaptati~~adaptive~~on~~ ~~capacity~~capacities of municipality i in year t and ~~t~~
- $X2_{physical\ i,t}$ = physical vulnerability reduction ~~capacity~~capacities of municipality i in year t.
- Explanatory variables include installation quantities (units or area) of each of the four technologies. Note that
- a~~A~~ll regressions use log-transformed dependent variables to reflect diminishing marginal effects and allow elasticity interpretation.

Based on the regression coefficients (δ_k, γ_k), we calculate the marginal effect of each technology k on adaptation or vulnerability reduction as equations (3) and (4).~~:~~

$$\frac{\partial X1_{physical}}{\partial Tech_k} = \delta_k \times X1_{physical}, \quad \text{where } k = 1,2,3,4 \quad (3)$$

$$\frac{\partial X2_{physical}}{\partial Tech_k} = \gamma_k \times X2_{physical}, \quad \text{where } k = 1,2,3,4 \quad (4)$$

These predicted values allow us to construct ~~total~~ the predicted ~~adaptati~~adaptive~~on~~ capacity index ($\widehat{X1}$) and ~~total~~ the predicted vulnerability reduction capacity index ($\widehat{X2}$) by summing across all sub-sector indices including economy, social, physical, governance and human domains

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~~domains~~ as equations (5), (6).

$$\widehat{X1} = X1_{economy} + X1_{social} + \widehat{X1}_{physical} + X1_{governance} + X1_{human} \quad (5)$$
$$\widehat{X2} = X2_{economy} + X2_{social} + \widehat{X2}_{physical} + X2_{governance} + X2_{human} \quad (6)$$

These values serve as inputs to the second stage of the analysis.

2.2.2. Step 2: ~~—~~Estimating the Impact on Damage Costs

Extreme weather events such as heatwaves are inherently stochastic in nature, and the resulting damages can be viewed as probabilistic outcomes. Accordingly, we treat heatwave damage as a random variable and analyze how it is influenced by ~~adaptation~~adaptive ~~capacity~~capacities, vulnerability reduction ~~capacity~~capacities, and weather conditions. This approach allows us to evaluate both the mean-level and variance-level analysis of the effects through policy capacities of economic losses.

To do so, we apply the stochastic production function framework of Just and Pope (1978, 1979), adapting it to a damage function context. The general form of the model is as follows:

$$y_{i,t}(x_{i,t}, z_{i,t}, \beta, \varphi, e_{i,t}) = f(x_{i,t}, \beta) + e_{i,t}[h(z_{i,t}, \varphi)] \quad (7)$$

Where:

- $y_{i,t}$: observed heatwave damage in municipality i and year t,
- $x_{i,t}$: variables in municipality i and year t affecting the mean of the damage (e.g., ~~adaptation~~adaptive ~~capacity~~capacities and vulnerability reduction capacities),
- $z_{i,t}$: vector of variables affecting the variance of the damage,
- β, φ: coefficient vectors for each of the mean and variance functions,
- $\varepsilon_{i,t}$: random error ~~term~~term with zero mean and constant variance,
- $h(z_{i,t}, \varphi)$: function capturing heteroskedasticity of variances (variation in damage uncertainty).

We conceptualize heatwave response technologies as influencing heatwave damage through two stages: Step 1: t~~T~~he marginal effects of unit technologies on ~~adaptation~~adaptive ~~capacity~~capacities and vulnerability reduction capacities and Step 2: t~~T~~he impact of those capacities on damage costs.

First, we distinguished between:

- Latent ex-ante damage ($y_{i,t}{}^{*}$): the hypothetical damage that would occur without any policy intervention,
- Observed ex-post damage ($y_{i,t}$): the damage that occurs after adaptation and

vulnerability reduction efforts.

The ex-ante damage is modeled as a function of vulnerability reduction ~~capacity~~capacities as equation (8) which reflects a possible structural relationship between vulnerability reduction ~~capacity~~capacities and the ex-ante damage.

$$y_{i,t}^{*} = \beta_2 \log(X2_{i,t}) + e_{1\,i,t} \qquad (8)$$

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Since stronger vulnerability reduction is expected to prevent damage before it occurs, we anticipate that the β_2 is to be negative. As we assume diminishing marginal returns to vulnerability reduction, likely adopting a linear-log specification makes sense. ~~.~~

Next, the difference between ex-ante and ex-post damage (i.e., the amount of damage absorbed by ~~adaptation~~adaptive efforts) is modeled as a function of ~~adaptation~~adaptive ~~capacity~~capacities as equation (9).

$$(y_{i,t}^{*} - y_{i,t}) = \beta_1 \log(X1_{i,t}) + e_{2\,i,t} \qquad (9)$$

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~~Adaptation~~Adaptive capacit~~y~~ies act~~s~~ as a stock variable accumulated over time and is expected to reduce residual damage after vulnerability reduction. Therefore, β_1 is anticipated to be positive. ~~A linear~~A linear-log form is again applied, ~~due to~~anticipating its diminishing marginal returns to ~~adaptation~~adaptive ~~capacity~~capacities.

To reflect structural vulnerability reduction or ~~adaptation~~adaptive ~~resilience~~ capacities based upon the first of the panel period, we employ a fixed effects model on the panel regression, removing intercept terms and assuming time-invariant unobserved heterogeneity across municipalities.

And by substituting Equations (8) and (9), ~~,~~ and incorporating a weather control variable $X3_{i,t}$ (e.g., number of consecutive heatwave days), we derive the full model for mean heatwave damage function as ~~e~~Equation (10). ~~:~~

$$f(x_{i,t}, \beta) = -\beta_1 \log(X1_{i,t}) + \beta_2 \log(X2_{i,t}) + \beta_3 X3_{i,t} \qquad (10)$$

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Here, $X3_{i,t}$ represents the number of consecutive days in which the daily maximum temperature exceeded 30°C. Although heatwaves are often defined using thresholds like 33°C, we adopt a 30°C threshold based on empirical evidence showing that heat-related illnesses increase rapidly above this level (Park et al., 2023). We assume a linear impact of heatwave duration on damage.

Finally, the marginal effects of policy capacities on damage are computed as ~~:~~

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$$\frac{\partial Y}{\partial \bar{X}1} = -\frac{1}{\bar{X}1} \times \beta_1 \tag{11}$$

$$\frac{\partial Y}{\partial \bar{X}2} = \frac{1}{\bar{X}2} \times \beta_2 \tag{12}$$

The total benefits of each unit of technology *k* in year *t* are then derived by combining the marginal effects of technology on policy capacities (from Step 1) with the marginal effects of those capacities on damage (from Step 2).~~:~~

$$\text{Benefit}_{i,k,t} = \left| \frac{\partial X1_{phy}}{\partial Tech_k} \times \frac{\partial Y}{\partial \bar{X}1} + \frac{\partial X2_{phy}}{\partial Tech_k} \times \frac{\partial Y}{\partial \bar{X}2} \right| = \left| \delta_k X1_{phy} \times \frac{\beta_1}{\bar{X}1} + \gamma_k X2_{phy} \times \frac{\beta_2}{\bar{X}2} \right| \tag{13}$$

This formula allows us to estimate how much economic damage is reduced by each additional unit of technology, depending on the existing levels of ~~adaptation~~adaptive capacities~~y~~ and vulnerability reduction capacities.

3. Estimation Results

3.1. Benefits and Cost Thresholds at Average Technology Levels

During the period, the average annual heatwave-induced damage of each municipality (Si-Gun-Gu) amounted to KRW 1.~~17~~ 12 billion approximately, hereinafter. The highest annual damage occurred in 2018, with an average of KRW 3.~~38~~ 15 billion, whereas the lowest was in 2020, recording only KRW 0.~~2.86~~316 m~~b~~illion (Table 4).

Table 4. Annual ~~1~~Averages of Key Variables

Year	Heatwave Damage (Mil. KRW)	Adaptive Capacity Index	Vulnerability Reduction Index	Number of continuous h~~H~~eatwave d~~D~~ays
2016	1,~~545~~381	2.19~~0.166~~	3.97~~0.302~~	44.5~~44.6~~
2017	~~751~~772	2.12~~0.163~~	3.97~~0.292~~	42.2~~40.3~~
2018	3,~~376~~149	2.13~~0.164~~	3.97~~0.293~~	48.3~~48.3~~
2019	~~875~~796	2.07~~0.161~~	3.99~~0.291~~	34.6~~34.0~~
2020	~~286~~316	2.08~~0.163~~	3.98~~0.293~~	30.7~~30.0~~
2021	~~747~~670	2.04~~0.159~~	4.02~~0.297~~	37.9~~38.4~~
2022	~~654~~753	2.22~~0.175~~	3.98~~0.294~~	42.5~~41.0~~
avg	**1,~~177~~120**	**2.12~~0.164~~**	**3.98~~0.295~~**	**40.1~~39.5~~**

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By province, the highest average damage was found in Seoul (KRW ~~60.99~~24.24 billion), followed by ~~Gyeonggi~~ Daegu Province (KRW ~~59.47~~21.07 billion) and ~~Busan~~ Geong-gi (KRW 19.~~44~~ 04 billion). The lowest average was observed in ~~Jeju~~ Gangwon at KRW ~~792~~ 122 million (Table 5).

Regarding the number of continuous heatwave days exceeding 30°C, 2018 had the most (48.3 days), followed by 2016 (44.~~6~~ 5 days) and 2022 (~~41~~ 42.5 days). The year 2020 experienced the fewest continuous heatwave days (30.7 days).

By region, Daegu had the most heatwave days (61.8), followed by Gwangju (58.2) and Sejong (52.0). Ulsan recorded the fewest with 22.~~6~~7 days.

Table 5. Regional Averages of Key Variables

Region	Heatwave d~~D~~amage (Mil. KRW)	Adaptive c~~C~~apacity	Vulnerability r~~R~~eduction	Number of continuous h~~H~~eatwave d~~D~~ays
Seoul	2,424~~60,990~~	5.43 ~~5.92~~	6.78 ~~7.09~~	44.2 ~~44.2~~
Busan	1,205~~19,420~~	2.27 ~~2.56~~	4.68 ~~4.7~~	31.4 ~~31.4~~
Daegu	2,107~~16,870~~	1.08 ~~1.14~~	2.26 ~~2.4~~	61.8 ~~61.8~~
Incheon	1,234~~12,460~~	1.35 ~~1.47~~	2.83 ~~2.81~~	27.9 ~~27.9~~
Gwangju	1,437~~7,267~~	0.71 ~~0.72~~	1.44 ~~1.45~~	58.2 ~~58.2~~
Daejeon	1,464~~7,351~~	0.77 ~~0.77~~	1.45 ~~1.46~~	45.6 ~~45.6~~
Ulsan	1,114~~5,619~~	0.59 ~~0.6~~	1.50 ~~1.5~~	22.7 ~~22.6~~
Sejong	1,188~~1,190~~	0.15 ~~0.12~~	0.30 ~~0.3~~	52.0 ~~52.0~~
Gyeong-gi	1,904~~59,470~~	8.73 ~~9.32~~	8.52 ~~8.67~~	37.6 ~~37.6~~
Gangwon	122~~2,206~~	1.80 ~~1.81~~	5.90 ~~5.58~~	26.2 ~~26.2~~
Chung-buk	609~~6,707~~	1.40 ~~1.32~~	3.43 ~~3.36~~	44.3 ~~44.3~~
Chung-nam	866~~13,010~~	1.92 ~~1.94~~	4.60 ~~4.51~~	37.2 ~~37.2~~
Jeon-buk	657~~9,273~~	1.66 ~~1.6~~	4.32 ~~4.24~~	39.9 ~~39.9~~
Jeon-nam	376~~8,362~~	2.53 ~~2.57~~	6.98 ~~6.72~~	41.6 ~~41.6~~
Gyeong-buk	718~~16,550~~	2.92 ~~2.99~~	7.02 ~~6.88~~	42.1 ~~42.1~~
Gyeong-nam	1,208~~21,890~~	2.55 ~~2.59~~	5.24 ~~5.23~~	44.8 ~~44.8~~
Jeju	400~~792~~	0.25 ~~0.22~~	0.49 ~~0.56~~	24.4 ~~24.4~~
Average	**1,120~~15,849~~**	**2.12 ~~2.22~~**	**3.98 ~~3.97~~**	**40.1 ~~40.1~~**

서식 지정된 표

서식 지정함: 글꼴: (한글) +본문 한글(맑은 고딕)

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서식 지정함: 글꼴: 굵게

Table 6 presents the estimated results of the regression model linking unit physical technologies to policy capacities. The current level of ado~~e~~ption of cooling fog systems, cool roofs, rooftop/wall greening, and shade canopies shows significant impact on vulnerability reduction ~~capacity~~capacities, but generally insignificant or even counterintuitive effects on ~~adaptation~~adaptive ~~capacity~~capacities.

This discrepancy ~~is likely due to~~results from the structural composition of each ~~capacity~~capacity index. The ~~adaptation~~adaptive capacity index includes elements such as welfare facilities and the extent of river or forest areas—features that units of technologies cannot easily influence. In contrast, the vulnerability reduction index comprises structural urban characteristics—such as the number and height of buildings, zoning classifications, road and rail areas, and building ~~coverage~~ area ratios—which can be directly affected by unit technologies through cooling or insulation functions.

Table 6. Regression Results: ~~—~~Effects of Unit Technologies on Physical dimensions ~~Capacity~~ of each capacit~~y~~ies

	Dependent Variable: log(X1$_{phy}$)		Dependent Variable: log(X2$_{phy}$)	
	Parameters	Coeff. Estimates (Standard Errors)	Parameters	Coeff. Estimates (Standard Errors)
Cooling Fog (per unit)	δ_1	-0.0004688 (0.000785)	γ_1	**0.0009017*** (0.0001814)**
Cool Roof (per m^2)	δ_2	**-0.0000083** (0.00000383)**	γ_2	**0.00000505*** (0.000000885)**
Green Roof/Wall (per m^2)	δ_3	**-0.0000244** (0.0000124)**	γ_3	**0.0000218*** (0.00000286)**
Shade Canopy (per unit)	δ_4	-0.000078 (0.000074)	γ_1	**0.0000789*** (0.0000171)**

Note: Robust standard errors in parentheses.
*, **, *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

~~Note: Robust standard errors in parentheses.~~
~~*, **, *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.~~

	~~Dependent Variable: log(X1$_{phy}$)~~		~~Dependent Variable: log(X2$_{phy}$)~~	
	~~Estimates~~	~~Standard Errors~~	~~Estimates~~	~~Standard Errors~~
~~Cooling Fog (per unit)~~	~~δ_1~~	~~-0.0004688 (0.000785)~~	~~γ_1~~	~~0.0009017*** (0.0001814)~~
~~Cool Roof (per m^2)~~	~~δ_2~~	~~-0.0000083** (0.00000383)~~	~~γ_2~~	~~0.00000505*** (0.000000885)~~

서식 있음: 표준
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Green-Roof/Wall (per m²)	δ_3	-0.0000244** (0.0000124)	γ_3	0.0000218*** (0.00000286)
Shade Canopy (per unit)	δ_4	-0.000078 (0.000074)	γ_4	-0.0000789*** (0.0000171)

Note: Robust standard errors in parentheses.
*, **, *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Cooling fog installations had no significant effect on adaptationadaptive capacitycapacitiesy, but did increased vulnerability reduction capacitycapacities by approximately 0.09% per unit. Similarly, cool roof installations decreased adaptationadaptive capacitycapacities by 0.0008% per 1㎡, but improved vulnerability reduction by 0.0005%. Per unit rRooftop/wall greening showed a 0.002% decrease in adaptationadaptive capacitycapacities but increased vulnerability reduction by 0.002%. Per unit sShade canopies had no statistically significant impact on adaptationadaptive capacitycapacities but increased vulnerability reduction capacitycapacities by 0.008%. These findings suggest that unit technologies are more effective in reducing structural vulnerability than in enhancing broader adaptationadaptive capacitycapacities.

Table 17. Regression Results – Estimated Impact on Heatwave Damage

	EstimatesParameters	Dependent Variable: Heatwave Damage (Mil. KRW)	
		Coeff. EEstimates	Standard Errors
$\log(\widehat{X1}_{i,t})$	β_1	**2077.382*** **	523.9441
$\log(\widehat{X2}_{i,t})$	β_2	**-8401.612*** **	2129.045
$X3_{i,t}$	β_3	**75.025651*** **	6.758295

Note: Robust standard errors in parentheses.
*, **, *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 7 presents the effect of each estimated policy and consecutive days over 30°C on actual heatwave damage. Both capacities were found to be statistically significant in reducing heatwave-related damage. An 1% increase in adaptationadaptive capacitycapacities leadsleads to a reduction of approximately KRW 2.1 billion, while an 1% increase in vulnerability reduction capacitycapacities corresponds to a reduction of KRW 8.4 billion. Each additional day of heatwave exceeding 30°C increases expected damage by KRW 75 million. This suggests that pre-disaster vulnerability mitigation yields greater benefits than post-disaster adaptationadaptive,

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서식 있음: MS바탕글, 줄 간격: 1줄, 테두리: 아래쪽: (테두리 없음)
서식 있음: 테두리: 아래쪽: (테두리 없음)
서식 있음: 양쪽
서식 지정함: 글꼴: (한글) Times New Roman, 10 pt, 무늬: 지우기
서식 있음: MS바탕글, 줄 간격: 1줄

emphasizing the importance of proactive measures as follows in equations (14).

$$f(x_{i,t}, \beta) = -2077.382 * \log(\widehat{X1}_{i,t}) - 8401.612 * \log(\widehat{X2}_{i,t}) + 75.026~~551~~ * X3_{i,t} \quad (14)$$

3.2. Marginal Benefits and Estimated Cost Thresholds~~ of Unit Technologies~~

3.2.1. Distribution of Marginal Benefits and Cost Thresholds per Unit Technology

We calculated the marginal benefit of each unit of the technologies by estimating the reduction in damage costs at the average level of installation. This was derived following the process outlined in Equation (13).~~,~~ T~~and t~~he total~~full~~ distribution of estimated benefits is presented in Table 8.

Table 2~~8~~. Distribution of Estimated Benefits per Unit Technology (in KRW)

Unit: KRW

Unit Technology	Minimum	2nd Quartile	Median	3rd Quartile	Maximum	**Mean**
Cooling Fog (per unit)	1,~~790~~788,~~603~~773	3,496,~~188~~041	3,728,~~746~~732	3,935,~~683~~089	4,~~601~~602,~~87~~8625	**3,691,~~131~~099**
Cool Roof (per m²)	2,~~121~~312	16,~~703~~692	18,~~625~~618	20,~~110~~105	25,~~334~~340	**18,074**
Green Roof/Wall (per m²)	21,~~225~~231	76,~~120~~083	83,~~527~~539	89,~~233~~248	~~110~~109,~~009~~991	**81,600**
Shade Canopy (per unit)	156,~~390~~520	305,~~923~~908	326,~~272~~269	344,~~417~~326	402,~~619~~736	**322,~~994~~976**

Figure 1. Distribution of Estimated Benefits per Unit Technology (in KRW)

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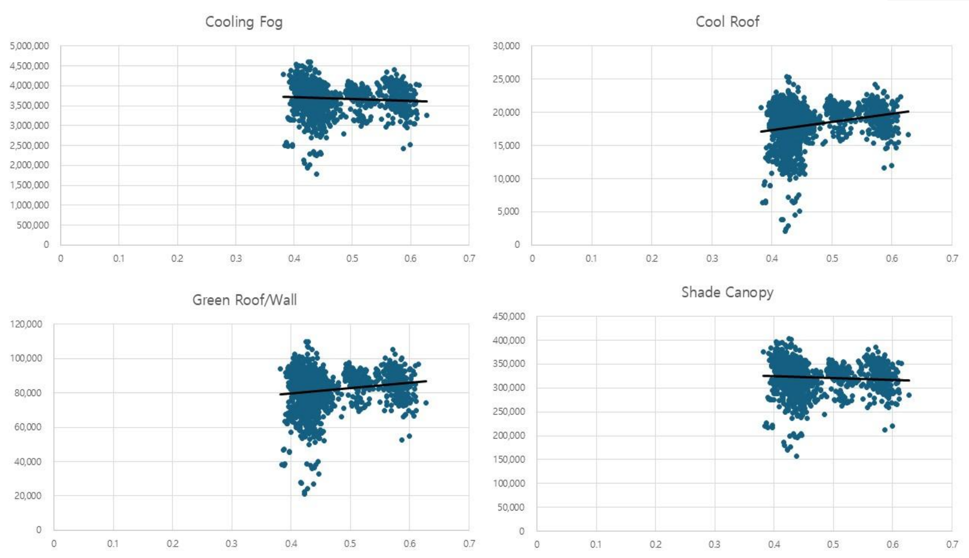
서식 지정함: 글꼴: (Intl) Times New Roman
서식 지정함: 글꼴: (한글) +본문 한글(맑은 고딕), (Intl) Times New Roman, 무늬: 지우기
서식 있음: MsoCaption, 줄 간격: 1줄



On average, a single cooling fog system generates a benefit equivalent to approximately 3.69 million KRW in avoided damage costs, with a range from 1.79 million to 4.60 million KRW.

For cool roofs, each additional square meter of installation yields a benefit of about 18,074 KRW, ranging from 2,~~122~~ 131 to 25,~~334~~ 340 KRW.

Green roofs and walls offer an average benefit of approximately 81,600 KRW per square meter, with a minimum of 21,~~225~~ 231 KRW and a maximum of ~~110~~109,~~009~~ 991 KRW.

Shade canopies reduce damages by about 322,~~994~~ 976 KRW per unit on average, ranging from 156,~~390~~ 520 to 402,~~619~~ 736 KRW.

The annualized installation costs for each unit of the technologies were estimated using previous studies and interviews with manufacturers when public data was not available (Bae et al., 2025).

Figure 1. presents scatter plots illustrating the marginal benefits of four technologies across varying levels of estimated policy scores. The horizontal axis represents total policy capacity level $(\hat{X})$ which consists of the sum of adaptive capacities and vulnerability reduction capacities. The vertical axis shows the corresponding reduction in heatwave-related damage costs.

Across all technologies, we observe significant heterogeneity in the distribution of marginal benefits. Cooling Fog exhibited a generally negative trend, suggesting diminishing or stagnant returns at higher policy levels. In contrast, Cool Roof and Green Roof/Wall demonstrated slight upward trends, implying that higher policy engagement may be associated with increased marginal benefits. The Shade Canopy shows a relatively flat or slightly decreasing pattern, indicating limited sensitivity in damage mitigation benefits to the policy level.

Figure 2. Distribution of total benefits across 229 municipalities in 2016 to 2022

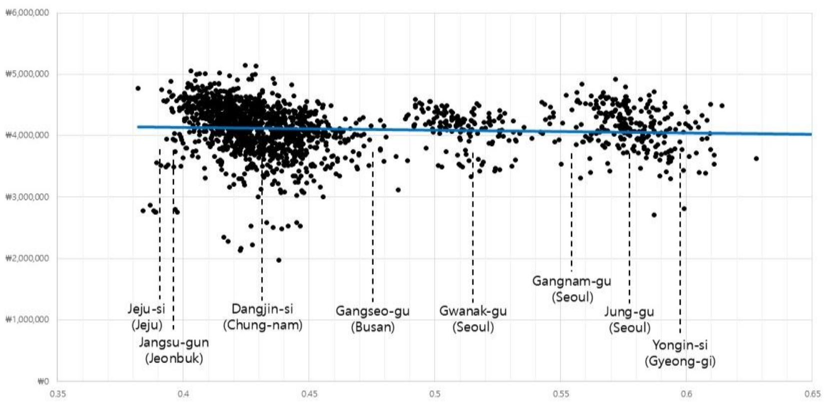


Figure 2. visualizes the trend between 229 municipalities' heatwave policy capacities and the corresponding economic benefits from damage reduction over 7 years. Each point represented municipality-year observation, with the horizontal axis indicating the composite policy level and the vertical axis denoting the estimated benefit in KRW.

The trend line suggests a slightly negative correlation and the differences in municipalities. Labeled points highlight representative cases across different percentiles of the policy level distribution. For instance, Jeju-si and Jangsu-gun are positioned near the lower end of the policy spectrum, associated with relatively scattered and often lower benefit values. In contrast, Gangnam-gu, Jung-gu (Seoul), and Yongin-si are in the upper tail of the policy score distribution and tend to exhibit consistently higher levels of benefit.

These findings suggest that the economic effectiveness varies not only in magnitude but also in how it responds to increased policy capacity. And there's a heterogeneous nature of policy implementation and effectiveness, suggesting that both structural capacity and execution strategies vary considerably across municipalities. Such insights provide empirical evidence for designing differentiated and targeted policy strategies against heatwaves.

According to these estimates (Table 6), the annual cost per unit was as follows.

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Table 39. Estimated Annual Cost per Unit Technology

Unit Technology	Installation Cost	Durability (Years)	Annual Maintenance	Annual Total Cost	Converted KRW (Applying the exchange rate on May the 27th 2025)
Cooling Fog (per unit)	₩100,000,000	25	₩7,200,000	**₩11,200,000**	-
Cool Roof (per m²)	$129	10	$2.58	$15.48	**₩20,650**
Green Roof/Wall (per m²)	$223	40	$28	$33.73	**₩44,996**
Shade Canopy (per unit)	₩950,000	9	₩300,000	**₩405,600**	-

서식 있음: 들여쓰기: 첫 줄: 0.39 cm

서식 지정함: 글꼴: (한글) +본문 한글(맑은 고딕)

Based on the estimated benefits and annual costs, we calculated the cost-effectiveness threshold, which represents the cost per 1 KRW of damage reduction. These results are shown in Table 10.

Table 410. Cost-Effectiveness Threshold per Unit Technology

Unit Technology	Minimum	2nd Quartile	Median	3rd Quartile	Maximum	Mean
Cooling Fog (per unit)	2.43	2.85	3.00	3.20	6.25	**3.07**
Cool Roof (per m²)	**0.84**	1.05	1.14	1.27	9.98	**1.23**
Green Roof/Wall (per m²)	**0.42**	**0.52**	**0.55**	**0.61**	2.17	**0.58**
Shade Canopy (per unit)	1.01	1.18	1.24	1.33	2.59	**1.27**

Among all technologies, green roofs and walls exhibited the lowest average cost-effectiveness threshold at 0.58, indicating that each 1 KRW of benefit costs only 0.58 KRW on average, thus meeting the economic viability threshold.

Although cooling fog systems provided the largest marginal benefit per unit, they also had the highest cost, resulting in a mean cost-effectiveness threshold of 3.07, ranging from 2.43 to 6.25.

Cool roofs showed economic feasibility only in the lower quartile, while shade canopies exhibited moderate feasibility, with a threshold ranging from 1.01 to 2.59 and a mean of 1.27.

3.2.2. Marginal Benefits and Cost Thresholds across Llevels of Ppolicy Ceapacitiesby Installation Level

Table 11 summarizes how the marginal effect of each unit technology changes across different installation adaptive and vulnerability reduction capacity levels. The analysis clearly shows that every marginal returns of technologies diminishesshing marginal returns for all technologiesfollowed by the quantiles of the policy levels..

Table 511. Marginal Effects acrossby the Ppolicy Ceapacity QqQuantiles levels of Unit Technology Installation

Unit: KRW

Unit Technology	Minimum	2nd Quartile	Median	3rd Quartile	Maximum	Mean
Cooling Fog (per unit)	1,788,772	1,432,619	1,294,551	1,325,856	1,301,586	**1,384,708**
Cool Roof (per m²)	9,993	7,984	7,216	7,385	7,267	**7,718**
Green Roof/Wall (per m²)	43,173	34,521	31,197	31,936	31,402	**33,367**
Shade Canopy (per unit)	156,520	125,356	113,275	116,014	113,891	**121,164**

For instance, in regions with relatively low installation llevels of the policy capacities cooling fog systems, the marginal benefit was as high as 1.79 million KRW, but this declined to around 1.30 million KRW in more saturated regions (4th quartile).

Similarly, the marginal benefit of cool roofs decreased from 9,993 KRW to 7,267 KRW as the installation policy level increased.

Green roofs/walls showed a decline from 43,173 KRW to 31,402 KRW, while shade canopies dropped from 156,520 KRW to 113,891 KRW.

These findings confirm the non-linear propertynature of the technologies' effects, emphasizing a diminishing returns structure. Also, tThis supports the policy implication that prioritizing

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investments in ~~areas~~which areas have had ~~with~~ relatively ~~low~~ inferior chances against ~~current~~heatwave in terms of policy intervention, ~~installation levels~~ would be ~~a~~ more efficiently allocat~~ed~~ion ~~of limited resources.~~.

The diminishing marginal returns for additional installation of the technologies also can be observed in the marginal effects of regions and unit technologies over the years. First, as shown on Table 12, there's a spatial difference between regions over the years. This showed spatial heterogeneity in the unit-level benefits of an additional combination of 4 technologies. Results indicate that the marginal benefits of an additional combination of technologies diminished as the year passed in all regions and were the highest in the first year. For example, Seoul had the highest amount of increase in the first year at KRW 1.59 million approximately, but it decreased to KRW 52,000 approximately in the last year.

In the average level, the marginal effects were particularly high in major metropolitan areas such as Gyeonggi (KRW 129.1 million in 2022), Seoul (KRW 102.1 million), Jeon-nam (KRW 92.4 million), and Gyeong-buk (KRW 94.6 million). In contrast, significantly lower benefits were observed in Sejong (KRW 3.9 million) and Jeju (KRW 6.3 million), reflecting regional disparities in how much the technologies are installed.

Table 62. Unit-level benefits for 17 regions over the years

Unit: 1,000 KRW

	2016	2017	2018	2019	2020	2021	2022	Average
Seoul	88,433	104,312	103,401	106,444	104,684	103,695	103,748	102,102
Busan	56,103	65,498	64,007	66,397	66,568	65,127	66,850	64,364
Daegu	28,265	31,830	31,622	31,992	31,157	30,613	30,980	30,923
Incheon	38,911	44,468	43,803	45,260	44,848	43,702	44,737	43,676
Gwangju	17,742	20,330	20,555	21,217	20,995	20,840	21,091	20,396
Daejeon	17,693	20,320	20,529	21,465	21,193	20,341	20,237	20,254
Ulsan	17,100	19,580	20,127	20,688	20,444	20,141	20,825	19,844
Sejong	3,642	3,979	3,950	4,045	4,005	4,019	3,927	3,938
Gyeong-gi	115,224	133,332	131,531	134,516	130,578	128,942	129,303	129,061
Gangwon	69,410	76,843	76,502	80,386	79,719	79,263	79,442	77,366
Chung-buk	40,351	46,387	43,194	45,365	44,529	44,155	45,613	44,228
Chung-nam	58,446	61,976	62,349	63,146	62,726	61,054	62,206	61,701
Jeon-buk	53,419	57,745	57,158	58,723	56,938	57,541	57,266	56,970

서식 지정함: 글꼴 색: 파랑

서식 있음: MsoCaption, 오른쪽

서식 지정된 표

Jeon-nam	87,818	93,621	92,256	94,714	91,366	92,835	93,921	92,362
Gyeong-buk	87,785	93,215	95,653	98,304	97,093	94,383	95,608	94,577
Gyeong-nam	68,013	73,227	72,280	75,717	75,527	75,715	77,623	74,014
Jeju	6,073	6,366	6,310	6,304	6,247	6,334	6,273	6,272

This pattern of diminishing marginal returns is also observed in the trend of unit-level benefits across individual technologies over time, as presented in Table 13. While all four technologies showed substantial levels of damage reduction per unit, the rate of increase in marginal benefits plateaued or slightly declined in later years. For instance, the unit benefit of cooling fog systems increased from KRW 3.35 million in 2016 to KRW 3.76 million in 2022, but the annual growth rate significantly slowed after 2017. Similar patterns are evident in cool roofs and green roofs/walls, where the unit-level benefits fluctuated within a narrow range, indicating a stabilization of marginal returns. This suggests that the accumulated deployment of technologies may lead to a saturation point, beyond which the effectiveness of each additional unit declines.

Table 73. Marginal Effects of unit technology over the years

Unit: KRW

	2016	2017	2018	2019	2020	2021	2022
Cooling Fog (per unit)	3,348,750	3,734,310	3,703,737	3,819,116	3,755,932	3,717,317	3,758,528
Cool Roof (per m²)	16,126	18,234	18,084	18,658	18,416	18,158	18,840
Green Roof/Wall (per m²)	73,234	82,403	81,728	84,305	83,106	82,050	84,372
Shade Canopy (per unit)	293,020	326,757	324,082	334,178	328,649	325,270	328,876

~~This appeared same in municipalities over the years.~~

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서식 있음: 테두리: 위쪽: (테두리 없음)

	~~88,433~~	~~104,312~~	~~103,401~~	~~106,444~~	~~104,684~~	~~103,695~~	~~103,748~~	~~714,717~~
	~~56,103~~	~~65,498~~	~~64,007~~	~~66,397~~	~~66,568~~	~~65,127~~	~~66,850~~	~~450,551~~
	~~28,265~~	~~31,830~~	~~31,622~~	~~31,992~~	~~31,157~~	~~30,613~~	~~30,980~~	~~216,460~~
	~~38,911~~	~~44,468~~	~~43,803~~	~~45,260~~	~~44,848~~	~~43,702~~	~~44,737~~	~~305,730~~
	~~17,742~~	~~20,330~~	~~20,555~~	~~21,217~~	~~20,995~~	~~20,840~~	~~21,091~~	~~142,771~~
	~~17,693~~	~~20,320~~	~~20,529~~	~~21,465~~	~~21,193~~	~~20,341~~	~~20,237~~	~~141,778~~
	~~17,100~~	~~19,580~~	~~20,127~~	~~20,688~~	~~20,444~~	~~20,141~~	~~20,825~~	~~138,905~~
	~~3,642~~	~~3,979~~	~~3,950~~	~~4,045~~	~~4,005~~	~~4,019~~	~~3,927~~	~~27,567~~
	~~115,224~~	~~133,332~~	~~131,531~~	~~134,516~~	~~130,578~~	~~128,942~~	~~129,303~~	~~903,426~~
	~~69,410~~	~~76,843~~	~~76,502~~	~~80,386~~	~~79,719~~	~~79,263~~	~~79,442~~	~~541,564~~
	~~40,351~~	~~46,387~~	~~43,194~~	~~45,365~~	~~44,529~~	~~44,155~~	~~45,613~~	~~309,595~~
	~~58,446~~	~~61,976~~	~~62,349~~	~~63,146~~	~~62,726~~	~~61,054~~	~~62,206~~	~~431,904~~
	~~53,419~~	~~57,745~~	~~57,158~~	~~58,723~~	~~56,938~~	~~57,541~~	~~57,266~~	~~398,790~~
	~~87,818~~	~~93,621~~	~~92,256~~	~~94,714~~	~~91,366~~	~~92,835~~	~~93,921~~	~~646,532~~
	~~87,785~~	~~93,215~~	~~95,653~~	~~98,304~~	~~97,093~~	~~94,383~~	~~95,608~~	~~662,041~~
	~~68,013~~	~~73,227~~	~~72,280~~	~~75,717~~	~~75,527~~	~~75,715~~	~~77,623~~	~~518,101~~
	~~6,073~~	~~6,366~~	~~6,310~~	~~6,304~~	~~6,247~~	~~6,334~~	~~6,273~~	~~43,907~~

4. Conclusion and Policy Implications

This study evaluated the economic viability of various heatwave ~~adaptation~~adaptive technologies by estimating their marginal benefits in reducing damage costs and comparing them to estimated annualized costs. By distinguishing between ~~adaptation~~adaptive ~~capacity~~capacities and vulnerability reduction, we investigated not only the direct effectiveness of technologies but also their relative contributions to ex-ante and ex-post damage mitigation.

Our findings highlight several key insights: (1)

Vulnerability reduction has greater economic benefits than ~~adaptation~~adaptive capacity improvement in reducing heatwave-related damages. Specifically, a 1% increase in vulnerability reduction ~~capacity~~capacities was associated with a greater reduction in damage costs than a similar increase in ~~adaptation~~adaptive ~~capacity~~capacities. (2)

Units of technologies generally contributed more to reducing vulnerability than improving

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~~adaptation~~adaptive ~~capacity~~capacities. Technologies such as cooling fog, cool roofs, green walls, and shade canopies were found to significantly reduce structural heat vulnerability, while having limited or even counterintuitive effects on overall ~~adaptation~~adaptive ~~capacity~~capacities. (3)

Cost-effectiveness along with other policies varies significantly across technologies and installation levels. While cooling fog systems delivered the highest marginal benefit per unit, their high installation and maintenance costs lowered their cost-effectiveness. In contrast, green roofs and walls exhibited both significant marginal benefits and the lowest cost-effectiveness threshold in the relations of technologies and other policies, making them the most economically viable among the technologies considered in this term. (4)

The marginal benefit of each technology declines as installation levels increase, indicating a diminishing returns structure. This suggests that allocating resources to under-equipped areas may yield higher policy effectiveness per unit of investment.

While this study provides a comprehensive assessment of the economic effectiveness of heatwave ~~adaptation~~adaptive technologies, several limitations remain:

(1) Data Constraints: Some cost estimates were based on manufacturer interviews or prior literature due to the lack of publicly available standardized cost data. Future studies could benefit from more granular, region-specific cost records that capture variability in installation, maintenance, and operational expenditures.

(2) Dynamic Effects and Time Lags: The study assumes immediate effects of ~~adaptation~~adaptive measures, while, in reality, policy effects may be delayed or cumulative over time. Incorporating dynamic models could improve the realism of future estimations.

Future research should expand the analysis to include heavy rainfall events, examine the role of these technologies in reducing uncertainty in heatwave damages, and explore dynamic cost–benefit analyses under various climate change scenarios.

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~~5.~~ References

서식 있음: 단락 앞에서 페이지 나누기

Bae DW. 2025. A regional benefit-cost analysis of heatwave climate resilience technologies in South Korea [dissertation]. Seoul: Seoul Nat'l University.

Baek YS, Kim KS, An DH. 2024. Spatial distribution analysis of climate resilience index in heavy rainfall: The case of Seoul (in Korean with English abstract). The Korea Spatial Planning Review 122: 119–138. doi: 10.15793/kspr.2024.122..007

Kwon YS, Jeong GU, Choi YJ. 2017. Urban heatwave response strategies in the Daegu metropolitan area in the era of climate change. Daegu-Gyeongbuk Development Institute.

Lee GE and Cho HN. 2024. Analysis and improvement of regional heatwave policy through in-depth interviews with public officials (in Korean with English abstract). Journal of Climate Change Research 15(6): 1051–1062. doi: 10.15531/KSCCR.2024.15.6.1051

Lee MJ. 2020. Current status of urban heatwave occurrence and damage reduction measures. Gukto (National Territory), August 2020;466: 15–20.

Park CY. 2023. The impact of climate change on hourly WBGT and working capacity. Risk Management Research 34(2): 2–11. uci: I410-ECN-151-24-02-088754021

Park SW, Hwang JY, Kim HE, Lee YJ, Kim JH, Ahn YJ. 2023. Results of the 2022 heat-related illness surveillance. Public Health Weekly Report 2023; 16(9): 241–252. doi: 10.56786/PHWR.2023.16.9.1

Pyon HS. 2022. Policy proposal for the effectiveness and promotion of rooftop greening. Chungbuk Research Institute. Chungbuk Focus: 207

Yi CY, Kwon HG, and Bae MK. 2024. Research on determination of heat wave damage in Korea and direction for management. Journal of Climate Change Research 15(2): 141–152. doi: 10.15531/KSCCR.2024.15.2.141

Manso M, Teotnio I, Silva CM, Cruz OC. 2021. Green roof and green wall benefits and costs: A review of the quantitative evidence. Renewable and Sustainable Energy Reviews 135: 110111. doi: 10.1016/j.rser.2020.110111

Just, R. E. & Pope, R. D. 1978. Stochastic specification of production functions and economic implications. Journal of Econometrics 7(1): 67-86

Just, R. E. & Pope, R. D. 1978. Production function estimation and related risk considerations. American Journal of Agricultural Economics 61(2): 276-284

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