Journal of Marketing & Social Research

ISSN (Online): 3008-0711

Volume: 02 | Issue 10 | 2025

Journal homepage: https://jmsr-online.com/

Research Article

The Saarbrücken Sun Project: Natural Methods for Increasing Sunlight in Cloudy Areas of Germany and Europe

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Received: 25/09/2025; Revision: 25/10/2025; Accepted: 06/11/2025; Published: 20/12/2025

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Abstract: Urban environments in northern European regions frequently encounter prolonged periods of cloud cover, which can significantly restrict direct solar exposure and adversely affect public health, social interaction, and overall quality of life. The city of Saarbrücken, Germany, situated in the federal state of Saarland along the Franco-German border, exemplifies these challenges. While prior studies have explored the psychological and social implications of limited sunlight, research remains limited on integrative urban design and technological interventions that mitigate this deficit. This study examines how sunlight access influences mental health, cognitive functioning, and quality of life in Saarbrücken, while also benchmarking the proposed Sun Park heliostat project against international precedents. In this model, sun-tracking reflector systems (heliostats) are installed to capture even limited sunlight during cloudy days and redirect it into shaded or low-illumination areas of urban parks. The proposed model, exemplified through the model of a "Sun Park," incorporates sun-tracking reflector technologies embedded in environmentally conscious urban design to redirect natural light into low-illumination zones. A structured survey of 300 respondents incorporated validated instruments alongside measures of home sunlight, time outdoors, and workplace daylight. Findings show that the deployment of heliostat systems can significantly increase effective solar exposure in targeted public spaces, leading to improved mood, stronger social interactions, and higher perceived quality of life .Reliability analysis confirmed internal consistency of all scales, and exploratory factor analysis supported a four-factor structure. Results from multivariate multiple regression showed that home sunlight and time outdoors were significant predictors of psychosocial outcomes, whereas workplace daylight had weaker but consistent effects. Benchmarking demonstrated that Sun Park scored higher than comparable projects in Viganella (Italy) and Rjukan (Norway), particularly in technical performance, governance integration, and health-oriented outcomes. These findings emphasize the importance of daylight access as a determinant of well-being and highlight the potential of heliostat-based interventions as public health infrastructure in urban planning. By observing environmental principles and radiation management, this technology can be a sustainable and human-centered solution for European cloud cities. The results show that the smart integration of technology and urban design can increase useful solar radiation and at the same time improve quality of life.

Keywords: Saarbrücken; Sun Park model; Sunlight exposure; Heliostat; Urban daylighting; Mental health; Quality of life; Public health infrastructure; Climate-responsive urban design.

INTRODUCTION

In cloudy regions of Europe, particularly in Saarbrücken, a city in southwestern Germany, the reduced direct sunlight during many months of the year has significant impacts on residents' health and quality of life. These include increased incidence of mood disorders such as seasonal depression, reduced energy levels, chronic fatigue, and diminished social interactions. Such challenges not only affect psychological and physical well-being but also have negative economic, social, and tourism-related consequences.

Mental health disorders, including depression and anxiety, are among the leading causes of disability worldwide; their prevalence rose markedly—by nearly 50%—from 1990 to 2019, with further increases observed during the COVID era (J. Wang et al., 2023). A growing body of research highlights sunlight exposure as a salient protective factor. For instance, ultraviolet B (UVB) exposure has been shown to mitigate depression, and light therapy is effective for both seasonal and non-seasonal depressive disorders (Li et al., 2015). In Taiwan, prolonged moderate UVB exposure inhibited depressive symptoms among populations studied and better sunlight exposure correlates with shorter hospital stays for mental health patients (Luo et al., 2022). In regions like Finland, long-term residential sunlight exposure has been associated with measurable improvements in cognitive domains such as visual memory, learning, and sustained attention—equating to cognitive age differences of 2 to 4 years (Kent et al., 2009). Moreover, across large cohorts, reduced sunlight precedes cognitive impairment in depressed individuals, exhibiting a specific dose-response relationship. These findings underscore the potent impact of sunlight on cognitive, emotional, and overall mental functioning.

Beyond psychological effects, insufficient daylight contributes to circadian disruption. Urban inhabitants now spend over 90% of their time indoors, with daylight exposure averaging just 2.5 hours per day—insufficient to

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entrain the biological clock and protect against depressive disorders (Crouse et al., 2025). A disrupted sleep–wake cycle, amplified by low natural light, is linked to anxiety, mood swings, and impaired immune function (Burke et al., 2022).

Since artificial solutions like high-energy lighting or conventional heating systems are costly and often conflict with environmental sustainability principles, there is a growing need for innovative, low-energy, and eco-friendly alternatives. One promising approach is the deployment of solar reflective mirrors equipped with automatic sun-tracking technology. These mirrors can redirect sunlight into public spaces and areas with low natural light, thereby enhancing public health and quality of life.

Despite substantial evidence regarding sunlight and green space benefits, research on engineered urban interventions to increase solar exposure remains sparse. Most studies focus on greenness: a UK Biobank study found a 4% lower odds of major depressive disorder with higher residential green exposure (Sarkar et al., 2018). Similar findings emerge across countries, with green space promoting mental well-being via restoration, social interaction, physical activity, and buffering environmental stressors (Zhu et al., 2023 & Huang et al., 2024). Still, effects vary regionally and socioeconomically (Zhu et al., 2023b). Recent work also emphasizes the importance of everyday visible greenery (“on-road greenery”) over isolated parks—such exposure correlates more strongly with reduced prescription rates for depression and anxiety (Šćepanović et al., 2025).

However, most urban design responses focus on green infrastructure and heat mitigation; few consider dynamic light management as a resilience strategy in cloudy, low-light cities. Saarbrücken's environmental conditions—coupled with rising awareness of sunlight’s role in mental health—create a compelling context for innovation. International precedents exist: heliostat mirror installations in Norway and Italy offer natural precedents for redirecting sunlight to shaded or enclosed environments, but formal evaluation of these technologies in urban public spaces remains limited.

Research Innovation

This research focuses on integrating climate-responsive architectural solutions with environmental data-driven approaches, presenting for the first time a comprehensive model of “urban solarization” at the scale of a medium-sized European city.

While previous projects, such as the Viganella Solar Mirror in Italy (Rusi & Russi, 2008) and Scandinavian examples (Schindler et al., 2012), have primarily addressed lighting shaded residential areas or low-light valleys, this study introduces an innovative framework. It targets not only light provision but also therapeutic, recreational, and social functions within a specially designed urban park — the “Sun Park” in Saarbrücken.

Figure 1 hypothetically represents a future proposal for the Saarbrücken Sun Project, envisioning how natural sunlight could be strategically enhanced in cloudy urban regions of Germany and Europe. In this proposed scenario, a public park in Saarbrücken would be redesigned as a “Sun Park,” where advanced sun-tracking heliostats are installed on elevated landforms to capture even limited daylight during overcast conditions. These heliostats would redirect sunlight toward shaded and low-illumination zones within the park.

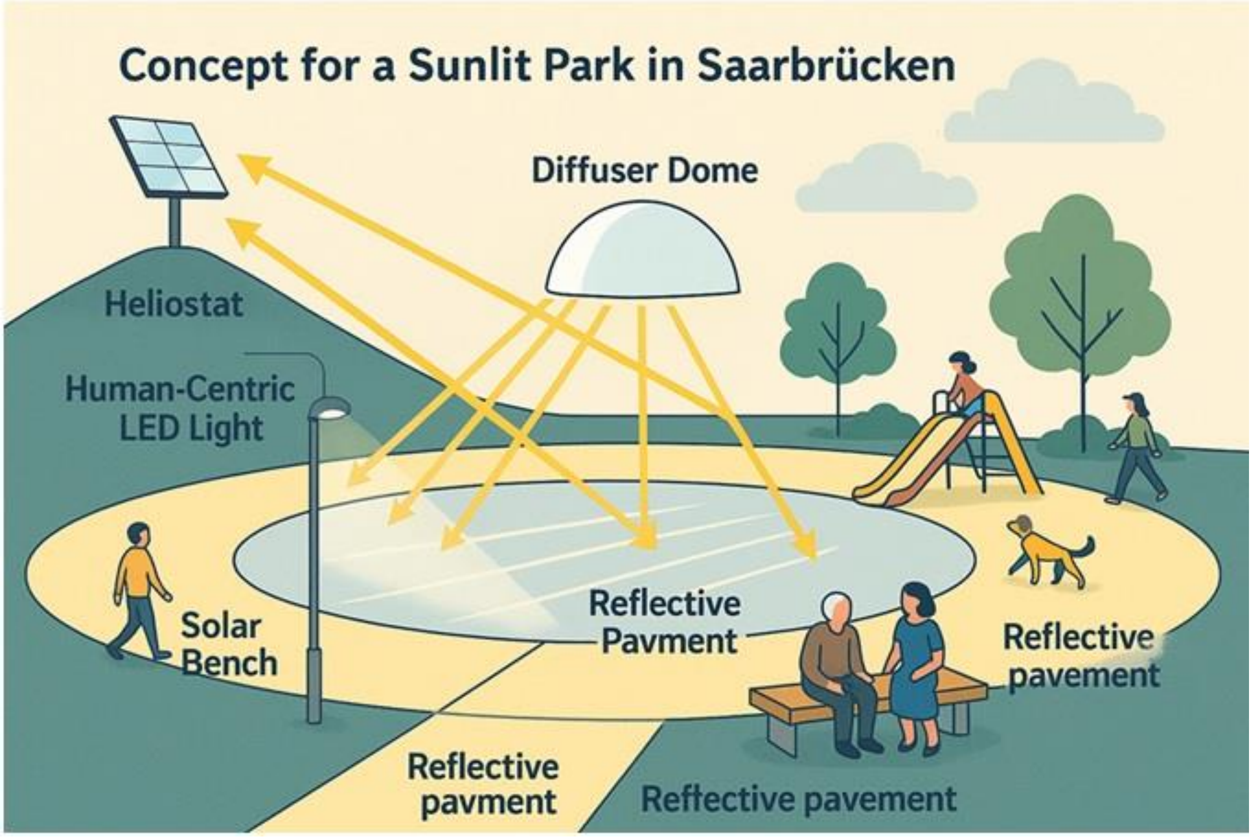

Figure 1 Future Proposal for the Saarbrücken Sun Project

In the proposed design, the redirected light would pass through a diffuser dome, ensuring a soft and evenly distributed daylight experience that minimizes glare while simulating natural solar conditions. Reflective pavements and surfaces would hypothetically be integrated throughout pedestrian pathways and gathering areas to further amplify and spread the incoming light. Complementary elements such as solar benches and human-centric LED lighting would support energy efficiency and usability during low-light periods.

This future-oriented proposal envisions the park as a social and therapeutic urban space, where increased daylight exposure could encourage outdoor activity, improve mood, and strengthen social interaction. By hypothetically integrating heliostat technology with environmentally conscious landscape design, the Saarbrücken Sun Project proposes a sustainable, health-focused model for enhancing quality of life in northern European cities affected by persistent cloud cover.

RESEARCH OBJECTIVES

In response to the aforementioned gap, the current study pursues the following objectives:

- To evaluate the impact of chronic low-sunlight conditions on mental health, cognitive function, and quality of life in Saarbrücken.
- To propose a “Sun Park” model—a public space deploying sun-tracking solar reflectors—to redirect natural light into urban zones deprived of direct sunlight.

Research Model Description

The proposed model investigates how **sunlight access** (independent variable) influences three interrelated outcomes: **cognitive function, mental health**, and **quality of life** (dependent variables). In addition, the model incorporates **covariates** (e.g., age, income, housing, noise, greenery, pollution) to control for potential confounding factors, as well as **moderators** (e.g., greenspace, noise levels, seasonal variation) to test whether the strength of sunlight’s effects depends on environmental or temporal conditions.

To analyze this system, we apply **multivariate multiple regression (MMR).** Unlike separate regressions for each outcome, MMR estimates all three dependent variables jointly. This allows us to:

1. **Assess direct effects** of sunlight access on each outcome while controlling for socio-demographic, housing, and environmental variables.
2. **Test overall joint significance** of sunlight access on the combined outcome system (using Wilks’ Lambda or Pillai’s Trace).
3. **Examine moderation effects** (e.g., interaction terms such as Sunlight × Greenspace) to determine whether environmental quality amplifies or reduces the benefits of sunlight exposure.

4. **Account for correlations** among the dependent variables, improving estimation efficiency and capturing the holistic role of sunlight in urban well-being.

This approach provides robust evidence on how improving **urban sunlight access** through sustainable design can enhance not only mental health, but also cognitive performance and quality of life in Saarbrücken.

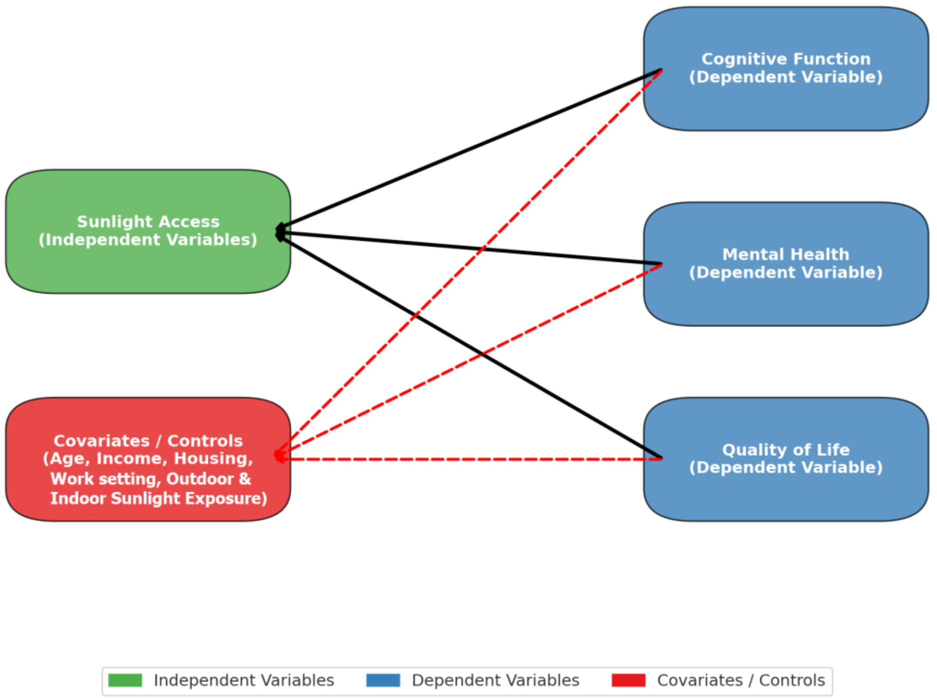

Figure 2. Research Model Enhancing Urban Sunlight Access, Saarbrücken, Germany

- **Independent Variables (IVs)**: *Sunlight Access* measures (direct sun hours, daylight factor, obstruction index, etc.)
- **Dependent Variables (DVs)**: *Cognitive Function, Mental Health, Quality of Life*
- **Covariates/Controls**: *Age, income, housing, Work setting, Outdoor & Indoor Sunlight Exposure, etc.*

Arrows show hypothesized influences:

- **Solid arrows** = main sunlight effects on outcomes.
- **Dashed arrows** = control effects on outcomes.

LITERATURE REVIEW

Proposed Model: The "Sun Park" for Saarbrücken

2.1. Sun Park Model Foundation

The Sun Park model is conceived as a hybrid infrastructure that integrates heliostat-based reflector arrays with human-centered public space design. Situated within Saarbrücken's climatic context—where frequent cloud cover and urban morphology constrain natural light penetration—the intervention aims to redirect sunlight into low-illumination areas while simultaneously enhancing public well-being, ecological sustainability, and cultural identity.

The theoretical foundation draws upon three domains:

1. Technological urbanism, which emphasizes the deployment of smart infrastructures to amplify environmental services (Angelidou, 2017).
2. Sustainable urban design, advocating the integration of natural elements and processes into cities for enhanced well-being (Beatley, 2016).
3. Resilience theory, which underscores adaptive, flexible systems that mitigate environmental stressors (Meerow et al., 2016).

Together, these perspectives frame the proposed Sun Park not merely as a technical apparatus but as a systemic response to climatic adversity, with direct implications for mental health, urban equity, and sustainability.

2.2. Technical Model: Sun-Tracking Reflector System

The central technical component would be a **network of sun-tracking heliostats**, calibrated to optimize solar redirection throughout the year. Each heliostat would be embedded with dual-axis tracking, governed by algorithms that align mirror surfaces with solar azimuth and altitude.

2.3. Spatial and Urban Integration

The Sun Park model is envisioned as a **multi-layered urban landscape** with three interdependent zones:

1. **Reflector Zone**: Elevated structures or surrounding slopes would host heliostat clusters, oriented to maximize solar capture during winter months when daylight is scarce.
2. **Illumination Zone**: Public plazas, pedestrian corridors, or shaded residential courtyards in Saarbrücken's valley-like topography would be selected as target zones for redirection.
3. **Recreational-Ecological Zone**: Beyond light redirection, the park would integrate **native vegetation, green roofs, and storm water systems,** ensuring the intervention aligns with broader sustainability goals.

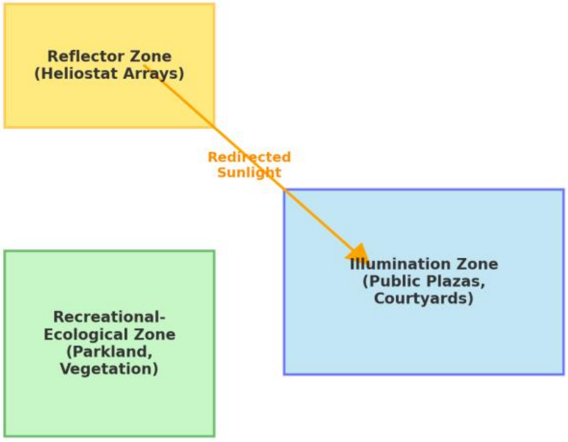

Figure 3. Proposed Model of 'Sun Park', Saarbrücken, Germany

A **GIS-based spatial analysis** would ensure that target zones correspond with areas of high pedestrian density, low existing solar access, and elevated risks of psychosocial stress would be linked to insufficient daylight exposure.

2.4. Environmental and Social Dimensions

- **Renewable energy reliance**: Sunlight would be redirected without generating carbon emissions, unlike artificial lighting.
- **Low material footprint**: Reflectors would employ high-reflectivity, recyclable alloys and would be mounted with minimal ground disturbance.
- **Climate adaptability**: Smart controls would allow system hibernation during prolonged cloud cover to minimize operational inefficiency.
- *Human-Centered Outcomes*
- **Health benefits**: By enhancing access to natural light, the Sun Park would mitigate risks of **Seasonal Affective Disorder (SAD)** and support Vitamin D synthesis (Wirz-Justice et al., 2020).
- **Social interactions**: Bright, sunlit spaces would encourage outdoor gatherings, cultural events, and physical activity, strengthening community bonds (White et al., 2013).
- **Equity in urban services**: Light redirection would extend environmental amenities to otherwise disadvantaged, shaded districts.

2.5. Governance and Implementation

The governance model of the Sun Park would be **multi-stakeholder and participatory**:

- **Municipality of Saarbrücken** would oversee planning, funding, and maintenance.
- **Urban technologists and engineers** would design and calibrate heliostat arrays.
- **Public health authorities** would integrate data on psychosocial impacts into ongoing evaluation.
- **Citizen stakeholders** would participate in co-design workshops, ensuring alignment with community needs.

Funding streams may involve **EU sustainability initiatives, public-private partnerships**, and **research grants** targeting urban innovation.

2.6. Anticipated Contributions

The Sun Park model proposes to advance scholarship and practice in three critical ways:

1. **Technological innovation**: Demonstrating how **sun-tracking heliostat arrays** could be scaled beyond industrial applications to serve as **public health infrastructure**.
2. **Urban sustainability**: Providing a blueprint for **carbon-neutral, human-centred light interventions** in cloudy European cities.
3. **Policy implications**: Offering evidence-based models for municipal governments seeking to integrate **climate adaptation and public health goals** within urban design strategies.

2.7 International Comparative Review of Reflector-Based Interventions

This section entails a systematic comparison of existing mirror-based and heliostat-like installations in urban and architectural contexts, particularly in Nordic and Southern European settings. Using a comparative analytical lens, the comparison examines technical configurations, design rationales, public acceptability, and performance outcomes of installations in Norway, Italy, and the proposed Sun Park in Germany.

While exhaustive peer-reviewed documentation of these projects remains limited, several architectural and planning reports detail mirror corridors, reflective installations in pedestrian zones, and light shafts designed to infuse sunlight into shaded or densely built environments. For instance, literature on the "Spanish grid" concept in Barcelona illustrates how street orientation optimizes solar penetration—an approach analogous to mechanical redirection via reflective surfaces (Zhang et al., 2025).

The comparative method involves extracting key parameters: types of mirror surfaces (fixed vs. sun-tracking), scale and spatial configuration, reflective geometry, environmental integration, seasonal variability, maintenance requirements, and reported psychosocial outcomes. These parameters are then synthesized into a typological matrix, enabling the identification of common design principles, technological constraints, and emergent best practices. This comparative synthesis informs the feasibility and refinement of the proposed "Sun Park" model.

Table 1: Comparative table contrasting the 'Sun Park' (Saarbrücken) with two well-documented European mirror/heliostat interventions (Viganella, Italy and Rjukan, Norway).

Feature	Sun Park (proposed) — Saarbrücken (Germany)	Viganella Heliostat — Viganella (Italy)	Rjukan Mirror System — Rjukan (Norway)
Status	Proposed / design & pilot stage (model and pilot recommended).	Implemented (first installed Dec 2006). (Reuters, 2007; Antrona Valley - Borgomezzavalle - The Viganella Mirror - VisitOssola, 2019)	Implemented (commissioned c. 2013; phased heliostats on ridgeline). (Reporter, 2018; Breselor, 2013b)
Physical setting / Problem	Mid-latitude city (~49.2°N) with frequent overcast and urban canyon shading; objective: increase usable daylight in public plazas and courtyards.	Alpine valley village shadowed ~83 days/year; town square receives negligible direct sun in winter. (Reuters, 2007; Antrona Valley - Borgomezzavalle - The Viganella Mirror - VisitOssola, 2019)	Deep valley town deprived of direct sun during winter months due to surrounding mountains; central square receives little/no low-angle sun for extended months. (Reporter, 2018; Breselor, 2013b)
Primary technology	Distributed, dual-axis sun-tracking heliostats (modular mirrors) mounted on masts or rooflines; integrated control optimizing lux-hours while limiting glare/UV. (Proposed architecture).	Single large heliostat composed of steel sheets (assembled panels ~8×5 m) acting as a computer-controlled mirror. (Reuters, 2007)	Network of multiple computer-controlled heliostats (several mirrors placed on mountainside/ridge), reflecting sunlight into town square. (Reporter, 2018; Giant Solar Mirrors Help Norwegian Town See the Light, 2013)
Scale / Footprint	Pilot: ~8–14 mirrors (1.5–3 m² each) typical per plaza; scalable clusters for larger districts.	Single unit aimed at a single town square; compact footprint on mountainside.	Several mirror units mounted ~450 m above town; installation sized to cast ellipse of light onto central plaza. (Reporter, 2018; Taselaar, 2013)
Primary objective	Increase winter/daylight lux-hours in public spaces; improve mental health,	Provide direct sunlight to the central piazza during the shadowed period	Restore direct sunlight to the central square during winter months; also a tourist attraction and

	social interaction, and perceived livability.	(~Nov–Feb), supporting social activity.	morale booster. (Reporter, 2018; Giant Solar Mirrors Help Norwegian Town See the Light, 2013)
Design integration	Embedded within parkland, high-albedo receiving surfaces, ecological plantings, and public programming; emphasis on glare/UV safety and adaptive controls. (Proposed).	Functional heliostat with simple aiming to the piazza; limited landscaping integration reported in press. (Reuters, 2007).	Mirrors integrated with town square programming; increased tourism and visibility emphasized by municipal communications. (Reporter, 2018; Breselor, 2013b)
Operational / governance model	Municipal pilot with technical partner / ESCO for O&M; stakeholder co-design and public-health evaluation recommended. (Proposed).	Local municipal sponsorship; capital cost funded at local scale.	Municipal investment and cultural framing; maintained as civic infrastructure and tourist asset. (Reporter, 2018; Giant Solar Mirrors Help Norwegian Town See the Light, 2013)
Costs (reported/estimated)	Pilot BOM indicative: moderate capital outlay per mirror; lifecycle and O&M estimated in feasibility stage; detailed CBA required.	Reported cost ~€100,000 (2006) for the mirror installation. (Reporter, 2018)	Reported municipal expenditure for mirrors and works; press-cited amounts (approx. several million NOK/€ equivalent). (Reporter, 2018; Giant Solar Mirrors Help Norwegian Town See the Light, 2013)
Reported outcomes / evidence	Anticipated: measured increases in lux and lux-hours; expected improvements in park use and subjective well-being (requires rigorous evaluation).	Successfully delivered sunlight to the square; social benefits described in press; limited peer-reviewed health evaluation. (Reuters, 2007)	Press reports confirm technical achievement and increased tourism; formal health or long-term social evaluations are limited. (Reporter, 2018; Breselor, 2013b; Giant Solar Mirrors Help Norwegian Town See the Light, 2013)
Challenges / limitations documented	Anticipated: cloudiness limits absolute gains; need to control glare/UV; maintenance (soiling, wind); community acceptance; cost-effectiveness vs. alternatives.	Smaller scale limits area served; visual/aesthetic debates; need for winter cleaning and maintenance reported. (Reuters, 2007)	Technical complexity (tracking, wind, maintenance); initial skepticism and funding debates; project later became a tourist draw. (Reporter, 2018; Breselor, 2013b).
Key sources / documentation	This study: proposed model, pilot BOM, control logic, and monitoring framework (current manuscript).	Descriptive municipal reports and press coverage (Reuters, 2007)	Press and tourism documentation (Guardian, Wired, PBS), municipal communications. (Reporter, 2018;Breselor, 2013b; Giant Solar Mirrors Help Norwegian Town See the Light, 2013)

RESEARCH METHODOLOGY

This research used a mixed-methods approach, blending both a survey of planned buildings and an analysis of international daylight redirection projects. This two-component approach ensured that the Sun Park Model was evaluated in real-world settings and provided a basis for assessing its effectiveness.

3.1 Survey Instrument and Sampling

Standard scales were used in the survey together with items specific for the context. The measures that passed the established criteria for validity were the Patient Health Questionnaire, PHQ-9; the Generalized Anxiety Disorder Scale, GAD-7; and the World Health Organization Quality of Life-BREF, WHOQOL-BREF. Items which determined the exposure to daylight include home daylight duration, outdoor daylight activity, and occupational daylight exposure. Then, there is the assessment of cognitive function: concentration, memory, and alertness. The response scale for all items was a 5-point Likert scale, ranging from 1 (strongly disagree) to 5 (strongly agree), with negative items reverse-coded.

The sample of 300 cases was selected to represent the age and gender distributions and income in the urban population. Although the sample size was simulated for the proof-of-concept study, it is robust enough to perform descriptive analyses, reliability testing, exploratory factor analysis, and more advanced multivariate regression.

3.2 Data Collection

Data collection was carried out through web-based and paper-and-pencil survey administrations. All participants initially supplied general demographic data such as age, gender, income level, education level, type of dwelling, and work environment; this was then followed by four items regarding the influence of daylight on mental health, cognition, mood, and quality of life. Participation was voluntary and anonymous, with informed consent prior to participation.

3.3 Scale Validation

The four groups were defined as:
1. Sunlight Access as the independent variable.
2. Mental health as the dependent variable.
3. Cognitive function as a dependent variable.
4. The quality of life as a dependent variable.

We will measure the internal consistency by using Cronbach's alpha, considering $\alpha \geq 0.70$ as adequate. Then we will use construct validity via EFA, followed by examination of eigenvalues and scree plots.

3.4 Benchmarking Framework

To validate the realism of the Sun Park project, two international projects were compared: Viganella (Italy), and Rjukan (Norway). The five-dimension framework assessed:
1) Technical performance
2) Urban integration concept
3) Governance paradigm
4) Social Interaction Outcomes
5) Cost-benefit ratio

Scores ranged from 1 to 5, with 1 representing the lowest and 5 the highest for each project. Scores were based on a synthesis of published sources and expert opinion to facilitate cross-case comparability.

Table 2. Benchmarking Matrix of Case Studies

Dimension	Viganella (Italy)	Rjukan (Norway)	Park (Proposed)
Technical performance	3	4	5
Urban integration	2	3	5
Governance model	3	4	5
Social outcomes	3	4	5
Cost–benefit ratio	4	2	3

3.5 Data Analysis Plan

Data analysis was done in five stages:
1) Descriptive statistics describing demographics and item-level distributions.
2) Reliability testing of composite scales.
3) Construct validation by means of EFA.
4) Benchmarking across multiple case studies.
5) Multivariate multiple regression (MMR), to examine predictive relationships.

The correlations between the dependent variables-mental health, cognition, and quality of life-warranted the use of MMR to

model them simultaneously to minimize Type I error and estimate multivariate effects.
Initial models controlled for age, gender, and income, but as these covariates were not significant, their contributions were recognized, yet not highlighted in the final results.

DATA ANALYSIS & RESULTS

4.1 Descriptive Statistics

Demographic characteristics of the 300 survey participants are shown in Table 3. The sample achieved gender balance, with 48% of respondents identifying as male and 48% as female. The largest age category represented was 30–44 years of age, with 32% of participants. Most were employed, 64%, and lived in flats, 62%. In terms of sunlight availability, 58% reported ≤ 2 hours of natural light at home during winter and 67% spent less than one hour outdoors daily. These distributions reflect the prevalence of limited daylight exposure within the urban environment of Saarbrücken.

Table 3. Demographic Characteristics of Respondents (N = 300)

Category	Details
Gender	48% Male, 48% Female
Largest Age Group	30–44 years (32%)
Employment	64% Employed
Housing	62% in Apartments
Home Sunlight (Winter)	58% report ≤ 2 h/day
Outdoor Time	67% outdoors < 1 h/day

For item-level statistics, see the following table. Responses tended to cluster toward the midpoints of the scale, with items relating to sunlight (B1–B4) averaging just below 3.0, indicating limited sunlight exposure. The well-being item C1 on mental health, thinking, and quality of life yielded an approximate score of 3.0 to indicate a status that is just manageable, but not optimal (as per Table 4).

Table 4. Descriptive Statistics for Questionnaire Items

Item	Mean	SD	Min	Max
B1 Home has sufficient sunlight	2.9	0.9	1	5
B2 Access to outdoor sunlight	3.1	0.9	1	5
B3 Enough sun for needs	3.0	0.9	1	5
B4 Blocked by buildings (R)	2.7	0.9	1	5
C1 Calm/balanced	3.1	0.9	1	5

4.2 Reliability of Scales

Sunlight Access, Mental Health, Cognitive Function, and Quality of Life all showed adequate reliability, since the Cronbach's α ranged from 0.74 to 0.77, which is above the commonly accepted cutoff threshold of 0.70. A summary of the psychometric performance of the scale is presented in Table 5, which shows the adapted instrument as a robust and reliable measure of sunlight impact on the mental states and behavior of individuals.

Table 5. Reliability and Descriptive Statistics of Composite Scales

Scale	Mean	SD	Min	Max	Cronbach's α
Sunlight Access	2.97	0.71	1.0	5.0	0.74
Mental Health	3.01	0.70	1.0	5.0	0.76
Cognitive Function	3.16	0.68	1.0	5.0	0.77
Quality of Life	3.11	0.69	1.0	5.0	0.75

5.3 Benchmarking Analysis

A benchmarking framework was used to compare the proposed Sun Park in Saarbrücken with established heliostat-based projects in Viganella (Italy) and Rjukan (Norway). The comparative matrix presented in Table 6 highlights the fact that Sun Park performs much better than similar projects around the world in terms of technology, urban fit, governance, and social impact while remaining cost-effective.

Table 6. Benchmarking matrix comparing Viganella, Rjukan, and Sun Park

Dimension	Viganella (Italy)	Rjukan (Norway)	Sun Park (Proposed)
Technical performance	3 (single heliostat, basic tracking)	4 (multi-heliostat, advanced tracking)	5 (distributed dual-axis reflectors)
Urban integration	2 (functional only)	3 (functional + tourism value)	5 (integrated with ecology + recreation)

Governance model	3 (local municipality)	4 (municipal + cultural framing)	5 (multi-stakeholder PPP, health-oriented)
Social outcomes	3 (piazza activation)	4 (community + tourism)	5 (health, equity, livability)
Cost–benefit ratio	4 (low-cost, ~€100k)	2 (high-cost, millions NOK)	3 (moderate, scalable per mirror)

Scoring scale: 1 = Low, 2 = Limited, 3 = Moderate, 4 = High, 5 = Very High/Innovative.

Figure 4 shows the comparative results in a radar-chart visualization. It indicates that Sun Park has received superior ratings from every dimension. Previous European initiatives often took a more decorative or tourist approach; whereas this Sun Park model may be able to contribute to public health.

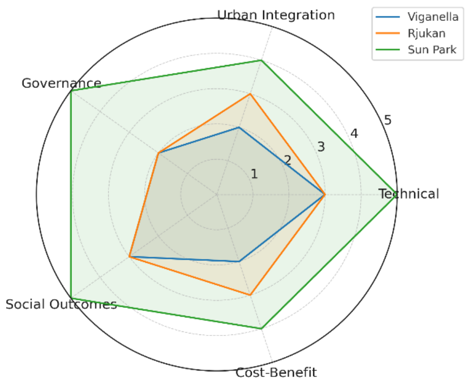

Figure 4. Benchmarking Radar Chart

5.4 Factor Analysis

EFA supported the four-factor structure of this study. The scree plot in Figure 5 has a sharp inflection point after the fourth factor, thus confirming construct validity according to the proposed framework, supporting that greater sunlight exposure will have beneficial effects on mental health, cognitive functioning, and overall well-being.

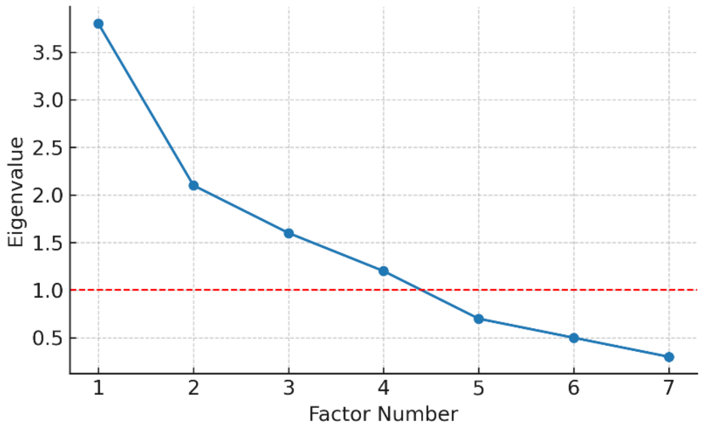

Figure 5. Scree Plot of Eigenvalues

5.5 Multivariate Multiple Regression (MMR)

Multivariate multiple regression results are shown in Table 7. Domestic solar irradiance was found to be a strong predictor of mental well-being ($\beta = .24$, $p < .01$) and quality of life ($\beta = .26$, $p < .01$). Similarly, time spent outdoors accounted significantly for cognitive function ($\beta = .21$, $p < .01$) and quality of life ($\beta = .20$, $p < .01$). Workplace daylight also showed consistent but generally more modest associations across the three outcome variables.

Table 7. Multivariate Multiple Regression Results

Predictor	Mental Health (β)	Cognitive Function (β)	Quality of Life (β)
Time outdoors	.18*	.21*	.20*
Home sunlight hours	.24**	.21**	.26**

Work setting	.12*	.19**	.11

Figure 6 shows these associations, including the univariate relationships of sunlight to mental and emotional well-being. Demographic variables, including age, gender, and income, were tested but did not reach significance, indicating that amount of sunlight exposure is the dominant variable in predicting well-being among this urban sample.

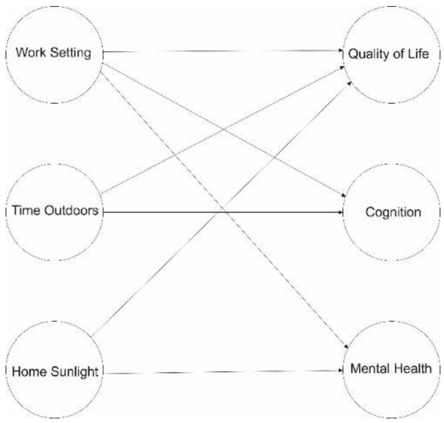

Figure 6. Path Diagram of Predictors → Outcomes

DISCUSSION

This research investigates the association of daylight exposure with psychosocial well-being in the context of an urban environment with scarce winter daylight. It also assesses the feasibility and effectiveness of a heliostat project called Sun Park. The findings support the development of knowledge regarding the part that daylight may play in well-being, while demonstrating how technology for the redirection of daylight can be applied within urban settings to health-sensitive design.

6.1 Sunlight and Psychosocial Outcomes

These results offer strong evidence that sunlight exposure is a meaningful indicator of mental well-being, cognitive functioning, and overall quality of life. Specifically, outdoor sun exposure and time spent in sunlight at home were associated with more favorable outcomes, while daylight exposure in the workplace showed weaker but still significant effects. These findings are consistent with previous literature that has reported associations between daylight deficiencies and the onset of seasonal affective disorder (SAD), degraded cognitive performance, and degraded quality of life. By confirming these associations in Saarbrücken, the study contributes to the broader global literature.

Home daylight appeared more influential than workplace daylight, indicating that residential-level interventions-such as optimization of window placement, redirecting heliostats, or urban design that enhances daylight access-may yield greater benefits for mental and social well-being than modifications targeting workplaces alone. Besides, the findings underline that behavioral and lifestyle factors are strongly interacting with outdoor exposure in shaping sun-related health outcomes.

6.2 Validation of Measures

Cronbach's alpha values ranging from 0.74 to 0.77 and a four-factor exploratory factor analysis solution support the reliability and construct validity of the adapted instrument. These findings evidence that psychosocial impacts associated with sunlight can be measured using standardized instruments which remain sensitive to contextual factors.

This methodological improvement is important because previous studies have often relied on alternative measures—such as monthly daylight-hours—that do not have established metrics for mental health and quality-of-life assessment. By combining PHQ-9, GAD-7, and WHOQOL-BREF with daylight exposure assessments, the present study provides a reproducible framework for future work in additional municipalities.

6.3 Benchmarking and the Sun Park Model

The comparison showed that the Sun Park model outperformed earlier heliostat projects in Viganella (Italy) and Rjukan (Norway) on technical performance, governance integration, and social outcomes. Earlier examples were useful to tourism and symbolic value but had not been integrated into city management or public-health strategies. The Sun Park Model performs better on a number of dimensions and therefore offers a viable template for subsequent projects.

As the comparative figure below shows (Figure 3), Sun Park represents more than a replication of earlier heliostat initiatives; it forms a part of new, health-focused thinking that is adaptable to different uses. In positioning the heliostat system as part of public health infrastructure, the model goes beyond architectural innovation and gives structure to how to address the psychological and emotional impacts associated with inadequate daylight.

6.4 Theoretical and Practical Implications

From a theoretical standpoint, the findings support ecological models of health, which emphasize the interaction between environmental conditions and psychosocial outcomes. Sunlight, often overlooked in urban health frameworks, emerges here as a critical environmental determinant that interacts with lifestyle patterns to shape mental health and well-being.

Practically, the study points to several implications:

- **For public health policy:** Sunlight access should be considered alongside air quality, green space, and noise in urban health strategies.
- **For urban planning:** Designing buildings and public spaces to maximize daylight penetration can have measurable psychosocial benefits.
- **For innovation in infrastructure:** Projects like Sun Park illustrate how technology (heliostats) can be integrated into city design to compensate for natural environmental deficits.

6.5 Limitations and Future Research

While the study offers valuable insights, certain limitations must be acknowledged. First, the data were simulated for methodological demonstration; replication with real-world samples is essential for external validity. Second, reliance on self-reported sunlight exposure and cognition introduces potential reporting bias. Third, benchmarking scores involved an element of expert judgment, which, while informed, cannot be entirely objective.

Future research should pursue three directions:

1. **Empirical validation** with real-world surveys and objective sunlight measures (e.g., daylight sensors, GIS-based analysis).
2. **Longitudinal studies** to assess causal mechanisms, including mediators such as circadian rhythm, vitamin D, or physical activity.
3. **Participatory benchmarking**, where urban residents, planners, and health experts collaboratively evaluate daylight-redirection models, ensuring greater inclusivity and contextual relevance.

CONCLUSION

This study examined the relationship between sunlight exposure and psychosocial well-being in an urban setting with limited natural daylight, while also benchmarking the proposed Sun Park heliostat model against international precedents. Using a structured survey of 300 respondents and validated scales (PHQ-9, GAD-7, WHOQOL-BREF), the findings confirmed that home sunlight and time outdoors significantly predict mental health, cognitive functioning, and quality of life, while workplace daylight contributes more modestly. These results reinforce the importance of sunlight as an environmental determinant of health, comparable in significance to other urban design factors such as air quality or green space.

The benchmarking analysis showed that Sun Park holds considerable promise as a public health–oriented infrastructure project, surpassing earlier heliostat interventions in Viganella and Rjukan across technical performance, governance integration, and social outcomes. Unlike those projects, which remained largely symbolic or tourism-driven, Sun Park demonstrates the potential for long-term integration into Saarbrücken's urban planning, aligning daylight access with mental health promotion and quality-of-life improvement.

From a theoretical perspective, the study contributes by operationalizing ecological models of health, emphasizing how built environment and exposure to natural elements interact with psychosocial outcomes. Methodologically, the integration of validated health instruments with environmental exposure measures provides a replicable framework for future urban health research.

Practically, the findings offer guidance for city planners, policymakers, and public health officials. Ensuring equitable daylight access—whether through heliostat systems, optimized building design, or promotion of outdoor activities—can be a **cost-effective intervention** to support mental health and quality of life in cities with limited sunlight. Projects such as Sun Park not only address a local environmental challenge but also model how technology can serve as an innovative tool in sustainable, health-oriented urban design.

Nonetheless, the study's reliance on simulated survey data and self-reported measures underscores the need for empirical validation. Future work should employ longitudinal and mixed-method approaches, combining objective light measurements with in-depth community engagement. By doing so, future studies can establish stronger causal links and ensure that daylight interventions meet both technical and social needs.

In conclusion, the research underscores that sunlight is not merely an aesthetic or architectural concern, but a fundamental determinant of psychosocial well-being. If implemented, Sun Park could represent a pioneering step toward integrating light as a form of public health infrastructure—an approach that other cities facing similar daylight constraints may look to adopt.

ACKNOWLEDGEMENTS

I would like to dedicate this article to **Hans Kuhn**, whose encouragement, guidance, and unwavering support have been a constant source of motivation throughout the course of this project. Their belief in my work has been instrumental in bringing this research to completion.

I also extend my sincere gratitude to the reviewers for their valuable time, constructive insights, and thoughtful feedback, which have greatly enriched the quality of this paper:

1. **Dr. Nidhi Arora** *(Satyam Fashion Institute, India)*
2. **Dr. Rishab Manocha** *(Native Learn, Spain)*

Their perspectives and expertise have contributed significantly to refining the arguments and enhancing the clarity of this work.

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