Development of models to evaluate the potential of building roofs to reduce air pollution: application to the case of Tehran

S. Hamed Banirazi Motlagh

POLYTECHNIC UNIVERSITY OF CATALONIA

Doctoral Programme

TECHNOLOGY OF ARCHITECTURE, BUILDING CONSTRUCTION AND URBANISM

PhD Thesis

Development of Models to Evaluate the Potential of Building Roofs to Reduce Air Pollution: Application to the Case of Tehran

Thesis for a compendium of publications

S. Hamed Banirazi Motlagh

Supervisor: Dr. Oriol Pons-Valladares
Co-supervisor: Dr. S. M. Amin Hosseini

Barcelona, Spain
October 2023

Acknowledgements

I offer my deepest and most profound gratitude for the precious gift of learning, a blessing from the Divine. A special note of appreciation goes to my esteemed advisors, Prof. Dr. Oriol Pons, primary supervisor, and Prof. Dr. Amin Hosseini, co-supervisor, for their exceptional guidance, the investment of their valuable time, and for nurturing my growth in this field. Their wisdom and support have been invaluable. Thanks a lot from the depths of my heart.

To my cherished parents, I extend my heartfelt thanks for their constant kindness and unwavering support. Their love has been the cornerstone of my journey, and because of that, I am forever grateful. To my beloved Raha, my journey's steadfast companion, I express my sincerest appreciation for her unwavering patience and love on this challenging path we have tread together. My dear daughter, Nura, who has walked alongside us on this demanding road, has not only shared in the challenges but also become the singular beacon of hope in my life. For her presence and inspiration, I am indeed thankful.

I extend my appreciation to the multidisciplinary experts and stakeholders whose contributions have enriched this research project. Their expertise and collaboration have played an indispensable role in its success.

Table of Contents

Figures index

Abstract

Environmental protection is a principle of both Millennium Development Goals and sustainable development, underscoring critical issues like greenhouse gases, global warming, and air pollution. Air pollution is a global challenge with severe consequences for the environment. Hence, city managers encounter an urgent need to explore the proper solutions to mitigate air pollution.

This doctoral dissertation addresses air pollution reduction by harnessing the untapped potential of rooftops while focusing on pollutant reducers and taking into account specific characteristics of urban buildings. The study follows a five-phase framework, including initial investigation, feasibility study, solution exploration, sustainability evaluation, and city-scale optimization.

The research method proposed in this thesis is validated for the first time in the context of Tehran, a densely populated and highly air-polluted megacity. The key achievements of this leading application encompass: feasible alternatives, sustainability assessment, optimal solutions, target building groups, and city-scale impact. Firstly, considering sustainability, effectiveness, and viability, the study identifies green roofs (GR) and photovoltaic (PV) systems as feasible rooftop-based alternatives. Second, novel sustainability assessment models are developed, combining methods like the Integrated Value Model for Sustainability Assessment (MIVES), Strengths-Weaknesses-Opportunities-Threats (SWOT), Analytic Hierarchy Process (AHP), simplified Life Cycle Assessment (LCA), and sensitivity analysis. These models enable the evaluation of pollutant reducers in terms of their environmental, economic, and social sustainability. The results reveal that the most suitable types of GR and PV are semi-intensive green roofs (SIGR) and building-attached photovoltaics (BAPV). This is while the quantitation analysis discloses that SIGR is capable of reducing 4.8 kg/m^2 CO_2 and 52.4 g/m^2 Particulate Matter (PM), and BAPV has the potential of mitigating 211 kg/m^2 CO_2 and 1.2 g/m^2 PM per year. Third, a compound alternative (CA), combining both GR and PV, is proposed as an optimal solution, effectively surmounting the individual shortcomings of these technologies. The optimization using mathematical patterns unveils more suitability of PV compared to GR for the case of Tehran. In this sense, the most effective combination ratio for the execution phase simplifies to 3:1 (PV:GR). Fourth, a synergistic strategy is adopted to consider optimized pollutant reducers and target buildings simultaneously. Using the Geographic Information System (GIS), the study recommends focusing on residential buildings of medium height in medium surface scale as the ideal targets. Fifth and finally, implementing the optimized CA on selected target buildings provides a significant potential to decrease over 9% of total PM and CO_2 emissions from all sources and sectors across Tehran. Furthermore, the study reveals the prospect of transforming selected groups of residential buildings into Zero-PM buildings in the operational phase.

This dissertation provides valuable insights into addressing rooftop-based air pollutant reducer technologies and also offers a systematic approach that can be adapted to various urban contexts. The developed framework, models, and proposed future works, can assist decision-makers in selecting the most appropriate strategies, contributing to cleaner, more sustainable, and resilient urban environments worldwide.

Keywords: *Climate change; Sustainability assessment; Urban air pollution; Residential buildings; Rooftops*

Resumen

La protección del medio ambiente es un principio de los Objetivos de Desarrollo del Milenio y del desarrollo sostenible, lo que evidencia cuestiones críticas como los gases de efecto invernadero, el calentamiento global y la contaminación del aire. Esta contaminación atmosférica es un desafío global con graves consecuencias para el medio ambiente. Por lo tanto, los gestores de las ciudades se enfrentan a una necesidad urgente de explorar las soluciones viables para mitigarla.

Esta tesis doctoral aborda la reducción de la contaminación del aire a partir del potencial sin explotar de los tejados, centrándose en reductores de contaminantes y considerando las características específicas de los edificios urbanos. El estudio sigue cinco fases: investigación inicial, estudio de viabilidad, exploración de soluciones, evaluación de sostenibilidad y optimización a escala ciudad.

El método de investigación propuesto en esta tesis se valida por primera vez en el contexto de Teherán, una megaciudad densamente poblada y altamente contaminada. Los logros clave de esta aplicación líder abarcan: alternativas viables, evaluación de la sostenibilidad, soluciones óptimas, grupos de edificios, e impacto a escala de ciudad. Primero, teniendo en cuenta la sostenibilidad, la eficacia y la viabilidad, el estudio identifica los tejados verdes (GR) y los sistemas fotovoltaicos (PV) como alternativas viables en tejados. En segundo lugar, se desarrollan nuevos modelos de evaluación de la sostenibilidad, que combinan métodos como el Modelo Integrado de Valor para una Evaluación Sostenible (MIVES), Fortalezas-Oportunidades-Debilidades-Amenazas (FODA), Proceso Analítico Jerárquico (AHP), Análisis de Ciclo de Vida (ACV) simplificado y análisis de sensibilidad. Estos modelos permiten evaluar los reductores de contaminantes en términos de su sostenibilidad ambiental, económica y social. Los resultados revelan que los tipos más adecuados de GR y PV son los tejados verdes semiintensivos (SIGR) y la energía fotovoltaica integrada en edificios (BAPV). El análisis de cuantificación revela que SIGR es capaz de reducir 4,8 kg/m^2 de CO_2 y 52,4 g/m^2 de materia particulada (PM), y BAPV tiene el potencial de mitigar 211 kg/m^2 de CO_2 y 1,2 g/m^2 de PM al año. En tercer lugar, se propone una alternativa compuesta (CA), que combina GR y PV, como solución óptima, superando las deficiencias individuales de estas tecnologías. La optimización, mediante patrones matemáticos, revela una mayor idoneidad de la energía fotovoltaica en comparación con la energía renovable para el caso de Teherán. En este sentido, la relación más efectiva para la fase de ejecución se simplifica a 3:1 (PV:GR). En cuarto lugar, se adopta una estrategia sinérgica para considerar simultáneamente reductores de contaminantes optimizados y edificios objetivo. Utilizando el sistema de información geográfica (GIS), el estudio recomienda centrarse en edificios residenciales de mediana altura y mediana escala de superficie. En quinto y último lugar, la implementación de la CA optimizada en edificios objetivo ofrece un potencial significativo para reducir más del 9% del total de las emisiones de PM y CO_2 de todas las fuentes y sectores en Teherán. Además, el estudio revela la posibilidad de transformar grupos seleccionados de edificios residenciales en edificios Zero-PM en la fase operativa.

Esta disertación proporciona información valiosa sobre cómo abordar las tecnologías de reducción de contaminantes del aire situadas en tejados y también ofrece un enfoque sistemático que puede adaptarse a diversos contextos urbanos. El marco desarrollado, los modelos y los trabajos futuros propuestos pueden ayudar a los tomadores de decisiones a seleccionar las estrategias más apropiadas, contribuyendo a entornos urbanos más limpios, más sostenibles y resilientes en todo el mundo.

Keywords: *Cambio climático; Evaluación de sostenibilidad; Contaminación del aire urbano; Edificios residenciales; Tejados*

Resum

La protecció del medi ambient és un principi dels Objectius de Desenvolupament del Mil·lenni i del desenvolupament sostenible, cosa que evidencia qüestions crítiques com els gasos d'efecte hivernacle, l'escalfament global i la contaminació de l'aire. Aquesta contaminació atmosfèrica és un desafiament global amb greus conseqüències per al medi ambient. Per tant, els gestors de les ciutats s'enfronten a una necessitat urgent d'explorar les solucions viables per mitigar-la.

Aquesta tesi doctoral aborda la reducció de la contaminació de l'aire a partir del potencial sense explotar dels terrats, centrant-se en reductors de contaminants i considerant les característiques específiques dels edificis urbans. L'estudi segueix cinc fases: investigació inicial, estudi de viabilitat, exploració de solucions, avaluació de sostenibilitat i optimització a escala ciutat.

El mètode de recerca proposat en aquesta tesi es valida per primer cop en el context de Teheran, una megaciutat densament poblada i altament contaminada. Els èxits clau d'aquesta aplicació capdavantera abasten: alternatives viables, avaluació de la sostenibilitat, solucions òptimes, grups d'edificis, i impacte a escala de ciutat. Primer, tenint en compte la sostenibilitat, l'eficàcia i la viabilitat, l'estudi identifica els terrats verds (GR) i els sistemes fotovoltaics (PV) com a alternatives viables als terrats. En segon lloc, es desenvolupen nous models d'avaluació de la sostenibilitat, que combinen mètodes com el Model Integrat de Valor per a una Avaluació Sostenible (MIVES), Fortaleses-Oportunitats-Debilitats-Amenaces (FODA), Procés Analític Jeràrquic (AHP), Anàlisi de Cicle de Vida (ACV) simplificat i anàlisi de sensibilitat. Aquests models permeten avaluar els reductors de contaminants en termes de sostenibilitat ambiental, econòmica i social. Els resultats revelen que els tipus més adequats de GR i PV són els terrats verds semiintensius (SIGR) i l'energia fotovoltaica integrada en edificis (BAPV). L'anàlisi de quantificació revela que SIGR és capaç de reduir 4,8 kg/m^2 de CO_2 i 52,4 g/m^2 matèria particulada (PM), i BAPV té el potencial de mitigar 211 kg/m^2 de CO_2 i 1,2 g/m^2 de PM a l'any. En tercer lloc, es proposa una alternativa composta (CA), que combina GR i PV, com a solució òptima, i supera les deficiències individuals d'aquestes tecnologies. L'optimització, mitjançant patrons matemàtics, revela una idoneïtat més gran de l'energia fotovoltaica en comparació amb l'energia renovable per al cas de Teheran. En aquest sentit, la relació més efectiva per a la fase d'execució se simplifica a 3:1 (PV:GR). En quart lloc, s'adopta una estratègia sinèrgica per considerar simultàniament reductors de contaminants optimitzats i edificis objectiu. Utilitzant el sistema d'informació geogràfica (GIS), l'estudi recomana centrar-se en edificis residencials de mitjana altura i mitjana escala de superfície. En cinquè i darrer lloc, la implementació de la CA optimitzada en edificis objectiu ofereix un potencial significatiu per reduir més del 9% del total de les emissions de PM i CO_2 de totes les fonts i sectors a Teheran. A més, l'estudi revela la possibilitat de transformar grups seleccionats d'edificis residencials en edificis Zero-PM a la fase operativa.

Aquesta dissertació proporciona informació valuosa sobre com abordar les tecnologies de reducció de contaminants de l'aire situades en terrats i també ofereix un enfocament sistemàtic que es pot adaptar a diversos contextos urbans. El marc desenvolupat, els models i els treballs futurs proposats poden ajudar els prenedors de decisions a seleccionar les estratègies més apropiades, contribuint a entorns urbans més nets, més sostenibles i resilients a tot el món.

Keywords: *Canvi climàtic; Avaluació de sostenibilitat; Contaminació de l´aire urbà; Edificis residencials; Terrats*

چکیده

حفاظت از محیط زیست از اصول اهداف توسعه هزاره وهمچنین توسعه پایدار است که بر مسائل حیاتی مانند گازهای گلخانه‌ای، گرمایش زمین، و آلودگی هوا تأکید دارد. آلودگی هوا یک چالش جهانی با عواقب شدید برای محیط زیست است. ازاین رو، مدیران شهری با نیاز مبرمی جهت کشف راه حل‌های مناسب برای کاهش آلودگی هوا مواجه می‌باشند.

رساله دکتری حاضر به کاهش آلودگی هوا با استفاده از پتانسیل بکر پشت‌بام‌ها و درعین حال تمرکز بر کاهش دهنده‌های آلاینده و در نظر گرفتن ویژگی‌های خاص ساختمان‌های شهری می‌پردازد. این مطالعه از یک چارچوب پنج مرحله‌ای پیروی می‌نماید که شامل بررسی اولیه، مطالعه امکان‌سنجی، کاوش راه‌حل، ارزیابی پایداری، و بهینه‌سازی در مقیاس شهر است.

روش تحقیق پیشنهادی در این پایان‌نامه برای اولین بار در محیط تهران، یک کلان‌شهر پرجمعیت با هوای بسیار آلوده، اعتبارسنجی می‌شود. دستاوردهای محوری این برنامه پیشرو شامل: آلترناتیوهای امکان‌پذیر، ارزیابی پایداری، راه‌حل‌های بهینه، گروه‌های ساختمانی هدف، و تأثیر در مقیاس شهر می‌باشند. اول، با در نظر گرفتن پارامترهای پایداری، اثربخشی، و تحقق‌پذیری، این مطالعه بام‌های سبز (GR) و سیستم‌های فتوولتائیک (PV) را به‌عنوان آلترناتیوهای ممکن مبتنی بر کاربرد در پشت‌بام شناسایی می‌نماید. دوم، مدل‌های جدید ارزیابی پایداری با ترکیب متدهایی مانند مدل ارزش یکپارچه برای ارزیابی پایداری (MIVES)، نقاط قوت، نقاط ضعف، فرصت‌ها، تهدیدها (SWOT)، فرآیند تحلیل سلسله مراتبی (AHP)، ارزیابی چرخه زندگی ساده شده (LCA)، و تحلیل حساسیت توسعه می‌یابند. این مدل‌ها امکان ارزیابی کاهش دهنده‌های آلاینده را از نظر پایداری زیست محیطی، اقتصادی، و اجتماعی فراهم می‌نمایند. نتایج نشان می‌دهد که مناسب‌ترین انواع GR و PV، بام‌های سبز نیمه فشرده (SIGR) و فتوولتائیک‌های پیوست شده بر ساختمان (BAPV) هستند. این در حالی است که تحلیل محاسباتی نشان می‌دهد که SIGR قادر به کاهش ۴/۸ کیلوگرم CO_2 در متر مربع و ۵۲/۴ گرم در متر مربع ذرات معلق (PM) در سال است و BAPV پتانسیل کاهش ۲۱۱ کیلوگرم در متر مربع CO_2 و ۱/۲ گرم در متر مربع PM در سال را دارد. سوم، آلترناتیو ترکیبی (CA) که هر دو سیستم GR و PV را ترکیب می‌کند، به‌عنوان یک راه‌حل بهینه پیشنهاد می‌شود که بطور موثر بر کاستی‌های فردی این فناوری‌ها غلبه می‌نماید. بهینه‌سازی با استفاده از الگوهای ریاضی نشان می‌دهد که درکل، PV گزینه مناسب تری نسبت به GR برای تهران محسوب می‌شود. در این راستا، موثرترین نسبت ترکیب برای مرحله اجرایی، بصورت ساده شده ۳ قسمت PV و ۱ قسمت GR تعریف می‌گردد. چهارم، استراتژی هم افزایی برای در نظر گرفتن همزمان آلترناتیوهای بهینه کاهش آلاینده و ساختمان‌های هدف اتخاذ می‌شود. این مطالعه به کمک سیستم اطلاعات جغرافیایی (GIS)، تمرکز بر ساختمان‌های مسکونی با ارتفاع متوسط در مقیاس متوسط سطح را به‌عنوان اهداف ایده‌آل توصیه می‌نماید. درنهایت پنجم، اجرای CA بهینه شده بر روی ساختمان‌های هدف منتخب، پتانسیل قابل توجهی برای کاهش بیش از ۹ درصد از کل انتشار PM و CO_2 در تهران (ناشی از همه منابع و بخش‌ها) را فراهم می‌آورد. همچنین، این مطالعه چشم انداز تبدیل گروه‌های منتخب ساختمان مسکونی به ساختمان‌های Zero-PM را در فاز بهره‌برداری نشان می‌دهد.

این پایان نامه بینش‌های ارزشمندی را در مورد پرداختن به فناوری‌های کاهش آلاینده هوا مبتنی بر کاربرد در پشت بام ارائه می‌نماید، درعین حال یک رویکرد سیستماتیک را تدارک می‌بیند که می‌تواند با محیط‌های مختلف شهری سازگار شود. چارچوب و مدل‌های توسعه یافته، همراه با کارهای پیشنهادی آتی، می‌تواند در انتخاب مناسب ترین استراتژی برای شهرهای مختلف به یاری تصمیم گیرندگان مربوطه آمده و به محیط‌های شهری پاک تر، پایدارتر، و انعطاف پذیرتر در سراسر جهان کمک نماید.

کلیدواژه: *تغییر اقلیم؛ ارزیابی پایداری؛ آلودگی هوای شهری؛ ساختمان مسکونی؛ بام*

Abbreviations

AHP	Analytic hierarchy process
AQCC	Air quality control company
AQI	Air quality index
a-Si	Amorphous silicon
BAPV	Building-attached PV
BAPV/T	Building-attached PV/T
BIPV	Building-integrated PV
BIPV/T	Building-integrated PV/T
CA	Compound alternative
CAA	Clean Air Act
CdTe	Cadmium telluride
CIGS	Copper indium gallium selenide
CIS	Copper indium selenide
CO_2	Carbon dioxide
CPBT	CO_2 payback time
CR	Consistency ratio
CV	Coefficient of variation
DHW	Domestic hot water
DSSC	Dye-sensitized solar cell
DT	Decision tree
EA	Extra-large area
EC	Embodied carbon
EE	Embodied energy
EGR	Extensive green roof
EOL	End of life
EPDs	Environmental product declarations
EVA	Ethylene-vinyl acetate

FIT	Feed-in tariffs
GHG	Greenhouse gas
GI	Green infrastructure
GIS	Geographic Information System
GR	Green roof
HH	High height
ICE	Inventory of carbon and energy
ICPL	Iranian construction price-list
IEA	International Energy Agency
IGR	Intensive green roof
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
ISCAUP	Iranian Supreme Council of Architecture and Urban Planning
ISES	International Solar Energy Society
LA	Large area
LCA	Life Cycle Assessment
MA	Medium area
MCDM	Multi-Criteria Decision-Making
MCR	Most common roof
MDGs	Millennium Development Goals
MH	Medium height
MIVES	Modelo integrado de valor para evaluaciones sostenibles
m-Si	Mono/single-crystalline silicon
NCV	Net calorific value
nZEBs	nearly Zero-Emission Building groups
ORI	Occupational risk index
OSC	Organic solar cell
PCM	Phase change materials

PM	Particulate (particle) matter
PO	Partial outcome
p-Si	Poly/multi-crystalline silicon
PUR	Polyurethane
PV	Photovoltaic
PV/T	photovoltaic thermal
ROI	Return on investment
R&D	Research & Development
SA	Small area
SAI	surface area index
SH	Short height
SI	Sustainability index
SIGR	Semi-intensive green roof
S-OBJ	Specific/sub-objective
STC	Standard test condition
SWOT	Strengths, weaknesses, opportunities, and threats
TF	Thin film
UHI	Urban Heat Island
UV	Ultra-violet
VF	Value function
WACC	Weighted average cost of capital
WHO	World Health Organization

Notations (symbols)

λ_i	Weight/importance coefficient of indicator (i)
C	Criterion
Ci	Severity consequence of risk (i)
C_i	Abscissa approximation for inflection point
$CO_{2\ emission}$	Emitted CO_2 during manufacturing
$CO_{2\ saving}$	Avoided/absorbed CO_2 emission
DCv	Decreasing concave
DCx	Decreasing convex
DL	Decreasing linear
DS	Decreasing S-shaped
$E_{consumption}$	Consumed energy during manufacturing
E_{ele}	Electrical efficiency
E_{GC}	Efficiency of GR to reduce CO_2
E_{GP}	Efficiency of GR to reduce PM
Ei	Exposure to risk (i)
E_{in}	Efficiency of pollutant-reducing alternative (i) to reduce pollutant (n)
E_{PC}	Efficiency of PV to reduce CO_2
E_{PP}	Efficiency of PV to reduce PM
$E_{production}$	Produced electrical/thermal energy
E_T	Total efficiency
E_{th}	Thermal efficiency
I	Indicator
ICv	Increasing concave
ICx	Increasing convex
IL	Increasing linear
IS	Increasing S-shaped
K_i	Ordinate approximation for point Ci

kWp	Peak kilowatts
Pi	Probability occurrence of risk (i)
P_i	Shape factor
P_{in}	Potential of alternative (i) to reduce pollutant (n)
R	Requirement
T_n	Total amount of the pollutant (n)
V	Satisfaction value
X_i	Abscissa value of the indicator (i)

Glossary

Air quality index: AQI is an index for reporting air quality divided into six categories. Each category corresponds to a different level of health concerns and has a specific colour [1].

Analytical hierarchy process: AHP is an MCDM ranking technique as a weighting tool for structuring a problem at the different levels of the hierarchy based on pairwise comparison logic [2].

Building-attached photovoltaic: BAPV is a photovoltaic solar energy system mostly added on top of the building's roof [3].

Building integrated photovoltaic: BIPV is a photovoltaic solar energy system integrated into building envelopes such as facades, roofs, skylights, and canopies [4].

Carbon footprint: The measure of the exclusive total amount of CO_2 emission that is directly and indirectly caused by an activity or is accumulated over the lifecycle stages of a product [5].

Circular economy: A model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible [6].

Concentrator collector: A non-flat plate type of solar collector enables enhancement of the radiation intensity achieved by solar cells using lens and mirror concentrators [7].

Consistency ratio: CR measures the degree of departure from pure inconsistency. Saaty defines it as the ratio of a consistency index to the mean consistency index from a large sample of randomly generated matrices [2].

CO_2 payback time: CPBT, an environmental indicator, determines the probable speed to compensate for the CO_2 impact in the solar panels manufacturing process by decreasing CO_2 emission via energy generation [8].

CO_2 saving: The potential amount of decreased CO_2 in the operational phase of a pollutant-reducing alternative during its service time.

Direct normal irradiation: DNI is the amount of solar radiation received per unit area by a surface that is always held perpendicular to the rays that come in a straight line from the direction of the sun at its current position in the sky [9].

Dye-sensitized solar cell: DSSC is a solar cell formed between a photo-sensitized anode and an electrolyte that benefits low processing costs, flexibility, the ability of screen printing, incorporation in paints, and semi-transparency [10].

Embodied carbon: EC is the sum of fuel-related carbon emissions and process-related carbon emissions [11].

Embodied energy: EE is the total primary energy consumed from direct and indirect processes associated with a procedure or service, i.e. all activities from material extraction, manufacturing, and transportation [11].

Emission factor: A representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with that air pollutant in order to estimate emissions from various sources [12].

Energy conversion efficiency: The ratio between the useful output energy that an energy conversion system provides and the input [13].

Extensive green roof: EGR is a type of green roof with a shallow and light layer of soil and the ability to embrace only a limited range of plants [14].

Feed-in tariffs: FIT is a policy mechanism designed to accelerate investment in renewable energy technologies by offering long-term contracts to renewable energy producers [15].

Glazed/Unglazed solar collector: A flat plate solar thermal collector can be uncovered (unglazed) or, in order to protect and minimize heat loss, can be covered (glazed) by an additional glass at a distance from the absorber surface [16].

Green infrastructure: GI intends to solve urban and climatic challenges by building with nature, i.e. issues of climate adaptation, air quality, sustainable energy, heat stress, stormwater, biodiversity, food, clean water and soil [17].

Heat pump system: An auxiliary system that enables thermal energy to transfer from a lower temperature source to a hotter sink using mechanical energy and a refrigeration cycle to improve solar collector efficiency [18].

Intensive green roof: IGR is the deepest, thickest, and heaviest type of green roof, with the ability to support many different kinds of plants [19].

Inventory of carbon and energy: ICE database included the EPDs database and follows a cradle-to-gate scope known as module A1–A3 in the EU-wide standards, EN 15804, and EN 15978 on the construction field sustainability assessment [11].

Life Cycle Assessment: LCA is a method to assess the potential environmental impacts and resources used throughout the life cycle of a product, process, or service [20].

MIVES: A customizable and agile integrated value model for sustainability assessment that enables the holistic objective assessment, precise comparison, and ranking of alternatives [21].

Multi-Criteria Decision-Making: MCDM is an approach that involves various choice analyses in a situation or research area, which can cover single or multi-objectives as targets to ensure that defined solutions satisfy the requirements [22].

nearly Zero-Emission Building groups: nZEBs is a nearly free-emission concept aligned with the longer-term climate neutrality goal by balancing the share of increasing emissions from a building group with its share of decreasing emissions [23].

Nanotechnology solar cell: A type of PV in the third generation in which some products, such as nanotubes, quantum dots, and hot-carrier cells, are emphasized due to more solar radiation absorption ability to improve efficiency [24].

Nanofluid solar collector: A type of PV/T contains nanoparticles – less than 100 nm – in the base fluid, e.g., water, glycol, and oil. These materials are used efficiently for solar energy conversion to improve thermal conductivity [25].

Net calorific value: NCV is the amount of usable heat energy released by combustion for a unit of the biofuel burned in oxygen and such that the amount of heat spent in transforming the water into steam is not counted in it [26].

Occupational risk index: ORI is an indicator to estimate the level of risk in building projects based on the type and volume of activities involved [27].

Organic solar cell: OSC is a type of PV in the third-generation category made of organic semiconductors, which benefits from disposability, flexibility, and affordability while faces to low efficiency, strength, and stability [24].

On-grid solar system: A utility-interactive solar system that connects to an electricity network and feeds it for electrical energy distribution to where it is demanded [3].

Off-grid solar system: A stand-alone independent solar system, un-connected to the utility grid, that supplies directly only the property's electricity demand [3].

Particulate (particle) matter: PM is one of the most critical air pollutants, including respirable fine particle matter with a diameter of fewer than 10 micrometres (PM_{10}) and fine particles less than 2.5 microns ($PM_{2.5}$) [28].

Phase change materials: PCMs are substances that absorb or release large amounts of so-called "latent" heat when they change their physical state [18].

Photocatalysts: Materials that can decompose detrimental substances under the sunlight contain UV rays. Mainly, TiO_2 is used as a photocatalyst that enables the absorption of NO_2 in the field of air quality improvement [29].

Photovoltaic: PV enables capturing solar energy to generate electricity directly. The photovoltaic effect absorbs photons and releases free electrons through a light-absorbing material presented within the cell structure [30].

Return on investment: ROI is a ratio between net income and investment to estimate the profitability of a system over its life service time.

Semi-intensive green roof: S-IGR is an intermediate type of green roof in terms of medium soil depth and potential variety for plant selection [14].

Sensitivity analysis: An evaluation of how the uncertainty in the output of a mathematical model or system can be divided and allocated to different sources of uncertainty in its inputs [31].

Silicon crystalline technology: c-Si is the first generation of PV technology that consists of single-junction crystal solar cells based on silicon wafers and categorized into mono/single (m-Si) and poly/multi-crystalline (p-Si) silicon cells [24].

Standard test condition: STC is a laboratory condition used to rate PV products. STC are 1000 Watts per square meter of solar irradiance, 25 degrees C of cell temperature, and 1.5 meters per second of airflow speed [32].

Surface area index: SAI is the surface area at the lateral resolution of the measured surface as compared to a perfectly smooth one. This dimensionless quantity, as the leaf area index, is used to characterize plant canopies [33].

Sustainability index: Sustainability is the ability to maintain or support a process over time such that SI indicates the level of balance between three core aspects: economic, environmental, and social [34].

Thin film technology: TF is the second generation of PV technology using thin films produced via thin layers' deposition on glass/stainless-steel substrates, based on single-junction sets (i.e. a-Si, CdTe, CIS, and CIGS) [24].

Urban Heat Island: UHI effect occurs in urban areas that experience higher temperatures than outlying areas due to the built environment, which absorbs and re-emits the sun's heat more than natural landscapes [35].

Value function: VF of an optimization problem, dependent on the problem's parameters, determines the value the objective function achieves at a solution [36].

Water/Air-based solar collector: Based on working fluid type, as the heat transfer medium, conventional flat plate photovoltaic thermal collectors are classified into two categories water/liquid-based and air-based types [37].

CHAPTER 1

Introduction

The first chapter presents the main foundation sections of the current doctoral dissertation. This preamble embraces a summary of the *Motivation* to perform this research project, the *Research questions* as the basis for the results commentary, the *Objectives* anticipated to be achieved, the *Boundaries* defined by the study scope with the limits set, the *Methods* and tools to attain the goals in a research framework, and the *Dissertation structure*.

1.1. Motivation

Environmental protection is one of the eight principles of the Millennium Development Goals (MDGs) for the 21st century and one of the three pillars of sustainable development [38]. In this sense, greenhouse gas (GHG) emissions, global warming, and air pollution are often considered leading environmental problems. The World Health Organization (WHO) estimated that air pollution causes 4.2 million deaths annually and that 91% of the world's population lives in areas where the air quality does not meet recommended standards [28]. This is despite the fact that the cost of air pollution was estimated to be 225 billion US dollars per year, just from premature mortality [39].

In this regard, reevaluating the future roles that cities can play in order to diminish these negative environmental impacts is one of the sustainable options that the Intergovernmental Panel on Climate Change (IPCC, April 2022) emphasizes [40]. Accordingly, city managers face an urgent need to develop a proper multi-level strategy and investigate the optimal sustainable solutions on a city scale based on prospective and practicable uses to reduce urban air pollution. This is while around 37% of global GHG emissions are attributed to the building sector [41]. At the same time, the building sector has the potential to significantly contribute to the reduction of urban air pollution. However, it is worth noting that the emissions generated during the operational phase of buildings constitute the largest share of their overall life cycle emissions [42]. Accordingly, among different possible strategies identified initially to reduce air pollution in cities – such as the contribution of urban planning, building utilization, construction technology, and construction material – this thesis concentrates on the potential of building utilization. To this end, rooftops, the most effective and promising building envelopes, can be calibrated to contribute to this decrement [43]. Rooftops are considered convenient context because they are: (a) extremely abundant, (b) capable of providing vast areas, (c) significantly exposed to sunlight, (d) facile available, and (e) underutilized [44]. Meanwhile, green infrastructure (GI) emerges as a potential substitute for incorporating climate resilience into the built environment [43,45,46]. This way, the potential of GI, such as greenery and renewable energy systems, is also another crucial aspect to help reduce ambient pollution [47].

Additionally, the thesis author’s personal motivation has also powered the aforementioned general stimulants to perform this doctoral dissertation. With over 20 years of professional experience in different disciplines of architectural engineering, building construction, and urban management in Tehran, an example of a heavily air-polluted and problematic megacity, the author can have a realistic perception of this city's needs and potential available in the building sector and can understand the importance of each sector's contribution to sustainable urban development. In this area, the author has also published three research articles as the main author in the Q1 indexed journals, while the subject matter of each paper fits well with the field and scope of the corresponding journal.

1.2. Research questions

The research questions, provided in the following lines, can serve as a basis for analysing and discussing the research findings and their implications for air pollution mitigation, sustainability, and urban planning in air-polluted cities.

1) What are the feasible pollutant-reducing alternatives for rooftop application in urban environments, and which parameters determine the feasibility of these alternatives?

2) Does combining these technologies provide more effective air pollution reduction compared to using them separately?

3) Aligned with the former research question, what is the most effective combination ratio for the implementation of the optimized compound alternative?

4) Can certain building groups show greater potential for air pollution reduction in the urban context?

5) To what extent can adopting a synergistic strategy for applying the most efficient alternative to target buildings contribute to air pollution reduction?

1.3. Objectives

This thesis aims to enhance understanding and investigate the suitability of air pollutant reducer technologies applicable on rooftops to develop buildings' performance. This research intends to provide optimal and systematic planning, as a sustainability-based tool, in assisting city managers when programming for air quality improvement and moving forward to sustainable urban development.

Additionally, the specific/sub-objectives (S-OBJ) that support the aforementioned main objective – as a broader goal of this thesis – are as follows:

- S-OBJ-1: Determining feasible solutions to apply on buildings' rooftops in order to decrease urban air pollution considering determinant indicators
- S-OBJ-2: Aligned with the former objective, developing sustainability assessment models to find the most suitable type for each feasible solution
- S-OBJ-3: Evaluating the capacity of suitable alternatives to mitigate urban air pollution
- S-OBJ-4: Creating a new model to define city-scale optimal planning via simultaneous incorporation of potential pollutant-reducing alternatives and potential target buildings
- S-OBJ-5: Assessing the ability rooftops provide to mitigate air pollution on a city scale

This research project and its objectives rely on the relevant technical literature. For instance, regarding the ability rooftops provide for GI applications, considering Zambrano-Prado et al. (2021) [48], M. Thebault et al. (2020) [49], S. Toboso-Chavero et al. (2019) [50], D. S. Salvador et al. (2019) [51], K. Dimond and A. Webb (2017) [52], and M. H. Chung (2018) [44]; in terms of sustainability assessment model, considering I. Josa et al. (2020) [53], A. de la Fuente et al. (2019) [54], G. Ledesma et al. (2020) [55], B. Maleki et al. (2019) [56], S. M. A. Hosseini et al. (2018) [57], and O. Pons et al. (2016) [58]; as for PV and GR environmental performance, considering D. Pinel et al. (2021) [59], S. S. Korsavi et al. (2018)

[60], Y. Fu et al. (2015) [61], F. Cucchiella et al. (2015) [62], F. Moran and S. Natarajan (2015) [63], M. Herrando et al. (2014) [64], J. Yang et al. (2008) [65], and B. A. Currie and B. Bass (2008) [66]; and for the integration of PV and GR, considering M. E. Abdalazeem et al. (2022) [67], M. C. Catalbas et al. (2021) [43], K. Bao et al. (2021) [68], A. Jahanfar et al. (2020) [69], M. Ramshani et al. (2020) [70], B. Y. Schindler et al. (2018) [71], M. S. P. Moren and A. Korjenic (2017) [72], Chr. Lamnatou and D. Chemisana (2015) [73].

1.4. Boundaries & Study area

The scope and limits of this research project have been rigorously defined as follows:

1) Amongst the growing environmental concerns, air pollution, one of the significant challenges worldwide, has been considered for investigation;

2) In this regard, this study has focused on reducing urban air pollution as the outdoor type among outdoor and indoor air pollution, with a more pervasive impact on citizens;

3) To this end, GI alternatives have been considered among others, as environmentally friendly solutions [45,46];

4) Meanwhile, feasible alternatives with the ability to mitigate air pollution by emphasizing their sustainability level have been considered in the line of realization of the sustainable development goals;

5) In addition, to apply these pollutant-reducing alternatives, rooftops – which are broadly abundant and underused – have been chosen among different urban elements [43,44];

6) In this sense, this research project has focused on the performance of rooftops only in their operational phase, which accounts for around two-thirds of the building sector share in emissions [42].

Additionally, to validate the proposed model during the whole process, Tehran has been considered as the case study among other megacities due to its remarkable potential of extremely vast-abundant and underused rooftops, as well as the urgent need to reduce urban air pollution. Tehran is one of the most densely populated megacities in Western Asia [74], hosting a population of around 8.8 million and an entire metropolitan area of nearly 15 million inhabitants. Air pollution issues are considered one of the main challenges that Tehran presently faces. Rapid population growth, industrial development, urbanization, and fossil fuel consumption increments are the most critical aspects connected to air pollution in Tehran. Besides, the temperature inversion phenomenon is added to these problems since Tehran is surrounded by a high mountain range, which traps air pollutants, especially in cold months [75]. During the recent decade, the air quality index (AQI) for Tehran has been measured in the moderate or lower range for more than 90% of days per year. In this regard, Particulate Matter (PM) accounts for Tehran's most critical air pollutants. The concentrations of PM measured in Tehran have exceeded the standard thresholds annual means so that, Tehran was ranked 12^{th} in PM among the 26 most air-polluted megacities around the world [76]. On the other hand, Tehran has been considered 14^{th} among 500 high-carbon footprint cities worldwide. This is while generally carbon dioxide is the most significant GHG emissions. Regarding the situation and characteristics of this case study, more extensive information and explanation have been provided in detail through three publications relevant to this thesis, which are available in the following chapters (Chapters 2 and 3).

Notable that some limitations have been set for this research project as well, as explained in detail in each corresponding published article. For instance, concerning solar energy systems, this study does not consider stand-alone/off-grid systems and focuses on utility-interactive/on-greed as domestic solar power plants and the most common type in Tehran. Additionally, the indirect effect of GR as a passive system that can help decrease energy use for indoor thermal conditioning is not considered. Moreover, to choose potential target building groups, non-physical parameters with indirect impacts are not considered in this research, those are often associated with the occupants' motivations and require other comprehensive demographic and specialized sociological studies.

1.5. Methods

This thesis follows the five-phase procedure presented in Figure 1.1, in order to carry out the study process for the development of the sustainable use of rooftops to reduce air pollution. The framework complexity requires a partial explanation of the phases in different chapters. The following lines explain in detail these phases, the targets of each, the methods and tools to reach them, and the relevant chapters regarding each phase. The organization of chapters and their relevant publications in the current dissertation is available in Section 1.6.

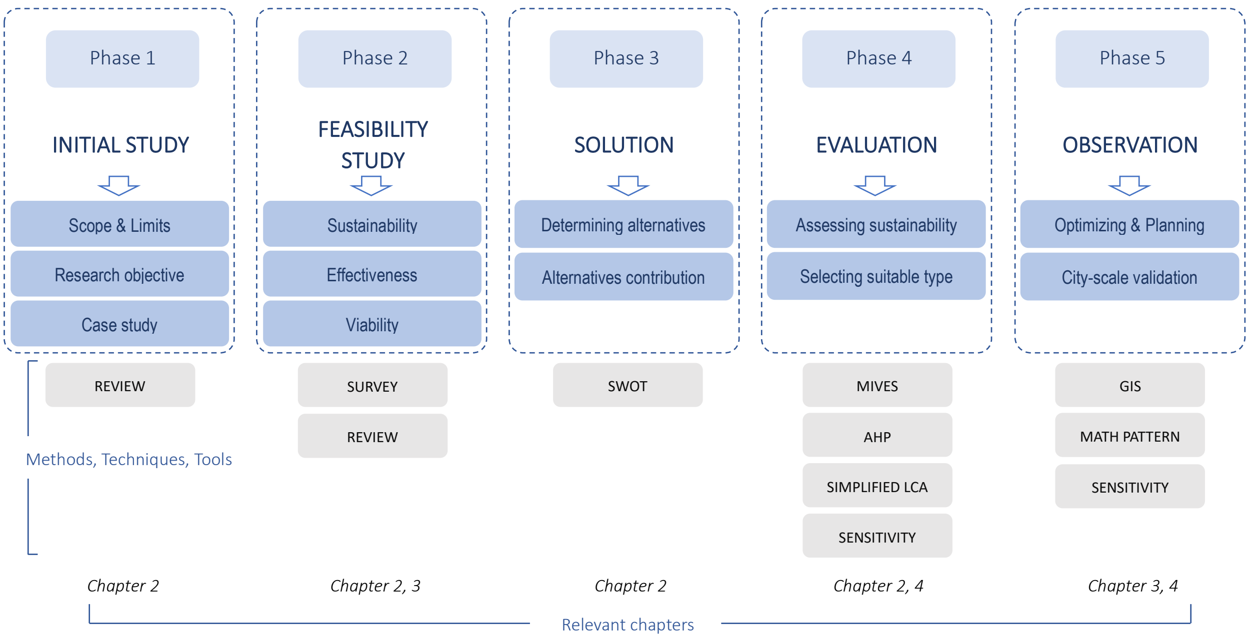


Figure 1.1. *General framework of the current thesis*

Phase 1) *Initial study* provides general input from each side of the research study scope, limits, and objective concerning the problem. Additionally, this phase determines a case study involved with the identified challenges and relevant to the defined scope in order to examine partial and general outcomes in each step. This first phase performs a comprehensive preliminary study – corresponding to Chapter 2 – to create a knowledge basis of outstanding technologies and their advancements for roof utilization, which lead to reducing air pollution.

Phase 2) *Feasibility study* considers the status of the context and the characteristics of the case study with its needs and potential. This second phase investigates the sustainability, effectiveness, and viability of pollutant-reducing alternatives for each specific case study, as presented in Chapters 2 and 3. This investigation is based on the contribution of professional experts and involved stakeholders – as explained in detail in the articles presented in Chapter 2 – as well as performing a simplified literature review and exploring available technical information on the sustainability and performance of pollutant-reducing alternatives.

Phase 3) *Solution* presents possible alternatives of roof refurbishment strategies based on the previously identified problems and the feasibility study. This middle phase uses a strategic planning approach to conduct a general analysis of different alternatives considering their strengths, weaknesses, opportunities, and threats (SWOT) [77], as explained in detail in the articles presented in Chapter 2. This elementary and straightforward analysis technique provides a clearer insight to support and facilitate the decision-making process and results in determining solution alternatives as well as identifying their associated internal and external contributions – that are either favourable or unfavourable – to the field.

Phase 4) *Evaluation* develops new sustainability assessment models based on the Multi-Criteria Decision-Making (MCDM) method and applies them to the determined feasible solutions for the case study. An MCDM approach can cover a single objective or multi-objectives as targets to ensure that the defined solutions satisfy the requirements [22]. These new models follow the Integrated Value Model for Sustainability Assessment (MIVES) [58] and the Analytic Hierarchy Process (AHP) [2]. MIVES is a customizable and agile sustainability assessment model that: 1) enables the holistic objective assessment, precise comparison, and ranking of alternatives [21]; 2) has the capability of adding up various indicators' values with qualitative or quantitative results measured by different scales and units [53,58,78]; and 3) has already satisfactorily applied to a variety of case studies containing architecture and building construction fields as a comprehensive sustainability assessment tool [58,79]. Meanwhile, AHP, as a supporting tool and well-known ranking technique: 1) is capable of combining with other methods; 2) benefits from a straightforward procedure based on the pairwise comparison to weigh several factors at the different levels of the hierarchy; and 3) has the potential in using the inconsistency index [80]. In addition, an assistant method to evaluate environmental performance is incorporated into the model. This supplementary tool is a simplified Life Cycle Assessment (LCA) – based on ISO 14040:2006 and ISO 14043:2006 standards [81,82] – applied previously in other MIVES models as well [83–85]. Finally, in this evaluation phase, a sensitivity analysis to examine the outcomes of considering different scenarios – based on the variety of weighting distributions – leads to robustness proof for the designed model. A comprehensive explanation of MIVES protocols, combined with AHP, simplified LCA, and sensitivity analysis for sustainability assessment and determining the most suitable type of each alternative, as well as the outcomes of this evaluation, are available in Chapters 2 and 4.

Phase 5) *Observation,* the ultimate phase in this research project, sets up the proposed model and defines optimal planning on a city scale via a systematic approach. This multi-objective planning can recommend the most adequate solutions and assist city managers in surveillance and analysis of the proposed plan performance to reach the highest achievements from the deployment of possible technologies for rooftop utilization. To this end, a collaboration of potential target building groups and optimized feasible pollutant-reducing alternatives are formed with the assistance of mathematical patterns, Geographic Information System (GIS), and sensitivity analysis as tools. Chapters 3 and 4 embrace the results of this phase, which is expected to motivate researchers and professionals for further developments in urban sustainability and air pollution reduction.

1.6. Dissertation structure

The structure of this doctoral dissertation has been organized into six chapters distributed among three main parts. The first part, which is Chapter 1, sets the project objectives, boundaries, and methods. The second part embraces the following Chapters 2 and 3, which contain the results obtained from this research project. The three published articles relevant to the current thesis are presented in this second part. The sections containing the aforementioned publications consist of the following information regarding each research article: (a) a summary, (b) the contribution to the thesis, and (c) the research paper with its main data, the thesis author contribution and a copy of the published version. Finally, the third analysis part (Chapters 4, 5, and 6) provides a discussion along with a collection of partial findings, as well as highlights the main findings and suggests possible future developments. Figure 1.2, as a guide map for readers, presents a flow chart corresponding to the current dissertation structure.

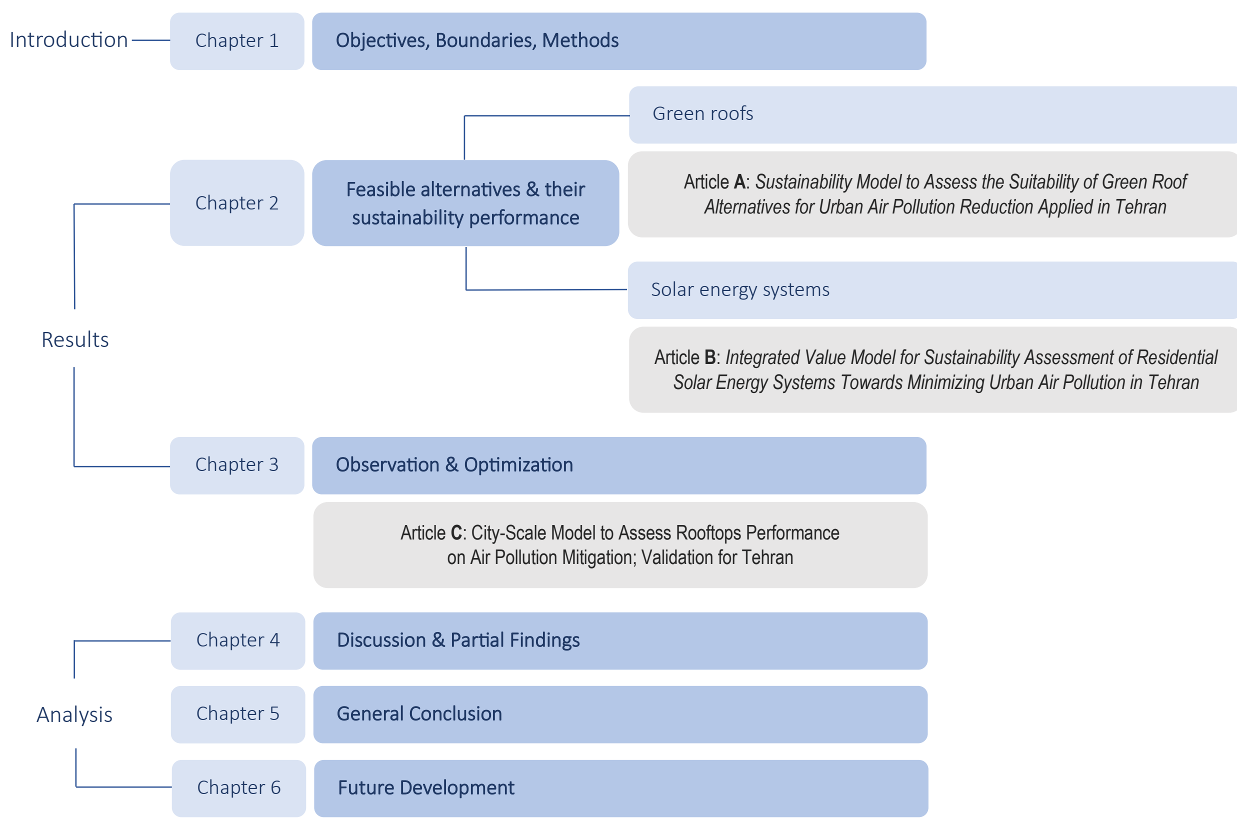


Figure 1.2. Guide map of the current dissertation structure

CHAPTER 2

Feasible alternatives and their sustainability performance

Determining feasible solution alternatives and their sustainability performance is explained in this second chapter. This section considers the sustainability, effectiveness, and viability in choosing feasible alternatives for rooftop installation, as previously mentioned in Section 1.5. In this sense, green roof (GR) and photovoltaic (PV) systems, identified as two of the highest trending among different urban green infrastructure (GI), are both sustainable practices that compete in the building sector [52,68,70]. In this respect, the sustainability level, a key performance indicator in sustainable urban development, has been considered based on three pillars: economic, environmental, and social [34].

Though other alternatives can also contribute to mitigating urban air pollution, the aforementioned are identified as effective ones considering the characteristics, requirements, and potential of the specific case study in this research. For instance, taking into account that NO_2 is not a main air pollutant in Tehran, photocatalyst materials such as TiO_2, which absorbs NO_2, are not adequately effective for this specific case study [76]. This is while GR and PV systems are considered effective measures to reduce both particulate matter (PM) and CO_2 – the most critical emissions in urban areas like Tehran – as described in detail in articles A and B.

Similarly, wind turbines as renewable energy producers are not viable to install in most residential buildings due to high expenses, vast needed spaces, structural stability problems in implementation and operation, etc. In contrast to wind turbines, GR and PV work securely and noiselessly, integrating with rooftop environments and maintaining the aesthetic attractiveness of residential areas. Furthermore, locating appropriate sites with enough wind speeds for wind turbine activity can be challenging in urban areas like Tehran. This is while Tehran experiences year-round high levels of sun radiation. Accordingly, Tehran is ideally situated for harnessing sunlight, which helps the viability of PV and GR alternatives.

2.1. Contribution to thesis

This chapter contributes to Phases 1, 2, 3, and 4 of this doctoral dissertation by conducting an initial study, carrying out the feasibility study, defining solution alternatives, and evaluating defined solutions.

Articles A and B contribute to performing a simplified literature review in the area of outstanding pollutant-reducing alternatives and their sustainability values in all aspects. This review serves as a beneficial basis for the remaining steps of this thesis. Moreover, this chapter contributes to providing convenient knowledge of the capability of feasible technologies to mitigate air pollution. The performed research studies and their subsequent conceptual frameworks provide a descriptive overview of different types of each alternative and their specific functions, which are helpful for the author to gain a good understanding of air pollutant reducers for building applications. Additionally, this chapter develops a new model specialized in the sustainability assessment for the feasible pollutant-reducing alternatives within the boundaries of the current research project. Accordingly, the main contribution of this second chapter through two presented articles is defining novel MIVES-based sustainability assessment models to determine the most suitable type of GR and PV systems as solution alternatives. Further, the findings of the thematic analysis in these research studies provide considerable information regarding current and future study directions. This analysis helps identify which sustainability areas face a gap to explore in this field.

2.2. Article A: Green roofs

Article A, entitled "Sustainability Model to Assess the Suitability of Green Roof Alternatives for Urban Air Pollution Reduction Applied in Tehran", published in the 194th vol. of *Building and Environment*, which is ranked in Q1 among indexed journals (doi: 10.1016/j.buildenv.2021.107683) [86].

The **contributions and individual roles of the thesis author** as the main author of this paper were conceptualization, data curation, investigation, methodology, formal analysis, resources, validation, visualization, writing the original draft, and revising. The other authors of the article are the thesis co-directors, who mainly supervised and advised the first author and reviewed the manuscript. In this study, GR, as a feasible environmentally-friendly alternative that contributes to improving air quality, has been analyzed and evaluated with its three common types of intensive green roof (IGR), semi-intensive green roof (SIGR), and extensive green roof (EGR) for urban settlement use. A copy of this research article is attached in the following.

Building and Environment 194 (2021) 107683

Contents lists available at ScienceDirect

Building and Environment

journal homepage: http://www.elsevier.com/locate/buildenv

Sustainability model to assess the suitability of green roof alternatives for urban air pollution reduction applied in Tehran

S. Hamed Banirazi Motlagh [a,*], Oriol Pons [a], S. M. Amin Hosseini [b]

[a] Department of Architectural Technology, The Polytechnic University of Catalonia (UPC), Av. Diagonal 649, 08028, Barcelona, Spain

[b] RESUME TECH (Resilience and Sustainability in Metropolitans TECH), America St., 08041, Barcelona, Spain

ARTICLE INFO

Keywords:
Urban agriculture
Sustainability assessment
MIVES
Residential buildings
Air quality

ABSTRACT

Green roofs are environmentally-friendly architectural solutions that contribute to air quality improvement, especially in an air-polluted metropolis like Tehran, where space is scarce and expensive. At present, there are different types of green roofs available, with the intensive, semi-intensive, and extensive the most feasible for urban settlements. This project aims to develop a new model to find the most suitable green roof to reduce air pollution in cities. To achieve this, after an initial study of strengths, weaknesses, opportunities, and threats, this study combines the agile multi-criteria decision-making method MIVES with an analytic hierarchy process and sensitivity analysis. This new model has successfully evaluated the suitability of the aforementioned three alternatives in Tehran's residential buildings. This assessment confirmed that this new approach can assist urban managers, architects, and constructors in selecting the most adequate green roof solution to contribute to improving air quality in cities. Nevertheless, all three evaluated solutions require improvement in terms of sustainability. This article recommends, for this specific case study, the application of an optimized version of the semi-intensive alternative by replacing its most expensive and large embodied energy components with eco-efficient and cost-effective materials, such as bio-waste and recycled materials.

1. Introduction

According to the World Health Organization (WHO), 4.2 million deaths every year are related to air pollution exposure while 91% of the world's population lives in places where air quality fails to meet guideline limits [1]. Additionally, air pollution contributes to the depletion of the ozone layer, the formation of acid rain, and global climate change [2]; and results in an estimated 225 billion US dollars in cost, just due to the mortality during a year [3]. Moreover, recent studies reveal the negative effect of some air pollutants on COVID-19 infection [4]. Notably, in the 21st century, environmental protection is one of the eight main points of the Millennium Development Goals and one of the three pillars of sustainable development [5]. Buildings, which are responsible for a considerable amount of resource consumption and greenhouse gas (GHG) emissions [6–9], could instead have positive impacts on air quality. Architecture can contribute to air pollution reduction via two different approaches: minimizing their negative environmental impacts, such as CO_2-equivalent emissions; and absorbing air pollutants, such as green strategies in buildings e.g. using green roofs (GRs) [10–16].

Yang et al. (2008) estimated that 1,835.23 metric tons of all pollutants could be annually mitigated in Chicago if the roofs in this city were completely covered with GRs [17]. Currie and Bass (2008) quantified the annual air pollution reduction - 7.87 metric tons of air pollution - for the city of Toronto by 109 ha of GRs [18]. GRs can decrease the urban heat island (UHI) effect by increasing evapotranspiration [19–23], which also cools buildings during hot summers [24]. Additionally, plants' photosynthesis sequesters carbon dioxide from the air and stores it as biomass [10–13,17,18,20,23,25]. GRs indirectly reduce CO_2 given off and improve energy consumption through their ability to insulate buildings [11,23,25,26]. According to Bass (2005), GRs can also reduce heat loss in winter conditions [27]. GRs allows buildings to better retain their heat during the cooler winter months while absorbing solar radiation through photosynthesis and reflecting solar radiation [24]. Therefore, evaluating as well as identifying the most proper GR alternative is considered striking in terms of sustainability. In this sense, until now numerous studies have assessed GR focusing on substrates [28,29], on energy consumption [26], on stormwater management [30], carrying

* Corresponding author. PhD. Candidate of the Architectural Technology, Building Construction and Urbanism, Polytechnic University of Catalonia (UPC), BarcelonaTech, Av. Diagonal 649, 08028, Barcelona, Spain.

E-mail addresses: seyed.hamed.banirazimotlagh@upc.edu (S.H. Banirazi Motlagh), oriol.pons@upc.edu (O. Pons), amin@resumetec.com (S.M.A. Hosseini).

https://doi.org/10.1016/j.buildenv.2021.107683
Received 30 November 2020; Received in revised form 18 January 2021; Accepted 4 February 2021
Available online 17 February 2021
0360-1323/

out life cycle assessments [20,31], assessing food-energy-water nexus [32] or focusing on the sustainability of urban agriculture in a specific case study [33].

This research project differs from these previous studies because it aims to develop a new model for the sustainability assessment of architectural GR alternatives that contributes to minimizing urban air pollution. This new model has been defined using the integrated value model for sustainability assessment (MIVES), incorporating the main sustainability requirements - economic, environmental, and social -. Therefore, this new model expects to assist municipalities when defining suitable solutions to improve air quality. In the following pages: a) Section 2 introduces GR types and components; b) Section 3 presents and justifies this case study; c) Section 4 explains the methodology used to define the new model; and d) Sections 5, 6, and 7, show the results, discussion, and conclusions.

2. Green roofs definition

This article focuses on the GR's role as an environmentally-friendly roof refurbishment solution that is partially or completely covered with vegetation and a growing medium [30]. GRs are mostly categorized into three types: (1) intensive (IGR), (2) semi-intensive (S-IGR), and (3) extensive (EGR) [29,34]. This distinction plays a critical role in determining the depth of the vegetation support course as well as the type of greening. Even though IGRs as a green park on a rooftop can support many different kinds of plants and increase the value of the property [35], this type is the thickest and heaviest GR, which needs additional structural support due to increasing roof loads. On the contrary, EGRs do not need to add structural support and can be easily installed during new construction or retrofitting of buildings due to their shallow and light layer of soil [36,37], though EGRs can embrace only a limited range of plants [23]. S-IGR is considered as an intermediate type of GR, in terms of medium soil depth and a potential variety for plants selected. These three types of GR have similar layers if they are applied for the same weather and roof type conditions, except for the planting soil medium, as shown in Fig. 1. This study has considered the typical minimum substrate depths from one of the most valid and common global GR guidelines named FLL [38].

This article considers GR constituted for vegetation, soil, drainage, root barrier, and other extra layers [20,39,40]. Fig. 1 illustrates, and Appendix B explains these GR layers on top of existing roof decks.

3. Case study

3.1. Characteristics of the case study - Tehran

The case study focuses on Tehran, one of the most air-polluted and most populated cities in western Asia [41]. Several investigations demonstrate rapid population growth, industrial development, urbanization, and increasing fuel consumption as the most important pressure points on the air quality in Tehran [42]. Topography and climate circumstances are the other determinant factors in air pollution since Tehran is surrounded by a high mountain range (Alborz), which traps air pollutants. In this sense, temperature inversion prevents diluting the pollutants, especially during the cold months [42].

Tehran, which has approximately 615 square kilometers area, is located in the north of Iran (35° 31′ - 35° 57′ N, 51° 4′ - 51° 47′ E), at high altitudes around 900–1,800 m above sea level. Fig. 2 shows its 22 districts that host a population of 8.8 million. The whole metropolitan area has 15 million inhabitants with a densely populated core and less-populated surrounding territories with industry, infrastructure, and housing [43]. Table 1 summarizes Tehran's attributes in which climatic information is collected from the geophysics meteorology synoptic station in 2019 [44].

The main components of urban air pollutants are carbon monoxide (CO), sulfur dioxide (SO_2), ozone (O_3), nitrogen dioxide (NO_2), respirable fine particle matter (PM) with a diameter of fewer than 10 μm PM_{10}, and fine particles less than 2.5 μm $PM_{2.5}$ [1]. Annual air quality reports for Tehran during the recent decade [45], reveal that the concentrations of CO, SO_2, O_3, and NO_2 were within healthy recommended limits. And in general, the air quality index (AQI) for Tehran measured in the moderate or lower range for more than 90% days per year, as explained in Appendix C (Table C.1). However, the concentrations of $PM_{2.5}$ and PM_{10} measured at all air quality monitoring stations in Tehran exceeded the national standard annual means [45]. $PM_{2.5}$ causes more than 4000 premature deaths annually in this city; which is ranked as 12th high PM_{10} levels megacities in the world [42]. PMs pose the highest risks to health since they are capable of penetrating the lungs and entering the bloodstream [46]. Sources of PMs emissions come from all types of combustion, including engines and solid-fuel combustion for energy production in housing and industry, as well as other industrial activities [1]. The annual mean of the European Union's maximum concentration limits is 25 μg m^{-3} for $PM_{2.5}$ and 40 μg m^{-3} for PM_{10}. The maximum level of PM proposed by the WHO is 10 μg m^{-3} for $PM_{2.5}$ and 20 μg m^{-3} for PM_{10}. The annual concentration of $PM_{2.5}$ in Tehran was approximately three times more than the maximum range considered by the national standards and the WHO. Furthermore, the annual ambient level of PM_{10} was almost four times more than the WHO's recommended threshold.

3.2. Potential for using GRs in Tehran

Rooftops are a valuable resource in cities, where large-scale vacant space is scarce and expensive [47]. Roofs of residential buildings cover a vast area of Tehran [48] due to the following reasons: 1) 77.32% of parcels (parts) in Tehran have residential land-use; 2) residential buildings embrace 78.6% of Tehran's total built areas; 3) the occupancy level of building relative to the surface in most residential land is at least 60%.

A rather short reconstruction period for residential buildings in

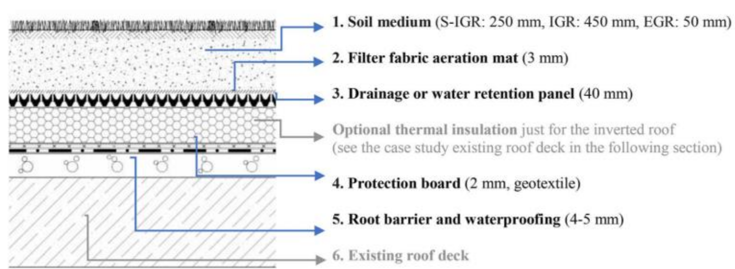


Fig. 1. GR layers detail on top of an existing deck. The next section details the roof deck in this case study.

Fig. 2. Natural side effects and districts in Tehran (Source: TMICTO [48]).

Tehran - on average 50 years -, provides an opportunity to easily and economically implement some alternatives during the construction phase. Furthermore, considering the climate conditions in this city, roofs could be one of the main building envelopes to exchange solar radiation and heating. Additionally, roofs provide more net area compared to the already occupied yard areas. All the above-mentioned factors promise the great potential to implement many GRs alternatives in a vast area during a short time. Fig. 3 shows the most common roofs (MCRs) in Tehran without any greening, which consist of some layers over the structural roof deck including a) nylon vapor barrier, b) polystyrene thermal insulation (0.05 m), c) light concrete (1.5 kN m^{-3} – 0.05 m), d) cement sand mortar (0.025 m), and e) prefabricated moisture insulation layer. Average maintenance works imply changing the last layer every ten years.

3.3. Specifications for GRs in this case study

Some features of GRs need to be customized regarding the Iranian building codes and local conditions. In this case, the plants selected should be: a) compatible with Tehran climatic conditions, b) abundant and economical in the Iranian market, c) preferably be alive during four seasons of the year to have ongoing advantages, and d) be needle-leaf to retain more moisture. These requirements are based on the fact that needle-leaf plants do not need remarkable irrigation most of the time when minimum sufficient rainfall and humidity are available [49]. Hence, due to the suitable moisture-retaining potential of needle-leaf plants, watering consumption is not considerable. Therefore, this project has selected Cedar shrubs based on the above-mentioned parameters to determine the type and attributes for plants on GRs, which satisfies the required specifications. One Cedar shrub with almost 0.05 m caliber - the diameter at breast height -, 1 m height, and grass has been considered as a mixture at a ratio of 50:50 for each square meter of S-IGR and IGR. EGR is covered just by grass without any shrub. The average depth considered for S-IGR, IGR, and EGR with bottom layers are equivalent respectively, 0.30 m, 0.50 m, and 0.10 m, respectively. According to the fourth topic of the Iranian National Building Regulations - section 4.9.7.1.1 -, the height of the roof edge wall should be a minimum of 1.10 m. In consequence, after adding approximately 0.10–0.50 m as a GR layer, it is not necessary to build an extension of the facade. Furthermore, as previously presented in Fig. 3 the finishing layer in MCR is moisture insulation because the waterproofing layer is usually the last layer to be installed. Therefore, no layer from MCR would be removed before the implementation of a GR.

4. Methodology

The following sections explain the methodology this research project employs, which has two main steps: 1) an initial analysis and 2) the design of the new model to assess the suitability of GRs for air pollution reduction in cities.

4.1. Initial analysis

This project conducted an initial analysis to study the feasibility of using GRs for residential buildings in Tehran. This initial analysis was based on the strengths, weaknesses, opportunities, and threats (SWOT) technique [50]. SWOT matrix can assist researchers to identify the internal and external factors of GRs in Tehran. Additionally, the results of SWOT, which are obtained based on extensive literature review, are useful for the definition of sustainability indicators in the following parts. It should be noted that strengths and weaknesses commonly follow internal issues, while opportunities and threats often focus on external factors.

4.2. Model design

Making the most appropriate decision requires a compromise solution considering all effective factors to approach the ideal alternatives. In this context, a wide variety of sustainability assessment tools for the building field are available, such as BREEAM, DGNB, LEED, VERDE, and CASBEE among others [51,52]. Considering the aforementioned objectives of this research study, MIVES, a multi-criteria decision-making model (MCDM), was applied to design a new model. MCDMs provide a systematized and more objective procedure to organize ideas into criteria and sub-criteria and quantify preferences to make decisions. Furthermore, MIVES, which was developed in the 2000s based on the multi-attribute utility theory [53], can use and add either qualitative or quantitative indicators together, that are measured by different scales and units. Besides, this method is specific for each deterministic or probabilistic case along with homogeneous or heterogeneous assessment. MIVES achieves so by using value function and satisfaction concepts [54–56]. This MCDM gives integrated sustainability indexes and can be combined with other methods and specific mathematical algorithms, thus uncertainly analyses can easily be integrated into the evaluation [54,55,57]. In consequence, MIVES allows researchers to carry out agile, objective, specific, and complete sustainability assessments. Also, being a tree-structured, easy-to-use, and straightforward implementation model, MIVES provides a suitable condition for even non-experts to comprehend and communicate with its results [55,57]. MIVES has already been successfully applied in numerous research projects generating holistic sustainability assessment tools in a broad range of study cases including architectural, civil engineering, and building fields [54,57,58]; such as: (1) buildings and components [59]; [56]; [60]; [61]; [62]; [55]; [58]; [63]; (2) concrete structures and slabs [64]; [65]; (3) infrastructure management [66]; [67]; [68]; [69]; (4) hydraulic structures [70]; [71]; (5) post-disaster housing management [72–75]; and (6) architecture learning processes [57,76].

MIVES incorporates the aforementioned three main sustainability requirements [77], as the first level of the decision tree (DT). The most general and qualitative aspects make the first level - requirements -, whilst the last level embraces the most specific and quantifiable ones - indicators -. The middle level is a breakdown, which is established for

Table 1
Summary of Tehran attributes (Source: [44,45,48]).

Land			Mean temperature						Precipitation			Wind			Air pollution	
Area	Elevation	Population	Annual	Spring	Summer	Autumn	Winter	Average low/high during 30 years	Gross	Net	Humidity	Dominant direction	Max speed	Mean speed	Organization	Main pollutant
km^2	m	Million	°C						mm		%	–	$m \cdot s^{-1}$		–	$\mu g \cdot m^{-3}$
615	**900–1800**	**8.8**	**17.2**	**19.3**	**29**	**13.3**	**7**	**13–22**	**424**	**327**	**23–66**	**West to east**	**21**	**3**	**AQCC**	**PM**

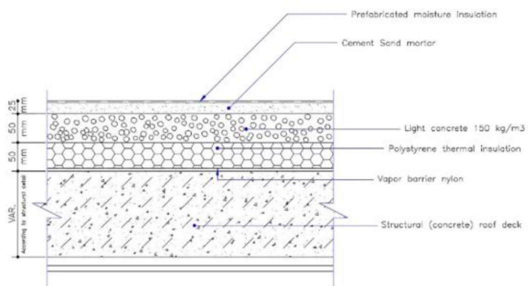


Fig. 3. Existing most common roof (MCR) type in Tehran on top of which a GR would be installed.

structuring the problem - criteria - [55,70,78]. MIVES approach requires three fundamental aspects: (1) boundaries to determine the scope of the analysis, (2) DT involved during the decision-making process, and (3) value functions to convert the associated units of each indicator into a-dimensional values [65]. The assessment is based on the value of a final index, which is obtained through the aggregation of the different indicators, criteria, and requirements evaluation. Fig. 4 presents the steps followed when applying MIVES.

According to Alarcon et al. (2011) [79], to determine sustainability indexes of alternatives, MIVES outlines a procedure consisting of the five stages: (1) DT design; (2) definition of the tendency - increasing or decreasing -; (3) determination of the X_{min} and X_{max} points corresponding to the minimum and maximum satisfaction value; (4) definition of the shape of the value function; and (5) using the mathematical expression of the value function. In the DT, apart from the previously mentioned three sustainability requirements, the final number of criteria and indicators in each tree branch must be the minimum; in other words, the number of indicators should not be excessive [54]. Moreover, to achieve a reliable assessment, the selected indicators should be representative to discriminate between the alternatives and be independent of each other to avoid overlapping. The values belonging to the different indicators of each alternative can be aggregated to achieve the global sustainability index (V) by applying Equation (1). $V_i\ (x_i)$ is a value function, which defines the assigned preferences to each value, obtained by the parameter (x_i). V_i is generated by Equation (2), and λ_i is the corresponding weight or relative importance coefficients. This formula should be applied to each level of the DT and enables quantifying the sustainability level of each alternative using value functions. These functions provide the magnitude that is intended to indirectly measure the satisfaction level, homogenize the indicators units, and normalize the variables to enable the aggregation of indicators [56]. Value functions unify indicators' units on an a-dimensional scale from 0 to 1 as the representation of the minimum and maximum degree of satisfaction in terms of sustainability. These functions can adopt several shapes [79], including (1) concave (Cv: rapid increasing or slight decrease of satisfaction); (2) linear (L: steady increasing/decreasing of satisfaction tendency); (3) convex (Cx: the contrary of the concave curve case); and (4) S-shaped (S: the combination of concave and convex functions).

$$V = \sum \lambda_i \cdot V_i\ (x_i) \quad (1)$$

Equation (2) shows the general expression of the value function (Vi) used in MIVES, which enables the assessment of each indicator's value or satisfaction in terms of sustainability.

$$V_i = A + B \cdot \left[1 - e^{-Ki \cdot (|Xind - Xmin|/Ci)^{Pi}}\right] \quad (2)$$

In Equation (2), X_{min} and X_{max} are, the minimum and maximum values of the assessed indicator; X_i is the abscissa value for the indicator, which is under assessment - between X_{min} and X_{max} -; A is the response

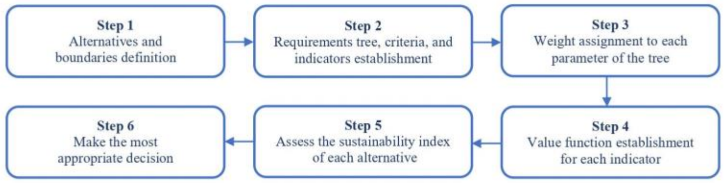


Fig. 4. The process to implement the MIVES method.

value X_{min} - indicator's abscissa -, generally $A = 0$; P_i is a shape factor that defines if the curve is concave ($P_i < 1$), linear ($P_i = 1$), convex or S-shaped ($P_i > 1$), further this factor approximately determines the slope of the curve at the inflection point; C_i approximates the abscissa at the inflection point - used if $P_i > 1$, to build convex or S-shaped curves -; K_i tends towards V_i at the inflection point and defines the value of the ordinate for point C_i, in the former case where $P_i > 1$; and B is the factor that keeps the function within the (0.00, 1.00) according to the satisfaction range, which is obtained by Equation (3) [54,56,70,79].

$$B = 1 / [1 - e^{-Ki \cdot (|Xmax - Xmin|/Ci)^{Pi}}] \quad (3)$$

5. Results

5.1. Preliminary outcomes

Table 2 presents the SWOT matrix, which demonstrates that GRs could be proposed as a worthy practice in urban residential buildings, especially for Tehran as a megacity, which faces the aforementioned unfavorable effects of urbanization and critical urban air pollution. Although the initial high construction cost of GRs is an important challenge, the construction of GRs contributes to the safety of a city, as well as sustainability and resilience to climate change.

Table 2
Initial analysis of GRs by SWOT matrix.

	Strengths, Weaknesses, Opportunities, Threats
S	**S1.** Roof heat transfer reduction by shading, evapotranspiration, insulation (thermal insulation) [23,25,26]
	S2. Roof sound transmission reduction (noise insulation) [23,25]
	S3. Improvement the visual quality and enabling innovation of design process [23]
	S4. Users' physical and mental health, as well as their life quality improvement [23,25,80]
	S5. Users' motivation due to the shortage of green and open space in apartments [23]
	S6. Revitalization and using the large unused space on buildings [23]
	S7. Increasing roof lifespan [23]
	S8. Increasing the value of the property [23,25,35]
W	**W1.** Increasing the construction cost of the building [23,25]
	W2. Increasing the maintenance costs of the building [23,25,81]
	W3. Increasing the static loading of the building [23]
	W4. Interference with traditional water-coolers, which usually are installed on the roof
O	**O1.** Increasing the per capita of green space [23]
	O2. Urban Heat Island (UHI) effect reduction [19–23]
	O3. Quantity and quality of urban sewer by rainfall harvesting and stormwater run-off reduction [20,25,82]
	O4. Contribution to employment and job creation [23]
	O5. Provision of incentives for owners and builders by government and municipality [23]
	O6. Contribution to urban biodiversity improvement [23,25,83]
	O7. Air pollution reduction and carbon sequestration [10–13,15–18,20,23,25]
	O8. Creation of suitable space for urban agriculture [23]
	O9. Urban landscape improvement [80]
	O10. Support for environmental education [80]
T	**T1.** Increasing the cost of housing production in general
	T2. Social interactions reduction at the neighborhood (and larger) scale due to more usage of GR as a non-public space

5.2. Decision tree (DT) definition

Table 3 shows the DT, which was designed relying on the experience of the authors and extensive literature review [54,56,58,59,65,69,73,84–86]. Additionally, DT and the importance of indexes were decided by experts during seminars. DT consists of three requirements, six criteria, and 12 quantifiable indicators. Economic requirement (R_1) considers the investment regarding construction, maintenance, and end life for each GR embracing two criteria, (C_1) *cost* and (C_2) *time*. Environmental requirement (R_2) considers the main environmental impacts for each roof from their (C_3) *resource consumption* and (C_4) *emissions*. Social requirement (R_3) takes into consideration the crucial (C_5) *safety* and (C_6) *compatibility* for the assessed GRs.

Criterion (C_1) encompasses three indicators: (I_1) *Implementation cost,* (I_2) *Maintenance cost,* and (I_3) *End of Life (EOL) cost.* (I_1) *Implementation cost* takes into account the construction cost of the GR, such as materials and labor costs [87]. I_1 data has been obtained from the average prices posted by seller companies in Tehran and the Iranian construction price-list (ICPL) database. The exchange rate of Rials and Euro currency is based on the official rate of the Iranian Central Bank [88]. (I_2) *Maintenance cost* embraces cost of those expected activities during service, such as labor cost - for plant management, irrigation, and fertilizing -, material cost - for fertilizer, additional soil, and pesticide -, and repairing cost - for reinstalling of GR every 25 years and fixing the main waterproofing layer before -. As previously mentioned, assuming 50 years as the lifespan of residential buildings in Tehran, and 25 years for the total life service of GRs. The maintenance costs are based on price lists posted by Iranian contractor companies. (I_3) *EOL cost* assesses the costs after the lifespan of the building, such as labor cost for demolition and waste disposal cost - for loading, unloading, and transportation -. According to the disposal waste locations in Tehran, the closest one to the studied cases is approximately 30 km.

Time (C_2) includes (I_4) *Implementation time* indicator, that accounts for the required hours for construction activities, such as installing a root barrier and extra waterproofing layer, sealing test time, installing other layers - protection board, drainage or water retention panel, filter fabric aeration mat -, then providing and filling the mix type soil, and at last planting. According to the collected data from the interviewed companies, the required time to implement S-IGR, IGR, and EGR are seven, eight, and six working days respectively. This information is based on implementing a green area on the top of an ordinary existing residential roof with almost 300 m^2 area by a typical contractor team - with an average of five workers -. Note that the implementation time of MCR by a typical contractor team, as three working days will be added for all types of GR. Each working day is considered equivalent to 8 h.

Resource consumption (C_3) contains two indicators: (I_5) *Energy balance* and (I_6) *Waste disposal.* (I_5) *Energy balance* considers the energy consumed during the production and manufacturing of materials. Energy inventory based on the technical specification data of common materials in the Iranian market has been obtained from the Inventory of carbon and energy (ICE) database (Hammond & Jones, 2011), and environmental product declarations (EPDs) database [89]. Regarding the database selection, there is not available a comprehensive national

Table 3
General requirement tree for sustainability assessment.

	Requirement	Weight		Criteria	Weight		Indicator	Weight
R_1	**Economic**	30%	C_1	Cost	66.7%	I_1	Implementation cost	60%
						I_2	Maintenance cost	30%
						I_3	End of Life (EOL) cost	10%
			C_2	Time	33.3%	I_4	Implementation time	100%
R_2	**Environmental**	50%	C_3	Resource consumption	33.3%	I_5	Energy balance	66.7%
						I_6	Waste disposal	33.3%
			C_4	Emissions	66.7%	I_7	CO_2 balance	40%
						I_8	UHI effect reduction	12%
						I_9	PM absorption	48%
R_3	**Social**	20%	C_5	Safety	33.3%	I_{10}	Occupational risk	100%
			C_6	Compatibility	66.7%	I_{11}	Customization potential	50%
						I_{12}	Adaptability (to change)	50%

database in this respect in Iran; on the other hand, the ICE database provided considerable advantages compared with others. The ICE database retains a cradle to gate (factory) scope. This is known as module A1–A3 in the EU wide standards, EN 15978, and EN 15804 on sustainability assessment of construction work. Since another environmental indicator - overheating and UHI effect reduction - has evaluated the effect of GR to make the roof surface cooler, energy-saving through decreasing the consumption for air conditioning has not been considered in I_5 again. The activity during the operation focuses just on plant management and gardening. Thus, energy consumption during the service time, which is negligible compared to other phases such as manufacturing and demolition, is not considered. (I_6) *Waste disposal* takes into account the amount of non-recyclable waste materials. The data of materials' recyclability potential has been obtained from 1) the literature review concerning the environmental assessment of GRs life cycle and 2) an environmental profiling system for building materials and components database [20,28,31,90,91].

The *emissions* (C_4) comprise three indicators: the (I_7) *CO_2 balance*, (I_8) *UHI effect reduction*, and (I_9) *PM absorption.* (I_7) *CO_2 balance* determines the amount of CO_2 emission as well as CO_2 saving. Appendix D explains in detail how this indicator is calculated based on technical literature [89,92–95] and using Equation (4).

$$CO_2 \text{ balance} = CO_2 \text{ emission} - CO_2 \text{ saving} \quad (4)$$

Decreasing the roof surface temperature is another advantage GR provides [96], which has an indirect positive effect on the CO_2 emission following an indoor cooling energy consumption decrease. Nevertheless, the following environmental indicator considers this issue. (I_8) *UHI effect reduction* takes into consideration of temperature decrease above the roof surface during the day, in case of using GRs, through the physical and biological properties vegetation have such as albedo and evapotranspiration among others. Results are based on a recent 70-day practical study by Moghbel and Salim (2017) [97] in Tehran, which demonstrates that the average air temperature 1 m above the GR was 3.7 °C cooler than ordinary roofs with bitumen finishing surface. UHI effect reduction is considered as the potential to improve the outdoor thermal condition in cities facing overheating and UHI effects [98]. Additionally, due to a photochemical reaction, the UHI effect enhances heat-stress-related diseases as well as increasing the ozone levels, as one of the air pollutants [99,100]. (I_9) *PM absorption* quantifies the capacity of GRs to absorb ambient PM as a passive way of filtering urban air by vegetation. To evaluate indicator (I_9), Equation (5), which is suggested by Powe and Willis (2004) [101] is used, which is relevant to the air pollutant specifications, plant type, and climatic condition. This Equation was also used previously to survey the amounts of PM_{10} absorption by greenery [17]. The annual PM_{10} absorption by one square meter of GR covered only by grass in Tehran has been estimated on average, 6.17 $gr{\cdot}m^{-2}{\cdot}\ year^{-1}$, according to the authors' calculations and previous studies [102]. Assuming a mixture of grass and needle-leaf trees at a ratio of 50:50, this amount will be 52.45 $gr{\cdot}m^{-2}{\cdot}\ year^{-1}$, as has been calculated in this research study. This significant increase is due to the strongly different characteristics between grass and conifer; especially, in surface area index (SAI) and deposition velocity. According to Yang et al. (2008) [17], the annual potential of a medium-size tree to remove air pollutants could be 19 times more than one square meter of EGR. The average annual concentration of PM_{10} - during the recent 10 years -, has been measured $84.5 \times 10^{-6}\ gr{\cdot}m^{-3}$ [45]. According to a study in the UK, a GR installation scenario for a 325 ha area of the Manchester City Centre mitigates almost 2.3% of 9.18 tones PM_{10} per year [103]. Another recently performed study in Iran estimated the potential of EGR in absorbing PM_{10} and shows the same result as the authors' calculation [102].

$$ABSORPTION = FLUX \times SURFACE \times PERIOD \quad (5)$$

where:

- *FLUX* = deposition velocity ($m{\cdot}s^{-1}$) × pollutant concentration ($\mu g{\cdot}m^{-3}$)
- *SURFACE* = considered land area (m^2) × SAI (m^2 per m^2 of the ground area)
- *PERIOD* = period of analysis (s) × proportion of dry days × proportion of in leaf days

This study, relying on technical literature [17,18,45,101,104], takes into account the conditions detailed in Appendix E. Considering 50 years for the life duration of residential buildings, during the lifespan of a building on average (50 × 52.45), 2622.5 gr of PM_{10} concentration per square meter will be absorbed by a combination of needle-leaf trees and grass. This amount will be (50 × 6.17), 308.5 $gr{\cdot}m^{-2}$ when covering only by grass. PM entrapment occurs when an airstream aerodynamically passes rough plant surfaces, while the particles move on in a straight line and strike the obstacle [101]. The surface resistance depends on the size of the particles, atmospheric conditions, and surface properties [17]. Although each surface can have some level of PM removal effect, the absorbent efficiency is mainly affected by surface roughness, moistness, and stickiness; vegetal leaf surfaces represent a highly efficient example [17,101]. Hence, concerning the finishing layer of MCR - prefabricated moisture insulation layer - as a soft surface without any of the needed properties, the dry deposition is really low. Furthermore, achieving an effective sink for air pollutants absorption requires a high surface area index [17]; but the finishing layer of MCR, which is the only exposed layer, is smooth and achieves the minimum SAI, surface per surface of the ground area as depicted in Equation (5). Accordingly, the PM absorption of MCR - as the basic type of roof in Tehran -, is negligible compared to the GRs. In this regard, the PM absorption of MCR is not considered in this research study.

Criterion *safety* (C_5) has (I_{10}) *Occupational risk* indicator, which takes into consideration possible risks during construction activities for each alternative. This indicator is based upon probability, the likelihood of occurrence, the severity of consequences, and exposure to hazardous situations based on several studies [105–107]. Falls to lower levels or on the same level are known as one of the most frequent accidents on construction sites [107,108]. Besides, for roofing projects, hand or finger, and back injuries due to cutting operations and manual load handling among others are considered other abundant injuries [109]. Occupational Risk Index (ORI) determines the risk level involved in construction projects and depends on the type and volume of related activities, which is derived by Equation (6) [110]. Although the ratings of probability and consequences depend on: a) the technological development of the region and construction company and b) the approach is taken to adopt preventive measures, the mentioned reference as a guideline can be reliable to compare the specified activities of the different alternatives, in case all of them are in the similar condition.

$$ORI = \Sigma_i\, ORI_i = \Sigma_i\, [(P_i \times C_i) \,/\, (\max\{\,_i \times C_i\,\} = 1000)] \times E_i \tag{6}$$

Where ORI_i is ORI of risk i, Pi is the probability of occurrence, C_i is the severity of consequences, and E_i is exposure (hours) to risk i.

The *compatibility* (C_6) embraces two indicators: (I_{11}) *Customization potential* and (I_{12}) *Adaptability (to change)*. (I_{11}) *Customization potential* represents the compatibility and adaption of GRs with surroundings and local characteristics, such as the form and physical space of the rooftop, climatic condition, market accessibility, and appearance. The percentage of customization potential has been estimated, based on dividing the total scores by the number of different issues in this respect. (I_{12}) *Adaptability (to change)* considers the flexibility of alternatives to be adapted to occupants' necessities during the operation phase. This indicator is applied to measure: a) the level of GRs disassembling potential, changing their parts - to renew, replace, and reuse them -, and b) access to service. The percentage of adaptability is estimated using the division of the total scores by the number of different issues.

Table 4 presents a summary of quantifications for all indicators belonging to the different alternatives (S-IGR with 30 cm depth, IGR with 50 cm depth, EGR with 10 cm depth, and MCR without any greening), during the building lifespan - 50 years - in Tehran. Tables F.1 to F.9 in Appendix F present calculations for all indicators in detail.

5.3. Index weighting - analytic hierarchy process (AHP)

Weightings for the DT's components have been assigned based upon the results of the seminars held by multidisciplinary professors and experts, local characteristics, and previous studies. Besides, as mentioned in section 5.2, the indicators, criteria, and requirements were discussed and agreed to by experts in the initial stage of the decision-making process. The main panel is composed of: a) a professor, founder of the architectural technology field in Iranian academic organization and head of UNESCO Chair Program in architecture; b) two deputies and a consultant to the Tehran mayor in the field of architecture & urbanization and the field of green space and urban services; c) six senior managers from the Tehran city government in the fields of architecture and construction, the codification of rules and regulations, construction supervision, urban detailed plans, urban planning, and environmental organization; d) a researcher from the Tehran Urban Research and Planning Center; and e) two supreme experts from the Tehran municipality in the field of architecture and sustainable development. This approach is followed to define the value functions and final indexes as well. In this context, objectivity, reality, and complexity are gained to improve the results in the assessment tool [54,59,69,70]. The weighting process followed the well-known analytical hierarchy process (AHP) method [111] and/or direct assignment. As a result, priorities - weightings - and a consistency ratio (CR ideally$<$ 10%) are obtained using the fundamental 1–9 AHP ratio scale [111,112]. Table 3 also shows these requirements, criteria, and indicator weights.

5.4. Value function establishment

The parameters, tendency, and shape for each indicator's value function were determined based on scientific literature and the mentioned experts' panel. Table 5 presents the constitutive parameters for these value functions. These functions had the following shapes: eight decreased, including four convex functions (DCx), two concave ones (DCv), one S-shaped (DS), and one linear (DL); four increased, including two concave functions (ICv) and two S-shaped ones (IS). More detailed descriptions of the indicator value function assignment have been reported elsewhere, such as [54,79]. Appendix G depicts the value functions for all indicators (Fig. G.1).

Table 4
Summary of indicators' quantification during the building lifespan (50 years).

Indicator	Consideration	MCR	S-IGR	IGR	EGR	Impact Pos/ Neg	Unit	Reference
I_1. **Implementation cost**	Material and labor cost	16.9	59.4	61.25	56.65	N	€·m^{-2}	ICPL database & Market
I_2. **Maintenance cost**	Material and labor cost	19.6	1249.25	1652.1	845.15	N	€·m^{-2}	ICPL database, market & contractors
I_3. **EOL cost**	Labor and waste disposal cost	0.7	2.55	3.55	1.2	N	€·m^{-2}	ICPL database
I_4. **Implementation time**	On-site implementation	24	80	88	72	N	h(s)	Contractor companies' data
I_5. **Energy balance**	Energy saving and consumption	476	1421.3	1461.2	1381.5	N	MJ·m^{-2}	Hammond et al. [89]
I_6. **Waste disposal**	Non-recyclable solid waste	20.5	22.7	22.7	22.7	N	kg·m^{-2}	Anderson et al. [91], Chenani et al. [28], Peri et al. [31], Faraca et al. [90]
I_7. **CO_2 balance**	CO_2 saving and emission	21.5	−197.7	−195.4	39.5	N	kg CO_2·m^{-2}	Hammond et al. [89], Weiler et al. [95], Toochi et al. [94], DeWald et al. [93]
I_8. **UHI effect reduction**	Overheating reduction	0	3.7	3.7	3.7	P	°C·m^{-2}	Moghbel et al. [97]
I_9. **PM absorption**	PM absorption potential	–	2622.5	2622.5	308.5	P	gr·m^{-2}	Mohammadi et al. [102], Powe et al. [101], Yang et al. [17], Currie et al. [18]
I_{10}. **Occupational risk**	Falls, hand and back injuries	2.61	13.52	14.87	12.16	N	Points	Casanovas et al. [110]
I_{11}. **Customization potential**	Climate, Market, Form, Appearance	11.1%	77.7%	88.8%	55.5%	P	Points	Experts seminar and information
I_{12}. **Adaptability (to change)**	Disassembling, Change elements, Access to service	16.6%	50%	50%	66.6%	P	Points	Experts seminar and information

Table 5
Parameters and coefficients for each indicator value function.

Indicator	Unit	Shape	X_{min}	X_{max}	C	K	P
I_1. Implementation cost	€·m^{-2}	DCx	15.21	76.56	60	0.001	2.5
I_2. Maintenance cost	€·m^{-2}	DS	17.64	2065.12	800	0.8	2.3
I_3. EOL cost	€·m^{-2}	DCv	0.63	4.43	2.5	2.6	0.9
I_4. Implementation time	h(s)	DL	21.5	110	22	0.001	1
I_5. Energy balance	MJ·m^{-2}	DCx	357	1826.5	1300	0.01	2
I_6. Waste disposal	kg·m^{-2}	DCx	15.37	28.37	22	0.2	2.5
I_7. CO_2 balance	kg CO_2·m^{-2}	DCx	−217.47	49.37	180	0.2	2.2
I_8. UHI effect reduction	°C·m^{-2}	ICv	0	4.07	1.5	0.9	1
I_9. PM absorption	gr·m^{-2}	ICv	0	2884.75	1350	1.5	1
I_{10}. Occupational risk	Points	DCv	2.35	18.58	10.5	3	0.9
I_{11}. Customization potential	Points	IS	0	100	28	0.2	2.5
I_{12}. Adaptability (to change)	Points	IS	0	100	28	0.2	2.5

5.5. *Sustainability indexes*

The previously explained designed model has been applied to evaluate global sustainability indexes (SIs) for each GR alternative. Table 6 and Fig. 5 presents the results for SIs, which have been obtained through the aggregation of the a-dimensional values from requirements (V_{Ri}), criteria (V_{Ci}), and indicators (V_{Ii}).

6. Discussion

Results demonstrate that, for Tehran, S-IGR is the most suitable alternative with the highest sustainability index (SI) among all alternatives. SI quantifies the four technologies from more to less sustainable: S-IGR, IGR, MCR, and EGR, with indexes of 0.56, 0.51, 0.45, and 0.37, respectively, as shown in Fig. 6. Besides, considering air pollution efficiency, S-IGR provides the most proper performance by achieving the highest satisfaction value for the emissions criterion. In this regard, S-IGR brings the best function in CO_2 balance; note that carbon dioxide is the most significant GHG [113]. Additionally, PM absorption by S-IGR is at the highest level when compared to the other alternatives; given that the ambient PM is the most important air pollutant in Tehran [45]. This alternative presents a suitable performance regarding the reduction of the UHI effect as well.

Figs. 5 and 6 and Table 6 depict the assessment for the indicators' satisfaction values for the four alternatives, which shows their strengths and weaknesses. S-IGR is weak in implementation cost (I_1) as all GRs alternatives; whilst its EOL cost (I_3) is satisfactory enough, and maintenance cost (I_2) causes relatively low pressure on users. In terms of environmental behavior, the worst attribute of S-IGR is its high energy consumption - related to (I_5) - in the manufacturing of some substrates' material. In contrast, this alternative causes a significant positive effect on air pollutants absorption and UHI effect reduction (I_7, I_8, and I_9). It has an acceptable occupational risk (I_{10}), provides a high potential for customization (I_{11}), and has a moderate level of adaptability to change (I_{12}).

Focusing on the sustainability main requirements, in terms of *environmental* aspects (V_{R2}), S-IGR and IGR entirely act much better than the MCR, whereas EGR is almost equal to MCR due to its weakness in PM absorption and CO_2 balance. Despite the fact that GRs are feeble in resource consumption criterion (V_{C3}), GRs perform successfully in terms of emissions criterion (V_{C4}), in accordance with previous studies [20]. From the environmental perspective, the essential defect of GRs is the energy consumption during the production of some substrates' material (V_{I5}) - in line with previous research projects [28,29] -, while S-IGR and IGR are appropriate in CO_2 balance, UHI effect reduction, and PM absorption (V_{I7}, V_{I8}, and V_{I9}). These potentials of GRs are literally considered as the valuable and significant advantage concerning this study, in minimizing urban air pollution. The *economic* evaluation (V_{R1}) indicates that all types of GRs are not affordable in this specific case study, specifically compared with the usual MCR in which the economic resources are optimized just to satisfy the slightest demands. This circumstance is established in both cost and time criteria (C_1, C_2). From the economic point of view, the greatest incapability of GRs refers to the implementation cost (V_{I1}) due to the expense for substrates, whilst the most acceptable economic indicator for GRs is EOL cost (V_{I3}). Contrarily, GRs are admirable in the *social* requirement (V_{R3}) and cause competent benefits in this sense. Although the safety criteria levels are lower than the MCR (V_{C5}), all types of GR satisfy occupants with significant differences from the MCR in the context of compatibility criterion (V_{C6}). From a social standpoint, the most suitable function of GRs concerns their customization potential (V_{I11}).

Finally, this discussion ends by 6.1) studying the potential for improvement by the most sustainable alternative in future works and 6.2) carrying out a sensitivity analysis to study the variation of the SI in other possible scenarios with different weights.

6.1. *S-IGR improvement potential*

According to the results, all alternatives should improve to obtain higher SIs; since the maximum SI is 0.56 of 1, even though this SI is higher than the moderate level. S-IGR covers most objectives of this research study, especially its impacts on air pollution reduction. However, as previously shown in the results, despite the strength of environmental and social performances of alternatives, the principal weaknesses of GRs are the substrates' cost and energy consumption during their manufacturing. In this case, the drainage panel and the root barrier layer are the most critical components of GRs, which have considerable impacts on both *implementation cost* (I_1) and *energy balance*

Table 6
Sustainability Index (I), Requirements (V_R), Criteria (V_C), and Indicators (V_I) Values for different alternatives.

		I	V_{R1}	V_{R2}	V_{R3}	V_{C1}	V_{C2}	V_{C3}	V_{C4}	V_{C5}	V_{C6}	
MCR		**0.45**	0.95	0.21	0.34	0.95	0.96	0.64	0.003	0.99	0.03	
S-IGR		**0.56**	0.29	0.65	0.76	0.28	0.33	0.08	0.94	0.79	0.75	
IGR		**0.51**	0.15	0.64	0.74	0.12	0.24	0.07	0.93	0.69	0.77	
EGR		**0.37**	0.39	0.20	0.78	0.39	0.42	0.09	0.26	0.86	0.75	
	V_{I1}	**V_{I2}**	**V_{I3}**	**V_{I4}**	**V_{I5}**	**V_{I6}**	**V_{I7}**	**V_{I8}**	**V_{I9}**	**V_{I10}**	**V_{I11}**	**V_{I12}**
MCR	0.924	0.999	0.998	0.966	0.845	0.258	0.009	0	0	0.999	0.019	0.053
S-IGR	0.039	0.567	0.882	0.338	0.076	0.109	0.876	0.980	0.985	0.794	0.930	0.578
IGR	0.029	0.160	0.641	0.248	0.062	0.109	0.862	0.980	0.985	0.693	0.980	0.578
EGR	0.057	0.880	0.983	0.427	0.092	0.109	0.001	0.980	0.302	0.861	0.674	0.832

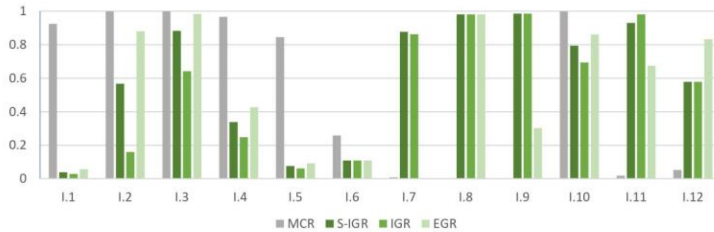


Fig. 5. Indicators' value.

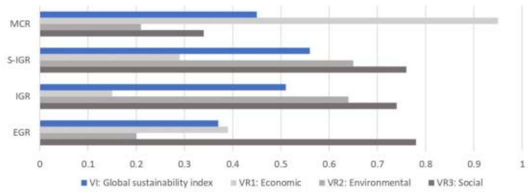


Fig. 6. Sustainability main requirements.

(I_5). These two substrates are responsible for more than 55% of energy consumption and 35% of implementation cost. As shown in Fig. 7, just by improving the features of these two substrates (layers) related to the (I_1) and (I_5), the sustainability index could increase by up to 0.67.

Consequently, the development of substrates should move forward to overcome these important weaknesses [20,28,29,114]. As already mentioned, it is required to modify the manufacturing process and probability to use renewable energy sources during the production of the materials, which this study considers important tasks for the next research steps beyond this present article. In this sense, it would be possible to use recycled materials - or preferably bio-waste -, as zero-cost material, without any manufacturing to decrease direct cost as well as energy consumption [28,31], instead of producing some substrates. This strategy could improve GR without subtracting any advantage. Overall, polymers should be avoided, specifically for drainage panel and root barrier, due to their high energy consumption. Furthermore, using local materials could contribute to the improvement of problem-solving by minimizing the required transportation and the availability of materials. Developing an optimized alternative from the existing S-IGR, with cheaper implementation and lower Embodied Energy (EE), would result in a feasible solution with a significantly higher sustainability index. This innovative alternative should be established based on these project results and be suitable for Tehran's particularities and context.

6.2. Sensitivity analysis

Additionally, besides the weights assigned by experts (Table 3), other weighting scenarios have been considered, with the purpose of both identifying those requirements that govern the sustainability performances by alternatives and the SIs of alternatives derived from each scenario. The weight distribution is based on the experts' proposals, including those considered outliers, and weights proposed in the most widely used sustainability rating system tools for buildings e.g., LEED, BREEAM, and DGNB [65].

The results shown in Fig. 8 confirm that the trends of S-IGR and IGR are similar. However, the most suitable alternative (S-IGR), earns the upper SIs based on all scenarios in which the stakeholders are sensitive to environmental requirements (equal or higher than 33%). The highest SI occurs when there is minimum economic sensitivity (15%). Nevertheless, this scenario has unacceptable due to low weights for economic requirements. None of the scenarios confirm the suitability of EGR even in comparison with the MCR, as this alternative neither satisfies the

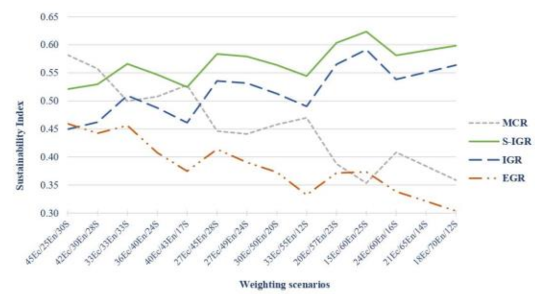


Fig. 8. Sustainability Indexes with different requirement weighting scenarios for each alternative. Economic (Ec), Environmental (En), and Social (S).

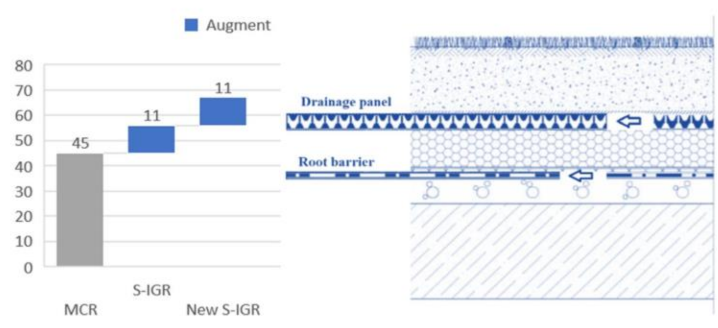


Fig. 7. New S-IGR potential to increase satisfaction value.

economic nor the environmental requirements. In general, by increasing sensitivity to environmental requirements (Fig. 8), SIs of S-IGR and IGR have incremental trends; contrarily, SIs of MCR and EGR have a decreasing tendency.

7. Conclusion

This research study presents a novel MIVES-based sustainability assessment model that has been specifically configured to analyze the suitability of architectural green roof refurbishment alternatives to reduce urban air pollution. The definition for this model has relied on SWOT, seminars composed by experts, AHP, and a sensibility analysis, providing assistance to stakeholders to achieve the objective decision because it easily gives comparable sustainability indexes for each alternative within different scenarios. This new model has been first applied in the air-polluted Tehran metropolis, assessing the sustainability for four architectural roof refurbishment alternatives - S-IGR, IGR, EGR, MCR - to determine the most suitable solution. This application concludes:

- S-IGR, which obtained the highest sustainability index (SI = 0.56), is the most suitable type of existing GR for this case study considering air pollution reduction and the most crucial sustainability indicators. Results indicate S-IGR is an outstanding social-environmental alternative.
- The suitability for S-IGR was proven to be robust in different weighting scenarios with diverse stakeholders' preferences, and its sustainability performance was greater when environmental requirements drove the decision-making process.
- The resulting SI for S-IGR in this specific case study required an analysis of the results, which found out that its implementation cost and energy balance are its main weaknesses. This analysis also confirmed that it would be possible to increase the SI by 11% by mitigating these drawbacks. In this regard, future research steps will develop a new version for S-IGR that solves these problems among others, to define more sustainable GRs that contribute to reduce air pollution in urban environs and move towards more sustainable urban settlements.

Declaration of competing interest

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

Acknowledgments

To the multidisciplinary experts who participated in the seminars. To J. Maas for his aid on the English Language.

Appendix A. (Abbreviations)

Abbreviations	*Relevant values*
AHP	Analytic hierarchy process
AQCC	Air quality control company
AQI	Air quality index
DCv	Decreasing concave
DCx	Decreasing convex
DL	Decreasing linear
DS	Decreasing S-shaped
DT	Decision tree
EC	Embodied carbon
EE	Embodied energy
EGR	Extensive green roof
EOL	End of life
EPDs	Environmental product declarations
GHG	Greenhouse gas
GR	Green roof
ICE	Inventory of carbon and energy
ICPL	Iranian construction price-list
ICv	Increasing concave
ICx	Increasing convex
IGR	Intensive green roof
IL	Increasing linear
IS	Increasing S-shaped
MCDM	Multi-criteria decision-making
MCR	Most common roof
MIVES	Modelo integrado de valor para evaluaciones sostenibles (integrated value model for sustainability assessment)
ORI	Occupational risk index
PM	Particulate (particle) matter
SAI	surface area index
SI	Sustainability index
S-IGR	Semi-intensive green roof
SWOT	Strengths, weaknesses, opportunities, and threats
UHI	Urban heat island

Appendix B

This study has considered, on top of the existing roof deck, the following GR layers:

1. Soil medium, which is soil-covering plants with grass, perennials, and/or shrubs. This is a nutrient-rich soil mix, consisting of lava, pumice, recycled crushed clay-based products and enriched with compost.
2. Filter fabric aeration mat, consists of superior geotextile, with strength and pressure resistance properties, made of polypropylene. This layer is capable of high vapor and water permeability.
3. Drainage or water retention panel, which is a light drainage/reservoir board with the appropriate load-bearing capabilities, takes into account drainage, reservoir, and aeration.
4. Protection board, that should be installed as a separator and protector layer, if compatibility problems exist between the different layers
5. Root barrier and waterproofing can be a sole root resistant and waterproofing membrane, while non-root resistant waterproofing membranes require a separate root resistant layer.

Appendix C

Table C.1presents the air quality index (AQI) calculated by the methods described in the Iranian National Standards. According to the Tehran annual air quality report by the Air quality control company (AQCC), the AQI of Tehran - which studied from 21 March 2018 to 20 March 2019 - shows that there were 28 clean days (AQI < 50), 278 days with healthy conditions ($50 <$ AQI < 100), and 59 days with unhealthy conditions for sensitive groups ($100 <$ AQI < 150) [45].

Table C.1
Air Quality Index (AQI)

Code	AQI
Clean	0–50
Moderate	51–100
Unhealthy for sensitive group	101–150
Unhealthy	151–200
Very Unhealthy	201–300
Hazardous	301–500

Appendix D

Indicator "I_7) *CO_2 balance*" determines the amount of CO_2 emission as well as CO_2 saving. Emission data has been obtained from the technical specification data of common materials in the Iranian market, ICE database, and EPDs database [89]. Regarding the operation activity, mainly limited to gardening and plant management, CO_2 emission during the service time is not considerable. Based on the chemical photosynthesis equation [CO_2 (264g) + H_2O (108g) → glucose (180g) + O_2 (193g)], the plants on GR can fix carbon dioxide in their body and cause it to become dry matter; moreover, release oxygen at the same time through their photosynthesis process [92]. One of the ways to estimate CO_2 sequestration by plants is through the determination of the tree's dry weight. The average tree is 72.5% dry matter and 27.5% moisture [93]. Therefore, to determine the dry weight of the tree, multiply the total green weight of the tree by 72.5%. The average carbon content is generally 50% of the tree's dry weight total volume [94]. Therefore, in determining the weight of carbon in the tree, multiply the dry weight of the tree by 50%. CO_2 has one molecule of carbon and two molecules of Oxygen. The atomic weight of carbon is 12 (u), and the atomic weight of Oxygen is 16 (u). The weight of CO_2 in trees is determined by the ratio of CO_2 to C is $44/12 = 3.67$ [94]. Therefore, to determine the weight of carbon dioxide sequestered in the tree, multiply the weight of carbon in the tree by 3.67 [94]. The green weight is the weight of the tree when it is alive. In a study done by the United States department of agriculture (USDA) and forest service, which spanned 15 years, the green weight for various species of trees, was weighted in the field and published in the study. Upon reviewing the data in the study, they find that the 100 lb. (0.45 kg) per inch caliper rule of thumb holds for small caliper tree - 8 inches caliper or less -, at heights less than 50 feet [95]. Assuming one shrub with almost 5 cm (≃2 inches) caliper in diameter per square meter - and 25 years as the lifespan - of GR:

W. total green weight $= 2 \times 100 \times 0.45 = 90$ kg.

W. dry weight $= 0.725 \times 90 = 65.25$ kg.

W. carbon $= 0.5 \times 65.25 = 32.625$ kg.

W. carbon-dioxide $= 3.67 \times 32.625 = 119.73$ kg.

Annual sequestration rate (Arate $= T_{(CO2)}$/tage) $= (119.73/25) = 4.79$ kg $CO_2 \cdot m^{-2} \cdot$ year^{-1}

To sum up, regardless of the grass's CO_2 sequestration - due to inconsiderable weight -, each square meter of S-IGR and IGR will be able to absorb 4.79 kg $CO_2 \cdot m^{-2} \cdot$ year^{-1}. Therefore, the CO_2 saving during the lifespan of the building will be $50 \times 4.79 = 239.5$ kg $CO_2 \cdot m^{-2}$. As a result, the total CO_2 balance during the lifespan of the building has been obtained from Equation (4).

CO_2 balance $=$ CO_2 emission – CO_2 saving (4)

Appendix E

This study, to calculate "(I9) PM absorption" considers the following conditions:

(1) The deposition velocity of PM_{10} for grasses is 0.001 $m{\cdot}s^{-1}$ and for needle-leaf trees is 0.008 $m{\cdot}s^{-1}$ [101].
(2) The average annual concentration of PM_{10} during the recent 10 years, which is derived from Tehran Annual Air Quality Report, is 84.5 $\mu g{\cdot}m^{-3}$ [45].
(3) SAI of grasses and trees are three and six respectively, according to Currie and Bass (2008) [18] and Yang et al. (2008) [17].
(4) 1 m^2 as the reference land area and one year as the period of analysis are considered.
(5) The average proportion of dry days - with less than 2 mm precipitation -, is calculated by subtracting the number of rainy days for five years.
(6) The proportion of in leaf days is 1, assuming needle-leaf as the evergreen plant.

The PM absorption calculations for the grass case are as follows:

- $FLUX = 0.001\ m\ s^{-1} \times 84.5\ \mu g\ m^{-3} = 0.0845\ \mu g\ m^{-2}\ s^{-1}$
- $SURFACE = 1\ m^2 \times 3 = 3\ m^2$
- $PERIOD = 31{,}536{,}000\ s \times 77.2\% \times 1 = 24{,}345{,}792\ s$
- $ABSORPTION_G = FLUX \times SURFACE \times PERIOD = 6.17\ g\ m^{-2}$ per year

The PM absorption calculations for the conifer case are as follows

- $FLUX = 0.008\ m\ s^{-1} \times 84.5\ \mu g\ m^{-3} = 0.676\ \mu g\ m^{-2}\ s^{-1}$
- $SURFACE = 1\ m^2 \times 6 = 6\ m^2$
- $PERIOD = 31{,}536{,}000\ s \times 77.2\% \times 1 = 24{,}345{,}792\ s$
- $ABSORPTION_C = FLUX \times SURFACE \times PERIOD = 98{,}74\ g\ m^{-2}$ per year

The PM absorption calculation for the combination of grass and conifer - at a ratio of 50:50 - is as follows:

- $(ABSORPTION_G + ABSORPTION_C)/2 = 52.45\ g\ m^{-2}$ per year

Appendix F. (Indicators' quantification)

Table F.1
Implementation cost

Costs' contents	MCR (€/m²)	S-IGR (€/m²)	IGR (€/m²)	EGR (€/m²)
Planting (Included labor cost)	–	1.25	1.25	0.35
Soil medium (Included labor cost)	–	2.3	4.15	0.45
Filter fabric aeration mat	–	10.45	10.45	10.45
Drainage or water retention panel	–	9.8	9.8	9.8
Protection board	–	3.5	3.5	3.5
Root barrier and waterproofing	–	10.85	10.85	10.85
Labor cost for installing GR layers	–	4.35	4.35	4.35
Prefabricated moisture insulation	4.9	4.9	4.9	4.9
Cement sand mortar	2.12	2.12	2.12	2.12
Light concrete (150 kg/m³)	1.5	1.5	1.5	1.5
Polystyrene thermal insulation	8.17	8.17	8.17	8.17
Vapor barrier nylon	0.23	0.23	0.23	0.23
Sum.	**16.9**	**59.4**	**61.25**	**56.65**

Table F.2
Maintenance cost during the building lifespan (50 years)

Costs' contents	MCR (€/m²)	S-IGR (€/m²)	IGR (€/m²)	EGR (€/m²)
Gardening (labor and material)	–	1200	1600	800
Demolition and waste disposal cost	–	1.85	2.85	0.5
Repairing the waterproofing layer	19.6	4.9	4.9	4.9
Reinstalling the GR (after 25 years)	–	42.5	44.35	39.75
Sum.	**19.6**	**1249.25**	**1652.1**	**845.15**

Table F.3
EOL cost

Costs' contents	Reference cost	MCR (€/m²)	S-IGR (€/m²)	IGR (€/m²)	EGR (€/m²)
Labor cost to remove planting	0.3 €/m²	–	0.3	0.3	–
Demolition cost	1.8 €/m³	0.25	0.55	0.9	0.18
Waste disposal cost	3.3 €/m³	0.45	1	1.65	0.33
Sum.	–	**0.7**	**1.85 + 0.7**	**2.85 + 0.7**	**0.5 + 0.7**

Table F.4Energy balance

Contents	Compounds	Density	EE (MJ/kg)	MCR (MJ/m²)	S-IGR (MJ/m²)	IGR (MJ/m²)	EGR (MJ/m²)
Planting soil medium	Planting loose mix type soil (0.25m³ per m²)	1200 kg/m³	0.083	–	24.9 × 2	44.82 × 2	4.98 × 2
Filter fabric aeration mat	Geotextile & Textured Polypropylene	0.15 kg/m²	99.20	–	14.88 × 2	14.88 × 2	14.88 × 2
Drainage/Water retention panel	Polypropylene Injection Moulding, Dia Drain-40	1.42 kg/m²	115.10	–	163.44 × 2	163.44 × 2	163.44 × 2
Protection board	Geotextile, formulated Polypropylene, VLU300	0.3 kg/m²	99.20	–	29.76 × 2	29.76 × 2	29.76 × 2
Root barrier & Waterproofing	Polymer Modified Bitumen (PMB)	4.7 kg/m²	51	–	239.7 × 2	239.7 × 2	239.7 × 2
Moisture insulation	Prefabricated Bitumen film	4.7 kg/m²	51	239.7	239.7	239.7	239.7
Cement sand mortar	Ratio 1:4	2100 kg/m³	1.11	58.27	58.27	58.27	58.27
Light concrete	150 kg/m³	2350 kg/m³	0.49	57.57	57.57	57.57	57.57
Thermal insulation	Extruded PS	1.25 kg/m²	86.4	108	108	108	108
Vapor barrier nylon	PET film	0.15 kg/m²	83.1	12.46	12.46	12.46	12.46
Sum.	-	-	-	**476**	**1421.3**	**1461.2**	**1381.5**

Note: The life duration of residential buildings in Tehran and the lifespan of GR respectively assumed 50 years and 25 years.

Table F.5
Waste disposal

Contents	Compounds	Density	Recyclability (%)	MCR (kg/m²)	S-IGR (kg/m²)	IGR (kg/m²)	EGR (kg/m²)
Filter fabric aeration mat	Geotextile & Textured Polypropylene	0.15 kg/m²	68	–	0.05 × 2	0.05 × 2	0.05 × 2
Drainage/Water retention panel	Polypropylene Injection Moulding, Dia Drain-40	1.42 kg/m²	68	–	0.45 × 2	0.45 × 2	0.45 × 2
Protection board	Geotextile, formulated Polypropylene, VLU300	0.3 kg/m²	68	–	0.1 × 2	0.1 × 2	0.1 × 2
Root barrier & Waterproofing	Polymer Modified Bitumen (PMB)	4.7 kg/m²	89	–	0.51 × 2	0.51 × 2	0.51 × 2
Moisture insulation	Prefabricated Bitumen film	4.7 kg/m²	89	0.51	0.51	0.51	0.51
Cement sand mortar	Ratio 1:4	2100 kg/m³	90	5.25	5.25	5.25	5.25
Light concrete	150 kg/m³	2350 kg/m³	88	14.1	14.1	14.1	14.1
Thermal insulation	Extruded PS	1.25 kg/m²	57	0.53	0.53	0.53	0.53
Vapor barrier nylon	PET film	0.15 kg/m²	40	0.09	0.09	0.09	0.09
Sum.	-	-	-	**20.5**	**22.7**	**22.7**	**22.7**

Note: 50 years as the life duration of residential buildings in Tehran and 25 years as the lifespan of GR have been considered.

Table F.6
CO_2 balance

Contents	Compounds	Density	EC (kg CO_2/kg)	MCR (kg CO_2/m^2)	S-IGR (kg CO_2/m^2)	IGR (kg CO_2/m^2)	EGR (kg CO_2/m^2)
Planting soil medium	Planting loose mix type soil (0.25m^3 per m^2)	1200 kg/m^3	0.0048	–	1.44 × 2	2.59 × 2	0.28 × 2
Filter fabric aeration mat	Geotextile & Textured Polypropylene	0.15 kg/m^2	2.97	–	0.45 × 2	0.45 × 2	0.45 × 2
Drainage/Water retention panel	Polypropylene Injection Moulding, Dia Drain-40	1.42 kg/m^2	3.93	–	5.58 × 2	5.58 × 2	5.58 × 2
Protection board	Geotextile, formulated Polypropylene, VLU300	0.3 kg/m^2	2.97	–	0.9 × 2	0.9 × 2	0.9 × 2
Root barrier & Waterproofing	Polymer Modified Bitumen (PMB)	4.7 kg/m^2	0.38	–	1.79 × 2	1.79 × 2	1.79 × 2
Moisture insulation	Prefabricated Bitumen film	4.7 kg/m^2	0.38	1.79	1.79	1.79	1.79
Cement sand mortar	Ratio 1:4	2100 kg/m^3	0.171	8.98	8.98	8.98	8.98
Light concrete	150 kg/m^3	2350 kg/m^3	0.06	7.05	7.05	7.05	7.05
Thermal insulation	Extruded PS	1.25 kg/m^2	2.71	3.38	3.38	3.38	3.38
Vapor barrier nylon	PET film	0.15 kg/m^2	2.04	0.30	0.30	0.30	0.30
CO_2 sequestration	Trees	–	–	–	−239.5	−239.5	–
Sum.	–	–	–	**21.5**	**−197.7**	**−195.4**	**39.5**

Note: 50 years as the life duration of residential buildings and 25 years as the lifespan of GR have been considered to calculate.

Table F.7
ORI for implementation of GRs

Contents	P_i (Probability)	C_i (Consequence)	MCR	S-IGR	IGR	EGR
E_i (Exposure)			24	80	88	72
Falls	3	20	60	60	60	60
Hand injuries	6	10	–	60	60	60
Back injuries	6	7	42	42	42	42
Burn	1	7	7	7	7	7
Sum.			**2.61**	**13.52**	**14.87**	**12.16**

Table F.8
Point assignment for customization aspects

Consideration and aspects	MCR **(points)**	S-IGR **(points)**	IGR **(points)**	EGR **(points)**
1. Allow different uses in the same roof	0	1	1	1
2. Allow use of components appropriate to climatic condition	0	1	1	1
3. Allow the possibility of using the diversity in the market	1	1	1	1
4. Allow different colors for the roof finishing	0	1	1	0
5. Allow different textures for the roof	0	0	1	0
6. Allow different volumetrics for the roof	0	1	1	0
7. Allow adaptation to the different shapes of the roof	0	1	1	1
8. Allow innovation during the design process	0	1	1	1
9. Allow use of technological fast improvement	0	0	0	0
Sum.	**11.1%**	**77.7%**	**88.8%**	**55.5%**

Table F.9
Point assignment for adaptability aspects

Consideration and aspects	MCR **(points)**	S-IGR **(points)**	IGR **(points)**	EGR **(points)**
1. Potential of disassembling	0	0	0	1
2. Ability to change parts	0	1	1	1
3. Possibility of reusing the elements	0	0	0	0
4. Ability to move	0	0	0	0
5. Access to service	0	1	1	1
6. Abundance of spare parts in the market	1	1	1	1
Sum.	**16.6%**	**50%**	**50%**	**66.6%**

Appendix G

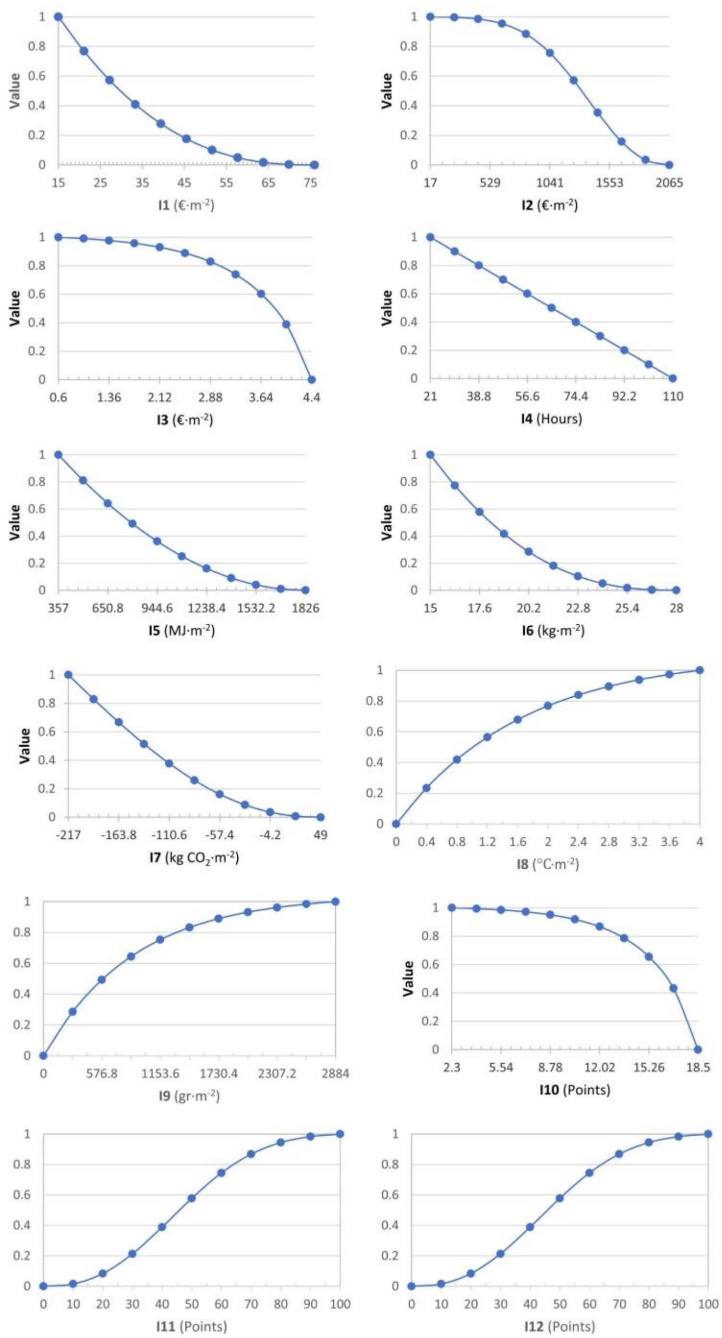


Fig. G.1. Value function of each indicator.

References

[1] "World Health Organization (WHO). https://www.who.int/airpollution/ambient/pollutants/en/. (Accessed 10 October 2020).

[2] F. Nejadkoorki, Advanced Air Pollution, BoD–Books on Demand, 2011.

[3] The World Bank. https://www.worldbank.org/en/news/press-release/2016/09/08/air-pollution-deaths-cost-global-economy-225-billion. (Accessed 10 October 2020).

[4] Y. Zhu, J. Xie, F. Huang, L. Cao, Association between short-term exposure to air pollution and COVID-19 infection: evidence from China, Sci. Total Environ. 727 (Jul. 2020) 138704, https://doi.org/10.1016/j.scitotenv.2020.138704.

[5] U.M. Declaration, Resolution Adopted by the General Assembly, 55/2, in: United Nations Millennium Declaration, vol. 4, " *Retrieved June*, 2015.

[6] M. Röck, et al., "Embodied GHG emissions of buildings – the hidden challenge for effective climate change mitigation, Appl. Energy 258 (Jan. 2020) 114107, https://doi.org/10.1016/j.apenergy.2019.114107.

[7] International Energy Agency and the United Nations Environment Programme, 2018 Global Status Report: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector, in: International Energy Agency and the United Nations Environment Programme Paris, 2018, pp. 11–14. https://www.unenvironment.org/resources/report/global-status-report-2018. (Accessed 18 February 2021).

[8] A. Invidiata, M. Lavagna, E. Ghisi, Selecting design strategies using multi-criteria decision making to improve the sustainability of buildings, Build. Environ. 139 (2018) 58–68.

[9] H. Yan, Q. Shen, L.C. Fan, Y. Wang, L. Zhang, Greenhouse gas emissions in building construction: a case study of One Peking in Hong Kong, Build. Environ. 45 (4) (2010) 949–955.

[10] D.B. Rowe, Green roofs as a means of pollution abatement, Environ. Pollut. 159 (8–9) (2011) 2100–2110.

[11] J. Li, et al., Effect of green roof on ambient CO2 concentration, Build. Environ. 45 (12) (2010) 2644–2651.

[12] C. Clark, P. Adriaens, F.B. Talbot, Green roof valuation: a probabilistic economic analysis of environmental benefits, Environ. Sci. Technol. 42 (6) (2008) 2155–2161.

[13] K.L. Getter, D.B. Rowe, G.P. Robertson, B.M. Cregg, J.A. Andresen, Carbon sequestration potential of extensive green roofs, Environ. Sci. Technol. 43 (19) (2009) 7564–7570.

[14] N. Simões, R. Almeida, A. Tadeu, M. Brett, J. Almeida, Comparison between cork-based and conventional green roof solutions, Build. Environ. (2020) 106812.

[15] F. Orsini, et al., Features and functions of multifunctional urban agriculture in the Global North: a review, Front. Sustain. Food Syst. 4 (2020) 228.

[16] B.B. Lin, S.M. Philpott, S. Jha, The future of urban agriculture and biodiversity-ecosystem services: challenges and next steps, Basic Appl. Ecol. 16 (3) (2015) 189–201.

[17] J. Yang, Q. Yu, P. Gong, Quantifying air pollution removal by green roofs in Chicago, Atmos. Environ. 42 (31) (2008) 7266–7273.

[18] B.A. Currie, B. Bass, Estimates of air pollution mitigation with green plants and green roofs using the UFORE model, Urban Ecosyst. 11 (4) (2008) 409–422.

[19] M. Santamouris, "Cooling the cities–a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments, Sol. Energy 103 (2014) 682–703.

[20] F. Bianchini, K. Hewage, "How 'green' are the green roofs? Lifecycle analysis of green roof materials, Build. Environ. 48 (2012) 57–65.

[21] C. Rosenzweig, S. Gaffin, L. Parshall, Green roofs in the New York metropolitan region: research report, Columbia Univ. Cent. Clim. Syst. Res. NASA Goddard Inst. Space Stud. 59 (2006).

[22] H. Takebayashi, M. Moriyama, Surface heat budget on green roof and high reflection roof for mitigation of urban heat island, Build. Environ. 42 (8) (2007) 2971–2979.

[23] S. Tabatabaee, A. Mahdiyar, S. Durdyev, S.R. Mohandes, S. Ismail, An assessment model of benefits, opportunities, costs, and risks of green roof installation: a multi criteria decision making approach, J. Clean. Prod. 238 (2019) 117956.

[24] "University of Toronto, ", https://web.archive.org/web/20080411230309/http://www.news.utoronto.ca/bin6/051117-1822.asp. (Accessed 10 October 2020).

[25] M. Shafique, R. Kim, M. Rafiq, "Green roof benefits, opportunities and challenges–A review, Renew. Sustain. Energy Rev. 90 (2018) 757–773.

[26] S. Saiz, C. Kennedy, B. Bass, K. Pressnail, Comparative life cycle assessment of standard and green roofs, Environ. Sci. Technol. 40 (13) (2006) 4312–4316.

[27] B. Bass, Green roofs and green walls: potential energy savings in the winter, Rep. Phase 1 (2007).

[28] S.B. Chenani, S. Lehvävirta, T. Häkkinen, Life cycle assessment of layers of green roofs, J. Clean. Prod. 90 (2015) 153–162.

[29] P. Vacek, K. Struhala, L. Matějka, Life-cycle study on semi intensive green roofs, J. Clean. Prod. 154 (2017) 203–213.

[30] B.R. Droguett, "Sustainability Assessment of Green Infrastructure Practices for Stormwater Management: A Comparative Emergy Analysis," PhD Thesis, State University of New York College of Environmental Science and Forestry, 2011.

[31] G. Peri, M. Traverso, M. Finkbeiner, G. Rizzo, "Embedding 'substrate' in environmental assessment of green roofs life cycle: evidences from an application to the whole chain in a Mediterranean site, J. Clean. Prod. 35 (2012) 274–287.

[32] S. Toboso-Chavero, et al., "Towards productive cities: environmental assessment of the food-energy-water nexus of the urban roof mosaic, J. Ind. Ecol. 23 (4) (Aug. 2019) 767–780, https://doi.org/10.1111/jiec.12829.

[33] G. Ledesma, J. Nikolic, and O. Pons-Valladares, "Bottom-up model for the sustainability assessment of rooftop-farming technologies potential in schools in Quito, Ecuador," J. Clean. Prod., vol. 274, p. 122993, Nov. 2020, doi: 10.1016/j.jclepro.2020.122993.

[34] K. Vijayaraghavan, Green roofs: a critical review on the role of components, benefits, limitations and trends, Renew. Sustain. Energy Rev. 57 (2016) 740–752.

[35] A. Mahdiyar, S. Tabatabaee, A.N. Sadeghifam, S.R. Mohandes, A. Abdullah, M. M. Meynagh, Probabilistic private cost-benefit analysis for green roof installation: a Monte Carlo simulation approach, Urban For. Urban Green. 20 (2016) 317–327.

[36] C.Y. Jim, S.W. Tsang, Modeling the heat diffusion process in the abiotic layers of green roofs, Energy Build. 43 (6) (2011) 1341–1350.

[37] T. Sun, E. Bou-Zeid, Z.-H. Wang, E. Zerba, G.-H. Ni, Hydrometeorological determinants of green roof performance via a vertically-resolved model for heat and water transport, Build. Environ. 60 (2013) 211–224.

[38] FLL, Guidelines for the Planning, Construction and Maintenance of Green Roofs, " Landscape Development and Landscaping Research Society e. v., 2018.

[39] "EPA, United States Environmental Protection Agency, ", https://www.epa.gov/heatislands/using-green-roofs-reduce-heat-islands. (Accessed 10 October 2020).

[40] S. Cascone, F. Catania, A. Gagliano, G. Sciuto, A comprehensive study on green roof performance for retrofitting existing buildings, Build. Environ. 136 (2018) 227–239.

[41] T. Brinkhoff, The Principal Agglomerations of the world Accessed Aug, vol. 16, 2011.

[42] M. Heger, M. Sarraf, Air Pollution in Tehran: Health Costs, Sources, and Policies, World Bank, 2018.

[43] G.D. Squires, Urban Sprawl: Causes, Consequences, & Policy Responses, The Urban Insitute, 2002.

[44] "Tehran Province Meteorological Administration, accessed Nov. 19, 2020, http://www.tehranmet.ir/Index.aspx?tempname=english&lang=1&sub=0.

[45] Tehran Annual Air and Noise Quality Report, Period of March 2018 - March 2019, " Air Quality Control Company, Tehran, Iran, May 2019. QM98/02/01(U)/1, http://air.tehran.ir/portals/0/ReportFiles/AirPollu-tion/TehranAirQuality1397.pdf.

[46] C.A. Pope, D.W. Dockery, Health effects of fine particulate air pollution: lines that connect, J. Air Waste Manag. Assoc. 56 (6) (2006) 709–742, https://doi.org/10.1080/10473289.2006.10464485. Jun.

[47] P. Ghisellini, C. Cialani, S. Ulgiati, A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems, J. Clean. Prod. 114 (2016) 11–32.

[48] Tehran municipality information and communication technology (ICT) organization," Tehran Times, accessed Nov. 05, 2020), https://www.tehrantimes.com/tag/Tehran+Municipality+Information+and+Communication+Technology+%28ICT%29+Organization.

[49] S. Zhou, B. Yu, Y. Zhang, Y. Huang, and G. Wang, "Partitioning evapotranspiration based on the concept of underlying water use efficiency: ET partitioning," Water Resour. Res., vol. 52, no. 2, pp. 1160–1175, Feb. 2016, doi: 10.1002/2015WR017766.

[50] M.T.C. Team, SWOT Analysis, Discover New Opportunities, Manage and Eliminate Threats, *Mind Tools*, 2018.

[51] N. Lazar and K. Chithra, "A comprehensive literature review on development of Building Sustainability Assessment Systems," J. Build. Eng., vol. 32, p. 101450, Nov. 2020, doi: 10.1016/j.jobe.2020.101450.

[52] E. Zarghami, D. Fatourehchi, Comparative analysis of rating systems in developing and developed countries: a systematic review and a future agenda towards a region-based sustainability assessment, J. Clean. Prod. 254 (May 2020) 120024, https://doi.org/10.1016/j.jclepro.2020.120024.

[53] R.L. Keeney, H. Raiffa, Decisions with Multiple Objectives: Preferences and Value Trade-Offs, Cambridge University Press, 1993.

[54] O. Pons, A. De la Fuente, A. Aguado, The use of MIVES as a sustainability assessment MCDM method for architecture and civil engineering applications, Sustainability 8 (5) (2016) 460.

[55] I. Josa, O. Pons, A. de la Fuente, A. Aguado, Multi-criteria decision-making model to assess the sustainability of girders and trusses: case study for roofs of sports halls, J. Clean. Prod. 249 (2020) 119312.

[56] O. Pons, A. de la Fuente, Integrated sustainability assessment method applied to structural concrete columns, Construct. Build. Mater. 49 (2013) 882–893.

[57] O. Pons, J. Franquesa, S.M. Hosseini, Integrated value model to assess the sustainability of active learning activities and strategies in architecture lectures for large groups, Sustainability 11 (10) (2019) 2917.

[58] G. Gilani, A. Blanco, A. De la Fuente, "A new sustainability assessment approach based on stakeholder's satisfaction for building facades, Energy Procedia 115 (2017) 50–58.

[59] O. Pons, A. Aguado, Integrated value model for sustainable assessment applied to technologies used to build schools in Catalonia, Spain, Build. Environ. 53 (2012) 49–58.

[60] J.P. Reyes, J.T. San-José, J. Cuadrado, R. Sancibrian, Health & Safety criteria for determining the sustainable value of construction projects, Saf. Sci. 62 (Feb. 2014) 221–232, https://doi.org/10.1016/j.ssci.2013.08.023.

[61] L.J.T. San-Jose, R.J. Cuadrado, Industrial building design stage based on a system approach to their environmental sustainability, Construct. Build. Mater. 24 (2010).

[62] J.-T. San-José Lombera and I. Garrucho Aprea, "A system approach to the environmental analysis of industrial buildings," Build. Environ., vol. 45, no. 3, pp. 673–683, Mar. 2010, doi: 10.1016/j.buildenv.2009.08.012.

[63] B. Maleki, M. d M. Casanovas Rubio, S.M.A. Hosseini, A. de la Fuente Antequera, Multi-criteria decision making in the social sustainability assessment of high-rise residential buildings, IOP Conf. Ser. Earth Environ. Sci. 290 (Jun. 2019), 012054, https://doi.org/10.1088/1755-1315/290/1/012054.

[64] A. Aguado, A. del Caño, M.P. de la Cruz, D. Gómez, A. Josa, Sustainability assessment of concrete structures within the Spanish structural concrete code, J. Construct. Eng. Manag. 138 (2) (Feb. 2012) 268–276, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000419.

[65] A. de la Fuente, M. del M. Casanovas-Rubio, O. Pons, J. Armengou, Sustainability of column-supported RC slabs: fiber reinforcement as an alternative, J. Construct. Eng. Manag. 145 (7) (2019), 04019042.

[66] A. De la Fuente, A. Blanco, J.B. Armengou, A. Aguado, Sustainability based-approach to determine the concrete type and reinforcement configuration of TBM tunnels linings. Case study: extension line to Barcelona Airport T1, Tunn. Undergr. Space Technol. 61 (2017) 179–188.

[67] M.L. Feldmann, et al., Architectural and engineering fees from the public institutional perspective, J. Manag. Eng. 24 (1) (2008) 2–11.

[68] J.J.C. Barros, M.L. Coira, M.P. De la Cruz López, A. del Caño Gochi, Assessing the global sustainability of different electricity generation systems, Energy 89 (2015) 473–489.

[69] A. de la Fuente, J. Armengou, O. Pons, A. Aguado, Multi-criteria decision-making model for assessing the sustainability index of wind-turbine support systems: application to a new precast concrete alternative, J. Civ. Eng. Manag. 23 (2) (2017) 194–203.

[70] A. de la Fuente, O. Pons, A. Josa, A. Aguado, Multi-Criteria Decision Making in the sustainability assessment of sewerage pipe systems, J. Clean. Prod. 112 (2016) 4762–4770.

[71] F. Pardo-Bosch, A. Aguado, Investment priorities for the management of hydraulic structures, Struct. Infrastruct. Eng. 11 (10) (2015) 1338–1351.

[72] S.A. Hosseini, A. de la Fuente, O. Pons, Multi-criteria decision-making method for assessing the sustainability of post-disaster temporary housing units technologies: a case study in Bam, Sustain. Cities Soc. 20 (2003) 38–51.

[73] S.A. Hosseini, A. de la Fuente, O. Pons, Multicriteria decision-making method for sustainable site location of post-disaster temporary housing in urban areas, J. Construct. Eng. Manag. 142 (9) (2016), 04016036.

[74] S.A. Hosseini, O. Pons, A. de la Fuente, A combination of the Knapsack algorithm and MIVES for choosing optimal temporary housing site locations: a case study in Tehran, Int. J. Disaster Risk Reduct. 27 (2018) 265–277.

[75] S.M.A. Hosseini, O. Pons Valladares, Sustainable building technologies for post-disaster temporary housing: integrated sustainability assessment and life cycle assessment, World Acad. Sci. Eng. Technol. 13 (4) (2019) 244–250.

[76] O. Pons Valladares, J. Franquesa Sànchez, S.M. Amin Hosseini, "Towards a new interactive tool of resources for active learning in university large groups' lectures," in *ICERI 2019: 12th International Conference of Education*. Research and Innovation: Conference Proceedings: Seville (Spain) 11-13 November 2019, 2019, pp. 2277–2286.

[77] U.G. Assembly, World summit outcome: resolution/adopted by the general assembly, 24 october 2005," A/RES/60/1, 2005 available at: http://www.refworld.org/docid/44168a910 http://www.refworld.org/docid/44168a910.html.

[78] A. Nadal, O. Pons, E. Cuerva, J. Rieradevall, A. Josa, Rooftop greenhouses in educational centers: a sustainability assessment of urban agriculture in compact cities, Sci. Total Environ. 626 (2018) 1319–1331.

[79] B. Alarcon, A. Aguado, R. Manga, A. Josa, A value function for assessing sustainability: application to industrial buildings, Sustainability 3 (1) (2011) 35–50.

[80] O. Pons, et al., Roofs of the future: rooftop greenhouses to improve buildings metabolism, Procedia Eng. 123 (2015) 441–448.

[81] J. Bowman, L. Kington, N. Julian, E. Grunewald, E. Greenslade, Green Job Training and Smart Roofs in Columbus, ", Ohio, 2015.

[82] J.C. Berndtsson, Green roof performance towards management of runoff water quantity and quality: a review, Ecol. Eng. 36 (4) (2010) 351–360.

[83] B.A. Currie, B. Bass, Using green roofs to enhance biodiversity in the City of Toronto, in: Discussion paper for Toronto City Planning, Apr. 2010, pp. 15–21. https://www.scribd.com/doc/306597945/Using-Green-Roofs-to-Enhance-Biodiversity-in-the-City-of-Toronto-2010. (Accessed 18 February 2021).

[84] O. Pons, A. de la Fuente, J. Armengou, A. Aguado, Towards the sustainability in the design of wind towers, Energy Procedia 115 (2017) 41–49.

[85] D.J. Harris, A quantitative approach to the assessment of the environmental impact of building materials, Build. Environ. 34 (6) (1999) 751–758.

[86] S. Quezada-García, G. Espinosa-Paredes, M.A. Polo-Labarrios, E.G. Espinosa-Martínez, M.A. Escobedo-Izquierdo, Green roof heat and mass transfer mathematical models: a review, Build. Environ. 170 (2020) 106634.

[87] R. Berto, C.A. Stival, P. Rosato, Enhancing the environmental performance of industrial settlements: an economic evaluation of extensive green roof competitiveness, Build. Environ. 127 (2018) 58–68.

[88] ", Central Bank of the Islamic Republic of Iran, accessed Jan. 28, 2020, https://www.cbi.ir/default_en.aspx.

[89] G. Hammond, C. Jones, E.F. Lowrie, P. Tse, "Embodied Carbon," *Inventory Carbon Energy ICE Version 20*, 2011.

[90] G. Faraca, T. Astrup, Plastic waste from recycling centres: characterisation and evaluation of plastic recyclability, Waste Manag. 95 (2019) 388–398.

[91] J. Anderson, D. Shiers, The Green Guide to Specification, John Wiley & Sons, 2009.

[92] L. Cai, X.-P. Feng, J.-Y. Yu, Q.-C. Xiang, R. Chen, Reduction in carbon dioxide emission and energy savings obtained by using a green roof, Aerosol Air Qual. Res. 19 (11) (2019) 2432–2445.

[93] S.J. DeWald, S.J. Josiah, R. Erdkamp, Heating with Wood: Producing, Harvesting and Processing Firewood, Cooperative Extension, Institute of Agriculture and Natural Resources, 2005.

[94] E.C. Toochi, Carbon sequestration: how much can forestry sequester CO2, For. Res. Eng. Int. J. 2 (3) (2018) 148–150.

[95] S. Weiler, K. Scholz-Barth, Green Roof Systems: a Guide to the Planning, Design, and Construction of Landscapes over Structure, John Wiley & Sons, 2009.

[96] T. Susca, Green roofs to reduce building energy use? A review on key structural factors of green roofs and their effects on urban climate, Build. Environ. 162 (2019) 106273.

[97] M. Moghbel, R.E. Salim, Environmental benefits of green roofs on microclimate of Tehran with specific focus on air temperature, humidity and CO2 content, Urban Clim. 20 (2017) 46–58.

[98] R. ARAbI, M. Fairu SHAHIdAn, M.M. Kamal, M. Jaafar, M. Rakhshandehroo, Mitigating urban heat island through green roofs, Curr. World Environ. 10 (1) (2015) 918–927.

[99] G. Swamy, S.S. Nagendra, U. Schlink, Urban heat island (UHI) influence on secondary pollutant formation in a tropical humid environment, J. Air Waste Manag. Assoc. 67 (10) (2017) 1080–1091.

[100] P. Ramasubramanian, O. Starry, T. Rosenstiel, E.T. Gall, Pilot study on the impact of green roofs on ozone levels near building ventilation air supply, Build. Environ. 151 (2019) 43–53.

[101] N.A. Powe, K.G. Willis, Mortality and morbidity benefits of air pollution (SO2 and PM10) absorption attributable to woodland in Britain,, J. Environ. Manag. 70 (2) (2004) 119–128.

[102] E. Mohammadi, S.H. Mirkarimi, M. Mohammadzadeh, An integrated method to valuate the function of green roofs in absorbing air pollutants, Case study: Tehran," *Environ. Resour. Res.* 7 (1) (2019) 1–8.

[103] A.F. Speak, J.J. Rothwell, S.J. Lindley, C.L. Smith, Urban particulate pollution reduction by four species of green roof vegetation in a UK city, Atmos. Environ. 61 (2012) 283–293.

[104] Y. Wang, F. Bakker, R. De Groot, H. Wörtche, Effect of ecosystem services provided by urban green infrastructure on indoor environment: a literature review, Build. Environ. 77 (2014) 88–100.

[105] O.A. Jannadi, S. Almishari, Risk assessment in construction, J. Construct. Eng. Manag. 129 (5) (2003) 492–500.

[106] M.R. Hallowell, J.A. Gambatese, Activity-based safety risk quantification for concrete formwork construction, J. Construct. Eng. Manag. 135 (10) (2009) 990–998.

[107] B.R. Fortunato III, M.R. Hallowell, M. Behm, K. Dewlaney, Identification of safety risks for high-performance sustainable construction projects, J. Construct. Eng. Manag. 138 (4) (2012) 499–508.

[108] S. Winge, E. Albrechtsen, B.A. Mostue, Causal factors and connections in construction accidents, Saf. Sci. 112 (2019) 130–141.

[109] T.K. Fredericks, O. Abudayyeh, S.D. Choi, M. Wiersma, M. Charles, Occupational injuries and fatalities in the roofing contracting industry, J. Construct. Eng. Manag. 131 (11) (2005) 1233–1240.

[110] M. del M. Casanovas, J. Armengou, G. Ramos, Occupational risk index for assessment of risk in construction work by activity, J. Construct. Eng. Manag. 140 (1) (2014), 04013035.

[111] K.D. Goepel, Implementation of an online software tool for the analytic hierarchy process (AHP-OS), Int. J. Anal. Hierarchy Process 10 (3) (2018).

[112] T.L. Saaty, How to make a decision: the analytic hierarchy process, Eur. J. Oper. Res. 48 (1) (1990) 9–26.

[113] Britanica, accessed, https://www.britannica.com/science/greenhouse-gas. (Accessed 10 October 2020).

[114] S.A. Walters, K. Stoelzle Midden, Sustainability of urban agriculture: vegetable production on green roofs, Agriculture 8 (11) (2018) 168.

2.3. Article B: Solar energy systems

Article B, entitled "Integrated Value Model for Sustainability Assessment of Residential Solar Energy Systems Towards Minimizing Urban Air Pollution in Tehran", published in the 249th vol. of *Solar Energy*, the official journal of the *International Solar Energy Society (ISES)*, which is ranked in Q1 among indexed journals (doi: 10.1016/j.solener.2022.10.047) [87].

The **contributions and individual roles of the thesis author** as the main author of this paper were conceptualization, data curation, investigation, methodology, formal analysis, resources, validation, visualization, writing the original draft, and revising. The other authors of the article are the thesis co-directors, who mainly supervised and advised the first author and reviewed the manuscript. In this study, solar energy – the most abundant, inexhaustible, and cleanest of all renewable energy sources – that contributes to improving air quality, has been analysed and evaluated with its two common systems of photovoltaic (PV) and hybrid photovoltaic/thermal (PV/T) for urban settlements. A copy of this research article is attached in the following.

Solar Energy 249 (2023) 40–66

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Integrated value model for sustainability assessment of residential solar energy systems towards minimizing urban air pollution in Tehran

S. Hamed Banirazi Motlagh [a,*], S.M. Amin Hosseini [b], Oriol Pons-Valladares [a]

[a] Department of Architectural Technology, The Polytechnic University of Catalonia (UPC), Av. Diagonal 649, 08028 Barcelona, Spain
[b] RESUME TECH (Resilience and Sustainability in Metropolitans TECH), America St., 08041 Barcelona, Spain

ARTICLE INFO

Keywords:
Renewable energy
Solar system
Residential buildings
Urban air pollution
Sustainability assessment

ABSTRACT

Renewable energy applications are lucrative alternatives to minimize urban environmental impacts. Solar energy, the most abundant, inexhaustible, and cleanest of all renewable sources, provides an opportunity to transform buildings from energy consumers into active energy producers. Nevertheless, photovoltaic (PV) and hybrid photovoltaic/thermal (PV/T) are considered the most viable alternatives for urban settlements. This study, as part of a broader research project, develops a new model to evaluate solar systems' air pollution mitigation capacity and assist decision-makers in adopting the most suitable solution. The approach is based on the integrated value model for sustainability assessment (MIVES), combined with the analytic hierarchy process (AHP) and sensitivity analysis. This multi-objective tool is applied to residential buildings in Tehran, a megacity example with unused rooftops, solar energy harvest potential, and air pollution reduction needs. Results reveal one square meter of PV and PV/T enables avoiding 211 and 488 kg CO_2 emissions annually, as well as 1.2 and 1.9 g PM pollutants, respectively. Although PV achieves higher sustainability indexes as a better socio-economic alternative, PV/T can be a robust solution when stakeholders are more sensitive to environmental requirements and air pollution decrement potential. The critical obstacle to PV/T deployment is the lack of financial incentives. However, allocating 38 % of solar electricity feed-in tariffs to solar thermal energy could solve this issue. Compared to green roofs, solar systems stand out with CO_2 saving and energy production potential. Researchers expect future solar collectors' improvements, such as lower resource consumption, thus, becoming more environmentally friendly and cost-effective solutions.

1. Introduction

Environmental issues – such as global warming, greenhouse gases (GHG), and air pollution – are considered significant challenges worldwide. Likewise, the increment of energy demand and exhaustion of primary sources are other global concerns. In this regard, replacing fossil fuels with eco-friendly and more sustainable energy sources is essential as one of the possible solutions (Johnsson et al., 2019; Abas et al., 2015; Bauer, 2016; Diwania et al., 2020; Barone et al., 2019). Besides, megacities are significantly responsible for the previously mentioned problematic issues while millions of people live there. Many populated and dense urban settlements – where land is scarce and costly – have remarkable unused space on roofs that provide the potential for uses that can improve the eco-sustainability in metropolises (Aslani and Seipel, 2022). This is the case for renewable energy systems implementation, which is a lucrative alternative that can reduce cities' environmental impact while contributing positively to socio-economic issues (González et al., 2013; Omer, 2008). In addition to the required renewable energy application for mitigation of environmental problems (Johnsson et al., 2019; Abas et al., 2015; Fazelpour et al., 2016; Jia et al., 2019) , reducing energy needs with measures such as less consuming devices and machinery (Zhou et al., 2016), and more responsible consumption habits are necessary as well (Paço and Lavrador, 2017). Meanwhile, both urban air pollution reduction and the supply of eco-efficient energy sources are considered striking management problems in metropolises due to urban growth and cities' expansion trends ((Sáez-Martínez et al., Jan. 2015)). Thus, urban managers need to achieve a proper strategy and explore the most suitable and sustainable environmental solutions based on potential and feasible applications. In this context, the significant growth of integrated renewable energy sources distributed within the built environment is considered one of the driving capabilities to accelerate the strategy for transition from centralized to

* Corresponding author.
E-mail address: seyed.hamed.banirazimotlagh@upc.edu (S. Hamed Banirazi Motlagh).

https://doi.org/10.1016/j.solener.2022.10.047
Received 26 February 2022; Received in revised form 18 October 2022; Accepted 24 October 2022
Available online 25 November 2022

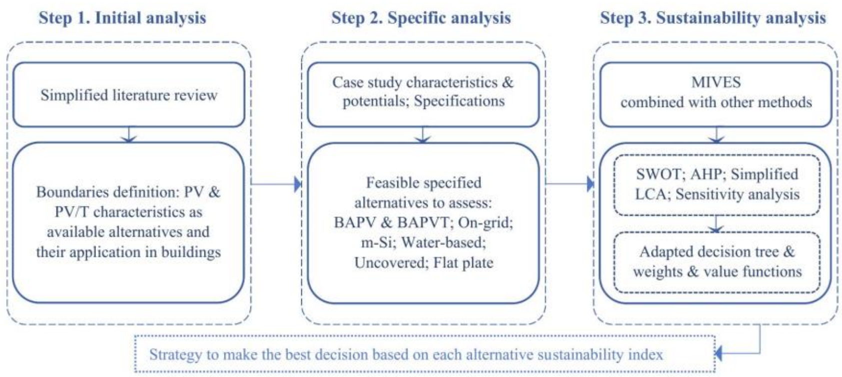


Fig. 1. Overview of this study methodology framework

decentralized energy systems (Hosseini, 2019). This growth often depends on the accomplishment and popularity of building envelope solutions (Zhang, 2018). Therefore, a suitable identification approach to decentralized and local energy production could be the most affordable and logical decision due to its contribution to (a) decrease costs of energy distribution, (b) reduce energy losses during transitions resulting in lesser environmental impacts (Seepromting et al., 2020; Sadeghi and Kalantar, 2013; Shukla et al., 2016); and (c) regain unused urban potentials. To this end, this research study takes into account rooftop applications to benefit from the aforementioned advantages obtained from the solar systems' intervention in the building sector. However, solar farms as an alternative solution could be used, with their potential and drawbacks. In this case, rooftop applications are more viable since, unlike large-scale solar farms, they do not require land acquisition (Ahmad Ludin et al., 2021). Furthermore, discarding a vast area of unused rooftops for solar applications while using extensive solar farm projects means decreasing the potential for agriculture, as well as losing the potential for buildings' self-sufficiency. In comparison, rooftop systems benefit from a lower cost and lower Levelised cost of energy than solar farms (Ahmad Ludin, et al., 2021; Mohanta et al., 2015). Additionally, solar farms are often held by absentee owners who are not residents in the surrounding communities, which makes maintenance more complex; Feed-in tariffs (FIT) revenue is also not retained in communities with minimal involvement in the operation and maintenance of the system (Tongsopit, 2015).

Renewable energy, with its consumption increasing by an average of 2.3 % per year – between 2015 and 2040 – is the fastest-growing energy source around the world (Barone et al., 2019). In this context, solar energy has gained outstanding promising interest as the most abundant, inexhaustible, and cleanest of all renewable energy resources (Barone et al., 2019; Sathe and Dhoble, 2017; Mishra and Tiwari, 2020). Solar radiation is mostly harvested via two matured technologies, which comprise converting this radiation to electrical and thermal energy (Sathe and Dhoble, 2017; Firouzjah, 2018). Electricity is ranked second energy type among the total energy consumption worldwide. Therefore, using solar energy for electrical power generation can significantly reduce GHG emissions, air pollution, and associated health impacts (Fazelpour et al., 2016; Korsavi et al., 2018; Adam and Apaydin, 2016; Coughlin and Kandt, 2011). Additionally, heat is the largest energy end-use worldwide and contributes to 40 % of global CO_2 emissions ("Heating - Fuels Technologies - IEA." https://www.iea.org/fuels-and-technologies/heating (2021). In this sense, photovoltaic (PV) as an appropriate approach enables solar radiation collection to produce electricity. Besides, solar irradiance can be harnessed by a hybrid photovoltaic thermal (PV/T) system to generate thermal and electrical energy simultaneously in one module (Diwania et al., 2020; Jia et al., 2019; Saurabh et al., 2020; Good et al., 2015). Since most radiant energy cannot be converted to electricity and causes raising PV cells' temperature, using PV/T increases the systems' total efficiency. This increase is obtained via two effects: harvesting more of the incident solar radiation by thermal energy generation as well as cooling PV panels by extracting waste heat during photovoltaic operation (Diwania et al., 2020; Barone et al., 2019; Jia et al., 2019; Sathe and Dhoble, 2017; Good et al., 2015).

Solar energy utilization technologies are improving significantly, expanding rapidly, and are the object of extensive research. As shown in Appendix A (Table A.1, which presents a sample of classified outcomes obtained from a simplified literature review), the logic of providing PVs on the rooftop leading to sustainability has been previously studied. However, from reviewing previous related literature to the authors' best knowledge, there is no available model for evaluating the sustainability of solar system alternatives installed on residential buildings while emphasizing urban air pollution. Accordingly, this research paper's main innovation is providing a novel model and systematic approach that proceeds beyond the previous works, which intends to assist decision-makers such as municipalities, contractors, and experts in adopting the most suitable and sustainable residential solar system alternatives to minimize cities' air pollution. This model comprises the three essential sustainability pillars – economic, environmental, and social (Assembly, 2005), based on the integrated value model for sustainability assessment (MIVES). Since the problem solution needs to be structured as a hierarchy, it is necessary to consider possible decision criteria and select the most significant criteria concerning the decision objective. Hence, the analytic hierarchy process (AHP) as a supporting tool for decision-making used in a wide range of applications is combined with MIVES in this study to make decisions more rationally and make them more transparent and better understandable. This combination performs following an initial investigation using a strategic planning approach to identify strengths, weaknesses, opportunities, and threats (SWOT) related to project planning. Its purpose is to specify the project goals and identify the internal and external factors that are favourable and unfavourable to accomplishing those objectives. Related to this study, the authors previously defined a model to choose the most suitable green roof (GR) systems (Banirazi Motlagh et al., 2021). The present article develops and applies a new model in Tehran, an example of a megacity with: (a) vast area of infra-used residential rooftops – 78.6 % of the total built-up area is residential ("Tehran Municipality Information and Communication Technology (ICT) Organization." https://tmicto.tehran.ir/ (2021) –, (b) potential for incorporating solar collector systems – almost annual 300 sunny days (Firouzjah, 2018; Najafi et al., 2015; "Solar resource maps and GIS data for 200+ countries | Solargis." https://solargis.com/maps-and-gis-data/download/iran (2021) –, and (c) high necessity for urban air pollution reduction, eco-efficient energy supply, and local energy production – ranked 14th among high carbon footprint cities and 12th amongst PM_{10} pollutants megacities worldwide (Heger and Sarraf, 2018; Moran et al., 2018). To sum up, considering the aforementioned potentials and challenges, as well as the motivations of Tehran city managers to have a multi-objective tool to evaluate the capacity of domestic solar energy systems to mitigate urban air pollution, this research study was conducted. Nevertheless, in this research study, a new model was developed that could assist decision-makers in other regions around the world with some modifications – such as index weights, as explained in the following sections.

A structural overview of this article is as follows: Section 2 explains the methodology and framework this study used to define its model; Section 3 provides the results obtained from the different stages of this research project; and Sections 4 and 5 present discussion and conclusions.

2. Methodology

The framework for this study is organized into three levels consisting of the *initial analysis*, *specific analysis*, and *sustainability analysis*. As previously said, the model developed in this study is a part of a broader research project to assess feasible rooftop alternatives attending to urban sustainability improvements with an emphasis on air pollution reduction. Fig. 1 presents the methodology structure in this article which is explained in the following subsections. It is worth mentioning that each section 2.1, 2.2, and 2.3 has corresponding results in sections 3.1, 3.2, and 3.3, respectively. Additionally, the outcomes of each aforementioned section are used to serve in the next section.

2.1. Initial analysis

This initial analysis process performs a simplified literature review regarding solar system technologies, specifically for the building sector. Web of Science, Scopus, and Google Scholar are the databases consulted. The main search words to find the hundreds of studies analyzed were: renewable energy, solar system technology/advances/applications, photovoltaic-thermal, environment, GHG, low carbon technology, urban air pollution, building, nearly zero-energy buildings (NZEB), life cycle assessment (LCA), sustainability assessment and multi-criteria decision-making model (MCDM). Selecting the papers from the aforementioned databases with the assistance of the search strings was based on the significance of their contribution to the scope and orientation of the current study in order to perform a simplified literature review. To this end, a systematic approach was implemented in three major phases: (1) *identification* to search within the current technical literature; (2) *screening* to determine the eligibility of studies that maintains a smaller number of eligible papers; and (3) *including* to extract required data from the selected studies. This systematic approach enables bringing robustness and specifically filtering the information. The main expected findings from this step are: state of the art, identification of available alternatives, recognition of the type and characteristics each alternative has, and definition of boundaries. These outcomes are the basis of future steps.

2.2. Specific analysis

By means of performing a simplified literature review in the previous step regarding solar system technologies, this middle stage explores and provides a more specific determination for feasible alternatives, which will be assessed in the final step. Reasonable alternatives determination results by considering: (1) characteristics of the area under study – such as climatic and air quality attributes –, (2) potentials of the case study for solar energy applications, and (3) justified selections for the specific types of solar collectors assessed with this model. This section collects, organizes, and studies the previous phase's proper solar systems for the specific case study, which will be considered in the following sections.

2.3. Sustainability assessment model

This novel sustainable model has been defined by a combination of MIVES, SWOT, AHP, simplified LCA, and sensitivity analysis, as shown in Fig. 1. This principal analysis step assesses the sustainability and suitability of each specific solar system, which are feasible and available alternatives for urban buildings. To this end, a preliminary investigation based on the SWOT method can facilitate and improve the accuracy of the decision-making process (M. T. C. Team, 2018). SWOT is a straightforward technique that assists researchers via a feasibility study in identifying internal and external factors. Although SWOT's strengths and weaknesses used to be closely related to internal issues, opportunities and threats often focus on more external factors. In this way, a comparison of advantages with drawbacks can provide a general picture concerning the feasibility of the subject for decision-makers. Afterwards, the main evaluation requires a smart user-friendly sustainability assessment model, which is combinable with other probable supplementary tools in order to obtain objective results. This model should also be applicable to a variety of scopes, including different contexts and potential alternatives. In this sense, this study applies the MIVES methodology, a recent MCDM from the 21st century based on the multi-attribute utility theory (Keeney, 1993). MCDM permit objective and systematic procedures to organize concepts into criteria and sub-criteria, resulting in quantifiable preferences for decision-makers. The capability of adding up different indicators' resulting values is the key benefit of MIVES as a specific method for deterministic or probabilistic instances, as well as homogeneous or heterogeneous evaluations. These indicators can be qualitative or quantitative, as well as measured by different scales and units. This additional ability comes from the use of satisfaction and value function (VF) concepts (Pons et al., 2016; Josa et al., 2020; Pons and de la Fuente, 2013). Moreover, MIVES can be used in conjunction with other techniques and precise mathematical algorithms as well as provide integrated sustainability indexes (SIs). Consequently, facile integration of uncertain analysis into evaluation is possible (Pons et al., 2016; Josa et al., 2020; Pons et al., 2019). Additionally, MIVES has been already applied to successfully define and apply comprehensive sustainability assessment tools in a variety of case studies containing architecture and building construction contexts (Pons et al., 2016; Pons et al., 2019). For instance: (1) architecture (Josa et al., 2020; Ledesma et al., 2020; Pons and Aguado, 2012; Maleki, 2019) ; (2) building structure and urban infrastructure (Pons and de la Fuente, 2013; de la Fuente, 2019; de la Fuente et al., Jun. 2016; de la Fuente et al., 2016) ; (3) post-disaster recovery program (Hosseini et al., 2016; Hosseini et al., 2018; Hosseini et al., 2019; Hosseini et al., 2020; Hosseini et al., 2021); and (4) active learning in architecture (Pons et al., 2019; Pons et al., 2019). Relying on the aforementioned MIVES applications, which have been satisfactorily carried out previously, and by applying the developed model as an eligible tool for the first time to the specific case of the current study, the validation of the MIVES model is authenticated. Overall, MIVES can provide flexible, objective, precise, and comprehensive sustainability assessments that allow even non-experts to comprehend its results via a simple tree-structured implementation approach (Josa et al., 2020; Pons et al., 2019).

MIVES method consists of three fundamental stages: (1) boundaries, (2) decision tree (DT), and (3) value functions (VF) (de la Fuente, 2019). The first level of DT constitutes the most general and qualitative issues – requirements –, which frequently incorporate the three basic sustainability pillars (Assembly, 2005). The middle level is a division set up for structuring the plan – criteria –, whilst the most specific and quantitative parameters are found at the last level – indicators (Josa et al., 2020; de la Fuente et al., 2016; Nadal et al., 2018). Each tree branch should not include an excessive number of criteria and indicators. Additionally, the defined indicators should be representative to discriminate amongst the alternatives in order to produce a reliable assessment (Pons et al., 2016). Generally, the procedure to determine the SIs of each alternative consists of five steps, including (1) DT designing; (2) tendency definition –

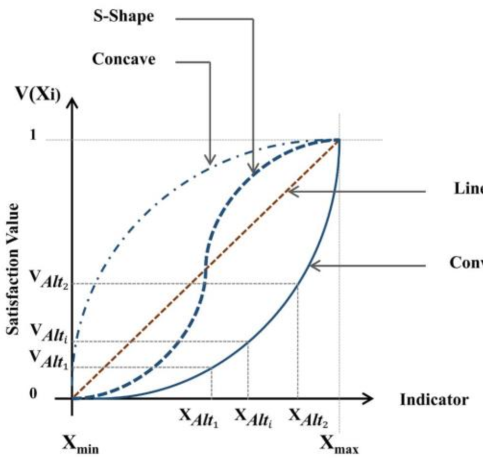


Fig. 2. Different forms of value functions (Note: X_{min} and X_{max} on the horizontal axis – corresponding to the minimum and maximum satisfaction value on the vertical axis – are the minimum and maximum abscissa values for the assessed indicator, quantified and measured by its relevant specific unit, which is different per each indicator. values for the current study are available in Tables D.1, 5, and 6).

Table 1
Parameter's definition to shape VFs

Parameter	Consideration
X_{min}-X_{max}	The assessed indicator's minimum and maximum abscissa values
X_i	Abscissa value of the under-assessment indicator (between X_{min} & X_{max})
P_i	Shape factor: concave (P_i *less than 1*), convex or S-shaped (P_i *greater than 1*), linear ($P_i = 1$)
C_i	Abscissa approximation at the inflection point (used if P_i *greater than 1*)
K_i	Tending towards V_i at the inflection point to define the ordinate value for point C_i

increasing or decreasing –; (3) X_{min} and X_{max} point determinations – corresponding to the minimum and maximum satisfaction value –; (4) shape definition for VFs; (5) mathematical expression utilization (Alarcon et al., 2010). The final index value of each alternative – obtained via the aggregation of different indicators, criteria, and requirements evaluation –, provides the sustainability assessment. This is required to calculate weights or relative importance coefficients for each branch of the DT once the value functions have been specified. At first, each requirement's weight is determined. Then within each requirement, weights for the related criteria are determined. Afterwards, using a similar procedure for each criterion provides the relevant indicators' weights. Index weighting has been applied in each branch of DT based on the outcomes of seminars held by experts and professors, local conditions, and previous favourable studies. The principal panel involved in the whole procedure of this study consists of 12 multidisciplinary experts – including a professor founder of the architectural technology field in Iranian academic organization; a deputy and a consultant from the Tehran mayor's office in urbanization and urban services fields; six senior managers from the Tehran city government in the fields of architecture & construction, codification of rules & regulations, construction supervision, detailed urban plans, urban planning, and environmental organization; a researcher from the Tehran Urban Research & Planning Center; and two leading experts from the Tehran municipality in the field of sustainable development. Discussion and agreement concerning requirements, criteria, and indicators, as well as the definition of VFs, follow the same approach. Utilization of this approach results in objectivity, actuality, and intricacy to improve the assessment using this model (Pons et al., 2016; Pons and Aguado, 2012; de la Fuente et al., 2016). The final weights have been obtained by eliminating the outliers and then finding the weights' means. However, to prove robustness, a final sensitivity analysis considers different weighting scenarios – taking into account uncertainties – based on the range of all weights received from the experts. This study's weighting process uses the AHP method (Goepel, 2018) and direct assignment. Using AHP amongst other commonly used MCDM ranking techniques – such as AHP, CP, ELECTRE, SAW, TOPSIS, VIKOR, and WPM – is due to its ability as a weighting tool to combine with other methods (Zamani-Sabzi et al., 2016). In AHP, it is easy to model a problem in a hierarchal framework based on pairwise comparison logic for structuring a decision problem and ranking a set of alternatives. Moreover, the potential to use the inconsistency index distinguishes AHP from other methods. Overall, AHP is considered a well-known approach due to its straightforward and easily-understood procedure, and its main power lies in the weighting of several factors at the different levels of the hierarchy. Consequently, priorities, also known as weightings, and a consistency ratio (CR) – CR ideally less than 10 % – result from using the fundamental 1–9 AHP scale factor (Goepel, 2018; Saaty, 1990). Equation (1) enables the aggregation of the values dependent on different indicators to establish the global SI (V). V_i (x_i) is a VF that determines the preferences allocated to each value; V_i is derived by Equation (2), and λ_i is the aforementioned corresponding weight.

$$V = \sum \lambda_i \cdot V_i(x_i) \tag{1}$$

V_i (x_i): Value functions of indicators, criteria, and requirements.

λ_i: Weights of indicators, criteria, and requirements.

Equation (1) is the general formula, which is applied to each DT level. In this equation, factor λ_i refers to indicators, criteria, and requirements weights when calculating criteria values, requirements values, and global sustainability indexes, respectively. It should be emphasized that – when considering different weights received from the experts – the coefficients of variation (CVs) of each λ_i did not exceed 10 %, except for the outliers that were initially rejected. Thus, the mean values of λi were used throughout the sustainability analysis. In this way, (1) the contribution of the experts, and (2) using the AHP method, alongside considering the local condition and relevant previous studies, the quality of the data and indicators is certified in three rounds of defining, refining, and weighting.

On an a-dimensional scale of 0 to 1 as the lowest and highest degree of satisfaction representation, VFs unify indicators' units (Pons and de la Fuente, 2013). This approach provides the magnitude, intended to indirectly measure the satisfaction level, homogenize indicators units, and normalize variables to enable aggregation of indicators. As depicted in Fig. 2, VFs can take on a variety of forms (Alarcon et al., 2010), including (1) concave (Cv: satisfaction levels may rise quickly or fall slowly); (2) linear (L: the satisfaction trend is steadily increasing/decreasing); (3) convex (Cx: in contrast to the situation of a concave curve); and (4) S-shaped (S: a concave and convex function combination).

The general expression of the MIVES VF (Vi) is shown in Equation (2), which allows for the evaluation of each indicator's value.

$$V_i = A + B \cdot \left[1 - e^{-K_i \cdot (|X_{ind} - X_{min}|/C_i)^{P_i}}\right] \tag{2}$$

Where A is the response value X_{min} – generally $A = 0$ – and B is the factor obtained by Equation (3), which keeps the function's value within (0.00, 1.00) corresponding to the lowest and highest satisfaction degree as a comparable and unifiable a-dimensional (unitless) scale, though X_{min} and X_{max} for each indicator are initially measured by its relevant specific unit. The definitions for other parameters are presented in Table 1 (Pons et al., 2016; Pons and de la Fuente, 2013; de la Fuente et al., 2016; Alarcon et al., 2010).

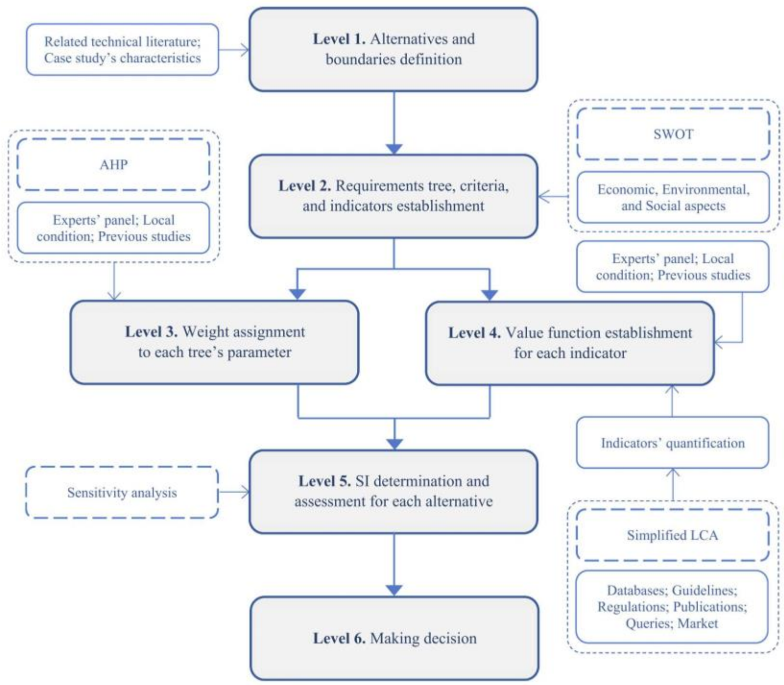


Fig. 3. Sustainability assessment MIVES-based model process

Table 2
Module efficiency and fill factor performance (Source: Solar cell efficiency, Ver. 55, 2020 (Green et al., Jan. 2020)

Classification	Efficiency (%)	Fill factor (%)	Test Centre	Description
m-Si	24.4 ± 0.5	80.1	AIST	Kaneka
p-Si	20.4 ± 0.3	77.2	FhG-ISE	Hanwha Q Cells
a-Si	12.3 ± 0.3	69.9	ESTI	TEL Solar, Trubbach Labs
CdTe	19.0 ± 0.9	76.6	FhG-ISE	First Solar
CIGS	19.2 ± 0.5	73.7	AIST	Solar Frontier
Nano c-Si	12.3 ± 0.3	69.9	ESTI	TEL Solar, Trubbach Labs
DSSC	11.9 ± 0.4	71.2	AIST	Sharp
OSC	8.7 ± 0.3	70.4	AIST	Toshiba

$$B = 1\Big/\left[1 - e^{-K_i \cdot (|X_{max} - X_{min}|/C_i)^{P_i}}\right] \quad (3)$$

A comprehensive and more extensive explanation of the MIVES method is available in the specific references concerning its conceptual formulation (Pons et al., 2016; Alarcon et al., 2010). At the same time, the contribution of MIVES to establish the proposed new tool in this study is served in the corresponding following section (3.3). Notable, in section 3.3 (subsection 3.3.2 for indicators' quantification), an assistant method for the evaluation of environmental performance is incorporated into the model. This supplementary method is a simplified LCA – based on ISO 14040:2006 and ISO 14043:2006 standards (I. O. for Standardization, Environmental management: life cycle assessment; Principles and Framework. ISO, 2006; Lecouls, 1999) – applied previously in other MIVES models as well (Pons and Aguado, 2012; Hosseini et al., 2019; Hosseini et al., Oct. 2021). Additionally, in the final step in this model's application, a sensitivity analysis to examine the obtained outcomes is required. This ultimate analysis considers different scenarios based on the variety of weighting distributions leading to robust proof for the designed model. The procedure to implement the sustainability assessment MIVES-based model in the current study is presented in Fig. 3.

3. Results

3.1. Initial analysis

3.1.1. PV technology

PV includes all technologies capable of capturing solar energy to directly generate electricity. The photovoltaic effect absorbs photons and releases free electrons through a light-absorbing material presented within the cell structure. Sunlight transmits needed energy to electrons when striking a PV cell, thus raising their energy level and releasing them. Consequently, the built-in potential barrier in cells acts on such electrons to generate a voltage. Finally, power generation is achieved by using solar PV modules comprised of several cells containing photovoltaic materials (Shukla et al., 2016; Sathe and Dhoble, 2017; Parida et al., 2011). PV history returns to Alexandre-Edmund Becquerel's observation in 1839 – and similar research by other scientists after several decades –, but it was the late 1940 s when the first generation of solar cells developed the industrial approach to achieve efficiency of 6 %, using solid-state devices (Chapin et al., 1954). Solar systems' output power efficiency depends on solar radiation intensity, total horizontal irradiance on the screen surface, and ambient temperature. In addition, this efficiency is affected by panel surface area, electronic converter efficiency, and solar cell efficiency, which also diminishes linearly over time (Firouzjah, 2018; Fthenakis, 2011). The upward development of PV technology aims to improve cells' efficiency and also to optimize modules' production costs. In order to make this technology more feasible for a variety of applications, the current deployment of solar energy also aims to improve PV environmental quality (El Chaar, 2011). Hence, the environmental benefits of PV technology, especially its impact on CO_2 emissions, have been investigated by many researchers such as Pinel et al. (2021), Fu et al. (2015), Cucchiella et al. (2015), and Moran and Natarajan (2015).

While the attempt to develop and improve this kind of energy collector is advancing, different solar cell types are available in the industry. These cells are mainly comprised of (1) crystalline, (2) thin film, (3) nanotechnology, and other emerging technologies (El Chaar, 2011), as described in Appendix B. Table 2 presents the efficiency and fill factor data from recorded terrestrial modules related to some PV types, which are considered crucial positive parameters to define the module performance that can contribute as a factor to selecting the most suitable PV type in the next step. Efficiency is the ratio of the highest power (that solar PV can generate) to the input power (from the sunlight radiation), which determines a solar panel's capacity to convert light energy to electric energy. Fill factor is the ratio of maximum power to the theoretical power (from the product of voltage and electric current), which shows the actual highest achievable power. These parameters are measured under the global AM1.5 spectrum at standard test conditions (STC, 1.0 kW/m^2 of solar radiation, 25 °C of ambient temperature, and 1.5 m/s of wind speed) (Sathe and Dhoble, Sep. 2017; Green et al., Jan. 2020; Zabihi Sheshpoli et al., Feb. 2021). However, the actual efficiencies during the operation phase would be less than these laboratories recorded amounts.

Overall, generating electricity via PV solar system enables more than 80 % emissions reduction compared with grid non-solar electricity. Conventional grid electricity sources consume much primary energy in the production, transmission, and distribution processes (Fthenakis et al., Mar. 2008; Kannan et al., May 2006).

3.1.2. PV/T technology

PV/T concept is based on that most incident sunlight on solar cells is converted into heat; Thus, the basic idea of PV/T systems is to use this waste heat from solar cells (Good et al., May 2015; Good, Mar. 2016). The first studies on PV/T technology were conducted in the mid-1970 s, and since then, several different concepts and ideas have been studied in this area (Sathe and Dhoble, Sep. 2017; Saurabh et al., Feb. 2020; Good et al., May 2015; Good, Mar. 2016). Due to the incremental demand for electricity and heat worldwide, PV/T technology has come out as a considerable research area in recent years. A PV/T unit generates electrical and thermal energy simultaneously from a combined system. Considering that high temperature may damage PV materials and decrease electrical conversion efficiency, thermal collectors can reduce PV modules' temperature and consequently enhance solar cell durability and improve power generation efficiency as well (Diwania et al., Mar. 2020; Jia et al., Mar. 2019; Sathe and Dhoble, Sep. 2017; Good et al., May 2015). Appendix C presents different types of PV/T systems.

Since both electrical and thermal energy are expected to be produced from PV/T simultaneously, the total efficiency (E_T) is needed to determine the system's capacity in converting light energy to electrical and thermal. To this end, E_T is obtained from the aggregation of electrical efficiency (E_{ele}) and thermal efficiency (E_{th}). E_{ele} and E_{th}, respectively, are the ratio of the highest electrical energy and thermal energy that PV/T can generate to the input energy from the sunlight radiation. Equation (4), commonly used in the literature (Diwania et al., Mar. 2020; Saurabh et al., Feb. 2020) , shows the E_T formula.

$$E_T = E_{ele} + E_{th} \tag{4}$$

The high temperature of solar cells decreases their electrical efficiency as far as the increase in PV cell temperature – higher than 25 °C – causes a nearly 0.45 % decrease per °C (Jia et al., Mar. 2019; Sathe and Dhoble, Sep. 2017; Saurabh et al., Feb. 2020). Consequently, E_{ele} increases by cooling PV, whereas – according to Equation (4) – this increment results in E_T simultaneous improvement (Barone et al., Jul. 2019). Additionally, hybrid PV/T systems efficiency is also affected by some other factors such as radiation intensity, ambient temperature, wind velocity, humidity, fluid flow rate, PV type, cooling fluid type, packing factor, system dimensions, components material, and coolant temperature (Diwania et al., Mar. 2020; Jia et al., Mar. 2019; Al-Waeli et al., Sep. 2017).

PV/T technology has a lot of potential including a remarkable improvement in its total energy efficiency. Compared to combinations between PV and thermal systems, PV/T brings: space usage optimization, roof architectural uniformity, installation cost and time reduction, smaller raw materials consumption, and low maintenance requirements. However, it has important drawbacks such as: high initial cost, limited commercial and market potential, low degree thermal output, lack of energy generation stability – during all seasons and times –, and weakness of benefits awareness. Overall, in case of overcoming present challenges, this clean technology could become an appropriate potential source to fulfil electricity and heat demand as two basic energy needs worldwide (Diwania et al., Mar. 2020; Barone et al., Jul. 2019; Jia et al., Mar. 2019; Sathe and Dhoble, Sep. 2017; Huide et al., May 2017).

3.1.3. Solar system application in buildings

According to the International Energy Agency report (IEA, 2016), the building industry accounted for approximately-one-third of global energy use and one-fifth of global GHG emissions. In this sense, solar-energy application maturity could be an opportunity to transform buildings from energy consumers into active energy producers (Zhang, Nov. 2018; Good et al., May 2015; Huide et al., May 2017; Oecd, 2016).

The application of solar PV technology in the building sector started in the 1970 s, installing aluminum-framed modules on rooftops in distant places where there was no access to electric power infrastructure. After around one decade, installing solar PV modules on buildings' roofs emerged, which were usually grid-connected buildings in centralized power station areas (Shukla et al., Sep. 2016). These systems are rated in peak kilowatts (kWp), which determines the amount of expected delivery of electrical power in case the sun is directly located overhead on a clear day. PV system components are mainly comprised of cells, connections, and means of modifying the output electricity (Parida et al., Apr. 2011). Laminated cells are commonly encapsulated between a protecting glass cover and a backplane made of aluminum alloy (Jia et al., Mar. 2019). An active PV/T system to supply Domestic hot water (DHW) mostly consists of PV components, a blackened thermal absorber surface, copper coil tubes, a thermal insulation layer, and ethylene–vinyl acetate (EVA) copolymer used as adhesive. The working fluid flows through tubes to transport thermal energy for preheating water, with the help of a circulation pump (Jia et al., Mar. 2019; Huide et al., May 2017). Solar cell systems applied to the building industry are generally categorized into two groups: (1) called off-grid or stand-alone – which is commonly suitable for remote areas without access to the electricity grid – and (2) named on-grid or utility-interactive. On-grid systems are small solar power plants composed of a PV array, which is a full power generation system made up of numerous photovoltaic panels and modules. These on-grid systems feed the produced power to the grid – to earn the FIT compensation – by metering devices after converting the electricity via an inverter (Firouzjah, Oct. 2018). This inverter converts the direct current power produced by the PV array into alternating current power consistent with the utility grid voltage and power quality requirements.

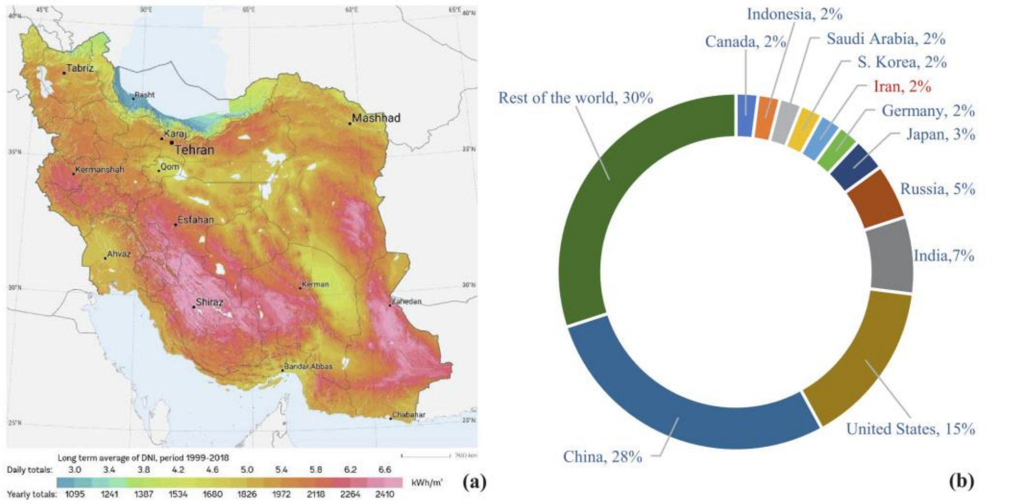


Fig. 4. **(a)** Solar GIS map for direct normal irradiation (DNI–kWh/m^2) ("Solar resource maps and GIS data for 200+ countries | Solargis." https://solargis.com/maps-and-gis-data/download/iran (accessed Apr. 08, 2021); **(b)** Share of global CO_2 emission (2018) ("Each Country's Share of CO2 Emissions | Union of Concerned Scientists." https://www.ucsusa.org/resources/each-countrys-share-co2-emissions#.W2RDa9L-g2x (accessed Apr. 08, 2021) (Tehran latitude: 35°N, longitude: 51°E, altitude: 900–1800 masl)

On the other hand, buildings can contribute to the utilization of PV/PVT technology via two different approaches: (1) building attached (add-on) photovoltaic/thermal-photovoltaic (BAPV/BAPVT) – mostly added on top of existing roofs –, and (2) building integrated photovoltaic/thermal-photovoltaic (BIPV/BIPVT) (Shukla et al., Sep. 2016; Debbarma et al., Jun. 2017; Peng et al., Dec. 2011). BIPV/BIPVT is the integration of PV/PVT systems into building envelopes such as facades, roofs, and canopies. In other words, the BIPV/BIPVT modules as a part of building elements serve the dual function of energy generation while replacing conventional building skin parts (Azami and Sevinç, Jul. 2021; Shukla et al., May 2016). In comparison to BIPV/BIPVT over BAPV/BAPVT modules, BIPV/BIPVT efficiency is lower; since it is usually made of thin-film technology (TF), which has lower efficiency over Silicon crystalline (c-Si). Moreover, it is difficult and more expensive to retrofit older buildings with BIPV/BIPVT considering their higher module costs and higher labour charges for installation. However, BIPV/BIPVT is more aesthetically pleasing, enables applications in different parts of buildings' skin, and can reduce building materials consumption (Shukla et al., Sep. 2016; Peng et al., Dec. 2011; Petter Jelle et al., May 2012).

To achieve the best efficiency, the PV array definition considers climatic and environmental issues. Energy production increases on cold and clear days, while hot and cloudy days reduce PV array output. Arrays in dry, dusty, and heavily polluted environments require washing to avoid an efficiency decrease. While the proper angle of panels can usually remove snow loads. Besides, surfaces reflecting light such as snow can contribute to increasing output efficiency. Therefore, location and orientation are other effectual issues. Thus, proper solar system applications avoid shade cast by nearby obstacles, for instance, buildings and trees, especially during the peak solar radiation collection period. The most important effect of shading results in the prevention of receiving maximum exposure to the sun – and consequently, energy efficiency losses – that occur in the case of horizontal shading (Korsavi et al., Feb. 2018). Moreover, tilted arrays can generate 50 %-70 % more electrical energy than vertical facades (Shukla et al., Sep. 2016). Notable, making a separation between panels and nearby walls can increase efficiency via creating air circulation to move heat away from solar cells (Baljit et al., Nov. 2016).

Approximately 40 % of PV installation worldwide is on buildings, and deployment on residential buildings is so significant that many countries adopt encouragement policies to support residential rooftop PV development (Pvps, 2017; Masson et al., 2016). Also, most PV/T systems are applied on buildings, and in consequence, edifices are recognized as the most suitable application area for PV/T technology. This application can provide a path toward NZEB due to the supply of both electricity and heat demand (Barone et al., Jul. 2019; Saurabh et al., Feb. 2020; Huide et al., May 2017) , especially when the available space for installation is limited and compact, like in urban residential buildings (Sathe and Dhoble, Sep. 2017; Good et al., May 2015; Huide et al., May 2017).

3.2. Specific analysis

3.2.1. Characterization of the area under study

Tehran is one of the western Asiatic most densely populated megacities (Brinkhoff, 2011) with 8.8 million citizens and up to 15 million inhabitants considering the whole metropolitan area. Although precise definitions of megacity vary between different sources, the definitions are based on the area's population. For instance, the United Nations Department of Economic and Social Affairs classified urban agglomerations with at least 10 million inhabitants as megacities ("World Urbanization Prospects - Population Division - United Nations." https://web.archive.org/web/, 2022), and the Bonn University report stated that megacities are metropolitan areas have populations of over 10 million (Kötter and Friesecke, 2009). This study follows the aforementioned references. Tehran has a land area of 615 square kilometers and is located in the north of Iran (35°N, 51°E), at high altitudes from around 900 to 1,800 m above sea level ("Tehran Municipality Information and Communication Technology (ICT) Organization." https://tmicto.tehran.ir/ (accessed Jul. 02, 2021). The average daily solar radiation is 5.3 kWh/m^2 (Fig. 4a), while mean temperatures in winter and summer times are 7 °C and 29 °C respectively, relative humidity is 23–66 %, and wind means speed is 3 m/s with a dominant direction from west to east (Tehran Province Meteorological Administration." http://www.tehranmet.ir/Index.aspxtempname=englishlang=1sub=0 (accessed Nov. 19,

Table 3
Summarized comparison between BAPV/BAPVT and BIPV/BIPVT

	Potentials	Drawbacks
BAPV/BAPVT	High efficiency Suitability to be used on existing roofs Minor initial costs Easy to install, replace, repair, and expand Ability to be disassembled Potential to move its array Diversity and abundance of modules on the market	High building materials consumption Application in buildings limited to their roofs Aesthetic aspect weakness and design limitation
BIPV/BIPVT	Greater aesthetic potential: pleasant, integrated Potential to be used in different buildings parts Low building materials consumption Double function: building element & energy generator	Low efficiency Difficult and costly to apply in existing buildings High module costs and high labour charges Less suitability for flat roofs More complexity Limited access to service due to narrow market

2020).

Population growth, industrialization, urbanization, and increases in fossil fuel use are the most critical aspects connected to air pollution in Tehran. Besides, the temperature inversion phenomenon is added to air pollution problems since Tehran is bordered by a high mountain range that retains pollutants in the air, particularly during the cold months (Heger and Sarraf, 2018). The previous study embraced extensive information concerning air pollution in Tehran (Banirazi Motlagh et al., 2021). Accordingly, Particulate Matters (PMs) are accounted for the most critical air pollutants in this specific case study (Tehran Annual Air and Noise Quality Report, period of March, 2020 - March 2021). Apart from available detailed explanations via the former research project, Appendix F presents a brief image with this respect in the current study.

3.2.2. Potentials of the case study

Iran has great potential for solar radiation, with almost 300 sunny days available on two-thirds of its land. In Iran the annual average daylight duration is 2800 h, and its solar radiation is on average 1800–2200 kWh/m^2 (Fig. 4a), higher than the global average (Firouzjah, Oct. 2018; Korsavi et al., Feb. 2018; Najafi et al., Sep. 2015; "Solar resource maps and GIS data for 200+ countries | Solargis." https://solargis.com/maps-and-gis-data/download/iran (accessed Apr. 08, 2021; Motahar and Bagheri-Esfeh, Jun. 2020). On the other hand, Iran with 0.72 GT of CO_2 emissions – in 2018 – is ranked 7th among the highest emitters worldwide (Fig. 4b), and 30th among the high electrical energy consumer countries. The main provider sources of electrical energy are fossil fuels (94 %), while hydro generates nearly 6 % and other renewable energy resources produce less than 1 % (Korsavi et al., Feb. 2018). As shown in Fig. 4, the abundance of solar energy and the high energy demand – resulting in excessive CO_2 emissions –, makes it advisable to develop solar energy production in Iran.

The Iranian government has prioritized renewable energy development and CO_2 emission reduction as key goals within its fifth five-year (articles 133, 138, and 139) and sixth five-year (article 50) development plan frameworks ("Renewable Energy and Energy Efficiency Organization." http://www.satba.gov.ir/en/home (accessed Feb. 10, 2021). In this regard, some adopted support policies to develop PV technologies are: (1) revised FIT, (2) national development funds by allocating oil and gas revenues to finance renewable energy projects, (3) budget to purchase electrical energy from renewable resources, and (4) job creation support in this field (Korsavi et al., Feb. 2018; Gorjian et al., May 2019; Asakereh et al., Oct. 2017). However, in Iran, there is still no incentive plan for solar thermal energy generation from PV/T systems. The most common short-term support strategies could be investment subsidies, tax cuts for renewable energy, carbon taxes on fossil fuels, and governmental loans (Firouzjah, Oct. 2018; Jalilzadehazhari et al., Mar. 2021). Moreover, regardless of some involved issues like Load Factor – as a measure of the utilization rate or efficiency of electrical energy usage defined by dividing the average load by the peak load in a specified period – in a recent encouragement action, Renewable Energy and Energy Efficiency Organization (SATBA) has provided a power purchase agreement model with private investors, which guarantees to purchase domestic solar-based electricity for at least 20 years. This guaranteed electricity purchase tariff for domestic solar power plant's capacity up to 20 kW was 10,400 Rials per kWh in 2020 – and regularly updates every year corresponding to the inflation official rate –, which is almost ten times larger than the typical selling tariff to subscribers ("Renewable Energy and Energy Efficiency Organization." http://www.satba.gov.ir/en/home (accessed Feb. 10, 2021).

Apart from the aforementioned solar potentials in this case study, Tehran residential rooftops provide great potential in this regard, as described in detail in the former study (Banirazi Motlagh et al., 2021).

3.2.3. Specifications in this study

This subsection analyses solar systems' main features for the application of these systems in residential buildings, based on Tehran conditions and facilities, codes, and policies. In this sense, this study focuses on BAPV/BAPVT systems instead of BIPV/BIPVT because of the following main reasons: (1) Tehran's mostly flat rooftops ("Tehran Municipality Information and Communication Technology (ICT) Organization." https://tmicto.tehran.ir/ (accessed Jul. 02, 2021) could not take advantage of BIPV/BIPVT capability of adapting to more irregular surfaces such as complex shaped façades and pitched roofs; (2) as previously said, BIPV/BIPVT have lower efficiency due to their TF; (3) BAPV/BAPVT are better candidates for roof refurbishment and existing buildings (Jia et al., Mar. 2019; Shukla et al., Sep. 2016). Table 3 presents a general comparison between BAPV/BAPVT and BIPV/BIPVT.

Grid-connected solar generators are frequently adopted in buildings, and more than 90 % of the total PV systems are on-grid (Firouzjah, Oct. 2018). This study takes into account on-grid small-scale power plants instead of stand-alone/off-grid ones due to the following reasons: (1) favourable Iranian government policies, incentives, and subsidies ("Renewable Energy and Energy Efficiency Organization." http://www.satba.gov.ir/en/home (accessed Feb. 10, 2021), as the largest probable drivers for solar installations development (Good et al., May 2015), concern on-grid systems; (2) needless for additional equipment – such as storage system, backup generator or electricity regulator –, which would make solar PV systems installation and maintenance more expensive and intricate; (3) avoiding mandatory size for PV system – to meet the peak demand energy production of the building –, as well as no need to provide the appropriate extra space to keep supplementary equipment, especially for existing buildings (Shukla et al., Sep. 2016). This project focuses on mono-crystalline (m-Si) technology for PV systems because it is: (1) the most commonly available in the market (Sathe and Dhoble, Sep. 2017; "IHS Markit - Leading Source of Critical Information," IHS Markit. https://ihsmarkit.com/index.html (accessed Mar. 05, 2021) ; (2) achievement of the highest performance among all PV types in terms of efficiency and fill factor (Green et al., Jan. 2020; Tomar et al., Jun. 2018) , as described in detail in section 3.1.1 and Table 2; and (3) appropriately durable and cost favourable (Shukla et al., Sep. 2016).

Table 4
SWOT preliminary analysis of BAPV and BAPV/T utilization for residential buildings in Tehran

(Strengths, Weaknesses, Opportunities, Threats)	
S	**S1.** Solar irradiance abundance in Tehran due to the climatic condition (Firouzjah, Oct. 2018; Korsavi et al., Feb. 2018)
	S2. Energy bill and financial savings via self-sufficiency (Shukla et al., Sep. 2016; Fikru, Apr. 2020; Fikru, Nov. 2019;Fikru, May 2019)
	S3. Governmental policies, incentives, and subsidies for solar system utilization (Good et al., May 2015; "Renewable Energy and Energy Efficiency Organization." http://www.satba.gov.ir/en/home (accessed Feb. 10, 2021)
	S4. Low operation and maintenance cost (Diwania et al., Mar. 2020; Jia et al., Mar. 2019; Firouzjah, Oct. 2018; Parida et al., Apr. 2011; Al-Waeli et al., Sep. 2017)
	S5. Building revitalization and the use of vast amounts of unused space (Aslani and Seipel, Jan. 2022; Sathe and Dhoble, Sep. 2017; Huide et al., May 2017)
	S6. Fast and upward technological advancement to improve efficiency and reduce the cost of modules (Shukla et al., Sep. 2016; El Chaar, 2011)
	S7. Combination possibility with other energy producer installations in buildings
—	**S8.** Facile installation due to be a modular system
W	**W1.** High initial capital costs (Diwania et al., Mar. 2020; Jia et al., Mar. 2019; Korsavi et al., Feb. 2018; El Chaar, 2011)
	W2. Efficiency reduction by overheating, shading, dust, and pollutants (Diwania et al., Mar. 2020; Barone et al., Jul. 2019; Shukla et al., Sep. 2016; Good et al., May 2015; Huide et al., May 2017)
	W3. Unstable energy production and limited energy generation during sunny days (Sathe and Dhoble, Sep. 2017; Huide et al., May 2017)
	W4. Vulnerability of modules against mechanical and physical damages (Diwania et al., Mar. 2020; Jia et al., Mar. 2019; Good et al., May 2015)
	W5. Interference with chimneys and traditional water coolers mostly installed on the roofs in Tehran
O	**O1.** Air pollution and GHG emissions reduction as well as being no direct emission technology (Fazelpour et al., May 2016; Korsavi et al., Feb. 2018; Adam and Apaydin, Jan. 2016; Coughlin and Kandt, 2011)
	O2. More saving of primary energy resources and fossil fuels (Johnsson et al., Feb. 2019; Abas et al., May 2015;Bauer, May 2016)
	O3. Free abundant and inexhaustible renewable energy to supply a steady increment of energy demand (Barone et al., Jul. 2019; Sathe and Dhoble, Sep. 2017; Mishra and Tiwari, Jan. 2020)
	O4. Generation of two basic and largest energy demands worldwide i.e., electricity and heat (Korsavi et al., Feb. 2018; "Heating - Fuels Technologies - IEA." https://www.iea.org/fuels-and-technologies/heating (accessed Mar. 30, 2021)
	O5. Downsizing the central equipment and reduction of transition/distribution costs and losses of energy (Seepromting et al., 2020; Sadeghi and Kalantar, 2013; Shukla et al., Sep. 2016)
	O6. Management of peak electricity demand (reduction of power failures on hot days) (Jia et al., Mar. 2019; Sadeghi and Kalantar, 2013; Sathe and Dhoble, Sep. 2017; Parida et al., Apr. 2011; Al-Waeli et al., Sep. 2017)
	O7. Contribution to the creation of jobs and the development of new jobs (Korsavi et al., Feb. 2018; Gorjian et al., May 2019)
	O8. Environmental knowledge support (Roberts et al., Apr. 2019)
T	**T1.** Considerable energy consumption and carbon footprint during solar cells manufacturing (Korsavi et al., Feb. 2018)
	T2. High subsidized energy price in Iran, discourages private sectors from investing in solar systems (Korsavi et al., Feb. 2018; Gorjian et al., May 2019)
	T3. Public awareness weakness, insufficient national standards & building codes (Sathe and Dhoble, Sep. 2017; Korsavi et al., Feb. 2018; Gorjian et al., May 2019; "Enabling PV Iran," German Solar Association – BSW-Solar / Bundesverband Solarwirtschaft e.V, Berlin, Germany, (Förderkennzeichen-FKZ): ZMVI6-, 2016; Roberts et al., Apr. 2019)
	T4. Limited access to international finance and high inflation rates in Iran (Korsavi et al., Feb. 2018; "Enabling PV Iran," German Solar Association – BSW-Solar / Bundesverband Solarwirtschaft e.V, Berlin, Germany, (Förderkennzeichen-FKZ): ZMVI6-, 2016)
	T5. Probability of aggravating the Urban Heat Island effect (Masson et al., Jun. 2014; Brito, May 2020)

Additionally, the solar system in this research project is considered a flat plate due to its: (1) higher availability on the market; (2) lower initial and maintenance cost; (3) uncomplicated mechanism compared to concentrator collectors (Diwania et al., Mar. 2020; Jia et al., Mar. 2019; Good et al., May 2015). For this case study, the researchers preferred the water-based PV/T system compared to the air-based type, because: (1) a water-based PV/T system obtains higher total efficiency (Barone et al., Jul. 2019; Sathe and Dhoble, Sep. 2017; Saurabh et al., Feb. 2020; Good et al., May 2015) ; (2) is more common (Sathe and Dhoble, Sep. 2017; Good et al., May 2015) ; and (3) provides ongoing DHW during the year (Jia et al., Mar. 2019). In this context, this study discards covered PV/T systems and considers uncovered systems because of their following strengths: (1) total efficiency; (2) affordability; (3) durability; (4) availability on the market (Diwania et al., Mar. 2020; Good et al., May 2015; Good, Mar. 2016). It is noted that though bifacial solar panels, which can produce electricity from reflective light too, are considered an emerging technology to increase efficiency, their feasibility is not approved for this specific case study due to their high capital costs and unavailability in the Iranian market.

Notable, as pointed out before, the value of delivered energy is inversely related to the system's lifetime (El Chaar, 2011). Project expectancy lifetime is assumed to be 25 years on average considering literature and typical module warranties (Fazelpour et al., May 2016; Korsavi et al., Feb. 2018; Good, Mar. 2016; "Renewable Energy and Energy Efficiency Organization." http://www.satba.gov.ir/en/home (accessed Feb. 10, 2021; Dehghan et al., Jun. 2021). Normally, a linear degradation is assumed for the mature PV technologies reaching 80 % of the initial efficiency at the lifetime end – on average, 0.7 % decrease per year – (Fthenakis, 2011; Toboso-Chavero, Aug. 2019; "Enabling PV Iran," German Solar Association – BSW-Solar / Bundesverband Solarwirtschaft e.V, Berlin, Germany, (Förderkennzeichen-FKZ): ZMVI6-, 2016). According to Iranian requirements and policies, the minimum efficiency of Silicon crystalline PV modules is expected to be 16 %. Additionally, the output power capacity of modules (Wp) must be at least 90 % of the initial power during the first ten years of operation, and the minimum Wp can be 80 % afterwards. Besides, considering technical and security issues regarding the connection to the grid, the maximum allowed capacity for the subscribers' allocated generators is up to twice their connection capacity – and will be a maximum of 100 kW ("Renewable Energy and Energy Efficiency Organization." http://www.satba.gov.ir/en/home (accessed Feb. 10, 2021). Thus, this study considers a 5-kWp solar system because it is compatible with most residential buildings in Tehran that utilize at least a 25A monophase connection, which results in around 5.5 kW capacity. Since the maximum absorption of radiated energy is in the case of perpendicularity to the irradiant source (Firouzjah, Oct. 2018), PV arrays are usually mounted at nearly the location latitude angle towards the south to achieve optimum performance throughout the year (Korsavi et al., Feb. 2018). However, the precise optimum angle will vary from season to season depending on the solar radiation angle. Typical adjustable structural supports employ hot galvanized iron bars fastened to solar panels and assembled using bolts and screws. The minimum distance between the roof edge and solar panels should be 1 m ("Renewable Energy and Energy Efficiency Organization." http://www.satba.gov.ir/en/home (accessed Feb. 10, 2021).

To sum up, the boundaries and main specifications for the current project in Tehran employ the (1) BAPV/BAPVT, (2) on-grid, (3) flat plate system composed of (4) m-Si PV panels, and (5 & 6) water-based & uncovered PV/T, (7) for residential utilization, (8) during a projected 25 years lifetime. This study considers the PV panel model TBM72-385 M – from the Iranian manufacturer certified by SATBA and a 25 years warranty. This panel consists of 72 cells with 19.8 % efficiency, dimensions of 1956 × 992 × 40 mm, and 22 kg weight. The studied PV array consists of 13 panels with 385 Wp to supply a 5-kWp domestic power plant. The thermal collector attached to the backside of a module with, on average, 50 % efficiency presumed at STC (Ibrahim, 2009; Jahromi et al., Aug. 2015; Zondag et al., Mar. 2003); consists of a copper absorbing plate, copper fluid flow pipes – 1.25 cm risers at every 10 cm plus two 2.5 cm headers, welded to the absorber plate –, 50 mm thickness of polyurethane (PUR) as thermal insulation, and 1 mm galvanized iron as a back end cover. Total area of solar panels is 25.2 m^2.

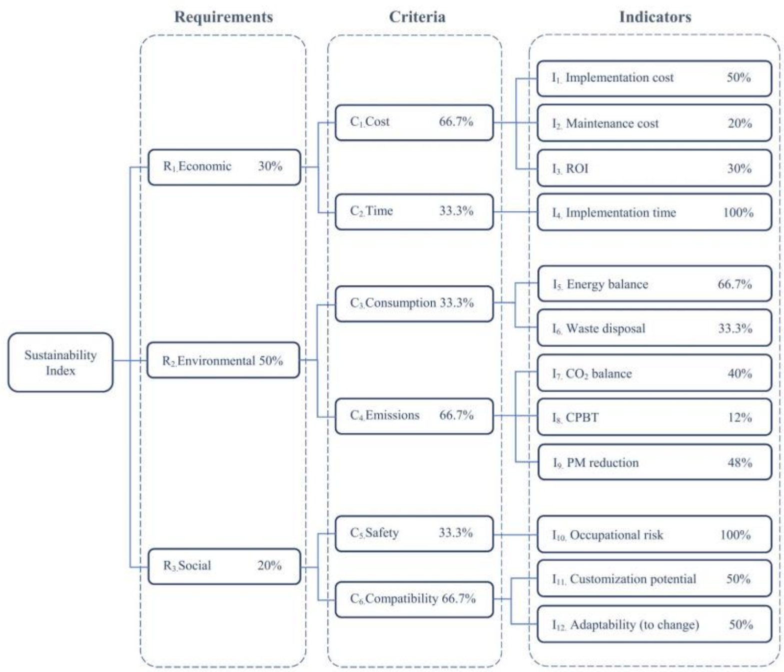


Fig. 5. General DT for this sustainability assessment model (*ROI: Return on Investment, CPBT: CO_2 payback time, PM: Particulate Matter)*

3.3. Sustainability assessment model

3.3.1. Elementary outcomes

Table 4 presents the SWOT matrix that analyses the feasibility of BAPV and BAPV/T for residential buildings in Tehran based on a simplified literature review as well as experts' panel contributions. These elementary outcomes can assist to define DT components and weightings in the next section. Despite the high initial capital cost and considerable energy consumption during the manufacturing process, the use of solar systems in Tehran's residential buildings might be suggested as proper practice. This happens because, as previously said, this city faces critical air pollution, high energy demand, and great potential for solar irradiance.

3.3.2. Decision tree definition

This study DT is based on the aforementioned MIVES general approach for urban rooftop alternatives towards better urban air quality. This DT planning and its indexes' importance determination rely on the authors' experience, experts' contributions during seminars, and a simplified literature review (Pons et al., May 2016; Pons and Aguado, Jul. 2012; de la Fuente, 2019; de la Fuente et al., Jun. 2016). In this research paper, DT is customized and regulated in accordance with the function and characteristics of domestic solar systems. For instance, the Urban Heat Island (UHI) effect indicator, which is a challenging matter of study but a neglectable issue for solar panels' effects on UHI, is not considered in this study since the utilization of solar systems may have different roles in micro/macro climatic changes, affected by different parameters such as energy conversion, making shadow space on the ceil, decreasing domestic fossil fuels combustion, etc. (Masson et al., Jun. 2014; Brito, May 2020). On the other hand, the performance indicator used to evaluate the investment profitability over a time period is maintained, which had been discarded in the previous GR study (Banirazi Motlagh et al., 2021). Overall, it is worth mentioning that the significance of urban air pollution reduction is considered a major effective parameter in DT establishment and its calibration in this study, which plays a key role in the whole process. For instance, the importance of this key performance point specifically affects the defining criteria and indicators – e.g. C_4, I_7, I_8, and I_9 – as well as weight assignment and distribution in DT. As presented in Fig. 5, DT comprises three requirements, six criteria, and 12 indicators and their related weighting coefficients. Economic requirement (R_1) takes into account the investment regarding installation and maintenance for each alternative consisting of two criteria, (C_1) *cost* and (C_2) *time*. Environmental requirement (R_2) investigates the significant environmental impacts of the (C_3) *resource consumption* and (C_4) *emissions* aspects. Social requirement (R_3) considers the (C_5) *safety* and (C_6) *compatibility* for the solar systems in residential buildings.

Criterion *cost* (C_1) embraces three indicators: (I_1) *Implementation cost*, (I_2) *Maintenance cost*, and (I_3) *Return on Investment* (ROI). (I_1) *Implementation cost* takes into account the costs of domestic solar systems assembly. I_1 includes panel pieces, electrical and mechanical accessories, and connections costs, as well as labour and skilled workers' salaries. I_1 data has been obtained from price lists available from solar retailers, provider companies, and contractors. However, the PV/T market is still very limited (Good et al., May 2015), especially in Iran. Ultimately, the average capital cost to mount each square meter of this solar system has been estimated. (I_2) *Maintenance cost* encompasses costs of expected activities during the alternatives 25 years' life service, such as cleaning of panels' surface, inspection, and accessories replacement, for instance, inverter renovation every 10 to 15 years (Fazelpour et al., May 2016; "Enabling PV Iran," German Solar Association – BSW-Solar / Bundesverband Solarwirtschaft e.V, Berlin, Germany, (Förderkennzeichen-FKZ): ZMVI6-, 2016). Annual operation and maintenance cost is commonly assumed on average 1 % of total initial costs

(Dehghan et al., Jun. 2021; "Enabling PV Iran," German Solar Association – BSW-Solar / Bundesverband Solarwirtschaft e.V, Berlin, Germany, (Förderkennzeichen-FKZ): ZMVI6-, 2016). (I_3) *ROI* as a financial ratio approximates the efficiency of investment over the 25-year service time of the PV panels via Equation (5). This estimation is based on assuming continuous solar radiation over the day hours at an average value to disregard the effect of shading at STC. In this regard, assuming the average daily solar radiation, the climatical shading effect – like cloudy times – is considered, while as mentioned in section 3.1.3, prevention of physical shading should be considered in locating the panels on the roof to minimize the difference between the actual situation and the theoretical estimation.

$$(Net\ profit\ /\ Total\ investment\ costs) \times 100 \tag{5}$$

Where *Net profit* is guaranteed electricity purchase tariff for domestic solar power plant and *Total investment costs* result from adding initial and operating costs. According to the International Renewable Energy Agency (IRENA) report ("Renewable Power Generation Costs in, 2020), the Weighted Average Cost of Capital (WACC) has improved and declined, especially in the recent decade due to very low-risk premiums for equity and debt in mature renewable markets. Based on the IRENA report (renewable power generation costs in 2020) ("Renewable Power Generation Costs in, 2020), though WACC for non-OECD countries – except for China – is considered 7.5 % for utility-scale renewable power generation technologies, this factor is assumed at 5 % for residential solar PV systems due to lower expected returns required by the owners in this sector, in which self-consumption is often a significant driver. The Iranian Central Bank's official rate is used to determine the exchange rate from Rials to Euros (Central Bank of the Islamic Republic of Iran, 2021).

Time (C_2) comprises (I_4) *Implementation time*, generally-one of the considerable economic resources in the building sector. This indicator includes the required hours for installation activities, such as roof fixing, assembly, mounting, cabling, and pipework. The average necessary time to implement BAPV and BAPV/T is three and five working days, respectively, based on the data obtained from the interviewed companies. This information refers to a solar system installation on top of an existing ordinary residential roof by a typical contractor team. A working day is considered to be 8 h long.

Resource consumption (C_3) consists of two indicators: (I_5) *Energy balance* and (I_6) *Waste disposal*. (I_5) *Energy balance* determines the total accessed energy using each square meter of solar panels. To achieve this, one must calculate the difference between the amount of electrical/thermal energy produced via harvesting solar energy during the service life ($E_{production}$), as well as the amount of energy consumed during the manufacturing of PV/PVT panels ($E_{consumption}$). This quantification is derived from Equation (6).

$$E_{balance} = E_{production} - E_{consumption} \tag{6}$$

Energy inventory has been taken from the Inventory of Carbon and Energy (ICE) database included the environmental product declarations (EPDs) database (Hammond et al., 2011). ICE database provides favourable advantages compared to others, and it follows a cradle-to-gate (factory) scope known as module A1–A3 in the EU-wide standards, EN 15804, and EN 15,978 on the construction field sustainability assessment. Electrical and thermal energy production has been estimated considering 5.3 kWh/m^2 as the average daily solar radiation in Tehran (1 kWh = 3.6 MJ) and the efficiency allocated to each system at STC – which also contains the energy loss when the solar systems working – during the 25 years' service time. (I_6) *Waste disposal* considers non-recyclable solid waste materials belonging to each square meter of solar panels at their end of life (EOL). Accordingly, the circular economy concept is taken into account by the current research project in the environmental context. Recycling potential data has been derived from Iranian guidelines ("Environmental, Health and Safety Guideline for Photovoltaic Solar Power Plants, No. 785, Last Edition: 01-11-, 2021) as well as a simplified literature review concerning solar panels and building materials waste assessment ((Faraca and Astrup; Kemona and Piotrowska; Paiano; STEEL IN BUILDINGS AND INFRASTRUCTURE | worldsteel, 2021)). However, there is still considerable photovoltaic waste deposited in landfills, and few studies have assumed panels' disposal at EOL (Souliotis et al., Oct. 2018; Bogacka, Dec. 2020). Modules' recycling approach in Iran is usually based on the separation of metal components, chemical and physical activities to extrude EVA and lamination materials, crushing and separating glass and silicon, and finally carrying out the recycling processes considering the features of these separated materials ("Environmental, Health and Safety Guideline for Photovoltaic Solar Power Plants, No. 785, Last Edition: 01-11-, 2021).

Emissions (C_4) criterion includes three indicators: (I_7) *CO_2 balance*, (I_8) *CPBT duration*, and (I_9) *PM reduction*. (I_7) *CO_2 balance* determines the total avoided CO_2 using each square meter of solar panels. To do so, one must calculate the difference between the amount of CO_2 saved/reduced via renewable energy generation during the service time ($CO_{2\ saving}$), as well as the amount of CO_2 emitted during the fabrication of PV/PVT panels ($CO_{2\ emission}$). This quantification is derived from Equation (7).

$$CO_{2\ balance} = CO_{2\ saving} - CO_{2\ emission} \tag{7}$$

CO_2 emission calculations utilize carbon footprint data obtained from the aforementioned ICE database. Estimation of CO_2 saving potential relies on a simplified literature review. For instance, according to Tripanagnostopoulos et al. (2005), thermal energy production can reduce natural gas consumption to avoid 0.3 kg CO_2/kWh (0.08 kg CO_2/MJ), and the electricity generation from the grid accounted for the emission factor of 0.6 kg CO_2/kWh (0.16 kg CO_2/MJ) (Tripanagnostopoulos et al., May 2005). Another study by Noorpoor and Kudahi (2015) estimated a similar emission factor for Iran (Noorpoor and Kudahi, Jul. 2015). Taking into account the aforementioned fossil fuels-based electricity net in Iran – more than 90 % – and the fact that natural gas accounts for almost 85 % of all fossil fuels utilized in the Iranian electrical energy industry (Jorli et al., Dec. 2017; "Key World Energy Statistics, 2020). (I_8) *CPBT duration* considers one of the most common indicators in environmental studies that evaluate solar systems. The CO_2 payback time (CPBT) indicator defines a rate to determine solar systems' environmental performance. I_8 indicates the probable speed to compensate for the GHG impact in the panels manufacturing process by decreasing CO_2 emission – the most significant GHG ("greenhouse gas | Definition, Emissions, Greenhouse Effect | Britannica." https://www.britannica.com/science/greenhouse-gas (accessed Jun. 13, 2022) – via energy generation. The present study estimates 1.1 and 0.6 years as the CPBT rate for the BAPV and BAPV/T, respectively. This estimation is based on the case study characteristics, national technology, and system efficiency. (I_9) *PM reduction* indicator intends to measure the capacity of each square meter of solar panels to reduce ambient PM via energy production potential. As aforementioned, the most appropriate estimation of avoided PM emission is also via less natural gas consumption for

Table 5
Each indicator VF's parameters and coefficients

Indicator	Unit	Shape	X_{min}	X_{max}	C	K	P
I_1. Implementation cost	€/m^2	DCx	422.8	1115.6	942	0.1	1.6
I_2. Maintenance cost	€/m^2	DS	105.6	278.8	70	0.7	2
I_3. ROI	%	ICv	160.2	353.75	250	2	0.9
I_4. Implementation time	hours	DL	21.5	50	22	0.01	1
I_5. Energy balance	MJ/m^2	ICv	22,309	145,072	83,000	1.2	0.8
I_6. Waste disposal	kg/m^2	DCx	1.08	13.24	7	0.2	2.3
I_7. CO_2 balance	KgCO_2 /m^2	ICv	3957	15,248	9500	1.2	0.8
I_8. CPBT	Year	DCx	0.45	1.37	1.1	0.1	1.5
I_9. PM reduction	g/m^2	ICv	23.28	60.58	41	1.2	0.8
I_{10}. Occupational risk	Points	DCv	4.95	11.82	8	1.5	0.9
I_{11}. Customization potential	Points	IS	0	100	28	0.15	2.5
I_{12}. Adaptability to change	Points	IS	0	100	28	0.15	2.5

Table 6
Sustainability Index (I), Requirements (V_R), Criteria (V_C), and Indicators (V_I) satisfaction values

		I	V_{R1}	V_{R2}	V_{R3}	V_{C1}	V_{C2}	V_{C3}	V_{C4}	V_{C5}	V_{C6}	
BAPV		**60.46 %**	0.823	0.373	0.856	0.785	0.897	0.460	0.330	0.960	0.803	
BAPV/T		**55.71 %**	0.260	0.845	0.283	0.218	0.346	0.851	0.841	0.535	0.158	
	V_{I1}	V_{I2}	V_{I3}	V_{I4}	V_{I5}	V_{I6}	V_{I7}	V_{I8}	V_{I9}	V_{I10}	V_{I11}	V_{I12}
BAPV	0.700	0.945	0.820	0.897	0.198	0.984	0.293	0.164	0.404	0.960	0.851	0.755
BAPV/T	0.167	0.355	0.214	0.346	0.909	0.735	0.878	0.773	0.828	0.535	0.109	0.208

both grid electricity generation and domestic boilers. Although thermal-based power plants are usually located out of municipal regions, their partial short distance from urban areas makes it logical to consider the impact of fossil fuel combustion from such power plants on urban air pollution. According to the EMEP EEA air pollutant emission inventory guidebook (European Environment Agency, 2019), PM emission factors for public electricity production using natural gas and residential boilers burning natural gas are 0.9 g/GJ and 0.2 g/GJ, respectively ("EMEP/EEA air pollutant emission inventory guidebook, 2019). A recent study in Iran used the same emission factor as well (Jorli et al., Dec. 2017). Despite the fact that each surface has some ability to remove PMs, surface roughness, moistness, and stickiness have a significant impact on absorbent efficiency (Powe and Willis, Feb. 2004), as explained in the previous study (Banirazi Motlagh et al., 2021). Hence, the PM absorption capacity of soft and smooth solar panels' surfaces – without any of the required features – is extremely poor and, therefore, negligible in this study.

Criterion *safety* (C_5) includes (I_{10}) ***Occupational risk*** indicator, which considers the main possible risks during installation tasks. Occupational risk index (ORI) estimates the level of risk in building projects based on the type and volume of activities involved. However, these two parameters are affected by regional technologies, companies' development, and the taken approach to adopting preventive measures. According to several studies, ORI system is based on the likelihood of occurrence, the severity of the consequences, and the amount of time spent in risk circumstances (Jannadi and Almishari, Oct. 2003; Hallowell and Gambatese, Oct. 2009; Fortunato et al., Apr. 2012). ORI is derived by Equation (8), where ORI_i is the ORI of $risk_i$, P_i is the occurrence probability, C_i is the consequence severity, and E_i is the $risk_i$ exposure (M. del M. Casanovas, J. Armengou, and G. Ramos,

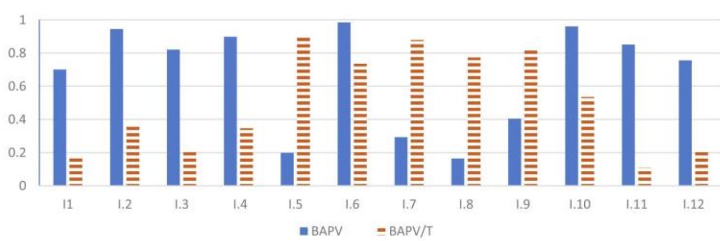


Fig. 6. Indicators' satisfaction value

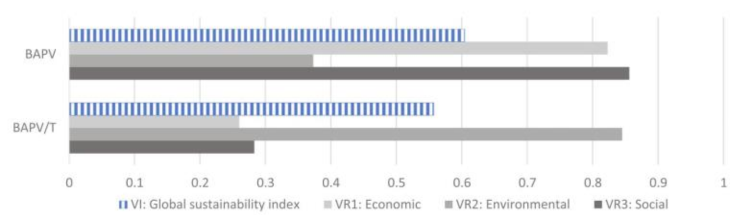


Fig. 7. Sustainability main requirements

Fig. 8. SIs based on different requirement weighting scenarios; *Economic (Ec), Environmental (En), Social (S)*

"Occupational Risk Index for Assessment of Risk in Construction Work by Activity," J. Constr. Eng. Manag., vol. 140, no. 1, p. 040, 2014). The product of frequency, severity, and exposure determines the cumulative risk. The average number of events per unit of time is referred to as frequency, severity is the degree of a possible event's consequence, and exposure is the length of time spent in contact with a potentially hazardous state. In most cases, frequency is measured in incident rates, severity is measured in the impact on the worker or company, and exposure is measured in time units. $P_i \times C_i$ defines the weight of risk$_i$, and dividing each risk's weight by the highest possible weight (1000) results in its standardized value (M. del M. Casanovas, J. Armengou, and G. Ramos, "Occupational Risk Index for Assessment of Risk in Construction Work by Activity," J. Constr. Eng. Manag., vol. 140, no. 1, p. 040, 2014).

$$ORI = \Sigma_i ORI_i = \Sigma_i[(P_i \times C_i) \,/\, (\max\{P_i \times C_i\} = 1000)] \times E_i \qquad (8)$$

Electrical works – especially, under wet conditions like rooftops – and burn, are both significant risks for solar systems mounting. Moreover, hand and back injuries are taken into account as other most frequent injuries due to hand contact with sharp parts and handling loads such as solar panels and structural supports ("Environmental, Health and Safety Guideline for Photovoltaic Solar Power Plants, No. 785, Last Edition: 01-11-, 2021; Fredericks et al., Nov. 2005). Additionally, falling to a lower or on the same level is considered one of the most usual dangers as a general risk on construction sites ("Environmental, Health and Safety Guideline for Photovoltaic Solar Power Plants, No. 785, Last Edition: 01-11-, 2021; Fortunato et al., Apr. 2012; Winge et al., Feb. 2019).

Compatibility (C_6) consists of two indicators: (I_{11}) *Customization potential* and (I_{12}) *Adaptability to change*. (I_{11}) *Customization potential* outlines the compatibility of domestic solar systems with their surroundings and local features, such as rooftop form and physical space, climate, appearance, and market access. Determination of these parameters took into account some studies concerning the architectural potentials of solar technologies and experts' seminars. For instance, IEA SHC Task 41 (Munari Probst, 2013), which defines the combination of functional and aesthetic aspects; and Farkas (2013), which describes architectural potentials such as formal flexibility – availability of different shapes, colours, and textures among others –, and product system adaptability – such as components and joints diversity (Farkas and Integration, 2013). (I_{12}) *Adaptability to change* takes into consideration the alternatives' flexibility to be adapted to the needs of the occupants within the panels' service life. This indicator considers some parameters such as the potential of disassembling, replacement, ability to move, and access to service. Carrying out scores' assignment is based on the outcomes of experts' seminars and the installers' comments concerning the aforementioned parameters. Eventually, the adaptation rate of each alternative is calculated by dividing the total acquired scores by the number of parameters.

Table D.1 in Appendix D summarizes the quantitative analysis of all BAPV and BAPV/T indicators as domestic solar system alternatives during their 25 years of life service in Tehran. Briefly, databases and information resources used for Indicators' quantification in the current study are ICE (Hammond et al., 2011), EMEP/EEA ("EMEP/EEA air pollutant emission inventory guidebook, 2019), a national guideline for PV ("Environmental, Health and Safety Guideline for Photovoltaic Solar Power Plants, No. 785, Last Edition: 01-11-, 2021), national policies and regulations ("Renewable Energy and Energy Efficiency Organization." http://www.satba.gov.ir/en/home (accessed Feb. 10, 2021), occupational risk index in construction work (M. del M. Casanovas, J. Armengou, and G. Ramos, "Occupational Risk Index for Assessment of Risk in Construction Work by Activity," J. Constr. Eng. Manag., vol. 140, no. 1, p. 040, 2014), relevant previous studies, queries from stakeholders, and commercial information. According to the national guideline for photovoltaic solar power plants (No. 785, November 2020) ("Environmental, Health and Safety Guideline for Photovoltaic Solar Power Plants, No. 785, Last Edition: 01-11-, 2021), Iranian PV modules consist of 76 % glass, 10 % polyethylene, 8 % aluminum, 5 % silicon, and less than 1 % of other materials – which this study considers neglectable.

3.3.3. Value function (VF) establishment

Determining the tendency, form, and parameters associated with the VF of each indicator relies on scientific literature, along with conclusions of the aforesaid experts' panel. These parameters e.g., X_{min}, X_{max}, C, K, and P, are presented in Table 5. More detailed descriptions concerning this VF assignment are available in previous literature (Pons et al., May 2016; Alarcon et al., Dec. 2010). Functions shapes in this study are as follows: six decreased, including three convex functions (DCx), one concave (DCv), one linear (DL), and one S-shaped (DS); six increased, including four concave functions (ICv) and two S-shaped ones (IS). Appendix E presents the value function for each indicator derived from Equations (2) and (3), in which each graph indicates the abscissa between the minimum and maximum satisfaction values for assessed alternatives, as well as the VF's shape and relevant coefficient parameters (P, K, and C) as shown in Fig. E.1.

3.3.4. Sustainability indexes (SIs)

Table 6 and Fig. 6. present the alternatives global SIs, which result from the sum of the a-dimensional satisfaction values of requirements (V_{Ri}), criteria (V_{Ci}), and indicators (V_{Ii}).

4. Discussion

SI as a global index quantifies domestic solar system alternatives with a sustainability level of 60.46 % and 55.71 % for BAPV and BAPV/T, respectively, as shown in Fig. 7. BAPV achieves an overall higher SI. However, BAPV/T provides more appropriate performance concerning the air pollution reduction issue by obtaining a higher satisfaction value for the emissions criterion.

BAPV performances prove admirable in both economic and social requirements. However, there is still room for improvement regarding its implementation cost (I_1) via the production of more cost-effective solar cells. This finding is also in accordance with the global strategy concerning photovoltaic technology development (Shukla et al., Sep. 2016; El Chaar, 2011). On the other hand, BAPV's most significant drawback is inadequate energy generation efficiency (Raverkar et al., 2020) since all related indicators' satisfaction levels are lower than moderate (50 %). This is the case for example of energy balance (I_5), CO_2 balance (I_7), CPBT duration (I_8), and PM reduction (I_9). Contrarily the most appropriate function of BAPV/T refers to total energy efficiency (I_5) (Wang, Apr. 2021; Lee et al., Aug. 2019) and its positive impact on air pollution reduction through (I_7), (I_8), and (I_9) indicators performance. BAPV/T economic requirement index is highly unsatisfactory, affected by implementation cost (I_1) and Return on Investment (I_3). Likewise, BAPV/T is still weak from the social point of view particularly, concerning its customization potential (I_{11}) and adaptability (I_{12}).

Overall, from the viewpoint of this study, solar systems can be considered worthy alternatives to improve Tehran's air quality. As mentioned previously, CO_2 is the most important GHG, and PM is the most critical air pollutant in this case study (Tehran Annual Air and Noise Quality Report, period of March, 2020 - March 2021; "greenhouse gas | Definition, Emissions, Greenhouse Effect | Britannica." https://www.britannica.com/science/greenhouse-gas (accessed Jun. 13, 2022). In this regard, by using BAPV and BAPV/T, authors predict results capable of avoiding 211 and 488 kg CO_2/m^2 per year, respectively. Likewise, avoided PM emission via utilization of BAPV and BAPV/T can reach 1.2 and 1.9 g PM/m^2 per year, respectively. On the other hand, compared to other feasible roof refurbishment alternatives and considering the results of the previous study (Banirazi Motlagh et al., 2021), the PM reduction potential of BAPV and BAPV/T is lower than GR, which is able to reduce 52.4 g PM/m^2 annually. However, GRs' lower CO_2 saving potential – 4.4 kg CO_2/m^2 per year – make solar systems applications more environmentally friendly due to: (a) these systems' higher CO_2 saving potential and (b) their ability to produce energy. In addition, from the economic point of view, though solar systems need much more initial capital costs than GRs, solar systems have considerably lower operation and maintenance costs (Diwania et al., Mar. 2020), as well as benefits of return on investment, which compensate for this shortcoming.

In this research project, different sources have been used to obtain the data for the indicators assessed, as it was impossible to find a single source which embraces all required data for quantifying the indicators. Additionally, due to the lack of some local databases for assessing the indicators, international databases, which are mostly applied to other regions as well as case studies, have been used in this research study. In this way, well-known valid international databases and information – such as ICE and EMEP/EEA – have been consulted for this research study. Nevertheless, gathering and considering data from different sources has been done rigorously and with the utmost care, as was previously performed in other MIVES models as well (Pons and Aguado, Jul. 2012; Hosseini et al., Apr. 2019). Although most reliable international databases were used for this study, the lack of a comprehensive national database, which is a limitation and obstacle of this current study, should be considered in future studies. In this regard, it will be essential to have a comprehensive national database concerning the sustainability requirements to provide more accurate results in the future. Moreover, this model could be fed with information from a new holistic source that will be developed in the future and thus can ensure more accuracy for the required Tehran data. Nonetheless, this model is an adaptable tool that could be applicable to other solar system alternatives, other contexts, and different boundaries; after studying the particularities in each case and adapting to them if necessary.

4.1. Sustainability value improvement potential

This study takes into account the potential plan of development for SIs via two approaches in financial and technical contexts as follows.

Considering the significant environmental potential of BAPV/T and this study's objective concerning the suitability of sustainable alternatives to air pollution reduction, the BAPV/T sustainability value level needs to improve so that its utilization becomes justifiable. To this end, economic issues are crucial since these are the weakest and most significant factors in dropping BAPV/T satisfaction levels. Apart from its high initial cost caused by the global market – which is beyond the scope of this study –, having a clear and incentive plan in local policies could remarkably contribute to solving this problem. Literature findings concerning incentives as the most significant drivers to develop solar system installations (Good et al., May 2015) confirm this assumption. Although the natural gas bills decrease proportionally to the produced solar thermal energy amount, this decrement cannot provide sufficient motivation for renewable thermal energy usage due to the cheap fossil fuels in Iran (Korsavi et al., Feb. 2018; Gorjian et al., May 2019). In this sense, assuming the allocation of 38 % of the guaranteed electricity purchase tariff by the energy ministry in 2020 ("Renewable Energy and Energy Efficiency Organization." http://www.satba.gov.ir/en/home (accessed Feb. 10, 2021), thus solar thermal energy would reach a further profit of 4,020 Rials per kWh (I_3). In this case, the BAPV/T index value would increase up to 60.5 % and equal to the BAPV index, but with more environmental benefits and a higher potential to reduce air pollution. This profit could be applied as a discount on natural gas bills to prevent hidden costs of using natural gas and air pollution. However, hidden social costs need another independent investigation and specialized sociological studies, which is beyond the scope of the present study. This is a feasible subside proposal since the amounts of generated electricity and produced thermal energy have linear relation together, the electrical and thermal efficiency of each system is known, and merely certified companies by SATBA are allowed to install and inspect private solar systems. Additionally, applying this encouragement strategy, which is expected to cause the development and deployment of BAPV/T installations, will probably also improve the social satisfaction value as well and consequently enable achieving higher global indexes over time due to growing up customization potential and adaptability (I_{11} and I_{12}).

The authors expect that further optimized solar collectors will be more environmentally friendly systems, with less resource consumption during the manufacturing process along with higher efficiency during their operation phase. In this regard, organic solar cell (OSC), which is still under the research and development (R&D) stage, could be an appropriate option in the future (Zhao et al., Apr. 2021). In this way, OSC would have significantly higher SIs by overcoming its current low efficiency and low stability during fast and upward technological advancements (Xiao et al., Mar. 2022). This occurs because OSC has a small amount of needed material that does not require high temperature or high vacuum conditions (Shukla et al., Sep. 2016), which results in higher energy and CO_2 balance (I_5 and I_7) as well as lower waste disposal and CPBT (I_6 and I_8). Moreover, one of OSC's strengths is its mechanical flexibility, which can improve customization potential (I_{11}). Additionally, OSC provides a cost-effective manufacturing process by using organic materials, which are low-cost raw materials with limited technical challenges for production (El Chaar, 2011), and can lead to further improvement of the cost criterion (C_1).

4.2. Sensitivity analysis

This study considers different weighting scenarios in order to both identify: (1) requirements that command sustainability accomplishments by alternatives and (2) the alternatives' SIs generated from each scenario. The weight distribution of this analysis considers both weights suggested in the most extensively used sustainability rating techniques for the building sector – such as BREEAM, DGNB, and LEED (Pons-Valladares and Nikolic, Nov. 2020) – and experts' proposals.

According to Fig. 8, by increasing sensitivity to economic requirements, SIs of BAPV and BAPV/T generally take two different tendencies. Based on all scenarios in which stakeholders are more sensitive to economic considerations (higher than 25 %), BAPV obtains higher SIs. On the contrary, the minimum SI for BAPV/T occurs when there is maximum economic sensitivity (45 %), and the highest SI of this alternative is in the case of the highest environmental sensitivity (70 %). However, this scenario is unacceptable due to the low weight assigned to economic requirements. Results show that whenever the environmental weight tends to 55 %, the SIs of both alternatives are almost equal, whereas, for cases in which the environmental requirements sensitivity is higher than 55 %, the BAPV/T can overcome BAPV.

5. Conclusion and future projects

To the best of the authors' knowledge, this study is the first attempt to develop a new model to assist decision-makers in order to choose the most suitable domestic solar systems focusing on urban air pollution reduction and its related environmental concerns, considering the steady increment of energy demand, and the exhaustion of fossil fuel resources. This model incorporates MIVES, SWOT, AHP, and sensitivity analysis and its application evaluates BAPV and BAPV/T utilization on top of the residential buildings in Tehran, one of the world's most air-polluted megacities. Nevertheless, the authors have designed this systematic approach so that, after studying each specific case and applying any required changes, it could be applied to different boundaries, cities, and solar system alternatives. In this sense, compared to GRs – another feasible alternative for rooftop refurbishment that contributes to urban air pollution reduction – solar systems' remarkable CO_2 saving potential and energy production capability distinguish these systems as more environmentally friendly solutions than GRs. Objective decision to determine the most suitable solution obtained from such a novel model provides comparable SIs for each alternative applying a variety of scenarios. The main conclusions of this application are as follows:

- BAPV has earned an overall higher sustainability value (60.47 %) whereas, results indicate this existing type of solar system is a distinguished socio-economic alternative for residential buildings in this case study, though its energy generation efficiency has important room for improvement.
- Although results prove that BAPV/T is neither an economical nor social alternative yet, it can be a robust solution when stakeholders are more sensitive to environmental requirements. This is due to this alternative high energy production performance and significant potential to reduce air pollution.
- Results reveal that using each square meter of domestic BAPV & BAPV/T respectively enables a reduction of 211 and 488 kg CO_2/m^2 per year. While, utilization of BAPV and BAPV/T can provide the capability to reduce PM emissions by 1.2 and 1.9 g PM/m^2 per year, respectively.
- The analysis of the resulting SI found that the most critical obstacle to BAPV/T development is its lack of a clear incentive plan considering inadequate motivation to avoid natural gas consumption in Iran. In this regard, it would be possible to improve BAPV/T's satisfaction level and provide equality of SI between two alternatives via a profit guarantee of produced thermal energy, even at the rate of 38 % tariff approved by the energy ministry to purchase solar electricity, that can compensate partially hidden costs of natural gas use and air pollution.
- Beyond these two assessed alternatives and the GRs assessed in the previous study, taking advantage of the capability of this model to evaluate different rooftop refurbishment alternatives, future research steps could investigate: (a) new solutions, (b) combination of alternatives, and (c) applications on different building typologies to achieve the most suitable and sustainable solution towards urban air quality improvement.

Declaration of Competing Interest

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

Acknowledgements

The authors would like to acknowledge the multidisciplinary experts who participated in the seminars. Additionally, the authors would like to thank J. Maas for his aid in the English Language.

Appendix A. (Outcomes of search within the technical literature)

Table A.1.

Table A1
Sample of classified outcomes obtained from a simplified literature review based on main findings area

Publication	PV technologies	PV/T technologies	Building level applications	Energy/economic performance	Environmental assessment
Debberma et al. (Debbarma et al., Jun. 2017)	*		*	*	
Sultan & Ervina Efzan (Sultan and Ervina Efzan, Oct. 2018)		*			
Assoa et al. (Assoa et al., Jun. 2017)			*		
Bhattarai et al. (Bhattarai et al., Aug. 2012)				*	
Herrando et al. (Herrando et al., Jun. 2014)			*	*	*
Buker et al. (Buker et al., Jun. 2014)			*	*	
Good SPS:refid::bib75 (Good, Mar. 2016)					*
Good et al. (Good et al., Dec. 2015)			*	*	
Lamnatou & Chemisana (Chr. Lamnatou and D. Chemisana, "Photovoltaic/thermal (PVT) systems: A review with emphasis on environmental issues," Renew. Energy, vol. 105, pp. 270–287, May, 2017)					*
Chow and Ji (Chow and Ji, 2012)					*
Shukla et al. (Shukla et al., Sep. 2016)			*		
Sathe and Dhoble (Sathe and Dhoble, Sep. 2017)		*			
Parida et al. (Parida et al., Apr. 2011)	*				
Firouzjah (Firouzjah, Oct. 2018)				*	
Fthenakis et al. (Fthenakis, 2011)					*
El Chaar et al. (El Chaar, 2011)	*				
Pinel et al. (Pinel et al., Jan. 2021)				*	*
Fu et al. (Fu et al., Jan. 2015)					*
Cucchiella et al. (Cucchiella et al., Jul. 2015)			*	*	*
Moran and Natarajan (Moran and Natarajan, Sep. 2015)			*		*
Zabihi Sheshpoli et al. (Zabihi Sheshpoli et al., Feb. 2021)				*	
Fthenakis et al. (Fthenakis et al., Mar. 2008)					*
Kannan et al. (Kannan et al., May 2006)					*
Good et al. (Good et al., May 2015)			*		
Saurabh et al. (Saurabh et al., Feb. 2020)				*	
Diwania et al. (Diwania et al., Mar. 2020)		*			
Jia et al. (Jia et al., Mar. 2019)		*			
Barone et al. (Barone et al., Jul. 2019)				*	
Huide et al. (Huide et al., May 2017)			*	*	
Zhang et al. (Zhang, Nov. 2018)			*	*	
Al-Waeli et al. (Al-Waeli et al., Sep. 2017)		*			
Azami and Sevinç (Azami and Sevinç, Jul. 2021)			*	*	
Peng et al. (Peng et al., Dec. 2011)			*		
Petter Jelle et al. (Petter Jelle et al., May 2012)			*		
Shukla et al. (Shukla et al., May 2016)			*	*	
Baljit et al. (Baljit et al., Nov. 2016)			*	*	
Korsavi et al. (Korsavi et al., Feb. 2018)			*	*	*

Appendix B. (PV technology types)

Silicon crystalline structure (c-Si): Crystalline silicon is considered the first generation of PV technology that consists of single-junction crystal solar cells based on silicon wafers. This PV type is generally categorized into mono/single (m-Si) and poly/multi-crystalline (p-Si) silicon cells. Despite the lower manufacturing cost of poly-crystalline PV panels, the efficiency of such cells is measured less than the mono-crystalline type (El Chaar, 2011). Si wafer-based PV technology accounted for more than 90 % of the total production in 2019 ("IHS Markit - Leading Source of Critical Information," IHS Markit. https://ihsmarkit.com/index.html (accessed Mar. 05, 2021), since crystalline silicon technology has lower costs and higher performance compared to other solar cell technologies (Diwania et al., Mar. 2020). The share of mono-crystalline – the most common type – is nearly 66 % of the whole production ("IHS Markit - Leading Source of Critical Information," IHS Markit. https://ihsmarkit.com/index.html (accessed Mar. 05, 2021). Mono-crystalline PV cells have provided evidence of reliability, durability, and cost favourability as far as several PV modules installed in the 1970 s are still operating (Shukla et al., Sep. 2016).

Thin film technology (TF): This second-generation of PV technologies intends to optimize material consumption, based on single-junction sets generally comprising amorphous (uncrystallized) silicon (a-Si), cadmium telluride (CdTe), copper indium selenide/diselenide or copper indium gallium selenide/diselenide (CIS/CIGS). This generation utilizes thinner films produced via the deposition of thin layers on glass or stainless-steel substrates, using sputtering tools to create flexible PV modules. TF technology results in lower manufacturing costs due to the decrease in material cost; Although the ability to deposit a wide range of materials and alloys has improved TF efficiency significantly, since its layers are much thinner and contain less photovoltaic material, the light absorption is reduced and consequently results in lower conversion efficiency compared with c-Si cells (Shukla et al., Sep. 2016; Parida et al., Apr. 2011; El Chaar, 2011).

Nanotechnology and other emerging technologies: Third-generation PV technologies have been not generally commercialized so far and are still following further improvements under the R&D stage. This generation embraces e.g., nanotechnologies for PV cell production, light-absorbing dyes, and OSC. *Nanotechnology* provides low-cost but low-efficiency PV cells, following a sustainable economic growth strategy. In this regard, some products such as nanotubes, quantum dots, and hot-carrier solar cells capable of more solar radiation absorption are emphasized to improve efficiency (El Chaar, 2011). *Dye-sensitized solar cell* (DSSC) is a photoelectrochemical system based on a semiconductor formed between a photo-sensitized anode and an electrolyte zz. DSSC is considered a low-cost TF innovative cell, and Michael Gratzel was awarded the 2010 millennium technology prize for this invention (Shukla et al., Sep. 2016). The volatile solvents in the electrolyte can permeate across plastic and result in sealing and potential environmental hazards problems. Thus, such a technology is not appropriate for outdoor usage. Despite some drawbacks such as heat, ultraviolet (UV) light, and the interaction of solvents, this technology seems futuristic due to some impressive advantages such as low processing costs, flexibility, the ability of screen printing, incorporation in paints, and semi-transparency. The achievement of more efficient light-absorbing dyes and improvement in reliability and safety have been considered the current development intentions for this technology (El Chaar, 2011). An *OSC* or plastic solar cell is a kind of PV made of thin films – commonly around 100 nm – including organic semiconductors such as polymers and small molecule compounds – like pentacene, polyphenylene vinylene, copper phthalocyanine, and carbon fullerenes – using organic electronics technology (El Chaar, 2011). The gains of this technology rely on disposability, mechanical flexibility, and affordability of the manufacturing process – due to using cheap materials and limited technical challenges without requiring high temperature or high vacuum conditions; Besides, a large amount of solar radiation can be absorbed by a small amount of material because of the high optical absorption coefficient of organic molecules (El Chaar, 2011). However, the main challenges associated with OSC are low efficiency, low strength, and low stability compared with the others, such as silicon solar cells (Shukla et al., Sep. 2016). Further, a *concentrated PV system* comprised of a more complex mechanism to concentrate and track solar radiation can be considered another emerging technology.

Appendix C. (PV/T system types)

Based on working fluid type – as heat transfer medium –, conventional flat plate PV/T collectors are classified into two categories of liquid-based and air-based types (Barone et al., Jul. 2019; Saurabh et al., Feb. 2020; Good et al., May 2015). An air-based solar collector is fundamentally similar to a liquid-based type, and the main difference is the substitution of ducts instead of fluid tubes (Jia et al., Mar. 2019). Generally, the most adopted and popular PV/T systems are liquid-based, and the most common liquid as heat transfer or working fluid is water. Hence, heated air applications are very few, though there is plenty of work concerning the air or a hybrid system of air–water applications. The overall thermal and electrical performance of water-based PV/T systems is higher and more stable compared with air-based ones due to much more heat-carrying capacity, density, and conductivity of water. In fact, thermal energy replacement for DHW preparation is considerably more valuable than thermal energy for space heating. Thus, water-based PV/T collectors are acknowledged as the most efficient way of preheating water over a whole year. However, air-based devices are simpler and have lower maintenance and capital costs (Barone et al., Jul. 2019; Saurabh et al., Feb. 2020; Good, Mar. 2016). A flat plate PV/T collector can be covered (glazed) or uncovered (unglazed). Covered PV/T collectors have an additional glass at a distance from the absorber surface to protect and minimize heat loss. Although glazing usage helps to increase thermal output, experimental and theoretical results demonstrate that uncovered PV/T collectors obtain higher total efficiency and are beneficial in economic terms as well. Thus, covered types are relatively rare in the market. Additionally, unglazed systems enable PV surfaces keeping cool, which results in a longer life service (Saurabh et al., Feb. 2020; Good et al., May 2015; Souliotis et al., Oct. 2018).

Meanwhile, several studies in progress optimize the performance and development of conventional PV/T systems (Barone et al., Jul. 2019; Sathe and Dhoble, Sep. 2017). While some recent research projects have introduced a few advanced concepts of PV/T technology, such as nanofluid, phase change materials (PCM), and heat pump integration systems (Diwania et al., Mar. 2020; Jia et al., Mar. 2019; Sathe and Dhoble, Sep. 2017). *Nanofluids* generally contain nanoparticle size – less than 100 nm – in the conventional base fluid such as water, glycol, and oil. These materials as heat transfer fluids can be used efficiently for solar energy conversion and result in thermal conductivity enhancement (Sathe and Dhoble, Sep. 2017). *PCM* is used with a PV/T system to reduce the solar cell temperature via a swing between its solid and liquid phases following ambient temperature changes (Diwania et al., Mar. 2020). *Heat pumps* enable thermal energy to transfer from a lower temperature source to a hotter sink using mechanical energy and a refrigeration cycle. Coupling this technic with PV/T to apply solar heating in a heat pump – for auxiliary heating as a part of the energy supply system – gains a significant efficiency improvement by cooling the PV module attached to the evaporator-collector. Thus, this system obtains higher energy output and lower power consumption (Diwania et al., Mar. 2020; Jia et al., Mar. 2019). *Concentrator collectors* need supplementary optical devices such as reflectors and lenses and intricate systems for sunlight tracking. In consequence, such systems are not suitable or feasible for residential building applications due to being scarce, costly, and complex compared to flat plate solar collectors (Diwania et al., Mar. 2020; Jia et al., Mar. 2019; Good et al., May 2015).

Appendix D. (Indicators' quantification)

Table D.1.

Table D1
Indicators' quantification summary over the 25 years' service time for the studied domestic solar systems

Indicator	Consideration	BAPV	BAPV/T	Impact	Unit	Reference
I_1. Implementation cost	Modules, accessories, connections, workers	563.8	892.5	Neg.	€/m^2	Market, manufacturers & providers
I_2. Maintenance cost	Cleaning, inspection, accessory replacement	140.9	223.1	Neg.	€/m^2	Literature review e.g., (Korsavi et al., Feb. 2018; Dehghan et al., Jun. 2021; "Enabling PV Iran," German Solar Association – BSW-Solar / Bundesverband Solarwirtschaft e.V, Berlin, Germany, (Förderkennzeichen-FKZ): ZMVI6-, 2016)
I_3. ROI	Profit probability over a time	283	178	Pos.	%	SATBA organization ("Renewable Energy and Energy Efficiency Organization." http://www.satba.gov.ir/en/home (accessed Feb. 10, 2021)
I_4. Implementation time	Roof fixing, assembly, cabling, pipework	24	40	Neg.	hours	Contractor companies' information
I_5. Energy balance	Energy-saving and consumption	29,746	116,058	Pos.	MJ/m^2	ICE database (Hammond et al., 2011)
I_6. Waste disposal	Non-recyclable solid waste	1.2	3.1	Neg.	kg/m^2	National guideline ("Environmental, Health and Safety Guideline for Photovoltaic Solar Power Plants, No. 785, Last Edition: 01-11-, 2021), literature review e.g., (Paiano, Jan. 2015; STEEL IN BUILDINGS AND INFRASTRUCTURE | worldsteel, 2021; Kemona and Piotrowska, Aug. 2020; Faraca and Astrup, Jul. 2019)
I_7. CO_2 balance	CO_2 saving and emission	5277	12,199	Pos.	kgCO_2/m^2	ICE database (Hammond et al., 2011)
I_8. CPBT	GHG impact compensation speed	1.1	0.6	Neg.	Year	Literature review e.g., (Tripanagnostopoulos et al., May 2005; Noorpoor and Kudahi, Jul. 2015)
I_9. PM reduction	PM emission reduction potential	31.05	48.47	Pos.	g/m^2	EMEP/EEA database ("EMEP/EEA air pollutant emission inventory guidebook, 2019), literature review e.g., (Jorli et al., Dec. 2017)
I_{10}. Occupational risk	Falls, electrical work, burn, hand & back injuries	5.5	9.46	Neg.	Points	Casanovas et al. (M. del M. Casanovas, J. Armengou, and G. Ramos, "Occupational Risk Index for Assessment of Risk in Construction Work by Activity," J. Constr. Eng. Manag., vol. 140, no. 1, p. 040, 2014), literature e.g. ("Environmental, Health and Safety Guideline for Photovoltaic Solar Power Plants, No. 785, Last Edition: 01-11-, 2021; Fortunato et al., Apr. 2012; Fredericks et al., Nov. 2005; Winge et al., Feb. 2019)
I_{11}. Customization potential	Market, appearance, climate, form	75	25	Pos.	Points	Experts' seminar and literature review e.g., (Munari Probst, 2013; Farkas and Integration, 2013)
I_{12}. Adaptability to change	Disassembling, service, movement, replacement	67	33	Pos.	Points	Experts' seminar and installers' information

Appendix E. (Value functions)

Fig. E.1

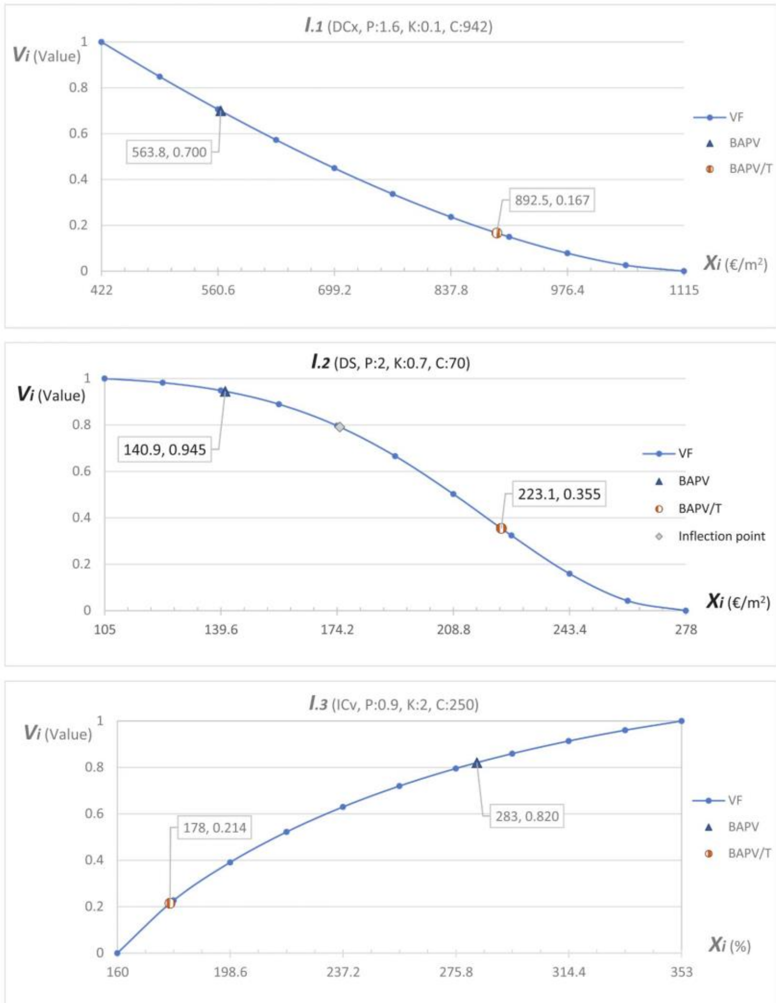
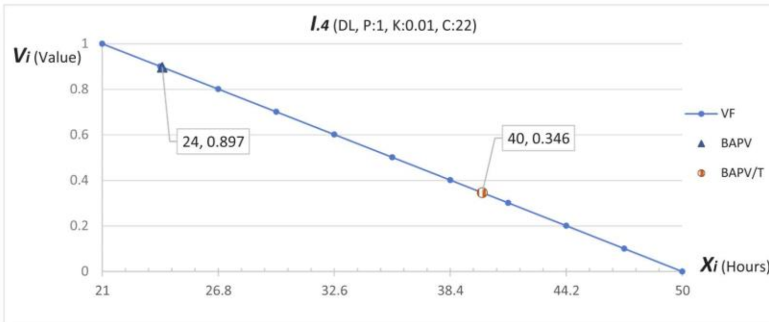
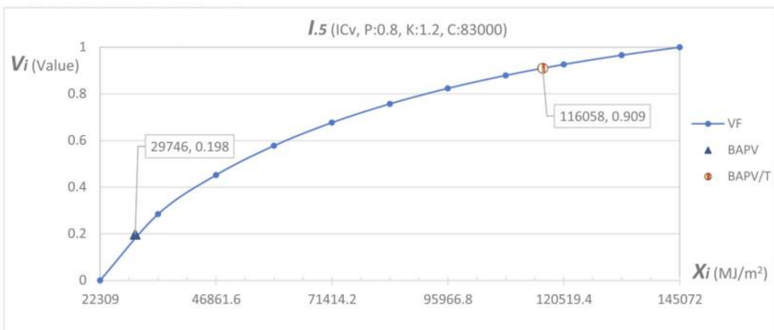


Fig. E1. Value function of each indicator derived from Equations (2) and (3).





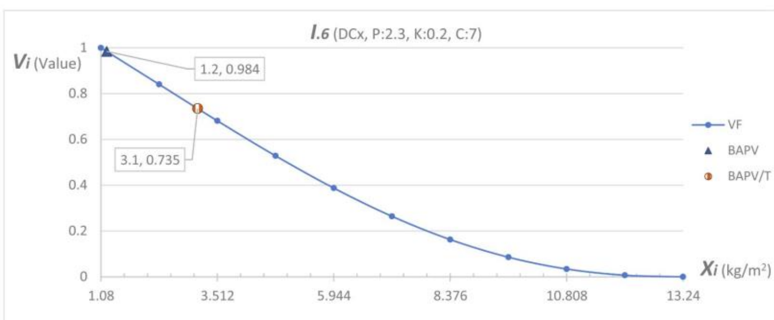


Fig. E1. (*continued*).

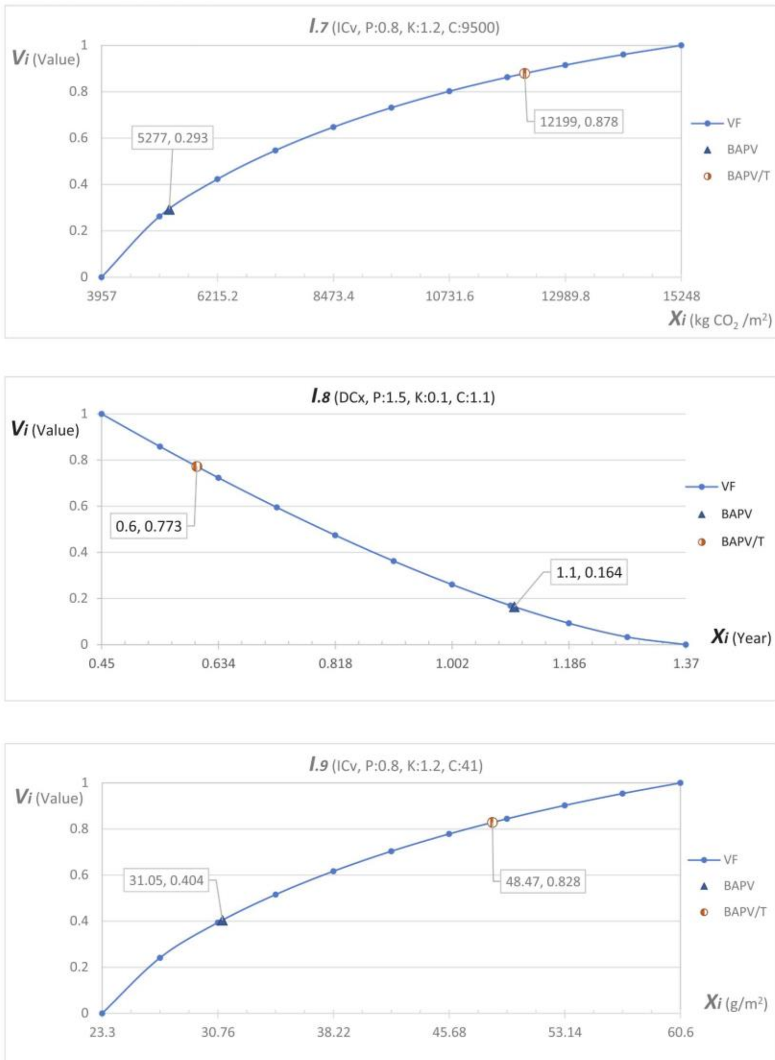
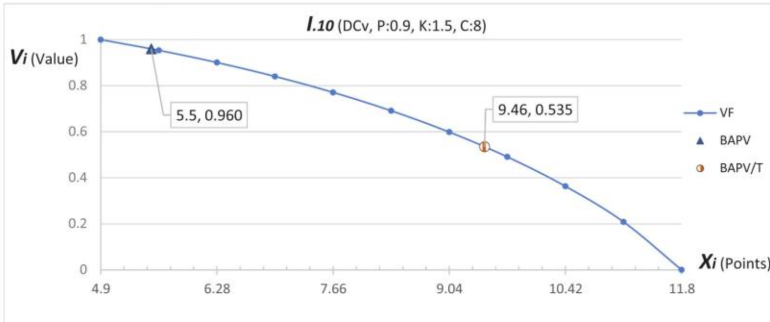
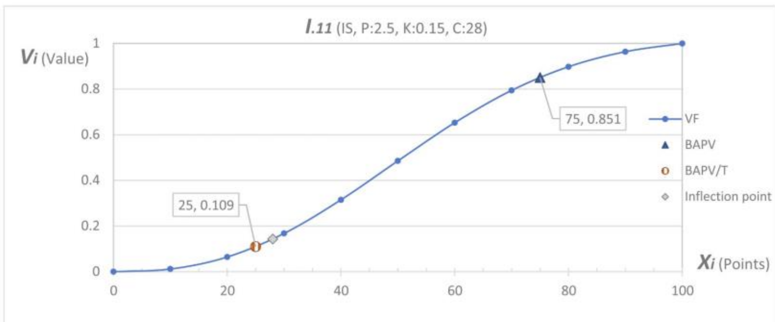


Fig. E1. (*continued*).





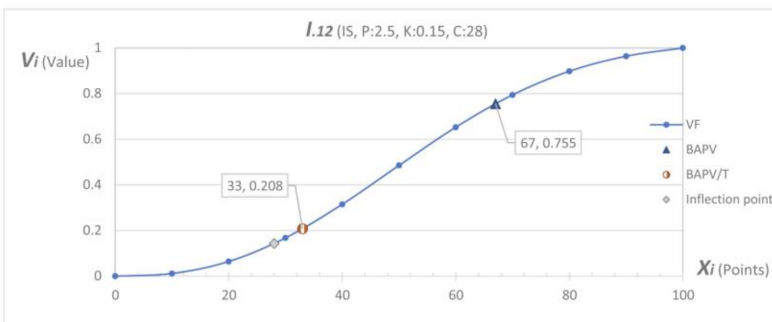


Fig. E1. (*continued*).

Appendix F. (Air pollution standards and values)

The data presented in Table F.1 and Figs. F.1 and F.2 is derived from the 10th Tehran Annual Air and Noise Quality Report (Tehran Annual Air and Noise Quality Report, period of March, 2020 - March 2021), which provides a comprehensive assessment of Tehran's air quality – during the period of March 20, 2020, to March 20, 2021 – alongside an investigation of the spatial and temporal variations in air pollutant concentrations. This report published by the Air Quality Control Company includes a summary of the performance evaluation of the Tehran Air Pollution Forecasting System for different time intervals.

Table F1
Air pollution international standards based on Air Quality Index (AQI) (Tehran Annual Air and Noise Quality Report, period of March, 2020 - March 2021)

Air pollution level	AQI
Clean	0–50
Moderate	51–100
Unhealthy for sensitive groups	101–150
Unhealthy	151–200
Very Unhealthy	201–300
Hazardous	300 +

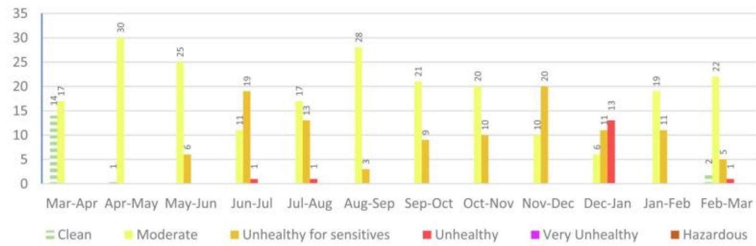


Fig. F1. AQI in Tehran during different months of March 2020 – March 2021 based on the days' number (Tehran Annual Air and Noise Quality Report, period of March, 2020 - March 2021) (Clean: 17 days, 5 %; Moderate: 226 days, 62 %; Unhealthy for sensitive groups: 107 days, 29 %; Unhealthy: 16 days, 4 %)

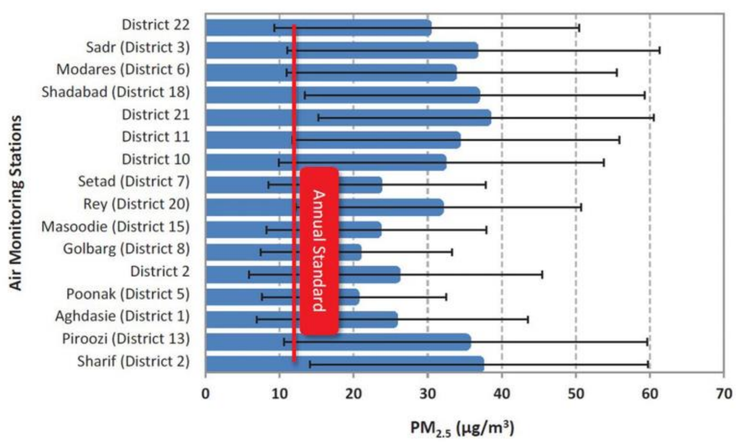


Fig. F2. Mean concentrations of Particulate Matter (the most critical air pollutant in Tehran) measured at different districts' monitoring stations (period of March 2020 – March 2021) (Tehran Annual Air and Noise Quality Report, period of March, 2020 - March 2021)

Appendix G. (Variables & Symbols)

Nomenclature	Relevant values
DCv	Decreasing concave
DCx	Decreasing convex
DL	Decreasing linear
DS	Decreasing S-shaped
ICv	Increasing concave
ICx	Increasing convex
IL	Increasing linear
IS	Increasing S-shaped
I	Indicator
C	Criterion
R	Requirement
V	Satisfaction value

(continued on next page)

(*continued*)

Nomenclature	Relevant values
λ_i	Weight/importance coefficient of indicator i
X_i	Abscissa value of indicator i
P_i	Shape factor
C_i	Abscissa approximation for inflection point
K_i	Ordinate approximation for point C_i
E_T	Total efficiency
E_{ele}	Electrical efficiency
E_{th}	Thermal efficiency
kWp	Peak kilowatts
$E_{production}$	Produced electrical/thermal energy
$E_{consumption}$	Consumed energy during panels' manufacturing
$CO_{2\,saving}$	Avoided CO_2 by renewable energy generation
$CO_{2\,emission}$	Emitted CO_2 during panels' fabrication
P	Occurrence probability
C	Consequence severity
E	Risk exposure

Appendix H. ***(Abbreviations)***

Abbreviations	Relevant values
AHP	Analytic hierarchy process
AQI	Air Quality Index
a-Si	Amorphous silicon
BAPV	Building-attached PV
BAPV/T	Building-attached PV/T
BIPV	Building-integrated PV
BIPV/T	Building-integrated PV/T
CdTe	Cadmium telluride
CIGS	Copper indium gallium selenide
CIS	Copper indium selenide
CV	Coefficient of variation
CPBT	CO_2 payback time
CR	Consistency ratio
DHW	Domestic hot water
DSSC	Dye-sensitized solar cell
DT	Decision tree
EOL	End of Life
EPDs	Environmental product declarations
EVA	Ethylene-vinyl acetate
FIT	Feed-in tariffs
GHG	Greenhouse gases
GR	Green roof
ICE	Inventory of Carbon and Energy
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LCA	Life Cycle Assessment
MCDM	Multi-Criteria Decision-Making
MIVES	Modelo integrado de valor para evaluaciones sostenibles (Integrated Value Model for Sustainability Assessment)
NZEB	Nearly zero-energy buildings
ORI	Occupational risk index
OSC	Organic solar cell
PCM	Phase change materials
PM	Particulate (particle) Matter
PUR	Polyurethane
PV	Photovoltaic
PV/T	photovoltaic thermal
ROI	Return on Investment
R&D	Research and development
SI	Sustainability index
STC	Standard test condition
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TF	Thin film
Urban Heat Island	UHI
UV	Ultra-violet
VF	Value function
WACC	Weighted Average Cost of Capital

References

Abas, N., Kalair, A., Khan, N., May 2015. Review of fossil fuels and future energy technologies. Futures 69, 31–49. https://doi.org/10.1016/j.futures.2015.03.003.

Adam, A.D., Apaydin, G., Jan. 2016. Grid connected solar photovoltaic system as a tool for green house gas emission reduction in Turkey. Renew. Sustain. Energy Rev. 53, 1086–1091. https://doi.org/10.1016/j.rser.2015.09.023.

N. Ahmad Ludin *et al.*, "Environmental Impact and Levelised Cost of Energy Analysis of Solar Photovoltaic Systems in Selected Asia Pacific Region: A Cradle-to-Grave Approach," *Sustainability*, vol. 13, no. 1, p. 396, Jan. 2021, doi: 10.3390/su13010396.

Alarcon, B., Aguado, A., Manga, R., Josa, A., Dec. 2010. A Value Function for Assessing Sustainability: Application to Industrial Buildings. Sustainability 3 (1), 35–50. https://doi.org/10.3390/su3010035.

Al-Waeli, A.H.A., Sopian, K., Kazem, H.A., Chaichan, M.T., Sep. 2017. Photovoltaic/Thermal (PV/T) systems: Status and future prospects. Renew. Sustain. Energy Rev. 77, 109–130. https://doi.org/10.1016/j.rser.2017.03.126.

Asakereh, A., Soleymani, M., Sheikhdavoodi, M.J., Oct. 2017. A GIS-based Fuzzy-AHP method for the evaluation of solar farms locations: Case study in Khuzestan province, Iran. Sol. Energy 155, 342–353. https://doi.org/10.1016/j.solener.2017.05.075.

Aslani, M., Seipel, S., Jan. 2022. Automatic identification of utilizable rooftop areas in digital surface models for photovoltaics potential assessment. Appl. Energy 306, 118033. https://doi.org/10.1016/j.apenergy.2021.118033.

U. G. Assembly, "World Summit Outcome: resolution/adopted by the General Assembly, 24 October 2005," A/RES/60/1, available at: http://www. refworld. org/docid/44168a910. html …, 2005.

Assoa, Y.B., Sauzedde, F., Boillot, B., Boddaert, S., Jun. 2017. Development of a building integrated solar photovoltaic/thermal hybrid drying system. Energy 128, 755–767. https://doi.org/10.1016/j.energy.2017.04.062.

Azami, A., Sevinç, H., Jul. 2021. The energy performance of building integrated photovoltaics (BIPV) by determination of optimal building envelope. Build. Environ. 199, 107856 https://doi.org/10.1016/j.buildenv.2021.107856.

Baljit, S.S.S., Chan, H.-Y., Sopian, K., Nov. 2016. Review of building integrated applications of photovoltaic and solar thermal systems. J. Clean. Prod. 137, 677–689. https://doi.org/10.1016/j.jclepro.2016.07.150.

S. H. Banirazi Motlagh, O. Pons, and S. M. A. Hosseini, "Sustainability model to assess the suitability of green roof alternatives for urban air pollution reduction applied in Tehran," *Build. Environ.*, vol. 194, p. 107683, May 2021, doi: 10.1016/j.buildenv.2021.107683.

Barone, G., Buonomano, A., Forzano, C., Palombo, A., Panagopoulos, O., Jul. 2019. Photovoltaic thermal collectors: Experimental analysis and simulation model of an innovative low-cost water-based prototype. Energy 179, 502–516. https://doi.org/10.1016/j.energy.2019.04.140.

Bauer, N., et al., May 2016. Global fossil energy markets and climate change mitigation – an analysis with REMIND. Clim. Change 136 (1), 69–82. https://doi.org/10.1007/s10584-013-0901-6.

Bhattarai, S., Oh, J.-H., Euh, S.-H., Krishna Kafle, G., Hyun Kim, D., Aug. 2012. Simulation and model validation of sheet and tube type photovoltaic thermal solar system and conventional solar collecting system in transient states. Sol. Energy Mater. Sol. Cells 103, 184–193. https://doi.org/10.1016/j.solmat.2012.04.017.

Bogacka, M., et al., Dec. 2020. PV Waste Thermal Treatment According to the Circular Economy Concept. Sustainability 12 (24), 10562. https://doi.org/10.3390/su122410562.

T. Brinkhoff, "The principal agglomerations of the world," *Accessed Aug*, vol. 16, p. 2011, 2011.

Brito, M.C., May 2020. Assessing the Impact of Photovoltaics on Rooftops and Facades in the Urban Micro-Climate. Energies 13 (11), 2717. https://doi.org/10.3390/en13112717.

Buker, M.S., Mempouo, B., Riffat, S.B., Jun. 2014. Performance evaluation and techno-economic analysis of a novel building integrated PV/T roof collector: An experimental validation. Energy Build. 76, 164–175. https://doi.org/10.1016/j.enbuild.2014.02.078.

"Central Bank of the Islamic Republic of Iran." https://www.cbi.ir/default_en.aspx (accessed Apr. 12, 2021).

Chapin, D.M., Fuller, C.S., Pearson, G.L., May 1954. A New Silicon *p-n* Junction Photocell for Converting Solar Radiation into Electrical Power. J. Appl. Phys. 25 (5), 676–677. https://doi.org/10.1063/1.1721711.

Chow, T.-T., Ji, J., 2012. Environmental Life-Cycle Analysis of Hybrid Solar Photovoltaic/Thermal Systems for Use in Hong Kong. Int. J. Photoenergy 2012, 1–9. https://doi.org/10.1155/2012/101968.

Chr. Lamnatou and D. Chemisana, "Photovoltaic/thermal (PVT) systems: A review with emphasis on environmental issues," *Renew. Energy*, vol. 105, pp. 270–287, May 2017, doi: 10.1016/j.renene.2016.12.009.

J. Coughlin and A. Kandt, "Solar Schools Assessment and Implementation Project: Financing Options for Solar Installations on K-12 Schools," NREL/TP-7A40-51815, 1027672, Oct. 2011. doi: 10.2172/1027672.

Cucchiella, F., D'Adamo, I., Lenny Koh, S.C., Jul. 2015. Environmental and economic analysis of building integrated photovoltaic systems in Italian regions. J. Clean. Prod. 98, 241–252. https://doi.org/10.1016/j.jclepro.2013.10.043.

de la Fuente, A., Armengou, J., Pons, O., Aguado, A., Jun. 2016. Multi-criteria decision-making model for assessing the sustainability index of wind-turbine support systems: application to a new precast concrete alternative. J. Civ. Eng. Manag. 23 (2), 194–203. https://doi.org/10.3846/13923730.2015.1023347.

de la Fuente, A., Pons, O., Josa, A., Aguado, A., Jan. 2016. Multi-Criteria Decision Making in the sustainability assessment of sewerage pipe systems. J. Clean. Prod. 112, 4762–4770. https://doi.org/10.1016/j.jclepro.2015.07.002.

A. de la Fuente, M. del M. Casanovas-Rubio, O. Pons, and J. Armengou, "Sustainability of Column-Supported RC Slabs: Fiber Reinforcement as an Alternative," *J. Constr. Eng. Manag.*, vol. 145, no. 7, p. 04019042, Jul. 2019, doi: 10.1061/(ASCE)CO.1943-7862.0001667.

Debbarma, M., Sudhakar, K., Baredar, P., Jun. 2017. Thermal modeling, exergy analysis, performance of BIPV and BIPVT: A review. Renew. Sustain. Energy Rev. 73, 1276–1288. https://doi.org/10.1016/j.rser.2017.02.035.

Dehghan, M., Rahgozar, S., Pourrajabian, A., Aminy, M., Halek, F.-S., Jun. 2021. Techno-economic perspectives of the temperature management of photovoltaic (PV) power plants: A case-study in Iran. Sustain. Energy Technol. Assess. 45, 101133 https://doi.org/10.1016/j.seta.2021.101133.

Diwania, S., Agrawal, S., Siddiqui, A.S., Singh, S., Mar. 2020. Photovoltaic–thermal (PV/T) technology: a comprehensive review on applications and its advancement. Int. J. Energy Environ. Eng. 11 (1), 33–54. https://doi.org/10.1007/s40095-019-00327-y.

"Each Country's Share of CO2 Emissions | Union of Concerned Scientists." https://www.ucsusa.org/resources/each-countrys-share-co2-emissions#.W2RDa9L-g2x (accessed Apr. 08, 2021).

L. El Chaar, L. A. lamont, and N. El Zein, "Review of photovoltaic technologies," *Renew. Sustain. Energy Rev.*, vol. 15, no. 5, pp. 2165–2175, Jun. 2011, doi: 10.1016/j.rser.2011.01.004.

"EMEP/EEA air pollutant emission inventory guidebook 2019 — European Environment Agency." https://www.eea.europa.eu/publications/emep-eea-guidebook-2019 (accessed May 11, 2021).

"Enabling PV Iran," German Solar Association – BSW-Solar / Bundesverband Solarwirtschaft e.V, Berlin, Germany, (Förderkennzeichen-FKZ): ZMVI6-2515AA0814, Mar. 2016. Accessed: Apr. 08, 2021. [Online]. Available: https://www.solarwirtschaft.de/fileadmin/media/pdf/AA_Report_BSW_Iran.pdf.

"Environmental, Health and Safety Guideline for Photovoltaic Solar Power Plants, No. 785, Last Edition: 01-11-2020," *Presidency Islamic Republic of Iran-Plan and Budget Organization*. https://sama.mporg.ir/sites/Publish/en/SitePages/ZabetehView.aspx?mdid=5434 (accessed Apr. 22, 2021).

Faraca, G., Astrup, T., Jul. 2019. Plastic waste from recycling centres: Characterisation and evaluation of plastic recyclability. Waste Manag. 95, 388–398. https://doi.org/10.1016/j.wasman.2019.06.038.

K. Farkas, *Architectural Integration of Photovoltaics: Formal and Symbolic Aesthetics of Photovoltaics*. Norges teknisk-naturvitenskapelige universitet, Fakultet for arkitektur og billedkunst, Institutt for byggekunst, historie og teknologi, 2013. Accessed: Jul. 10, 2021. [Online]. Available: https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/231101.

Fazelpour, F., Soltani, N., Rosen, M.A., May 2016. Economic analysis of standalone hybrid energy systems for application in Tehran, Iran. Int. J. Hydrog. Energy 41 (19), 7732–7743. https://doi.org/10.1016/j.ijhydene.2016.01.113.

Fikru, M.G., May 2019. Electricity bill savings and the role of energy efficiency improvements: A case study of residential solar adopters in the USA. Renew. Sustain. Energy Rev. 106, 124–132. https://doi.org/10.1016/j.rser.2019.02.028.

Fikru, M.G., Nov. 2019. Estimated electricity bill savings for residential solar photovoltaic system owners: Are they accurate enough? Appl. Energy 253, 113501. https://doi.org/10.1016/j.apenergy.2019.113501.

Fikru, M.G., Apr. 2020. Determinants of electricity bill savings for residential solar panel adopters in the U.S.: A multilevel modeling approach. Energy Policy 139, 111351. https://doi.org/10.1016/j.enpol.2020.111351.

Firouzjah, K.G., Oct. 2018. Assessment of small-scale solar PV systems in Iran: Regions priority, potentials and financial feasibility. Renew. Sustain. Energy Rev. 94, 267–274. https://doi.org/10.1016/j.rser.2018.06.002.

Fortunato, B.R., Hallowell, M.R., Behm, M., Dewlaney, K., Apr. 2012. Identification of Safety Risks for High-Performance Sustainable Construction Projects. J. Constr. Eng. Manag. 138 (4), 499–508. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000446.

Fredericks, T.K., Abudayyeh, O., Choi, S.D., Wiersma, M., Charles, M., Nov. 2005. Occupational Injuries and Fatalities in the Roofing Contracting Industry. J. Constr. Eng. Manag. 131 (11), 1233–1240. https://doi.org/10.1061/(ASCE)0733-9364(2005)131:11(1233).

Fthenakis, V., et al., 2011. Methodology guidelines on life cycle assessment of photovoltaic electricity. IEA PVPS Task 12.

Fthenakis, V.M., Kim, H.C., Alsema, E., Mar. 2008. Emissions from Photovoltaic Life Cycles. Environ. Sci. Technol. 42 (6), 2168–2174. https://doi.org/10.1021/es071763q.

Fu, Y., Liu, X., Yuan, Z., Jan. 2015. Life-cycle assessment of multi-crystalline photovoltaic (PV) systems in China. J. Clean. Prod. 86, 180–190. https://doi.org/10.1016/j.jclepro.2014.07.057.

Goepel, K.D., Dec. 2018. Implementation of an Online Software Tool for the Analytic Hierarchy Process (AHP-OS). Int. J. Anal. Hierarchy Process 10 (3). https://doi.org/10.13033/ijahp.v10i3.590.

González, A., Donnelly, A., Jones, M., Chrysoulakis, N., Lopes, M., Jan. 2013. A decision-support system for sustainable urban metabolism in Europe. Environ. Impact Assess. Rev. 38, 109–119. https://doi.org/10.1016/j.eiar.2012.06.007.

Good, C., Mar. 2016. Environmental impact assessments of hybrid photovoltaic–thermal (PV/T) systems – A review. Renew. Sustain. Energy Rev. 55, 234–239. https://doi.org/10.1016/j.rser.2015.10.156.

Good, C., Chen, J., Dai, Y., Hestnes, A.G., May 2015. Hybrid Photovoltaic-thermal Systems in Buildings – A Review. Energy Procedia 70, 683–690. https://doi.org/10.1016/j.egypro.2015.02.176.

Good, C., Andresen, I., Hestnes, A.G., Dec. 2015. Solar energy for net zero energy buildings – A comparison between solar thermal, PV and photovoltaic–thermal (PV/T) systems. Sol. Energy 122, 986–996. https://doi.org/10.1016/j.solener.2015.10.013.

Gorjian, S., Zadeh, B.N., Eltrop, L., Shamshiri, R.R., Amanlou, Y., May 2019. Solar photovoltaic power generation in Iran: Development, policies, and barriers. Renew. Sustain. Energy Rev. 106, 110–123. https://doi.org/10.1016/j.rser.2019.02.025.

Green, M.A., Dunlop, E.D., Hohl-Ebinger, J., Yoshita, M., Kopidakis, N., Ho-Baillie, A.W. Y., Jan. 2020. Solar cell efficiency tables (Version 55). Prog. Photovolt. Res. Appl. 28 (1), 3–15. https://doi.org/10.1002/pip.3228.

"greenhouse gas | Definition, Emissions, & Greenhouse Effect | Britannica." https://www.britannica.com/science/greenhouse-gas (accessed Jun. 13, 2022).

Hallowell, M.R., Gambatese, J.A., Oct. 2009. Activity-Based Safety Risk Quantification for Concrete Formwork Construction. J. Constr. Eng. Manag. 135 (10), 990–998. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000071.

Hammond, G., Jones, C., Lowrie, E.F., Tse, P., 2011. Embodied carbon. Inventory Carbon Energy ICE Version 20.

"Heating - Fuels & Technologies - IEA." https://www.iea.org/fuels-and-technologies/heating (accessed Mar. 30, 2021).

Heger, M., Sarraf, M., 2018. Air pollution in Tehran: health costs, sources, and policies. World Bank.

Herrando, M., Markides, C.N., Hellgardt, K., Jun. 2014. A UK-based assessment of hybrid PV and solar-thermal systems for domestic heating and power: System performance. Appl. Energy 122, 288–309. https://doi.org/10.1016/j.apenergy.2014.01.061.

Hosseini, S.E., Dec. 2019. "Development of solar energy towards solar city Utopia", *Energy Sources Part Recovery Util.* Environ. Eff. 41 (23), 2868–2881. https://doi.org/10.1080/15567036.2019.1576803.

Hosseini, S.M.A., de la Fuente, A., Pons, O., Sep. 2016. Multicriteria Decision-Making Method for Sustainable Site Location of Post-Disaster Temporary Housing in Urban Areas. J. Constr. Eng. Manag. 142 (9), 04016036. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001137.

Hosseini, S.M.A., Pons, O., de la Fuente, A., Mar. 2018. A combination of the Knapsack algorithm and MIVES for choosing optimal temporary housing site locations: A case study in Tehran. Int. J. Disaster Risk Reduct. 27, 265–277. https://doi.org/10.1016/j.ijdrr.2017.10.013.

Hosseini, S.M.A., Pons Valladares, O., de la Fuente Antequera, A., Apr. 2019. "Sustainable building technologies for post-disaster temporary housing: integrated sustainability assessment and life cycle assessment", *World Acad. Sci.* Eng. Technol. 13 (4), 244–250. https://doi.org/10.5281/zenodo.

Hosseini, S.M.A., Yazdani, R., de la Fuente, A., Apr. 2020. Multi-objective interior design optimization method based on sustainability concepts for post-disaster temporary housing units. Build. Environ. 173, 106742 https://doi.org/10.1016/j.buildenv.2020.106742.

Hosseini, S.M.A., Farahzadi, L., Pons, O., Oct. 2021. Assessing the sustainability index of different post-disaster temporary housing unit configuration types. J. Build. Eng. 42, 102806 https://doi.org/10.1016/j.jobe.2021.102806.

Huide, F., Xuxin, Z., Lei, M., Tao, Z., Qixing, W., Hongyuan, S., May 2017. A comparative study on three types of solar utilization technologies for buildings: Photovoltaic, solar thermal and hybrid photovoltaic/thermal systems. Energy Convers. Manag. 140, 1–13. https://doi.org/10.1016/j.enconman.2017.02.059.

I. O. for Standardization, *Environmental management: life cycle assessment; Principles and Framework*. ISO, 2006.

Ibrahim, A., et al., 2009. Performance of photovoltaic thermal collector (PVT) with different absorbers design. WSEAS Trans. Environ. Dev. 5 (3), 321–330.

"IHS Markit - Leading Source of Critical Information," *IHS Markit*. https://ihsmarkit.com/index.html (accessed Mar. 05, 2021).

Jahromi, S.N., Vadiee, A., Yaghoubi, M., Aug. 2015. Exergy and Economic Evaluation of a Commercially Available PV/T Collector for Different Climates in Iran. Energy Procedia 75, 444–456. https://doi.org/10.1016/j.egypro.2015.07.416.

Jalilzadehazhari, E., Vadiee, A., Johansson, J., Mar. 2021. Subsidies required for installing renewable energy supply systems considering variations in future climate conditions. J. Build. Eng. 35, 101999 https://doi.org/10.1016/j.jobe.2020.101999.

Jannadi, O.A., Almishari, S., Oct. 2003. Risk Assessment in Construction. J. Constr. Eng. Manag. 129 (5), 492–500. https://doi.org/10.1061/(ASCE)0733-9364(2003)129:5(492).

Jia, Y., Alva, G., Fang, G., Mar. 2019. Development and applications of photovoltaic–thermal systems: A review. Renew. Sustain. Energy Rev. 102, 249–265. https://doi.org/10.1016/j.rser.2018.12.030.

Johnsson, F., Kjärstad, J., Rootzén, J., Feb. 2019. The threat to climate change mitigation posed by the abundance of fossil fuels. Clim. Policy 19 (2), 258–274. https://doi.org/10.1080/14693062.2018.1483885.

Jorli, M., Van Passel, S., Sadeghi, H., Nasseri, A., Agheli, L., Dec. 2017. Estimating Human Health Impacts and Costs Due to Iranian Fossil Fuel Power Plant Emissions through the Impact Pathway Approach. Energies 10 (12), 2136. https://doi.org/10.3390/en10122136.

Josa, I., Pons, O., de la Fuente, A., Aguado, A., Mar. 2020. Multi-criteria decision-making model to assess the sustainability of girders and trusses: Case study for roofs of sports halls. J. Clean. Prod. 249, 119312 https://doi.org/10.1016/j.jclepro.2019.119312.

Kannan, R., Leong, K.C., Osman, R., Ho, H.K., Tso, C.P., May 2006. Life cycle assessment study of solar PV systems: An example of a 2.7kWp distributed solar PV system in Singapore. Sol. Energy 80 (5), 555–563. https://doi.org/10.1016/j.solener.2005.04.008.

R. L. Keeney, K. R. L, and H. Raiffa, *Decisions with Multiple Objectives: Preferences and Value Trade-Offs*. Cambridge University Press, 1993.

Kemona, A., Piotrowska, M., Aug. 2020. Polyurethane Recycling and Disposal: Methods and Prospects. Polymers 12 (8), 1752. https://doi.org/10.3390/polym12081752.

"Key World Energy Statistics 2020 – Analysis - IEA." https://www.iea.org/reports/key-world-energy-statistics-2020 (accessed Jun. 10, 2021).

Korsavi, S.S., Zomorodian, Z.S., Tahsildoost, M., Feb. 2018. Energy and economic performance of rooftop PV panels in the hot and dry climate of Iran. J. Clean. Prod. 174, 1204–1214. https://doi.org/10.1016/j.jclepro.2017.11.026.

T. Kötter and F. Friesecke, "Developing urban indicators for managing mega cities," *Land Gov. Support MDGs Responding New Chall. Wash. DC USA*, p. p4, 2009.

H. Lecouls, "ISO 14043: Environmental management · life cycle assessment · life cycle interpretation," *Int. J. Life Cycle Assess.*, vol. 4, no. 5, pp. 245–245, Sep. 1999, doi: 10.1007/BF02979166.

Ledesma, G., Nikolic, J., Pons-Valladares, O., Nov. 2020. Bottom-up model for the sustainability assessment of rooftop-farming technologies potential in schools in Quito, Ecuador. J. Clean. Prod. 274, 122993 https://doi.org/10.1016/j.jclepro.2020.122993.

Lee, J.H., Hwang, S.G., Lee, G.H., Aug. 2019. Efficiency Improvement of a Photovoltaic Thermal (PVT) System Using Nanofluids. Energies 12 (16), 3063. https://doi.org/10.3390/en12163063.

M. del M. Casanovas, J. Armengou, and G. Ramos, "Occupational Risk Index for Assessment of Risk in Construction Work by Activity," *J. Constr. Eng. Manag.*, vol. 140, no. 1, p. 04013035, Jan. 2014, doi: 10.1061/(ASCE)CO.1943-7862.0000785.

M. T. C. Team, "SWOT Analysis, Discover New Opportunities, Manage and Eliminate Threats," *Mind Tools*, 2018.

B. Maleki, M. d M. Casanovas Rubio, S. M. A. Hosseini, and A. de la Fuente Antequera, "Multi-Criteria Decision Making in the Social Sustainability Assessment of High-Rise Residential Buildings," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 290, p. 012054, Jun. 2019, doi: 10.1088/1755-1315/290/1/012054.

Masson, V., Bonhomme, M., Salagnac, J.-L., Briottet, X., Lemonsu, A., Jun. 2014. Solar panels reduce both global warming and urban heat island. Front. Environ. Sci. 2 https://doi.org/10.3389/fenvs.2014.00014.

Masson, G., Briano, J.I., Baez, M.J., 2016. Review and analysis of PV self-consumption policies. IEA Photovolt. Power Syst. Programme PVPS 1 (28), pp.

Mishra, P.K., Tiwari, P., Jan. 2020. Solar Photovoltaic Technology—A Review. Adv. Sci. Eng. Med. 12 (1), 5–10. https://doi.org/10.1166/asem.2020.2512.

Mohanta, P.R., Patel, J., Bhuva, J., Gandhi, M., 2015. A Review on solar Photovoltaics and Roof Top application of it. Int. J. Adv. Res. Sci. Eng. Technol. 2, 2394–2444.

Moran, D., Kanemoto, K., Jiborn, M., Wood, R., Többen, J., Seto, K.C., Jun. 2018. Carbon footprints of 13 000 cities. Environ. Res. Lett. 13 (6), 064041 https://doi.org/10.1088/1748-9326/aac72a.

Moran, F., Natarajan, S., Sep. 2015. PV in historic dwellings: The potential to reduce domestic CO2 emissions. J. Build. Eng. 3, 70–78. https://doi.org/10.1016/j.jobe.2015.06.004.

Motahar, S., Bagheri-Esfeh, H., Jun. 2020. Artificial neural network based assessment of grid-connected photovoltaic thermal systems in heating dominated regions of Iran. Sustain. Energy Technol. Assess. 39, 100694 https://doi.org/10.1016/j.seta.2020.100694.

Munari Probst, M.C., et al., 2013. Solar energy systems in architecture - Integration criteria and guidelines. accessed Jul. 10, 2021 Infoscience. https://infoscience.epfl.ch/record/197097.

Nadal, A., Pons, O., Cuerva, E., Rieradevall, J., Josa, A., Jun. 2018. Rooftop greenhouses in educational centers: A sustainability assessment of urban agriculture in compact cities. Sci. Total Environ. 626, 1319–1331. https://doi.org/10.1016/j.scitotenv.2018.01.191.

Najafi, G., Ghobadian, B., Mamat, R., Yusaf, T., Azmi, W.H., Sep. 2015. Solar energy in Iran: Current state and outlook. Renew. Sustain. Energy Rev. 49, 931–942. https://doi.org/10.1016/j.rser.2015.04.056.

Noorpoor, A.R., Kudahi, S.N., Jul. 2015. CO_2 emissions from Iran's power sector and analysis of the influencing factors using the stochastic impacts by regression on population, affluence and technology (STIRPAT) model. Carbon Manag. 6 (3–4), 101–116. https://doi.org/10.1080/17583004.2015.1090317.

I. OECD, "Energy and Air Pollution: World Energy Outlook Special Report 2016," 2016.

Omer, A.M., Dec. 2008. Energy, environment and sustainable development. Renew. Sustain. Energy Rev. 12 (9), 2265–2300. https://doi.org/10.1016/j.rser.2007.05.001.

Paço, A., Lavrador, T., Jul. 2017. Environmental knowledge and attitudes and behaviours towards energy consumption. J. Environ. Manage. 197, 384–392. https://doi.org/10.1016/j.jenvman.2017.03.100.

Paiano, A., Jan. 2015. Photovoltaic waste assessment in Italy. Renew. Sustain. Energy Rev. 41, 99–112. https://doi.org/10.1016/j.rser.2014.07.208.

Parida, B., Iniyan, S., Goic, R., Apr. 2011. A review of solar photovoltaic technologies. Renew. Sustain. Energy Rev. 15 (3), 1625–1636. https://doi.org/10.1016/j.rser.2010.11.032.

Peng, C., Huang, Y., Wu, Z., Dec. 2011. Building-integrated photovoltaics (BIPV) in architectural design in China. Energy Build. 43 (12), 3592–3598. https://doi.org/10.1016/j.enbuild.2011.09.032.

Petter Jelle, B., Breivik, C., Drolsum Røkenes, H., May 2012. Building integrated photovoltaic products: A state-of-the-art review and future research opportunities. Sol. Energy Mater. Sol. Cells 100, 69–96. https://doi.org/10.1016/j.solmat.2011.12.016.

Pinel, D., Korpås, M., Lindberg, K.B., Jan. 2021. Impact of the CO 2 factor of electricity and the external CO 2 compensation price on zero emission neighborhoods' energy system design. Build. Environ. 187, 107418 https://doi.org/10.1016/j.buildenv.2020.107418.

Pons, O., Aguado, A., Jul. 2012. Integrated value model for sustainable assessment applied to technologies used to build schools in Catalonia, Spain. Build. Environ. 53, 49–58. https://doi.org/10.1016/j.buildenv.2012.01.007.

Pons, O., de la Fuente, A., Dec. 2013. Integrated sustainability assessment method applied to structural concrete columns. Constr. Build. Mater. 49, 882–893. https://doi.org/10.1016/j.conbuildmat.2013.09.009.

Pons, O., de la Fuente, A., Aguado, A., May 2016. The Use of MIVES as a Sustainability Assessment MCDM Method for Architecture and Civil Engineering Applications. Sustainability 8 (5), 460. https://doi.org/10.3390/su8050460.
Pons, O., Franquesa, J., Hosseini, S.M.A., Nov. 2019. TOWARDS A NEW INTERACTIVE TOOL OF RESOURCES FOR ACTIVE LEARNING IN UNIVERSITY LARGE GROUPS' LECTURES. Seville, Spain, pp. 2277–2286.
Pons, O., Franquesa, J., Hosseini, S.M.A., May 2019. Integrated Value Model to Assess the Sustainability of Active Learning Activities and Strategies in Architecture Lectures for Large Groups. Sustainability 11 (10), 2917. https://doi.org/10.3390/su11102917.
Pons-Valladares, O., Nikolic, J., Nov. 2020. Sustainable Design, Construction, Refurbishment and Restoration of Architecture: A Review. Sustainability 12 (22), 9741. https://doi.org/10.3390/su12229741.
Powe, N.A., Willis, K.G., Feb. 2004. Mortality and morbidity benefits of air pollution (SO2 and PM10) absorption attributable to woodland in Britain. J. Environ. Manage. 70 (2), 119–128. https://doi.org/10.1016/j.jenvman.2003.11.003.
I. Pvps, "Snapshot of global photovoltaic markets," *Rep. IEA PVPS T1-31*, 2017.
D. Raverkar, U. Chauhan, V. Singh, and A. Rani, "An Improved Fractional Voltage Based MPPT Technique for PV Generation System," in *2020 International Conference on Advances in Computing, Communication & Materials (ICACCM)*, Dehradun, India, Aug. 2020, pp. 267–271. doi: 10.1109/ICACCM50413.2020.9212995.
"Renewable Energy and Energy Efficiency Organization." http://www.satba.gov.ir/en/home (accessed Feb. 10, 2021).
"Renewable Power Generation Costs in 2020," */publications/2021/Jun/Renewable-Power-Costs-in-2020*. https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020 (accessed Jun. 24, 2022).
Roberts, M.B., Bruce, A., MacGill, I., Apr. 2019. Opportunities and barriers for photovoltaics on multi-unit residential buildings: Reviewing the Australian experience. Renew. Sustain. Energy Rev. 104, 95–110. https://doi.org/10.1016/j.rser.2018.12.013.
Saaty, T.L., Sep. 1990. How to make a decision: The analytic hierarchy process. Eur. J. Oper. Res. 48 (1), 9–26. https://doi.org/10.1016/0377-2217(90)90057-I.
Sadeghi, M., Kalantar, M., 2013. In: Allocation of Solar Units to Reduce Annual Costs of the Distribution System. Wroclaw, Poland, Nov, pp. 132–137. https://doi.org/10.1109/EEEIC.2.2013.6737896.
Sáez-Martínez, F.J., Mondéjar-Jiménez, J., Mondéjar-Jiménez, J.A., Jan. 2015. The energy challenge: energy and Environment Knowledge Week E2KW 2013. J. Clean. Prod. 86, 471–473. https://doi.org/10.1016/j.jclepro.2014.08.044.
Sathe, T.M., Dhoble, A.S., Sep. 2017. A review on recent advancements in photovoltaic thermal techniques. Renew. Sustain. Energy Rev. 76, 645–672. https://doi.org/10.1016/j.rser.2017.03.075.
Saurabh, A., Atheaya, D., Kumar, A., Feb. 2020. Study of hybrid photovoltaic thermal systems. IOP Conf. Ser. Mater. Sci. Eng. 748, 012016 https://doi.org/10.1088/1757-899X/748/1/012016.
K. Seepromting, R. Chatthaworn, P. Khunkitti, A. Kruesubthaworn, A. Siritaratiwat, and C. Surawanitkun, "Distribution company investment cost reduction analysis with grid-connected solar PV allocation in power distribution system," *Int. J. Smart Grid Clean Energy*, pp. 230–235, 2020, doi: 10.12720/sgce.9.1.230-235.
Shukla, A.K., Sudhakar, K., Baredar, P., May 2016. Exergetic assessment of BIPV module using parametric and photonic energy methods: A review. Energy Build. 119, 62–73. https://doi.org/10.1016/j.enbuild.2016.03.022.
Shukla, A.K., Sudhakar, K., Baredar, P., Sep. 2016. A comprehensive review on design of building integrated photovoltaic system. Energy Build. 128, 99–110. https://doi.org/10.1016/j.enbuild.2016.06.077.
"Solar resource maps and GIS data for 200+ countries | Solargis." https://solargis.com/maps-and-gis-data/download/iran (accessed Apr. 08, 2021).
Souliotis, M., Arnaoutakis, N., Panaras, G., Kavga, A., Papaefthimiou, S., Oct. 2018. Experimental study and Life Cycle Assessment (LCA) of Hybrid Photovoltaic/Thermal (PV/T) solar systems for domestic applications. Renew. Energy 126, 708–723. https://doi.org/10.1016/j.renene.2018.04.011.
"STEEL IN BUILDINGS AND INFRASTRUCTURE | worldsteel." https://www.worldsteel.org/steel-by-topic/steel-markets/buildings-and-infrastructure.html (accessed May 04, 2021).
Sultan, S.M., Ervina Efzan, M.N., Oct. 2018. Review on recent Photovoltaic/Thermal (PV/T) technology advances and applications. Sol. Energy 173, 939–954. https://doi.org/10.1016/j.solener.2018.08.032.
"Tehran Annual Air and Noise Quality Report, period of March 2020 - March 2021," Air Quality Control Company, Tehran, Iran, QM1400/02/01(U)/1, May 2021. Accessed: Feb. 22, 2022. [Online]. Available: https://air.tehran.ir/Default.aspx?tabid=471.
"Tehran Municipality Information and Communication Technology (ICT) Organization." https://tmicto.tehran.ir/ (accessed Jul. 02, 2021).
"Tehran Province Meteorological Administration." http://www.tehranmet.ir/Index.aspx?tempname=english&lang=1&sub=0 (accessed Nov. 19, 2020).
Toboso-Chavero, S., et al., Aug. 2019. Towards Productive Cities: Environmental Assessment of the Food-Energy-Water Nexus of the Urban Roof Mosaic. J. Ind. Ecol. 23 (4), 767–780. https://doi.org/10.1111/jiec.12829.
Tomar, V., Tiwari, G.N., Bhatti, T.S., Norton, B., Jun. 2018. Thermal modeling and experimental evaluation of five different photovoltaic modules integrated on prototype test cells with and without water flow. Energy Convers. Manag. 165, 219–235. https://doi.org/10.1016/j.enconman.2018.03.039.
Tongsopit, S., Dec. 2015. Thailand's feed-in tariff for residential rooftop solar PV systems: Progress so far. Energy Sustain. Dev. 29, 127–134. https://doi.org/10.1016/j.esd.2015.10.012.
Tripanagnostopoulos, Y., Souliotis, M., Battisti, R., Corrado, A., May 2005. Energy, cost and LCA results of PV and hybrid PV/T solar systems. Prog. Photovolt. Res. Appl. 13 (3), 235–250. https://doi.org/10.1002/pip.590.
Wang, Y., et al., Apr. 2021. Modeling and operation optimization of an integrated ground source heat pump and solar PVT system based on heat current method. Sol. Energy 218, 492–502. https://doi.org/10.1016/j.solener.2021.03.003.
Winge, S., Albrechtsen, E., Mostue, B.A., Feb. 2019. Causal factors and connections in construction accidents. Saf. Sci. 112, 130–141. https://doi.org/10.1016/j.ssci.2018.10.015.
"World Urbanization Prospects - Population Division - United Nations." https://web.archive.org/web/20200722025234/https://population.un.org/wup/Publications/ (accessed Sep. 07, 2022).
Xiao, P., Zhang, M., Wu, X., Ding, K., Pan, J., Jie, J., Mar. 2022. Enhancing the efficiency and stability of Organic/Silicon solar cells using graphene electrode and Double-layer Anti-reflection coating. Sol. Energy 234, 111–118. https://doi.org/10.1016/j.solener.2022.01.063.
Zabihi Sheshpoli, A., Jahanian, O., Nikzadfar, K., Aghajani Delavar, M., Feb. 2021. Numerical and experimental investigation on the performance of hybrid PV/thermal systems in the north of Iran. Sol. Energy 215, 108–120. https://doi.org/10.1016/j.solener.2020.12.036.
Zamani-Sabzi, H., King, J.P., Gard, C.C., Abudu, S., 2016. Statistical and analytical comparison of multi-criteria decision-making techniques under fuzzy environment. Oper. Res. Perspect. 3, 92–117. https://doi.org/10.1016/j.orp.2016.11.001.
Zhang, X., et al., Nov. 2018. A review of urban energy systems at building cluster level incorporating renewable-energy-source (RES) envelope solutions. Appl. Energy 230, 1034–1056. https://doi.org/10.1016/j.apenergy.2018.09.041.
Zhao, Y., Yu, L., Sun, M., Apr. 2021. Recent progress in emerging 2D layered materials for organic solar cells. Sol. Energy 218, 621–638. https://doi.org/10.1016/j.solener.2021.02.066.
Zhou, L., Li, J., Li, F., Meng, Q., Li, J., Xu, X., Jan. 2016. Energy consumption model and energy efficiency of machine tools: a comprehensive literature review. J. Clean. Prod. 112, 3721–3734. https://doi.org/10.1016/j.jclepro.2015.05.093.
Zondag, H.A., de Vries, D.W., van Helden, W.G.J., van Zolingen, R.J.C., van Steenhoven, A.A., Mar. 2003. The yield of different combined PV-thermal collector designs. Sol. Energy 74 (3), 253–269. https://doi.org/10.1016/S0038-092X(03)00121-X.

CHAPTER 3

Observation and optimization

The results obtained on the building scale in the previous chapter are enriched and become more practical by monitoring and set-up in order to achieve the highest performance and feasibility on the city scale, which is followed in this third chapter. To this end, a unified multi-scale and systematic approach for planning and optimization is the essential prospective strategy developed, in order to facilitate and accelerate real future accomplishments for the involved stakeholders and decision-makers.

3.1. Contribution to thesis

This chapter contributes to Phases 2 and 5 of the thesis project by considering the feasibility study and providing an observation and monitoring plan.

Article C contributes to generating an innovative model to define and prioritize optimal planning on a city scale and recommends the most suitable solutions through a systematic approach. This chapter investigates the feasibility for choosing potential pollutant-reducing alternatives and also for selecting potential target building groups to be applied to. Since pollutant-reducing alternatives vary in potential, the subsequent contribution of this study is suggesting the most efficient set in their combination to attain the highest total performance. Moreover, this study and its framework also contribute to the definition of a multi-level indicators tree for target buildings classification and specifying the significant determinative indicators for the specific case study. In addition, this third chapter contributes to determining the capability of rooftops in mitigating urban air pollution and following the concept of nearly Zero-Emission Building groups (nZEBs) on a city scale. Meanwhile, the planning and future prospects outlined in this research study can help realize sustainable urban development in general.

3.2. Article C: City-scale planning and optimization

Article C, entitled "City-Scale Model to Assess Rooftops Performance on Air Pollution Mitigation; Validation for Tehran", published in the 244^{th} vol. of *Building and Environment*, which is ranked in Q1 among indexed journals (doi: 10.1016/j.buildenv.2023.110746) [88].

The **contributions and individual roles of the thesis author** as the main author of this paper were conceptualization, data curation, investigation, methodology, formal analysis, resources, validation, visualization, writing the original draft, and revising. The other authors of the article are the thesis co-directors, who mainly supervised and advised the first author and reviewed the manuscript. In this study, the proposed model incorporates potential pollutant-reducing alternatives with target building groups to define and evaluate different possible scenarios. A copy of this research article is attached in the following.

Building and Environment 244 (2023) 110746

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

City-scale model to assess rooftops performance on air pollution mitigation; validation for Tehran

S. Hamed Banirazi Motlagh [a], Oriol Pons-Valladares [a,*], S.M. Amin Hosseini [b]

[a] Department of Architectural Technology, Polytechnic University of Catalonia (UPC), Av. Diagonal 649, 08028, Barcelona, Spain
[b] RESUME TECH (Resilience and Sustainability in Metropolitans TECH), America St., 08041, Barcelona, Spain

ARTICLE INFO

Keywords:
Climate change
Air pollution
Cities
Green infrastructure
Residential buildings
Rooftops

ABSTRACT

Cities have a significant role in the current climate change and air pollution crisis; hence, it is urgent to mitigate the negative effects of pollution in urban settlements. This situation requires developing agile plans to simultaneously investigate the efficiency of green infrastructures and feedback from their targets. A crucial consideration for these plans is the potential rooftops have – broadly abundant and underused in urban areas – to harbour sustainable, effective, and viable alternatives. This study aims to develop a new model to optimize the utilization of feasible pollutant reducers, investigate the ability rooftops present to reduce air pollution and recommend the most suitable city-scale solutions. The proposed model combines mathematical patterns, GIS, and sensitivity analysis. This systematic and adaptable approach was first applied to heavily air-polluted Tehran city, which has vastly unused rooftops. This leading application identified: i) two appropriate pollutant reducing alternatives – photovoltaic and green roofs –; ii) optimized total performance alternative when simultaneous mitigation of PM and CO_2 is required – compound alternative –; iii) three significant indicators for target building groups – land use, building height, and surface scale –; and iv) the most suitable group – residential medium height in medium surface scale buildings. Applying a compound alternative with a 3:1 ratio (photovoltaic:green roof) to all potential target buildings enables a 9% decrease in the total city level for PM and CO_2 emissions.

1. Introduction

Climate change urgency is highlighted by a significant UN report that warns of a dangerous path toward global catastrophe unless governments act quickly and broadly to revise their strategies [1]. The Climate Change Conference (COP27, November 2022, Egypt) amplified this imperative, urging for a monumental leap in climate ambition and the immediate reduction of emissions [2]. This urgency aligns with the commitments by nations under the Paris Agreement (2015) to curtail greenhouse gas (GHG) emissions [3]. Likewise, the energy crisis attracts more attention than ever worldwide, especially in the case of severe dependence on fossil fuels [4]. In this area, the right policies, infrastructures, and technologies are expected to result in a 40%–70% decrease in GHG emissions by 2050 [1]. As such, governments are compelled to enact prospective strategies equipped with multifaceted support systems and regulations to address these pressing challenges.

Aligned with this urgency, the Intergovernmental Panel on Climate Change (IPCC, April 2022) underscored the potential of reevaluating urban functions in mitigating the impacts of climate change [1]. The centrality of cities in the built environment magnifies the imperative for urban settlements to counteract the adverse effects of pollution on public health. Furthermore, cities possess the capacity to play a significant role in ambient emissions mitigation, where rooftops, as efficacious building envelopes, emerge as a potent tool [5]. Rooftops provide a promising context due to their abundance, extensive coverage, exposure to sunlight, accessibility, and underused potential [6–8]. Alongside this, green infrastructure (GI) is a potential option to embed climate resilience within the built environment [5,9,10]. This way, the GI potential is an essential consideration to contribute to mitigating ambient pollution [11]. Although scientific strides have bolstered the efficacy and profitability of GI, their full potential remains unrealized, necessitating a holistic, synergistic approach [12]. This has prompted urban authorities to invest actively in research and development not only to enhance the technical GI efficiency but also to unravel feedback mechanisms [12]. This sphere of inquiry also encompasses the identification of distinct target groups with varying suitability levels, guiding the prioritized GI deployment [13].

* Corresponding author.
E-mail addresses: seyed.hamed.banirazimotlagh@upc.edu (S.H. Banirazi Motlagh), oriol.pons@upc.edu (O. Pons-Valladares), amin@resumetec.com (S.M.A. Hosseini).

https://doi.org/10.1016/j.buildenv.2023.110746
Received 30 June 2023; Received in revised form 13 August 2023; Accepted 16 August 2023
Available online 22 August 2023

Abbreviations

BAPV	Building-attached photovoltaic
CA	Compound alternative
CAA	Clean Air Act
EA	Extra-large area
GHG	Greenhouse gas
GI	Green infrastructure
GIS	Geographic Information System
GR	Green roof
HH	High height
IPCC	Intergovernmental Panel on Climate Change
LA	Large area
MA	Medium area
MH	Medium height
NCV	Net calorific value
nZEBs	nearly Zero-Emission Building groups
PO	Partial outcome
PM	Particulate matter
PV	Photovoltaic
SA	Small area
SH	Short height
SIGR	Semi-intensive GR

In this context, systematic frameworks are essential, particularly in heavily air-polluted cities. Thus, this study aims to develop a new agile model to optimize feasible pollutant reducers utilization, assess the ability rooftops provide to mitigate air pollution and recommend the most suitable solutions on a city scale. This objective comes from reviewing related technical literature and finding gaps. For instance, scholars such as J. Irga et al. (2022) have critically compared the efficacy of green roofs in ambient air pollutant removal to conventional roofs [14], while J. Yuan et al. (2022) have scrutinized the sustainability and energy balance green roofs provide in desert climates [15]. A. F. Antoniolli et al. (2022) have developed a statistical algorithm to assess energy yield from large rooftop photovoltaic systems [16], and S. Rafael et al. (2021) have investigated the direct and indirect impacts green roofs have on air quality [17]. Other studies have delved into the technical feasibility of combining urban agriculture, rainwater collection, and solar systems on rooftops [18], examined green roof species for urban air pollution mitigation [19], and evaluated photovoltaic energy balance for rooftop scenarios [20]. The exploration extends to the use of ENVI-met models to improve urban air quality through green roofs and green walls [21], the assessment of rooftop suitability for solar installations based on criteria like economy, aesthetics, and energy [22], and the proposal of rooftop area determination techniques for solar PV deployment [23]. Furthermore, innovative concepts such as roof mosaics have been introduced to examine the feasibility of collecting food, energy, and rainwater from rooftop installations [24] and the potential of rooftop installations in urban self-sufficiency projects [25]. The multifaceted potential rooftops provide include photovoltaic panels for electricity production [26], rooftop greenhouses for schools [27], and considerations in choosing between vegetated roofs and solar systems [28]. Overall, these previous studies concluded that rooftop installations like green roofs (GR) and photovoltaic panels (PV) provide multiple benefits, including urban air quality improvement, energy balance, and other diverse functionalities.

Nevertheless, to the best of the authors' knowledge, this research project is the first attempt to develop an approach for simultaneously considering potential target buildings and feasible pollutant reducers, furthermore combining them in the most efficient ratio. It is expected that this multi-scale approach can provide clearer insights for decision-makers and professionals in developing performance-based and place-based knowledge in the field. This novel approach is first applied in Tehran, a city with untapped rooftop potential and a serious air pollution problem. While the immediate focus rests on Tehran's unique characteristics, specific pollutant-reducing alternatives, and existing technologies, the applicability of this approach could extend beyond its current boundaries – embracing diverse case studies, pollutant reducers, and technological solutions – after considering the particularities of each case study and applying the necessary modifications to the approach steps.

A structural summary of this study is as follows. Section 2 defines the framework, methods, and proposed model for this project, which combines different tools, such as mathematical patterns, Geographic Information System (GIS), and sensitivity analysis. Section 3 presents the area under study by evaluating the potential and needs of the case study, as well as determining the inclusive domain of the study. Section 4 applies this model to the case study and provides initial results by presenting the feasible alternatives selection, optimization for these alternatives, main indicators determination, data classification, and potential scenarios definition. Section 5 aims to analyze these initial results and discuss the final outcomes through performance assessment, prioritization of scenarios, sensitivity analysis, and investigation nearly zero-emission building groups (nZEBs) on a city scale. Finally, Section 6 draws conclusions based on the significant interpretations and key findings supported by the data presented while proposing future research projects.

2. Methodology

The framework for the current research project has three main phases, as presented in Fig. 1. First, the *Boundaries* phase specifies the area under the study (Section 3). Second, the *Model setting* develops the novel model through three steps (Section 4). Finally, the *Results commentary* accomplishes analysis (Section 5). Notably, as shown in Fig. 1, in the application process of this model, each step has partial outcomes (PO) that are considered in the next steps.

Phase 1 (*Boundaries*, including step 1): this first phase determines the requirements and capabilities of the case study while considering the study scope. The PO for this step is the need for the city to reduce its air pollution, the potential roofs provide to reduce air pollution for each specific case study, and the limits determined for this research project.

Phase 2 (*Model setting*, including steps 2–4): the selection and optimization of feasible alternatives in step 2 lead to the determination of different potential pollutant-reducing alternatives. Then, the main indicators determination and data classification in step 3 result in the determination of different potential target building groups. Step 4 defines different potential scenarios to attain initial general results by combining potential pollutant-reducing alternatives with potential target building groups considering their possible permutations with each other. In step 4, initial general results are obtained by means of (a) results from feasibility studies to quantify the performance of each pollutant-reducing alternative; (b) mathematical patterns to optimize the combination ratio of these alternatives; and (c) GIS to combine different data layers and surface quantification as well, on target building groups; as explained in detail in Section 2.1.

Phase 3 (*Results commentary*, including step 5): follows the model planned in the previous phase to evaluate and examine the results. Analysis in this step intends to (a) assess the capability of defined scenarios to mitigate air pollution on a city scale, (b) suggest proper prioritization to find the most suitable scenarios in the area under study, and (c) prove the robustness of the proposed model with the help of sensitivity analysis. Finally, decision-making is achieved by applying the

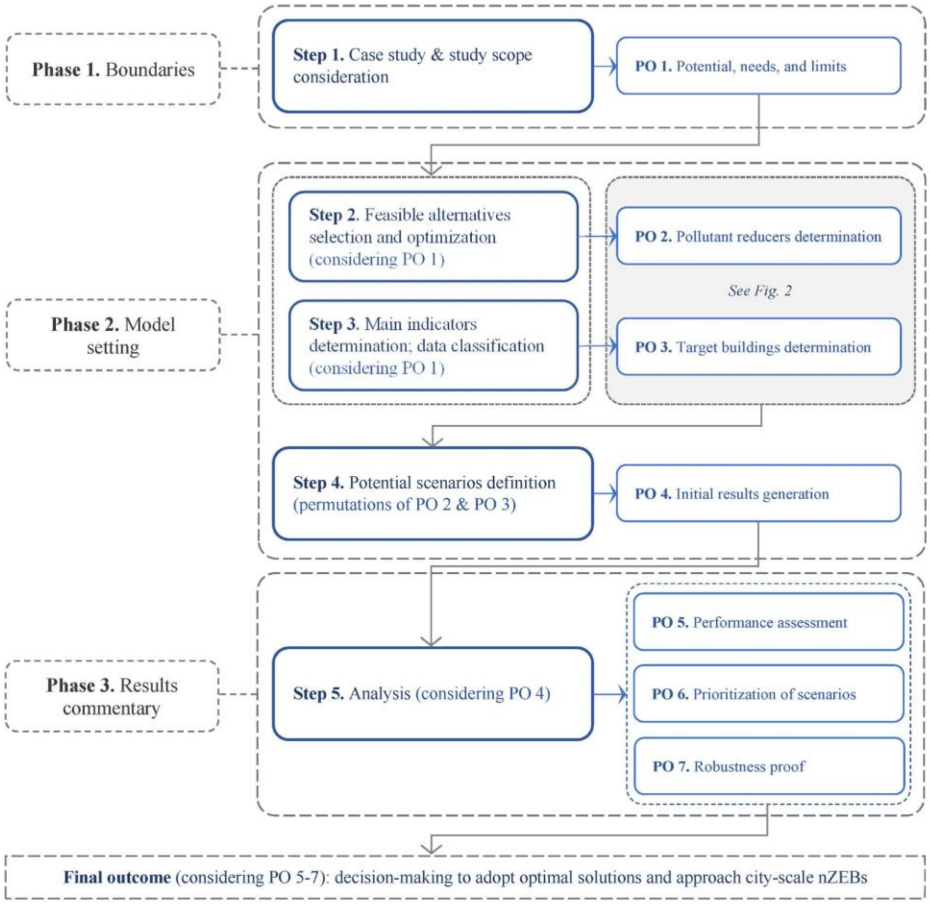


Fig. 1. Framework to implement the model established in this study (PO: Partial outcome).

proposed model and finalizing the findings investigation to adopt the optimal solutions and approach nZEBs on a city scale.

2.1. Model setting

The presented method in Fig. 2 involves two research steps (steps 2 & 3) to define the potential scenarios in step 4, as described in the following paragraphs.

This model selects the feasible pollutant-reducing alternatives for each case study by considering (a) sustainability, (b) effectiveness, and (c) viability, following the research within available technical literature, according to the environmental assessment, performance evaluation, stakeholder engagement, and relevant standards. More explanation regarding feasible alternatives selection for the case study is presented in the corresponding results section (Section 4.1.1). Additionally, since different pollutant-reducing alternatives vary in their potential and advantages, a suggestion to use both systems simultaneously can result in the highest benefits. In this regard, by defining the proper combination ratio, sustainability activities may be better coordinated to improve their fit under varied and unique settings to optimize performance efficiency [28]. The aforementioned step 2 applies mathematical patterns for optimizing and determining the most efficient combination ratio. An example of the way to utilize mathematical patterns in optimizing the combination of feasible pollutant-reducing alternatives for the case study is available in detail in the corresponding results section (Section 4.1.2).

This study determines potential target building groups for prioritization of the rooftops to apply because it is an essential strategy to achieve the highest performance by facilitating and accelerating the real future implementation [22]. This acceleration is obtained by concentrating governance supporting systems and incentives, such as facilities, special regulations, tax exemption, financial loans, extra education, etc. Defining these potential target buildings is done based on the characteristics of each case study regarding the applicability of rooftops in the area under study. To this end, it appears that determining suitable building groups to apply pollutant reducers necessitates considering nuancing and a variety of relevant parameters [29]. To achieve this, the determinant indicators are defined generally, and then the significant ones for each specific case study are investigated and determined. Choosing the crucial indicators also makes the proposed model agile to apply by the stakeholders. A more detailed explanation of the way to define general determinant parameters is presented in the following.

The categorization of different indicators to determine target buildings is established on three aspects of urban, building, and construction,

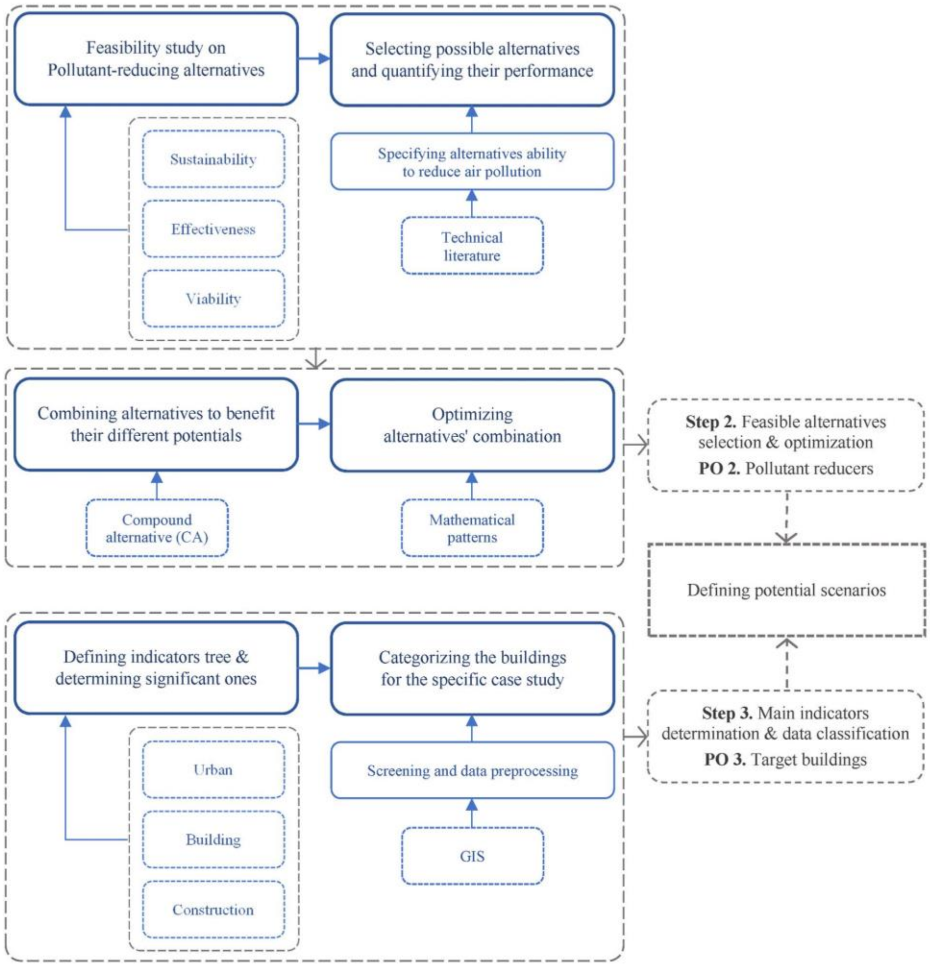


Fig. 2. Procedure to define potential scenarios (See steps 2 and 3 in Fig. 1).

as shown in Fig. 3. This consideration and its investigation are based on authors' knowledge, seminars held by multidisciplinary experts, and current technical literature. Overall, along with influence, it is necessary to attempt to discriminate enough when defining each indicator to avoid overlapping and similarity. Additionally, some parameters without significant effects, such as building geometry, or some factors with a similar

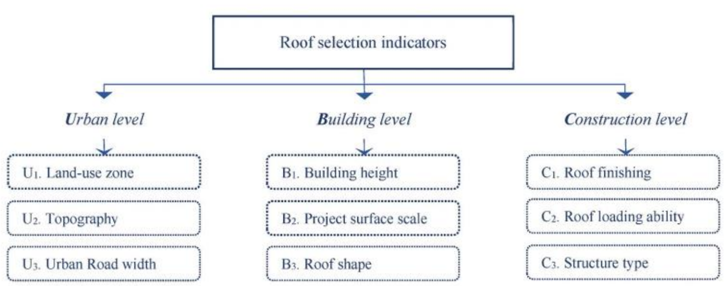


Fig. 3. Indicators tree for rooftops selection by physical/direct-impact parameters.

impact on the whole city, like urban form, are not considered in this study.

This research project focuses on physical indicators with a direct impact that is summarized in the following lines. (U_1) *Land-use zone* includes, for example, residential, services, etc. (U_2) *Topography* can be a considerable factor for some alternatives, such as wind turbines affected by wind force to work since the intensity and direction of airflow are influenced by the topography of the region [30,31]. (U_3) *Urban Road width* would be effective when two buildings of different heights are located on opposite sides of a road's edges. Consequently, the shorter building can be in the shadow of the taller one. (B_1) *Building height* is the number of storeys and approximates the height scale of the building. (B_2) *Project surface scale* is the plot area and indicates the surface scale of the building. (B_3) *Roof shape* in cities may contain different forms in section – i.e., flat, pitched – or in the plan – i.e., rectangular, U-shape. (C_1) *Roof finishing* takes into account the building materials which cover the external layer of the roof. (C_2) *Roof loading ability* is considered a technical matter to adding rooftop installations, which can become a barrier for buildings without enough structural stability to accept new dead loads [32]. (C_3) *Structure type* of buildings can play a role in the compatibility of rooftop applications with underlayers for installation and utilization [32].

After determining the main indicators for each specific case – which is described specifically for the case study in the corresponding results section (Section 4.2.1) – the aforementioned step 3 uses GIS for data screening. Because of that, screening and data classification based on various indicators need a tool capable of combining different data layers – belonging to different indicators – at the same time. In this sense, GIS as a location-based platform provides the required possibility [33,34]. To do so, it is needed a detailed urban plan with the specific attributes of each parcel (lot) in the GIS format. After determining the main indicators for the target buildings of the case study, it is necessary to generate a data layer based on the first indicator and extract the parcels that have the chosen feature relevant to this first indicator. Then filter the generated layer by assigning the next indicator values and extract the parcels have the chosen feature relevant to this second indicator again, and continue this approach until applying the last indicator. In this way, the final level provides an overlapped analysis of various data layers containing diverse information. GIS is used again to quantify the roof area of target building groups as well. An example of applying this approach to the case study is available in the results section (Section 4.2.2).

3. Area under study

3.1. Case study

Tehran, the most populated and largest city in Iran [7,8], is considered the case study in this research project (Fig. B.1). Tehran is one of the most heavily air-polluted megacities on the globe due to urbanization, population growth, industrial development, and increasing fossil fuel consumption [35,36]. The air pollution situation in Tehran – explained in detail in the former study [7] – reveals that particulate matters (PMs) are the most critical urban air pollutant in this case study; meanwhile, CO_2 emissions account for the most significant GHG in general [37,38].

According to a world bank report (April 2018), Tehran was ranked 12^{th} worldwide in terms of PM_{10} air pollutants among 26 megacities [35]. This occurs while Tehran's ranking has been 9^{th} across the same 26 megacities in terms of $PM_{2.5}$ in 2021 [39]. Moreover, among 500 high carbon footprint cities, Tehran was ranked 14^{th} in the world [40]. Air pollution not only poses critical problems for citizens' health and life quality but also causes a force on economic costs [41–46]. In this sense, more than 4000 annual premature deaths are caused merely by $PM_{2.5}$ emissions, and 2.6 billion US dollars in losses per year are due just to the side effects air pollution has on human health in Tehran [35].

Accordingly, Tehran faces an urgent need for a proper strategy to mitigate urban air pollution in different sectors. For instance, the transportation and traffic department head for the Tehran municipality carried out the "proposed plan to mitigate Tehran's air pollution" from its specific viewpoint. Meanwhile, there is considerable potential in the building sector for unused rooftops to contribute to improving air quality in Tehran, which has not been addressed yet. This occurs while city managers in Tehran require such a contribution since the air pollution problem has always been one of the government's serious concerns. In this regard, Iran passed its first national clean air regulation in 1975 and 20 years later adopted its first Clean Air Act (CAA) in 1995 [47]. The last CAA version was approved by parliament and announced by the president in 2017 [48]. Moreover, significant potential sunlight is available in Iran, with nearly 300 sunny days on most of its land. The average daylight duration is 2800 h per year, higher than the universal mean [49].

3.2. Study scope

Besides the geographical scope defined in the case study section (Section 3.1), the main study scope considered in this research project focuses on rooftops in different urban areas. In this sense, this study also focuses on feasible pollutant-reducing alternatives, among available pollutant reducers, to install on rooftops.

Moreover, it is important to note that this research considers the simultaneous need to mitigate PM and CO_2 emissions as the main pollutants of interest for the case study. Additionally, this research project focuses on environmental outcomes, though economic assessment concerning costs and benefits from different aspects can examine the model's acceptability for implementation from the financial viewpoint.

Furthermore, as mentioned in Section 2, only physical parameters are considered to determine potential target buildings in this study. Non-physical parameters with indirect impacts are often associated with the occupants' needs and motivations, which require other demographic evaluation and specialized sociological studies beyond this study. However, since all criteria can be useful and bear weight for other boundaries, a brief description concerning examples of non-physical indicators is provided in Appendix A.

4. Results

This section explains in detail the second phase of the research framework for the validation case, as defined in the methodology section (Section 2).

4.1. Pollutant-reducing alternatives

This section determines pollutant-reducing alternatives for the case study (step 2, PO 2) by selecting feasible alternatives (Section 4.1.1) and optimizing these alternatives (Section 4.1.2).

4.1.1. Feasible alternatives selection

Following the aforementioned in Section 2, (a) sustainability, (b) effectiveness, and (c) viability are considered to choose feasible pollutant-reducing alternatives in this study, as described here.

(a) *Sustainability:* GR and PV systems, two of the highest trending options, are both sustainable practices that compete in building projects [12,28,50]. Previous relevant studies have already developed models capable of selecting the most sustainable domestic GR and PV applications for the case study [7,8]. The sustainability level, a key performance indicator in sustainable urban development, was considered based on three pillars; economic, environmental, and social aspects [51]. Accordingly, building-attached photovoltaics (BAPV) and semi-intensive green roofs (SIGR) represent the most suitable types with the highest sustainability level in each alternative group for the case study.

(b) *Effectiveness*: GR and PV systems are considered effective measures to mitigate both PM and CO_2 emissions in urban areas like Tehran due to the following reasons:

PM reduction: 1) GRs possess the capability to alleviate PM levels by acting as filters. The layers of vegetation on GRs capture and absorb PM from the air, reducing its presence. The plants' foliage plays a crucial role in capturing airborne particles [7]. 2) PV panels do not directly contribute to PM reduction; However, their generation of clean electricity offers an indirect benefit. By diminishing reliance on fossil fuel-based power plants, which are significant PM emitters, PV systems can help decrease PM emissions associated with electricity generation. This transition to solar energy can also substitute the habitants' consumption of fossil fuel-based resources, such as natural gas [8].

CO_2 reduction: 1) GRs indirectly contribute to CO_2 reduction by acting as carbon sinks. Through photosynthesis, the plants on GRs absorb carbon dioxide, thus mitigating its concentration in the atmosphere [7]. 2) PV panels play a direct role in reducing CO_2 emissions. They generate electricity from sunlight, a renewable and sustainable energy source, thereby replacing fossil fuel-based electricity generation. Additionally, PV systems can substitute the consumption of fossil fuel-based end-use resources like natural gas, resulting in further CO_2 reduction [8].

Results from relevant previous studies revealed that BAPV enables avoiding 211 kg/m^2 CO_2 emissions and 1.2 g/m^2 PM pollutants annually; Likewise, SIGR can mitigate 4.8 kg/m^2 CO_2 emissions and 52.4 g/m^2 PM pollutants per year [7,8]. In this sense, some other alternatives, like photocatalytic materials – such as TiO_2, which absorbs NO_2 pollutants [52] – are not effective for Tehran since NO_2 is not a critical air pollutant in this specific case study [53].

(c) *Viability:* Although other alternatives can contribute to urban air pollution mitigation, GR and PV are known viable ones for Tehran city as a specific case study. For instance, wind turbines as renewable energy producers are not viable nor affordable to apply to most residential buildings due to their high costs, vast needed spaces, and structural stability problems in implementation and operation. Unlike wind turbines, GR and PV operate silently and safely, seamlessly integrating with the rooftop environment and preserving the visual appeal of residential areas. Additionally, it can be challenging to find suitable locations with sufficient wind speeds for wind turbines in urban areas, such as Tehran. Bear in mind that Tehran has a predominantly high solar irradiation level throughout the year. As a result, Tehran is an ideal location for harnessing sunlight, which helps make PV and GR viable options for residential rooftops.

It is important to note that while PV and GR as feasible alternatives provide environmental benefits, the magnitude of their impact on reducing air pollution depends on various factors, such as coverage, implementation scale, and the potential of their combined use.

4.1.2. Optimization of alternatives used in combination

Since the potentials of PV and GR vary, determining the most efficient set in their combined use would be necessary to achieve the highest total performance. Several studies have been conducted in the PV and GR integration area. For instance, M. E. Abdalazeem et al. (2022) [54], M. C. Catalbas et al. (2021) [5], K. Bao et al. (2021) [50], A. Jahanfar et al. (2020) [55], M. Ramshani et al. (2020) [12], B. Y. Schindler et al. (2018) [56], M. S. P. Moren and A. Korjenic (2017) [57], Chr. Lamnatou and D. Chemisana (2015) [58], Chr. Lamnatou and D. Chemisana (2014) [59] submit studies. Unlike these studies, mixing two alternatives (installing PV panels in the lawn area) is not taken into account in this research. Because of that, the integration of SIGR – consisting of shrubs – with BAPV panels in the same platform faces problematic technical issues for implementation and maintenance in this case study, as well as interference in the function of each system. Compound alternative (CA) in this study puts potential alternatives together for simultaneous utilization side by side. According to the statistical information relevant to Tehran city, the total annual carbon footprint is 104.4×10^9 kg CO_2 [40], and total PM emission is 8.601×10^9 g PM per year [60,61]. Considering the ability of each alternative to reduce air pollutants – as mentioned in Section 4.1.1 – calculating the annual efficiency of one square meter of each alternative to reduce emissions is derived from Equation (1) as follows:

$$E_{in} = P_{in} / T_n \tag{1}$$

where E_{in} is the annual efficiency of pollutant-reducing alternative (i) to reduce pollutant (n) per square meter; P_{in} is the potential of alternative (i) to reduce pollutant (n) per square meter per year; and T_n is the total amount of the pollutant (n) emitted in the case study per year.

- Efficiency of BAPV to reduce CO_2: $(E_{PC}) = 211/(104.4 \times 10^9) = (2.021 \times 10^{-9})\ \%$
- Efficiency of SIGR to reduce CO_2: $(E_{GC}) = 4.8/(104.4 \times 10^9) = (0.046 \times 10^{-9})\ \%$
- Efficiency of BAPV to reduce PM: $(E_{PP}) = 1.2/(8.601 \times 10^9) = (0.139 \times 10^{-9})\ \%$
- Efficiency of SIGR to reduce PM: $(E_{GP}) = 52.4/(8.601 \times 10^9) = (6.092 \times 10^{-9})\ \%$

Assuming a combination of two alternatives at a ratio of x% GR (E_{GC}, E_{GP}) with y% PV (E_{PC}, E_{PP}), total efficiency to mitigate CO_2 and PM is obtained from two functions of $f\ (x,\ y)$ and $f'\ (x,\ y)$ (Equation (2)), respectively as follows:

$$f\,(x, y) = x \cdot E_{GC} + y \cdot E_{PC} \tag{2}$$

$$f'(x, y) = x \cdot E_{GP} + y \cdot E_{PP}$$

Where the aforementioned efficiency factors are constant values, and $(y = 1\text{–}x)$; Consequently, these two functions are simplified as follows (Equation (3)):

$$f\,(x) = (2.021 - 1.974 \cdot x) \times 10^{-9} \tag{3}$$

$$f'(x) = (0.139 + 5.951 \cdot x) \times 10^{-9}$$

Both total efficiencies to reduce CO_2 and PM emissions must be at the highest possible levels at the same time to find the best combination ratio, considering that simultaneous mitigation of PM and CO_2 are required in this case. In other words, simultaneously indicating the highest value points of two functions is required. To do so, it is necessary to draw two functions' graphs and then specify their intersection points. The graphs would be in a linear model since, as aforementioned, it is assumed each alternative has a specific potential to reduce pollutants, and the total amount of the pollutants emitted in the case study is specified as well; thus, efficiencies would be as constant values depending on its contribution share in the CA, which would vary between 0% and 100%, as illustrated in Fig. 4. The area under graph $f\ (x)$ indicates the possible efficiency to reduce CO_2; In the same way, the area under graph $f'\ (x)$ shows the possible efficiency to reduce PM. As a result, the highest total efficiency value is measured at a point of 24% SIGR – and consequently 76% BAPV – in the case of sharing two sets. Likewise, when converting the variable of x to y, where $(x = 1\text{–}y)$, a similar outcome will be obtained from the integration of $f\ (y)$ and $f'\ (y)$ functions. Accordingly, by considering the aforementioned ratio and each alternative's ability, an optimized CA is capable of preventing 161.5 kg/m^2 CO_2 and 13.5 g/m^2 PM per year. To sum up, a 3:1 combination ratio can be assumed to simplify the executive stage to achieve the most efficient set.

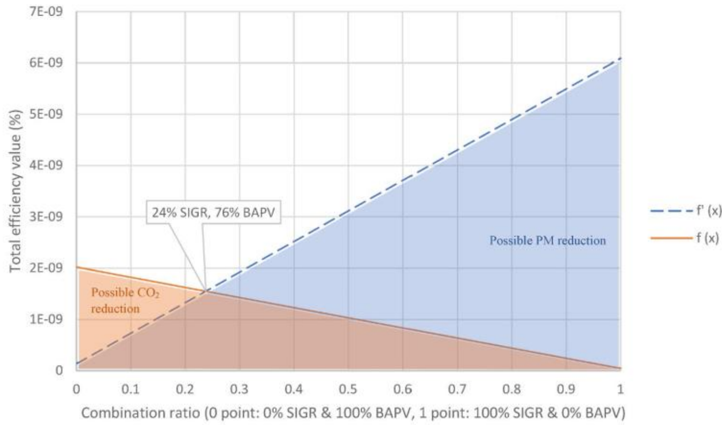


Fig. 4. Adaptive graphs to determine most efficient combination ratio.

4.2. *Target building groups*

This section determines target building groups for Tehran (step 3, PO 3) by determining the main indicators (Section 4.2.1) and presenting the data classification in detail (Section 4.2.2).

4.2.1. *Main indicators determination*

According to the strategy described in Section 2, determining the main indicators in this study is obtained based on the authors' knowledge, technical literature – such as Chung (2018) [6] & Thebault et al. (2020) [22] –, and the experts' panel contribution. The main panel contains twelve multidisciplinary experts, including environmental scientists, engineers, urban planners, city managers, and policymakers, the same as consulted – and explained – in the relevant previous studies [7,8]. As a result, the three determined main indicators for the case study are: (U1) *land-use zone*, (B1) *building height*, and (B2) *project surface scale*.

1) Included indicators: (U1) *Land-use zone* is a crucial parameter for rooftop applications because, besides the dependency of occupants' requirements and stimulants on the usage type [62], it is necessary to determine the most common zone type to achieve the highest performance and feasibility on the city scale. (B1) *Building height* is a significant indicator considering that the sun exposure rate is a vital issue for rooftop applications and short height buildings have a greater probability for less sun exposure due to lying in the shadow of more surrounding obstacles than taller ones [63]. (B2) *Project surface scale* is also a substantial issue in this study since the availability of the area needed on a rooftop affects the feasibility and performance of the applications.
2) Excluded indicators: The other indicators have not been considered as main issues for this specific case study due to the following reasons – however, they may be considered for other potential case studies depending on the characteristics of each case: (U2) *Topography* is excluded after considering GR and PV systems as feasible alternatives relying on previous studies [7,8], as described in detail in Section 4.1.1. (U3) *Urban Road width*, in this case, the narrower the pathway, the more intense this effect will be. However, regardless of minor diversities in the buildings' form, it is assumed that normally all buildings on each side of the road comply with a similar general pattern in typology and are placed together without distance – as in Tehran. According to Tehran's detailed urban plan, by default, the built area must locate on the north side of the land – unless in exceptional cases – as shown in Fig. 5. Such planning results in creating courtyards as buffer areas between buildings located on opposite sides of the road thus can considerably neutralize the road width effect. Hence, in this regard, there is usually no serious problem for this specific case study. (B3) *Roof shape* is not chosen for this case study considering that the vast majority of Tehran's roofs are flat and other shapes are scarce. (C1) *Roof finishing* is not considered for this case study because most buildings in Tehran use cement tiles or asphalt as roof finishing, and both of them are suitable pavements for rooftop installations. (C2) *Roof loading ability*, according to the 8th topic of the Iranian Building National Regulations (Section 8.5.5.2), buildings with less than three storeys – in which the roof level is not higher than 8 m from the ground's average level – do not need reinforcing structure and can be constructed by masonry materials [64]. Therefore, there is more probability of loading capability weakness for buildings of less than three-storey. Hence, excluding this indicator depends on considering or discarding less than three-storey buildings for this case study, which is explained in the following section (Section 4.2.2). (C3) *Structure type* is not considered for this case study because most building structures in Tehran are concrete or steel frames, both of which are suitable for rooftop installations.

4.2.2. *Data classification*

The data used for this classification is obtained from Tehran's detailed urban plan, approved by the Iranian Supreme Council of

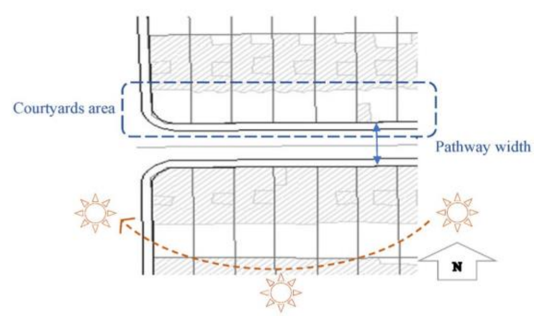


Fig. 5. Typical arrangement of buildings (built area) and courtyards (open area) in Tehran urban planning.

Architecture and Urban Planning (ISCAUP). Using GIS to overlap different data layers – containing diverse information on U1, B1, and B2 as significant indicators – results in the building groups categorization for this case study, as shown in Appendix B and explained in the following lines.

(U_1): Land-use general zones in Tehran's detailed urban plan are demonstrated in Fig. B.2. Residential zone, including 84.15% of the total number of parcels, is the most common land-use type in Tehran, as presented in Table B.1. Hence, this study chooses the residential land-use zone due to the following reasons: 1) being the most abundant and common type, this usage format enables the highest performance achievement for rooftop applications on a city scale; 2) inhabitants' permanent motives and needs can help rooftop revitalization and usability – especially in the case of residential apartments faced with a shortage of open spaces; 3) a rather short reconstruction term for residential buildings in Tehran (on average 50 years), allows for the quick and cost-effective implementation of rooftop installations during the construction stage.

(B1): Building height features based on Tehran's residential detailed urban plan are shown in Fig. B.3; Additionally, Table B.2 presents the corresponding classification in this study. The current study focuses on medium height (MH) and high height (HH) residential buildings. Short height (SH) buildings are not considered suitable cases for rooftop applications in this study due to these reasons: 1) it is highly probable these short buildings are located in the shadow of adjacent taller buildings or obstacles [6]; 2) as previously mentioned in Section 4.2.1, buildings without the reinforced structure are mostly less than three-storey, which face construction loading capability problems to add more loads; 3) according to the 15th topic of the Iranian Building National Regulations (Section 15.2.1.2), buildings with a vertical path length of more than 7 m from the main entrance (normally, more than three-storey) require an elevator [64]. Therefore, most SH buildings have no elevator, thus causing difficulty in rooftop access for occupants; 4) SH buildings include one, two, or three storeys – that accommodate one or a limited number of families – usually do not provide enough motivation for occupants to use rooftops due to the simple access to their private courtyard. Fig. B.4 shows examples of SH, MH, and HH buildings in Tehran.

(B2): Project surface scale classification, derived from plots area scale, is presented in Table B.3 for medium height (MH) and high height (HH) residential buildings in Tehran. This study focuses on residential buildings located in medium, large, and extra-large area plots (MA, LA, and EA). Buildings in the small area (SA) plots are not considered suitable cases in this study due to the shortage of available rooftop space after subtracting the courtyard surface (the courtyard usually encompasses at least 40% of the plot area). This problem becomes more apparent considering interference by elevators & staircases, chimneys, air conditioning equipment, etc., on the roof. Notable, the small area plot definition in this research is based on the ISCAUP standards.

Further information on building regulations for Tehran residential zone is available in Appendix C.

4.3. Potential scenarios

Based on the data provided previously in Section 4.1, it is possible to consider three pollutant-reducing alternatives consisting of PV, GR, and CA. Likewise, what was mentioned in Section 4.2 leads to defining six potential residential groups (U_1), including different potential features of height (B_1) and surface scale (B_2). These possible target building groups consist of medium height buildings in medium area plots (MH-MA), medium height buildings in large area plots (MH-LA), medium height buildings in extra-large area plots (MH-EA), high height buildings in medium area plots (HH-MA), high height buildings in large area plots (HH-LA), and high height buildings in extra-large area plots (HH-EA). Consequently, the integration of potential pollutant-reducing alternatives with potential target building groups results in 18 possible scenarios, as presented in Table 1. This way, the ability of each potential scenario to reduce CO_2 and PM is estimated by means of 1) the capability of each pollutant-reducing alternative as explained in detail in Sections 4.1.1 & 4.1.2; 2) a combination of different GIS-based data layers on a city scale for quantitation of each scenario's land area; and 3) building regulations for each specific 3-digit residential code, available in Table C.1, to estimate total roof area for each scenario. In theory, for quantitation, it is assumed the entire roof is covered by a pollutant-reducing alternative, though in the executive stage, some obstacles can arise, such as chimneys, elevator rooms, and air conditioning equipment. Quantities in the last column in Table 1 indicate the total potential of the residential sector (R) – excluding SH and SA residential groups – using each pollutant reducer in the entire city of Tehran.

5. Analysis and discussion

5.1. Performance assessment & prioritization of scenarios

In terms of different *pollutant-reducing alternatives*, as presented in Fig. 6 strength of the PV alternative is in reducing CO_2 emissions, while its weakness is in mitigating PM pollutants. Contrarily, the GR alternative is outstanding in PM pollutant mitigation, whilst its defect is in CO_2 emissions reduction. Nevertheless, a CA appears strongly significant in both CO_2 and PM decrement. The results demonstrate that in the case of applying an optimized CA to six groups of potential residential buildings, it is possible to obtain a crucial achievement of more than a 9% reduction in both total CO_2 and PM emissions in Tehran at the city level. In this sense, total CO_2 and PM emissions imply CO_2 and PM emitted from all sectors, i.e. the building sector in both operation and construction phases, the industry sector, the transport sector, and others.

This way, though CA causes a decrease in PV efficiency to reduce CO_2 emissions as well as GR efficiency to mitigate PM pollutants, this optimal alternative enables a significant increase in CO_2 reduction potential compared with GR alternative (more than 33 times) meanwhile provides

Table 1
Potential of different scenarios to reduce CO_2 & PM pollutants in Tehran per year.

	MH-MA	MH-LA	MH-EA	HH-MA	HH-LA	HH-EA	Total
Roof area (m^2)	29,566,807	10,681,285	17,952,911	2078	237	165,507	58,368,825
Pollutant reducing							
PV							
CO_2 (kg)	6,238,596,277	2,253,751,135	3,788,064,221	438,458	50,007	34,921,977	12,315,822,075
PM (g)	35,480,168.4	12,817,542	21,543,493.2	2493.6	284.4	198,608.4	70,042,590
GR							
CO_2 (kg)	141,920,673.6	51,270,168	86,173,972.8	9974.4	1137.6	794,433.6	280,170,360
PM (g)	1,549,300,686.8	559,699,334	940,732,536.4	108,887.2	12,418.8	8,672,566.8	3,058,526,430
CA							
CO_2 (kg)	4,775,039,330.5	1,725,027,527	2,899,395,126.5	335,597	38,275.5	26,729,380.5	9,426,565,237
PM (g)	399,151,894.5	144,197,347	242,364,298.5	28,053	3199.5	2,234,344.5	787,979,137

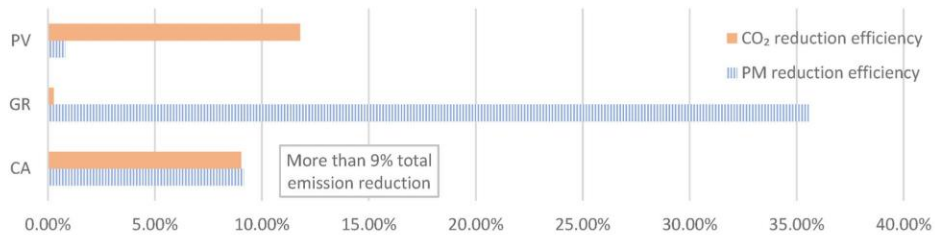


Fig. 6. Total efficiency of each alternative using six groups of potential residential target buildings on the city-scale.

a remarkable increase in PM mitigation potential compared with PV alternative (more than 11 times), as shown in Fig. 6. Notably, the total efficiency of each alternative was obtained by dividing its total potential estimate (quantities in the last column in Table 1) by the total amount of the pollutant (n) emitted in the case study per year (T_n as mentioned in Section 4.1.2).

In terms of different *target building groups* in the residential zone (U_1), the results presented in Fig. 7 reveal that MH-MA (medium height buildings in medium area scale) is the most appropriate collection for all three alternatives – i.e., PV, GR, and CA – either to reduce CO_2 emissions or to mitigate PM pollutants. Regarding the building height indicator (B_1), the residential HH group (high height) could not be as effective as the residential MH group (medium height). Additionally, when considering the project surface scale indicator (B_2) for the MH group, residential MA (medium area) is the most effective group, and the subsequent priorities are EA (extra-large area) and LA (large area), respectively, for all pollutant-reducing alternatives to both CO_2 and PM decrement. From the viewpoint of different pollutants: 1) in the case of

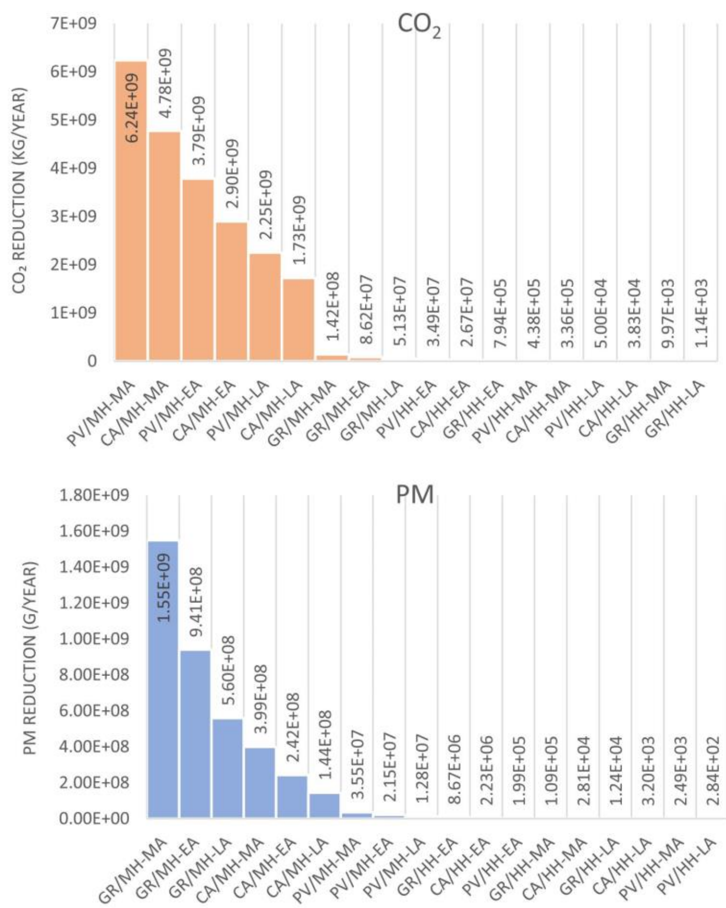


Fig. 7. Ranking histogram on annual ability of different scenarios to reduce CO_2 and PM in Tehran.

exploring CO_2 reduction, the three first-ranked scenarios are PV/MH-MA, CA/MH-MA, and PV/MH-EA, respectively; 2) while in the case of tracking PM mitigation, GR on MH buildings in all potential area scales accounts for the best solutions (GR/MH-MA, GR/MH-EA, and GR/MH-LA, respectively).

5.2. Robustness proof (sensitivity analysis)

This study considers a variety of ratios to combine pollutant-reducing alternatives besides the optimized ratio acquired in the results section (Section 4.1.2). This assumption, as additional analysis, provides more evidence to prove the validity and reliability of the results and check the possibility of findings an investigation error. In this way, the stacked bar chart presented in Fig. 8 demonstrates the proportion between the contribution of each assumed CA in reducing CO_2 and the contribution of the same option in mitigating PM. This investigation reveals the combination ratio of 3:1 (PV:GR) is the optimum option when the stakeholders require efficiency to mitigate PM and CO_2 emissions simultaneously. Additionally, the optimized CA is closer to the PV alternative, which confirms that, generally, PV is more suitable than GR in Tehran as a specific case study. However, a higher rate of PV presence in CA leads to more satisfactory solutions when stakeholders are more sensitive to reducing CO_2; meanwhile, a higher rate of GR presence in CA results in more reliable solutions when stakeholders are more sensitive to mitigating PM. The equality of contribution share in the case of optimized CA to decrease PM and CO_2 emissions (50:50) verifies the optimization accuracy attained by this study. In other words, when optimized CA is approached, more balance will appear in overall performance. This way, despite the highest achievement of CO_2 reduction using PV, this alternative is not acceptable enough due to the low PM mitigation ability. Likewise, though GR coincides with the maximum PM mitigation, this alternative cannot be adequate alone due to its feeble capability to reduce CO_2 emissions. This fact reconfirms that the CA can achieve an acknowledged apt performance in both CO_2 and PM mitigation while enabling compensation for the weaknesses of PV and GR simultaneously.

5.3. Approaching residential nearly zero-emission building groups (nZEBs)

Different strategies developing to attain nZEBs are of major importance and require swift application in the real economy, especially given that the building sector is responsible for around 37% of global GHG emissions [65]. This is while, among the operation and construction phases, the operational accounts for around two-thirds of the building sector share, and among the residential and non-residential, the residential operation is responsible for 63% of emissions in the buildings' operational phase [66]. Considering that the emissions related to the building utilization process account for the highest proportion of the total life cycle emission, they have drawn great research attention in recent years [67]. The nZEBs approach in this study follows the correlation between the share of increasing and decreasing of the most significant emissions by the residential sector in the operation phase. This concept intends to identify a group of residential buildings – on a city scale – capable of balancing its share of the household sector in emitting by its possible positive role in pollutant mitigating. As mentioned previously, CO_2 and PM account for the most significant pollutants in this study; Therefore, compensation for their emissions can lead to reaching nZEBs in this research project. Two parameters must be taken into account to determine the share of CO_2 and PM relevant to the household sector: 1) the emission factors on combustion by power plants to supply electricity, as well as from domestic natural gas consumption; 2) the amount of electricity and natural gas consumption in the household sector. It is worth mentioning that fossil fuels account for 94% of all sources of electricity generation in Iran [68], and natural gas is by far the dominant fossil fuel type used in Iranian power plants [69,70].

1) Emission factors: According to international emission inventory guidelines – such as IPCC and EMEP EEA [71,72] – and related technical literature – e.g. Refs. [8,69,73,74], – the emission factors relevant to this study are as follows.
   - CO_2 emission factor by powerplant electricity generation: 6×10^5 kg/GWh
   - CO_2 emission factor from domestic natural gas consumption: 3×10^5 kg/GWh
   - PM emission factor by powerplant electricity generation: 3.2×10^3 g/GWh
   - PM emission factor from domestic natural gas consumption: 7.2×10^2 g/GWh
2) Energy consumption: According to the official Iran Energy Balance Sheet, the annual shares by the household sector for energy consumption in Tehran are as follows [75].
   - Domestic electricity consumption: *12058.*1 GWh/*year*
   - Domestic natural gas consumption: 11169.6×10^6 $m^3/year$

Additionally, based on the IPCC guidebook, the Net Calorific Value (NCV) for natural gas is estimated at 35.7 MJ/m^3 (equal to 9.91 kWh/m^3 or 9.91×10^{-6} GWh/m^3) [72]. As a result, estimating the annual CO_2

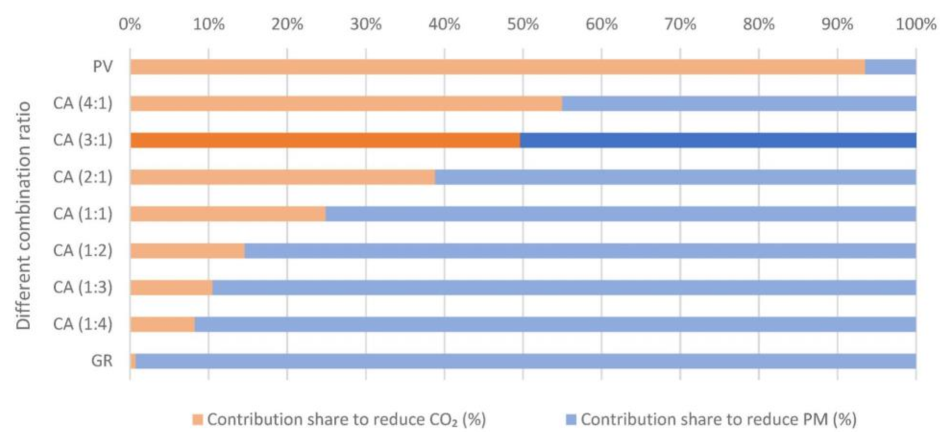


Fig. 8. Contribution of different assumptions (on combination ratio) to CO_2 and PM reduction efficiency.

and PM emissions shares by the residential sector in Tehran, derived from Equation (4), which presents the basic idea of emission calculation using process-based methods [76], is as follows.

$$Emission\ share = Emission\ factor \times Activity\ level\ data \quad (4)$$

Where the emission factor refers to the emissions per unit of energy used depending on the building energy types, and activity level data refers to the items consumed in each sector (e.g., residential, industry, transport, and others).

- Share of the household sector in CO_2 emissions: *40,442,080,*800 kg/*year*
- Share of the household sector in PM pollutants: *118,283,250 g/year*

Comparing the aforementioned quantities to the contents of Table 1 reveals that utilizing an optimized CA in each residential MH group enables a well-acceptable balance of the household share in PM emissions. In other words, the residential MH group in each potential plot area scale (MH-MA, MH-LA, and MH-EA) can singly account for a Zero-PM Buildings collection. This occurs while applying a CA to six groups of potential residential target buildings (MH-MA, MH-LA, MH-EA, HH-MA, HH-LA, HH-EA) at the same time can compensate for around one-fourth of the household share in CO_2 emissions. Accordingly, considering two aforementioned parameters (emission factors and energy consumption), in order to achieve Zero-CO_2 Buildings collection, it is necessary to: 1) replace fossil fuels with other clean energy sources; 2) decrease energy demand by revising some measures, such as using less consuming & higher efficiency devices [77] and modification of consumption patterns while adopting more responsible consumption habits [78,79].

6. Conclusion

In conclusion, this study advances the current related literature presented in the introduction by offering an innovative approach to air pollution mitigation through rooftop utilization. The findings underscore the potential of integrating feasible technologies while considering specific urban characteristics. This research project investigates the performance of rooftop installations to mitigate urban air pollution and recommends optimum solutions on a city scale via a systematic approach. Taking into account the proposed model, technical literature, and specific findings, the novelty of this study relies on considering feasible pollutant reducers and combining these feasible alternatives at the most efficient ratio, meanwhile considering potential target buildings to achieve optimal city-scale solutions. This forward-thinking strategy reflects a trend in contemporary literature that advocates for synergistic approaches to environmental challenges [80–82]. Related to Tehran, the first application for this new approach, the main specific findings are as follows.

1) PV and GR are determined as sustainable, effective, and viable pollutant-reducing alternatives, while the significant indicators to categorize target building groups are land-use zone, building height, and project surface scale.
2) Considering the weaknesses of GR – in reducing CO_2 – and PV – in mitigating PM – the CA concurrently enables compensating for their flaws while achieving an acceptable performance in CO_2 reduction and PM mitigation.
3) The analytic mathematical outcomes reveal more contribution by PV than GR in an optimized CA, which generally discloses more suitability by PV for the specific case study of Tehran. In this way, the most efficient ratio for the executive stage is simplified as 3:1 to combine PV and GR.
4) Residential medium height in medium surface scale is the most suitable target building group for all three pollutant-reducing alternatives (PV, GR, and CA), either in reducing CO_2 emissions or in mitigating PM pollutants.
5) Residential medium height in each potential surface scale is singly capable of being a Zero-PM Buildings collection; this occurs while applying CA to all six groups of residential target buildings enables compensating for approximately one-fourth of CO_2 emitted by the household sector.
6) It is conceivable to accomplish a significant achievement of more than a 9% reduction in both total CO_2 and PM – emitted by all resources and sectors in Tehran city – provided an optimized CA is applied to six groups of potential residential target buildings.

By presenting a quantitative model that estimates the potential reduction in emissions across different building groups, this study contributes to the emerging field of urban air quality modelling. This systematic approach has satisfied the initial aim of being applicable to different boundaries, locations, and air pollutant-reducing alternatives – even new emerging options – in order to assist decision-makers and city managers when programming to mitigate air pollution by providing new insights and advancing the subject matter understanding. This adaptation requires considering the particular boundaries, requirements, and characteristics of each case study.

In light of the multidimensional nature of urban air pollution, the proposed future directions for research align with the broader trend toward integrated and data-driven decision-making [83,84]. Future research projects are expected to follow and enrich the developed approach by considering how different target buildings are distributed throughout the city, as well as the concentration of air pollutants in various urban regions. The coordination of these two data sets will lead to more accurate local decision-making, as well as improve general performance at the city level. In this sense, while maintaining the total city-scale ratio to combine pollutant-reducing alternatives (for instance, 3:1 for PV:GR in this case), the assignment of dynamic ratio to specific locations based on local parameters, such as type and source of the critical pollutant, would be a beneficial possibility. Moreover, future research regarding several critical urban air pollutants with various coefficients is expected to incorporate multivariable equations and more complex mathematical patterns. These are expected to be the next steps towards an optimal city-scale model to assess rooftops performance on air pollution mitigation. As the field of urban air quality management continues to evolve, this study serves as a foundational stepping stone toward more effective and tailored pollution reduction strategies in cities.

CRediT authorship contribution statement

S. Hamed Banirazi Motlagh: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Oriol Pons-Valladares:** Writing – review & editing, Supervision, Methodology. **S.M. Amin Hosseini:** Writing – review & editing, Supervision, Methodology.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgements

The authors would like to thank the multidisciplinary experts who contributed to this research project. The authors also acknowledge J. Maas for his assistance to review English language usage.

Appendix A. (Brief description of non-physical/indirect-impact indicators for roof selection)

At the urban level, *per-capita income* can affect the supply of the financial needs to develop environmentally friendly applications in the private sector. In this regard, the high initial cost to implement most rooftop alternatives is a significant obstacle [85]. Residents' financial afford, with the assistance of local city management's economic power, can solve this problem to equip buildings, whether for self-use or for increasing the property value [86]. *Population density & growth rate* may become effective indicators when city managers and urban planners program per-capita urban services, especially green spaces. In this regard, GI roof applications can be considered supplementary opportunities [87]. *Public awareness* helps to deploy and develop rooftop environmentally friendly alternatives [88,89].

At the building level, *family size & age range* in the building scale are effective parameters for the rate of rooftop facilities usage. Large families, elders, and children need more such facilities as GRs, thus resulting in a higher possibility of their implementation. *Private/Multi-family usage* affects the inhabitants' needs and motivation for the implementation and operation of rooftop facilities. Apartments' inhabitants, consisting of multi-families, are more faced with a shortage of open space [87] than private buildings, which can provide the desired area in the courtyard.

At the construction level, *common rebuilt periods* in each city ecosystem can affect owners' motivation for rooftop revitalization. The short time for buildings reconstruction makes it hard to justify the economic investment in old buildings more exposed to demolition and vice versa.

Appendix B. (Data classification for the case study)

Fig. B.1. Tehran general plan including districts (area: 615 km^2, latitude: 35°N, longitude: 51°E, altitude: 900–1800 masl).

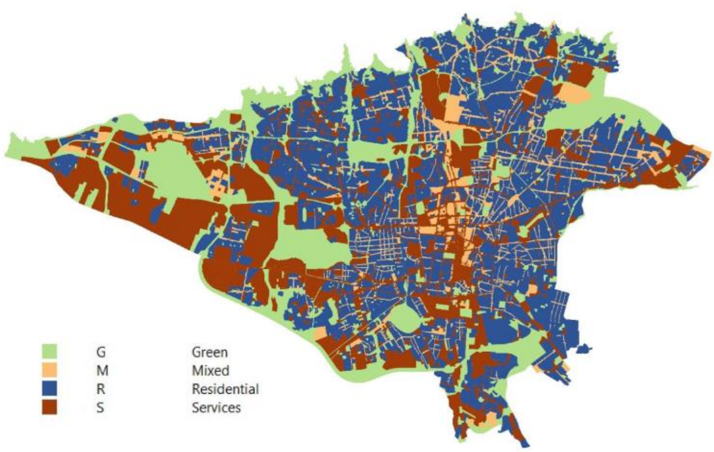


Fig. B.2. Detailed urban plan based on land-use general zones in Tehran.

Table B.1
(Indicator U_1): Land-use general zones in Tehran's detailed urban plan

Zoning	Land-use	Parcels number (No)	Portion (%)
S	Services	48152	5.32
R	Residential	761013	84.15
M	Mixed	83256	9.21
G	Green	11968	1.32
Total		904389	100

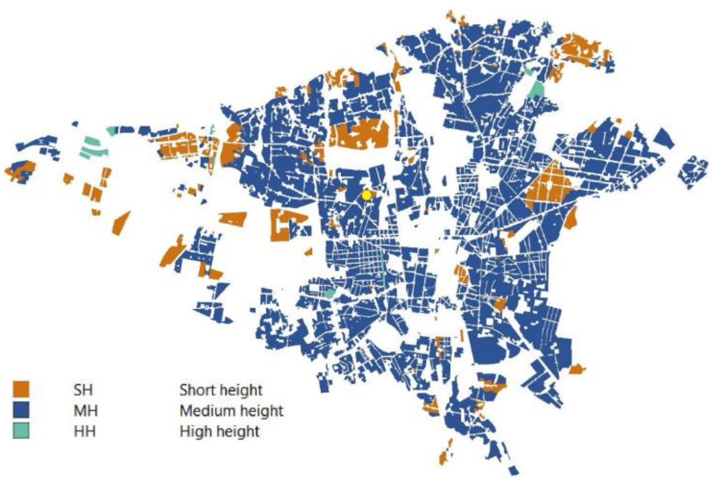


Fig. B.3. Residential detailed urban plan based on height features in Tehran.

Table B.2
(Indicator B_1): Building height classification for the residential zone (R) based on Tehran's detailed urban plan

	Specific 3-digit code	Parcels number (No)	Portion (%)
SH (storeys ≤3)	R_{111}, R_{112}, R_{211}, R_{212}, R_{221}, R_{231}, R_{241}	64148	8.43
MH (4 ≤ storeys ≤6)	R_{121}, R_{122}, R_{131}, R_{251}	696698	91.55
HH (7 ≤ storeys)	R_{261}, R_{262}, R_{263}	167	0.02
Total		761013	100

Note. SH = Short height; MH = Medium height; HH = High height.

Fig. B.4. The proximity of buildings with different height features in the existing part of the city (marked in Fig. B.3 in yellow) & Demonstrating examples of real SH, MH, and HH buildings in Tehran city.

Table B.3
(Indicator B_2): Plot area classification for (MH) and (HH) residential (R) based on Tehran's detailed urban plan

	Parcels number (No)	Area (m^2)	Portion, S (%)
SA ($S < 200\ m^2$)	487908	52491147	34.59
MA ($200\ m^2 \leq S < 500\ m^2$)	172340	50348843	33.18
LA ($500\ m^2 \leq S < 1000\ m^2$)	26876	18155249	11.97
EA ($1000\ m^2 \leq S$)	9741	30732677	20.26
Total	696865	151727916	100

Note. SA = Small area; MA = Medium area; LA = Large area; EA = Extra-large area.

Appendix C. (Specific building regulations for 3-digit residential codes)

Table C.1
Residential (R) zone classification in Tehran's detailed urban plan

2^{nd} level zoning	Sub-zone	Specific 3-digit code	Number of storeys (No)	Built area ratio (%)	Density (%)
R_1 (General residential)	R_{11} (Low density)	R_{111}	2	60	120
		R_{112}	3	60	180
	R_{12} (Medium density)	R_{121}	4	60	240
		R_{122}	5	60	300
	R_{13} (High density)	R_{131}	6	60	360
R_2 (Special residential)	R_{21} (Rural valuable)	R_{211}	2	50	100
		R_{212}	3	40	120
	R_{22} (Historical valuable)	R_{221}	2	50	100
	R_{23} (Contemporary valuable)	R_{231}	Stabilization of current status		
	R_{24} (Green valuable)	R_{241}	Extremely limited under special instructions		
	R_{25} (Special central zone)	R_{251}	5	50	250
	R_{26} (Special axles & zones)	R_{261}	7	40	280
		R_{262}	9	35	315
		R_{263}	12 & more	30	Up to 600

References

[1] UN Climate Report: It's 'now or Never' to Limit Global Warming to 1.5 Degrees, UN News, 2022. https://news.un.org/en/story/2022/04/1115452. (Accessed 5 April 2022).

[2] ClimateChange | United Nations. https://www.un.org/climatechange?gclid=Cj0KCQiAg_KbBhDLARIsANx7wAyH6SbWOjMoh10SCC1fuFipLFb0uPRHS8E-GnqmHxRu0PoIjI1QSNAaAlo2EALw_wcB, 2022. (Accessed 22 November 2022).

[3] The Paris Agreement | UNFCCC, (2022). https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (accessed April 21, 2022).

[4] R. Fardi Asrami, A. Sohani, E. Saedpanah, H. Sayyaadi, Towards achieving the best solution to utilize photovoltaic solar panels for residential buildings in urban areas, Sustain. Cities Soc. 71 (2021), 102968, https://doi.org/10.1016/j.scs.2021.102968.
[5] M.C. Catalbas, B. Kocak, B. Yenipınar, Analysis of photovoltaic-green roofs in OSTIM industrial zone, Int. J. Hydrogen Energy 46 (2021) 14844–14856, https://doi.org/10.1016/j.ijhydene.2021.01.205.
[6] M.H. Chung, Potential analysis of a target area selection for photovoltaic-based distributed generation in cases of an existing city in Korea, Sustain. Cities Soc. 41 (2018) 341–348, https://doi.org/10.1016/j.scs.2018.05.056.
[7] S.H. Banirazi Motlagh, O. Pons, S.M.A. Hosseini, Sustainability model to assess the suitability of green roof alternatives for urban air pollution reduction applied in Tehran, Build. Environ. 194 (2021), 107683, https://doi.org/10.1016/j.buildenv.2021.107683.
[8] S. Hamed Banirazi Motlagh, S.M.A. Hosseini, O. Pons-Valladares, Integrated value model for sustainability assessment of residential solar energy systems towards minimizing urban air pollution in Tehran, Sol. Energy 249 (2023) 40–66, https://doi.org/10.1016/j.solener.2022.10.047.
[9] P. Irga, R. Fleck, E. Wooster, F. Torpy, T. Pettit, R. Gill, J. Ball, Green Roof & Solar Array–Comparative Research Project Final Report July 2021, 2021.
[10] Y. Barwise, P. Kumar, A. Tiwari, F. Rafi-Butt, A. McNabola, S. Cole, B.C.T. Field, J. Fuller, J. Mendis, K.J. Wyles, The co-development of HedgeDATE, a public engagement and decision support tool for air pollution exposure mitigation by green infrastructure, Sustain. Cities Soc. 75 (2021), 103299, https://doi.org/10.1016/j.scs.2021.103299.
[11] D. Patra, V. Chanse, A. Rockler, S. Wilson, H. Montas, A. Shirmohammadi, P. T. Leisnham, Towards attaining green sustainability goals of cities through social transitions: comparing stakeholders' knowledge and perceptions between two Chesapeake Bay watersheds, USA, Sustain. Cities Soc. 75 (2021), 103318, https://doi.org/10.1016/j.scs.2021.103318.
[12] M. Ramshani, X. Li, A. Khojandi, O. Omitaomu, An agent-based approach to study the diffusion rate and the effect of policies on joint placement of photovoltaic panels and green roof under climate change uncertainty, Appl. Energy 261 (2020), 114402, https://doi.org/10.1016/j.apenergy.2019.114402.
[13] X. Cipriano, G. Gamboa, S. Danov, G. Mor, J. Cipriano, Developing indicators to improve energy action plans in municipalities: an accounting framework based on the fund-flow model, Sustain. Cities Soc. 32 (2017) 263–276, https://doi.org/10.1016/j.scs.2017.03.004.
[14] P.J. Irga, R. Fleck, E. Arsenteva, F.R. Torpy, Biosolar green roofs and ambient air pollution in city centres: mixed results, Build. Environ. 226 (2022), 109712, https://doi.org/10.1016/j.buildenv.2022.109712.
[15] J. Yuan, I. Patra, A. Majdi, N. Ketut Acwin Dwijendra, M. Jade Catalan Opulencia, P. Chetthamrongchai, Fundamental green roof performance of residential building in desert climate: in terms of sustainability and decrease in energy consumption, Sustain. Energy Technol. Assessments 53 (2022), 102574, https://doi.org/10.1016/j.seta.2022.102574.
[16] A.F. Antoniolli, H.F. Naspolini, J.F. De Abreu, R. Rüther, Development of technical and statistical algorithm using Business Intelligence tools for energy yield assessment of large rooftop photovoltaic system ensembles, Sustain. Energy Technol. Assessments 49 (2022), 101686, https://doi.org/10.1016/j.seta.2021.101686.
[17] S. Rafael, L.P. Correia, A. Ascenso, B. Augusto, D. Lopes, A.I. Miranda, Are green roofs the path to clean air and low carbon cities? Sci. Total Environ. 798 (2021), 149313 https://doi.org/10.1016/j.scitotenv.2021.149313.
[18] P. Zambrano-Prado, J. Muñoz-Liesa, A. Josa, J. Rieradevall, R. Alamús, S. Gasso-Domingo, X. Gabarrell, Assessment of the food-water-energy nexus suitability of rooftops. A methodological remote sensing approach in an urban Mediterranean area, Sustain. Cities Soc. 75 (2021), 103287, https://doi.org/10.1016/j.scs.2021.103287.
[19] Y. Arbid, C. Richard, M. Sleiman, Towards an experimental approach for measuring the removal of urban air pollutants by green roofs, Build. Environ. 205 (2021), 108286, https://doi.org/10.1016/j.buildenv.2021.108286.
[20] J. Heusinger, A.M. Broadbent, E.S. Krayenhoff, S. Weber, Adaptation of a photovoltaic energy balance model for rooftop applications, Build. Environ. 192 (2021), 107628, https://doi.org/10.1016/j.buildenv.2021.107628.
[21] M. Viecco, H. Jorquera, A. Sharma, W. Bustamante, H.J.S. Fernando, S. Vera, Green roofs and green walls layouts for improved urban air quality by mitigating particulate matter, Build. Environ. 204 (2021), 108120, https://doi.org/10.1016/j.buildenv.2021.108120.
[22] M. Thebault, V. Clivillé, L. Berrah, G. Desthieux, Multicriteria roof sorting for the integration of photovoltaic systems in urban environments, Sustain. Cities Soc. 60 (2020), 102259, https://doi.org/10.1016/j.scs.2020.102259.
[23] N. Mukisa, R. Zamora, T.T. Lie, Feasibility assessment of grid-tied rooftop solar photovoltaic systems for industrial sector application in Uganda, Sustain. Energy Technol. Assessments 32 (2019) 83–91, https://doi.org/10.1016/j.seta.2019.02.001.
[24] S. Toboso-Chavero, A. Nadal, A. Petit-Boix, O. Pons, G. Villalba, X. Gabarrell, A. Josa, J. Rieradevall, Towards productive cities: environmental assessment of the food-energy-water nexus of the urban roof mosaic, J. Ind. Ecol. 23 (2019) 767–780, https://doi.org/10.1111/jiec.12829.
[25] D.S. Salvador, S. Toboso-Chavero, A. Nadal, X. Gabarrell, J. Rieradevall, R.S. da Silva, Potential of technology parks to implement Roof Mosaic in Brazil, J. Clean. Prod. 235 (2019) 166–177, https://doi.org/10.1016/j.jclepro.2019.06.214.
[26] J. Bazán, J. Rieradevall, X. Gabarrell, I. Vázquez-Rowe, Low-carbon electricity production through the implementation of photovoltaic panels in rooftops in urban environments: a case study for three cities in Peru, Sci. Total Environ. (2018) 622–623, https://doi.org/10.1016/j.scitotenv.2017.12.003, 1448–1462.
[27] A. Nadal, O. Pons, E. Cuerva, J. Rieradevall, A. Josa, Rooftop greenhouses in educational centers: a sustainability assessment of urban agriculture in compact cities, Sci. Total Environ. 626 (2018) 1319–1331.
[28] K. Dimond, A. Webb, Sustainable roof selection: environmental and contextual factors to be considered in choosing a vegetated roof or rooftop solar photovoltaic system, Sustain. Cities Soc. 35 (2017) 241–249, https://doi.org/10.1016/j.scs.2017.08.015.
[29] W.M.P.U. Wijeratne, R.J. Yang, E. Too, R. Wakefield, Design and development of distributed solar PV systems: do the current tools work? Sustain. Cities Soc. 45 (2019) 553–578, https://doi.org/10.1016/j.scs.2018.11.035.
[30] X. Wu, W. Hu, Q. Huang, C. Chen, Z. Chen, F. Blaabjerg, Optimized placement of onshore wind farms considering topography, Energies 12 (2019) 2944, https://doi.org/10.3390/en12152944.
[31] J. Kim, Y.K. Yi, A. Malkawi, Topography integration to wind downscaling, Build. Environ. 115 (2017) 306–315, https://doi.org/10.1016/j.buildenv.2017.01.024.
[32] A. Mahdiyar, S. Tabatabaee, A. Abdullah, A. Marto, Identifying and assessing the critical criteria affecting decision-making for green roof type selection, Sustain. Cities Soc. 39 (2018) 772–783, https://doi.org/10.1016/j.scs.2018.03.007.
[33] S. Guillén-Lambea, J. Sierra-Pérez, S. García-Pérez, A.L. Montealegre, M. Monzón-Chavarrías, Energy Self-Sufficiency Urban Module (ESSUM): GIS-LCA-based multi-criteria methodology to analyze the urban potential of solar energy generation and its environmental implications, Sci. Total Environ. 879 (2023), 163077, https://doi.org/10.1016/j.scitotenv.2023.163077.
[34] A.L. Montealegre, S. García-Pérez, S. Guillén-Lambea, M. Monzón-Chavarrías, J. Sierra-Pérez, GIS-based assessment for the potential of implementation of food-energy-water systems on building rooftops at the urban level, Sci. Total Environ. 803 (2022), 149963, https://doi.org/10.1016/j.scitotenv.2021.149963.
[35] M. Heger, M. Sarraf, Air Pollution in Tehran: Health Costs, Sources, and Policies, World Bank, 2018.
[36] O. Ghaffarpasand, S. Nadi, Z.D. Shalamzari, Short-term effects of anthropogenic/natural activities on the Tehran criteria air pollutants: source apportionment and spatiotemporal variation, Build. Environ. 186 (2020), 107298, https://doi.org/10.1016/j.buildenv.2020.107298.
[37] (n.d. Britanica. https://www.britannica.com/science/greenhouse-gas. (Accessed 10 October 2020).
[38] Q. Guo, Z. He, Z. Wang, Long-term projection of future climate change over the twenty-first century in the Sahara region in Africa under four Shared Socio-Economic Pathways scenarios, Environ. Sci. Pollut. Res. 30 (2022) 22319–22329, https://doi.org/10.1007/s11356-022-23813-z.
[39] World's Most Polluted Cities in 2021 - PM2.5 Ranking | IQAir, (2023). https://www.iqair.com/world-most-polluted-cities (accessed January 23, 2023).
[40] D. Moran, K. Kanemoto, M. Jiborn, R. Wood, J. Többen, K.C. Seto, Carbon footprints of 13 000 cities, Environ. Res. Lett. 13 (2018), 064041, https://doi.org/10.1088/1748-9326/aac72a.
[41] Q. Guo, Z. He, Z. Wang, Prediction of hourly PM2.5 and PM10 concentrations in chongqing city in China based on artificial neural network, Aerosol Air Qual. Res. 23 (2023), 220448, https://doi.org/10.4209/aaqr.220448.
[42] Q. Guo, Z. He, Z. Wang, Predicting of daily PM2.5 concentration employing wavelet artificial neural networks based on meteorological elements in Shanghai, China, Toxics 11 (2023) 51, https://doi.org/10.3390/toxics11010051.
[43] Q. Guo, Z. He, Z. Wang, Change in air quality during 2014–2021 in jinan city in China and its influencing factors, Toxics 11 (2023) 210, https://doi.org/10.3390/toxics11030210.
[44] Z. He, Q. Guo, Z. Wang, X. Li, Prediction of monthly PM2.5 concentration in liaocheng in China employing artificial neural network, Atmosphere 13 (2022) 1221, https://doi.org/10.3390/atmos13081221.
[45] Q. Guo, Z. Wang, Z. He, X. Li, J. Meng, Z. Hou, J. Yang, Changes in air quality from the COVID to the post-COVID era in the beijing-tianjin-tangshan region in China, Aerosol Air Qual. Res. 21 (2021), 210270, https://doi.org/10.4209/aaqr.210270.
[46] Q. Guo, Z. He, S. Li, X. Li, J. Meng, Z. Hou, J. Liu, Y. Chen, Air pollution forecasting using artificial and wavelet neural networks with meteorological conditions, Aerosol Air Qual. Res. 20 (2020) 1429–1439, https://doi.org/10.4209/aaqr.2020.03.0097.
[47] V. Hosseini, H. Shahbazi, Urban air pollution in Iran, Iran, For. Stud. 49 (2016) 1029–1046, https://doi.org/10.1080/00210862.2016.1241587.
[48] Laws and regulations portal of IRI. https://qavanin.ir/Law/TreeText/184557, 2022. (Accessed 15 March 2022).
[49] G. Najafi, B. Ghobadian, R. Mamat, T. Yusaf, W.H. Azmi, Solar energy in Iran: current state and outlook, Renew. Sustain. Energy Rev. 49 (2015) 931–942, https://doi.org/10.1016/j.rser.2015.04.056.
[50] K. Bao, D. Thrän, B. Schröter, Simulation and analysis of urban green roofs with photovoltaic in the framework of water-energy nexus, in: CITIES 2050–Creating Habitats 3rd Millenn. Smart–Sustainable–Climate Neutral Proc. REAL CORP 2021 26th Int. Conf. Urban Dev. Reg. Plan. Inf. Soc., CORP–Competence Center of Urban and Regional Planning, 2021, pp. 671–680.
[51] U.G. Assembly, World Summit Outcome: Resolution/adopted by the General Assembly, 2005, 24 October 2005, A/RES/60/1.
[52] X. Tang, L. Ughetta, S.K. Shannon, S. Houzé De l'Aulnoit, S. Chen, R.A.T. Gould, M. L. Russell, J. Zhang, G. Ban-Weiss, R.L.A. Everman, F.W. Klink, R. Levinson, H. Destaillats, De-pollution efficacy of photocatalytic roofing granules, Build. Environ. 160 (2019), 106058, https://doi.org/10.1016/j.buildenv.2019.03.056.
[53] Tehran Annual Air and Noise Quality Report, Period of March 2020 - March 2021, Air Quality Control Company, Tehran, Iran, 2021. https://air.tehran.ir/Default.aspx?tabid=471. (Accessed 22 February 2022).

[54] M.E. Abdalazeem, H. Hassan, T. Asawa, H. Mahmoud, Review on integrated photovoltaic-green roof solutions on urban and energy-efficient buildings in hot climate, Sustain. Cities Soc. 82 (2022), 103919, https://doi.org/10.1016/j.scs.2022.103919.
[55] A. Jahanfar, J. Drake, B. Gharabaghi, B. Sleep, An experimental and modeling study of evapotranspiration from integrated green roof photovoltaic systems, Ecol. Eng. 152 (2020), 105767, https://doi.org/10.1016/j.ecoleng.2020.105767.
[56] B.Y. Schindler, L. Blaustein, R. Lotan, H. Shalom, G.J. Kadas, M. Seifan, Green roof and photovoltaic panel integration: effects on plant and arthropod diversity and electricity production, J. Environ. Manag. 225 (2018) 288–299, https://doi.org/10.1016/j.jenvman.2018.08.017.
[57] M.S.P. Moren, A. Korjenic, Green buffer space influences on the temperature of photovoltaic modules, Energy Build. 146 (2017) 364–382, https://doi.org/10.1016/j.enbuild.2017.04.051.
[58] Chr Lamnatou, D. Chemisana, Evaluation of photovoltaic-green and other roofing systems by means of ReCiPe and multiple life cycle–based environmental indicators, Build. Environ. 93 (2015) 376–384, https://doi.org/10.1016/j.buildenv.2015.06.031.
[59] Chr Lamnatou, D. Chemisana, Photovoltaic-green roofs: a life cycle assessment approach with emphasis on warm months of Mediterranean climate, J. Clean. Prod. 72 (2014) 57–75, https://doi.org/10.1016/j.jclepro.2014.03.006.
[60] Hossein Shahbazi, Mostafazadeh Ali, Masood Ahmadi, Sina Taghvaee, Mahdi Babaei, Yasamin Salamat, Hossein Afshin, Vahid Hosseini, Tehran Pollution Emission List (General Report), Air Quality Control Company, Tehran, Iran, 2015. https://air.tehran.ir/Default.aspx?tabid=160. (Accessed 12 May 2022).
[61] Hossein Shahbazi, Sina Taghvaee, Vahid Hosseini, Hossein Afshin, in: Iran Tehran (Ed.), Tehran Pollution Emission List, 2015. http://mech.sharif.ir/~fce/content/publication/0027.pdf. (Accessed 22 March 2022).
[62] A. Zalejska-Jonsson, S.J. Wilkinson, R. Wahlund, Willingness to pay for green infrastructure in residential development—a consumer perspective, Atmosphere 11 (2020) 152, https://doi.org/10.3390/atmos11020152.
[63] M. Tripathy, S. Yadav, P.K. Sadhu, S.K. Panda, Determination of optimum tilt angle and accurate insolation of BIPV panel influenced by adverse effect of shadow, Renew. Energy 104 (2017) 211–223, https://doi.org/10.1016/j.renene.2016.12.034.
[64] Ministry of Roads and Urban Development, Deputy for Housing and Construction, Iran. Build. Natl. Regul. Off (2022). https://inbr.ir/?page_id=2032 (accessed April 5, 2022).
[65] D. Maierhofer, M. Röck, M. Ruschi Mendes Saade, E. Hoxha, A. Passer, Critical life cycle assessment of the innovative passive nZEB building concept 'be 2226' in view of net-zero carbon targets, Build. Environ. 223 (2022), 109476, https://doi.org/10.1016/j.buildenv.2022.109476.
[66] Buildings – Analysis - IEA, (2023). https://www.iea.org/reports/buildings (accessed May 26, 2023).
[67] N.H. Sandberg, J.S. Næss, H. Brattebø, I. Andresen, A. Gustavsen, Large potentials for energy saving and greenhouse gas emission reductions from large-scale deployment of zero emission building technologies in a national building stock, Energy Pol. 152 (2021), 112114, https://doi.org/10.1016/j.enpol.2020.112114.
[68] S.S. Korsavi, Z.S. Zomorodian, M. Tahsildoost, Energy and economic performance of rooftop PV panels in the hot and dry climate of Iran, J. Clean. Prod. 174 (2018) 1204–1214, https://doi.org/10.1016/j.jclepro.2017.11.026.
[69] M. Jorli, S. Van Passel, H. Sadeghi, A. Nasseri, L. Agheli, Estimating human health impacts and costs due to Iranian fossil fuel power plant emissions through the impact pathway approach, Energies 10 (2017) 2136, https://doi.org/10.3390/en10122136.
[70] Key World Energy Statistics 2020 – Analysis - IEA, (n.d.). https://www.iea.org/reports/key-world-energy-statistics-2020 (accessed June 10, 2021).
[71] EMEP/EEA air pollutant emission inventory guidebook 2019 — European Environment Agency, (n.d.). https://www.eea.europa.eu/publications/emep-eea-guidebook-2019 (accessed May 11, 2021).
[72] Publications - IPCC-TFI, (n.d.). https://www.ipcc-nggip.iges.or.jp/public/(accessed May 17, 2022).
[73] A.R. Noorpoor, S.N. Kudahi, CO_2 emissions from Iran's power sector and analysis of the influencing factors using the stochastic impacts by regression on population, affluence and technology (STIRPAT) model, Carbon Manag. 6 (2015) 101–116, https://doi.org/10.1080/17583004.2015.1090317.
[74] Y. Tripanagnostopoulos, M. Souliotis, R. Battisti, A. Corrado, Energy, cost and LCA results of PV and hybrid PV/T solar systems, Prog. Photovoltaics Res. Appl. 13 (2005) 235–250, https://doi.org/10.1002/pip.590.
[75] Energy balance sheet, (n.d.). https://isn.moe.gov.ir (accessed May 18, 2022).
[76] X.-J. Li, J. Lai, C. Ma, C. Wang, Using BIM to research carbon footprint during the materialization phase of prefabricated concrete buildings: a China study, J. Clean. Prod. 279 (2021), 123454, https://doi.org/10.1016/j.jclepro.2020.123454.
[77] L. Zhou, J. Li, F. Li, Q. Meng, J. Li, X. Xu, Energy consumption model and energy efficiency of machine tools: a comprehensive literature review, J. Clean. Prod. 112 (2016) 3721–3734, https://doi.org/10.1016/j.jclepro.2015.05.093.
[78] A. Paço, T. Lavrador, Environmental knowledge and attitudes and behaviours towards energy consumption, J. Environ. Manag. 197 (2017) 384–392, https://doi.org/10.1016/j.jenvman.2017.03.100.
[79] W. O'Brien, I. Gaetani, S. Carlucci, P.-J. Hoes, J.L.M. Hensen, On occupant-centric building performance metrics, Build. Environ. 122 (2017) 373–385, https://doi.org/10.1016/j.buildenv.2017.06.028.
[80] C. Li, W. Xia, L. Wang, Synergies of green policies and their pollution reduction effects: quantitative analysis of China's green policy texts, J. Clean. Prod. 412 (2023), 137360, https://doi.org/10.1016/j.jclepro.2023.137360.
[81] Y. Ouyang, F. Ye, K. Tan, The effect of strategic synergy between local and neighborhood environmental regulations on green innovation efficiency: the perspective of industrial transfer, J. Clean. Prod. 380 (2022), 134933, https://doi.org/10.1016/j.jclepro.2022.134933.
[82] W. Lu, H. Wu, S. Yang, Y. Tu, Effect of environmental regulation policy synergy on carbon emissions in China under consideration of the mediating role of industrial structure, J. Environ. Manag. 322 (2022), 116053, https://doi.org/10.1016/j.jenvman.2022.116053.
[83] J. Ding, C. Zhang, D. Li, A.K. Sangaiah, Hyperautomation for air quality evaluations: a perspective of evidential three-way decision-making, Cogn. Comput. (2023), https://doi.org/10.1007/s12559-022-10101-8.
[84] S. Myeong, K. Shahzad, Integrating data-based strategies and advanced technologies with efficient air pollution management in smart cities, Sustainability 13 (2021) 7168, https://doi.org/10.3390/su13137168.
[85] M. Shafique, R. Kim, M. Rafiq, Green roof benefits, opportunities and challenges–A review, Renew. Sustain. Energy Rev. 90 (2018) 757–773.
[86] A. Mahdiyar, S. Tabatabaee, A.N. Sadeghifam, S.R. Mohandes, A. Abdullah, M. M. Meynagh, Probabilistic private cost-benefit analysis for green roof installation: a Monte Carlo simulation approach, Urban For. Urban Green. 20 (2016) 317–327.
[87] S. Tabatabaee, A. Mahdiyar, S. Durdyev, S.R. Mohandes, S. Ismail, An assessment model of benefits, opportunities, costs, and risks of green roof installation: a multi criteria decision making approach, J. Clean. Prod. 238 (2019), 117956.
[88] M.B. Roberts, A. Bruce, I. MacGill, Opportunities and barriers for photovoltaics on multi-unit residential buildings: reviewing the Australian experience, Renew. Sustain. Energy Rev. 104 (2019) 95–110, https://doi.org/10.1016/j.rser.2018.12.013.
[89] S. Gorjian, B.N. Zadeh, L. Eltrop, R.R. Shamshiri, Y. Amanlou, Solar photovoltaic power generation in Iran: development, policies, and barriers, Renew. Sustain. Energy Rev. 106 (2019) 110–123, https://doi.org/10.1016/j.rser.2019.02.025.

CHAPTER 4

Discussion and partial findings

This chapter contributes to Phases 4 and 5 of this research framework by evaluating the results and observing optimized planning on a city scale. Both the collaboration and complicity of the organized and relevant publications in this thesis project lead to a unified analysis of findings and achieve an applicable evaluation. Overall, this research highlights the pressing problem of environmental degradation, with a focus on air pollution in urban areas. It emphasizes the significance of addressing these issues in line with global development goals and sustainable development principles. The study underscores the need for cities to take proactive measures, including optimizing rooftops and implementing green infrastructure (GI), to reduce air pollution and contribute to a more sustainable future. In this sense, after the definition of the boundaries and context of this research and following the first specific/sub-objective (S-OBJ-1) – mentioned in Chapter 1 – feasibility studies resulted in determining green roof (GR) and photovoltaic (PV) systems as feasible alternatives for the specific case study. Determinant parameters considered to specify feasible pollutant-reducing alternatives were (a) sustainability, (b) effectiveness, and (c) viability, as explored in the first research question – mentioned in Chapter 1 – and explained in detail in the publications.

Following S-OBJ-2, the next step was analyzing the suitability of different types of GR to reduce urban air pollution via developing a new MIVES-based sustainability assessment model. The definition for this model relied on aids of SWOT, AHP, and sensitivity analysis to assist stakeholders in achieving the objective decision since it gives easily comparable sustainability indexes (SI) for each alternative within different scenarios. This novel model was first applied to assess the sustainability of three GR alternatives – semi-intensive, intensive, and extensive GR (SIGR, IGR, and EGR) – to determine the most suitable solution for the air-polluted Tehran city. Results revealed that SIGR is the most suitable type for this case study, obtaining the highest global SI (56%) with an ability to increase by up to 67%. As presented in Figure 4.1, SIGR provides the best performance among others in terms of environmental requirements (V_{R2}: 65%). Taking into account the most crucial indicators in reducing air pollution, this alternative achieved the highest satisfaction value for the emission criterion (94%). This is while, after excluding non-residential lots, short-height buildings, and small-area plots, Tehran has 208,957 potential rooftops with an area of 58,368,825 m^2 (as explained in detail in article C). Following the S-OBJ-3, relevant analysis based on Tehran's characteristics and specifications estimated that each square meter of SIGR is capable of reducing 52.4 g PM/m^2 and 4.8 kg CO_2/m^2 per year. The capacity to absorb PM was calculated taking into account: 1) *flux* – considering the deposition velocity and pollutant concentration, 2) *surface* – considering surface area index (SAI) and surface area under analysis, and 3) *period* – considering the analysis period, proportion of dry days, and proportion of in leaf days. Meanwhile, the CO_2 reduction capacity was gauged considering the *CO_2 sequestration* potential by shrubs. Consequently, annual decrements of 3,058,526,430 g PM and 280,170,360 kg CO_2 are possible by applying SIGR on merely selected potential rooftops. From the sustainability aspects point of view, SIGR accounts for an outstanding social-environmental alternative as shown in Figure 4.1. The suitability for SIGR was proven to be robust in different weighting scenarios with diverse preferences. Whilst, its sustainability performance was greater when environmental requirements drove the decision-making process. The analysis of the resulting SI for SIGR in this specific case study found that the implementation cost – with a satisfaction value of 3.9% – and energy balance – with a satisfaction value of 7.6% – are the main weaknesses of this alternative. Nevertheless, this analysis also confirmed that it would be possible to achieve 11% higher SI in the case of resolving these flaws.

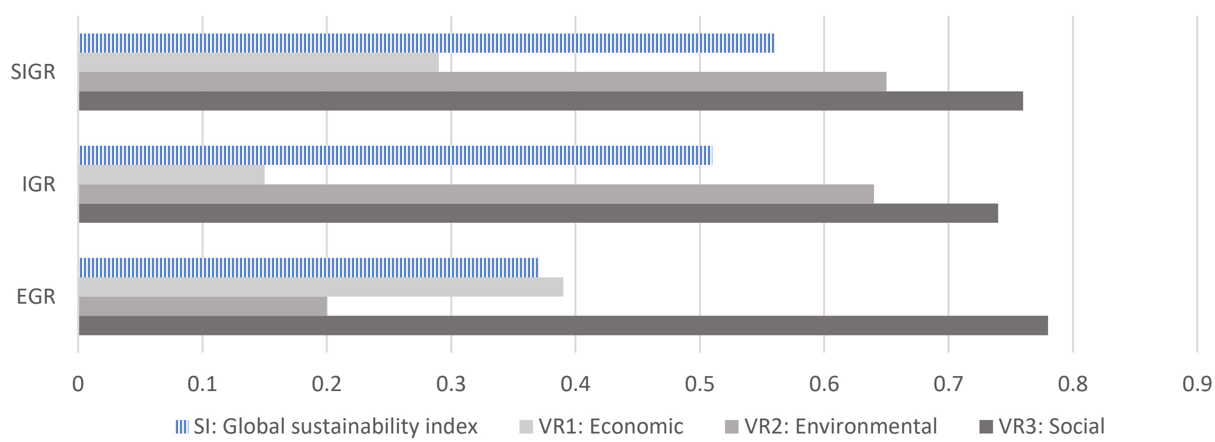


Figure 4.1. *Sustainability main requirements for green roofs*

In the same way and also following S-OBJ-2, a model to assist decision-makers in choosing the most suitable domestic solar energy systems was developed focusing on urban air pollution mitigation. This model incorporated MIVES, SWOT, AHP, and sensitivity analysis to evaluate building-attached photovoltaic and building-attached photovoltaic/thermal (BAPV and BAPV/T) utilization for Tehran residential rooftops. The objective decision to determine the most suitable solution, obtained from this new model, provides comparable SIs for each type of solar system applying a variety of scenarios. This assessment revealed that BAPV is a more suitable option than BAPV/T for this case study, obtaining a higher sustainability value with a global SI of 60.5%. Taking into account S-OBJ-3, results revealed that for the context of Tehran BAPV is capable of mitigating 211 kg CO_2/m^2 and 1.2 g PM/m^2 per year. The potential of avoided CO_2 and PM were estimated considering: 1) *emission factors* of each on combustion by power plants to supply electricity, and 2) *emission factors* of each for domestic boilers burning natural gas. Consequently, annual avoiding of 12,315,822,075 kg CO_2 and 70,042,590 g PM are attainable by applying PV on only selected potential rooftops with an area of 58,368,825 m^2. As presented in Figure 4.2, from the sustainability aspects viewpoint, this type of solar system accounts for a prominent socio-economic alternative for residential buildings, though its energy generation efficiency still has significant room for improvement. Although findings proved that BAPV/T is neither an economical nor social alternative so far (V_{R1}: 26% and V_{R3}: 28%), it can be a reliable solution when stakeholders are more sensitive to environmental requirements (V_{R2}: 84.5%) considering its high energy production ability and significant potential to reduce air pollution. This is while the analysis of the resulting SI found that the most critical obstacle to BAPV/T development in Iran is the lack of a clear financial incentive plan to avoid natural gas consumption. In this regard, it would be possible to improve the BAPV/T satisfaction level up to the SI of the BAPV through a purchase guarantee of produced solar thermal energy, even at the rate of 38% tariff to purchase solar electrical energy. Overall, compared to GRs, solar energy systems are outstanding in energy production and CO_2 saving potential, while the PM reduction potential of solar systems is lower than GRs.

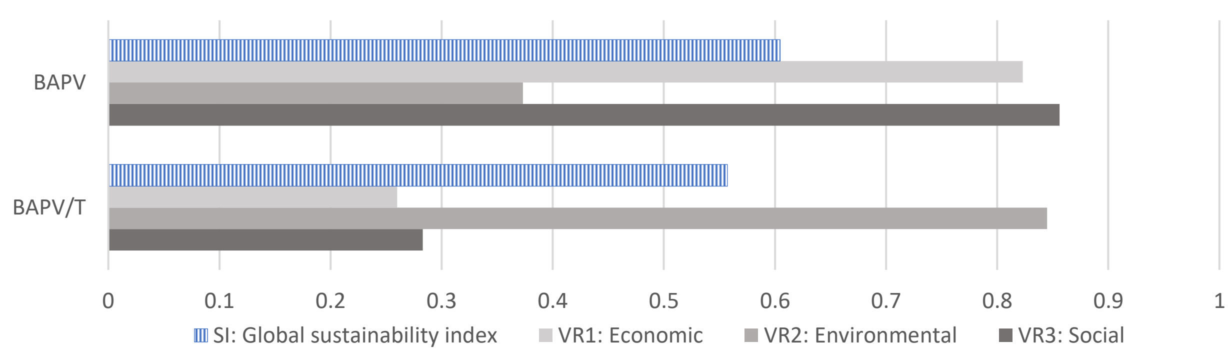


Figure 4.2. *Sustainability main requirements for solar systems*

It is crucial to note that while PV and GR are feasible alternatives with positive environmental effects, the magnitude of their actual impact on air pollution mitigation will rely on various parameters, including their potential for combined use, implementation scale, and coverage. This way, the immense potential of seamlessly integrating feasible technologies while taking into account specific urban characteristics was highlighted in this step. To do so, the proposed synergistic strategy examined feasible pollutant reducers and combined these alternatives at the most efficient ratio, meanwhile considering potential target buildings. Developing this model followed S-OBJ-4 and delved into the performance of rooftop installations in alleviating urban air pollution and proposed optimal city-scale solutions through a systematic process. Related to Tehran, which validated this new model being its initial application, the significant indicators to categorize target buildings were land-use zone, building height, and project surface scale – after refining a variety of direct-impact indicators in different levels. Whilst, the PV alternative's primary strength lies in its ability to reduce CO_2 emissions, it falls short when it comes to mitigating PM pollutants. Conversely, the GR alternative excels in mitigating PM pollutants but has a weakness in reducing CO_2 emissions. This is while the compound alternative (CA) offers a unique advantage by simultaneously addressing these shortcomings and achieving satisfactory performance in both CO_2 reduction and PM mitigation. This statement responded to the second research question. As shown in Figure 4.3, even though CA decreases PV efficiency to reduce CO_2 emissions and GR efficiency to mitigate PM pollutants, this optimal alternative enables a notable increase in CO_2 reduction potential compared to GR (more than 33 times) and provides a remarkable increase in PM mitigation potential compared to PV (more than 11 times). Notably, the mathematical analysis indicates that PV contributes more than GR in the optimized CA, suggesting its greater suitability for Tehran's specific case. Consequently, the most effective combination ratio for the implementation stage simplifies to 3 parts PV and 1 part GR in response to the third research question. In terms of target buildings to clarify the fourth research question, residential medium height in medium surface scale stands out as the most appropriate target building group for all three pollutant-reducing alternatives (PV, GR, and CA), either in decreasing CO_2 emissions or mitigating PM pollutants.

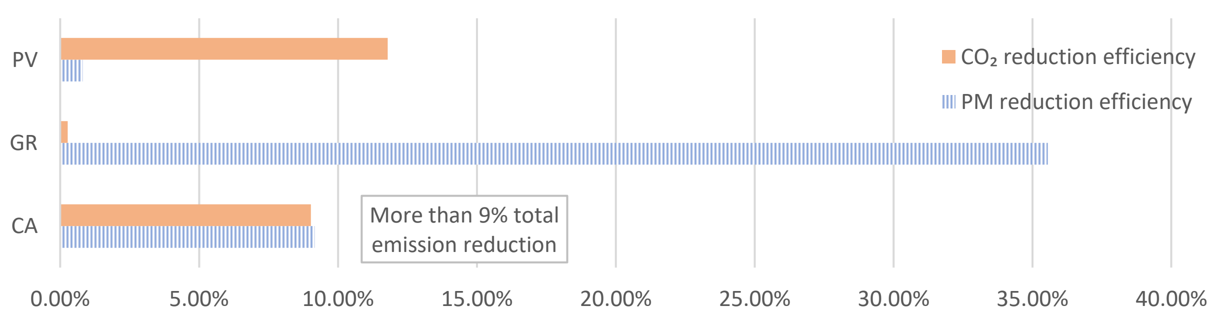


Figure 4.3. *Total efficiency of each alternative using potential residential target buildings on the city-scale*

Following the S-OBJ-5, by adopting this novel model, a significant milestone is achievable, as demonstrated in Figure 4.3 – a reduction of over 9% in both total CO_2 and PM emissions from all sources and sectors across Tehran – which was in response to the fifth research question. This achievement is possible by applying the optimized CA to six groups of potential residential target buildings. Ultimately, aligned with the concept of nearly Zero-Emission Building groups (nZEBs), the analysis of the results revealed that residential medium height in each potential surface scale holds the ability to become individually a collection of Zero-PM Buildings in the operational phase via applying CA. Moreover, the application of CA to all six groups of residential target buildings has the potential to offset roughly one-fourth of the CO_2 emissions stemming from the household sector in the operational phase.

As a result, this approach can lead to substantial mitigation of pollutant emissions, offering a promising solution in the field to the city's air pollution challenges. Reducing air pollution by applying the proposed model provides the potential to bring about economic savings, improve social well-being, and contribute to a cleaner and more sustainable environment.

CHAPTER 5

Conclusion

This study highlights the significant potential for sustainable technologies like green roofs (GR) and photovoltaic (PV) systems to mitigate air pollution in cities. The systematic approach in this thesis project represents a crucial step in strategies and solutions development for the contribution of urban buildings to improve air quality, which can be adopted by the potential of rooftops. The models developed to assess the feasibility and sustainability of these technologies offer decision-makers valuable tools to select suitable plans based on specific urban contexts, stakeholder priorities, and environmental requirements. This is while the value of considering specific urban characteristics to implement these technologies is also underscored. The proposed framework has been intentionally crafted to be adaptable across various contexts, including different boundaries, cities, and pollutant-reducing alternatives – even any novel options that may emerge – after considering the particularities in each case and adapting to them if necessary. Related to Tehran, the initial case to apply this systematic approach, and considering the specific objectives mentioned in Chapter 1 (S-OBJ-1 to S-OBJ-5), the key findings and main achievements are as follows.

1) Underlining feasible urban solutions for rooftop applications to address the detrimental issue of air pollution and contribute to urban environmental improvement. Greenery, solar energy systems, and optimized rooftop utilization were specified as integral strategies in this pursuit (Ref. to S-OBJ-1).

2) As expected, reconfirming that MIVES is a flexible sustainability assessment method which allows the use of different resources adapted to the context of each analysis, enables facing the challenges through prevention strategies, and can contribute to achieving sustainable development goals (Ref. to S-OBJ-2).
3) Applying this new model to the specific case of Tehran revealed that semi-intensive green roof (SIGR) as a social-environmental alternative accounts for the most sustainable type of GR and enables mitigating 4.8 kg/m^2 CO_2 emissions and 52.4 g/m^2 particulate matter (PM) per year (Ref. to S-OBJ-2 and S-OBJ-3).
4) Meanwhile, building-attached photovoltaic (BAPV) as a socio-economic alternative obtains the highest sustainability level among solar energy systems, capable of reducing 211 kg/m^2 CO_2 emissions and 1.2 g/m^2 PM pollutants annually (Ref. to S-OBJ-2 and S-OBJ-3).
5) As expected, the results on the building scale were enriched and more practical by monitoring and set-up on the city scale to obtain the highest performance via developing a novel quantitative model to define optimal planning (Ref. to S-OBJ-4).
6) In this line, although PV systems are somewhat limited in mitigating PM, and GR faces shortcomings in reducing CO_2, the compound alternative (CA) efficiently addresses these weaknesses, as expected. This way, CA achieved commendable CO_2 reduction and PM mitigation outcomes (Ref. to S-OBJ-4).
7) As expected, PV emerges as the more suitable choice than GR for the specific case of Tehran. In practical terms, the most efficient ratio for CA implementation is simplified to 3:1, combining PV and GR (Ref. to S-OBJ-4).
8) Furthermore, residential buildings of medium height in medium surface scale are the most appropriate targets in this case for all three pollutant-reducing alternatives (PV, GR, and CA), whether the goal is to reduce CO_2 emissions or mitigate PM pollutants (Ref. to S-OBJ-4).
9) An outstanding unexpected achievement with over a 9% reduction in both total CO_2 and PM emissions – emitted from all sources and sectors – can be attained by applying an optimized CA to the selected potential residential target building groups (Ref. to S-OBJ-5).
10) Following the nZEBs concept, an unexpected achievement revealed that residential buildings of medium height in each potential surface scale have the possibility to form a group of Zero-PM Buildings in the operational phase via applying CA (Ref. to S-OBJ-5).

CHAPTER 6

Future works

As urban air quality management continues to evolve, this research serves as a foundation – to be further explored – to develop more efficient and customized pollution reduction strategies in urban areas. Accordingly, partial future works were proposed in the included publications; for instance, suggesting: 1) increasing the sustainability value of GR by reducing its manufacturing energy consumption and implementation costs, 2) enhancing the energy generation efficiency of PV, and 3) considering the distribution of different target buildings across the city and the concentration of air pollutants in various urban regions to make more precise local decisions and enhance overall city-level performance. Thus, investigating the possibility to improve the efficiency of pollutant-reducing alternatives in different districts. In this way, aligned with the effort made in this thesis project, holistic recommendations and suggestions for future works and research directions are provided in the following lines.

- *Validation and expansion of models:* Validating and broadening the sustainability assessment models (e.g., MIVES) developed in this research via testing these models in various urban contexts and under varying circumstances to ensure their robustness and applicability in diverse settings.

- *Technological advancements:* Staying updated with the latest advancements in GR technologies, PV systems, and other sustainable urban alternatives. Research and development of novel technologies that can further enhance their effectiveness in addressing air pollution.
- *Long-term monitoring:* Undertaking long-term monitoring and evaluation of the implemented pollutant reducers to investigate their real-world performance in mitigating air pollution. This can provide valuable data for refining models and improving the efficiency of these technologies.
- *Optimizing urban planning:* Investigating the integration of the methodical approach proposed in this study into urban planning and development processes. Collaborating with urban planners and policymakers to incorporate rooftop utilization strategies into city planning and zoning regulations.
- *Interdisciplinary research:* Encouraging cross-disciplinary research that involves experts from various fields, such as architectural engineering, building construction, urban planning, decision analysis, environmental science, sociology, and economics. This approach can foster a more comprehensive understanding of multifaceted challenges and opportunities associated with sustainable urban development.
- *Community engagement:* Exploring approaches to actively involve local communities and stakeholders in adopting sustainable rooftop alternatives. Acquiring insights into the social and cultural factors that might influence the acceptance and implementation of these solutions.
- *Policy development:* Advocating to develop policies and incentives that promote the widespread adoption of green infrastructures (GI) in urban areas. Collaborating with governmental bodies and organizations in order to establish supportive regulatory frameworks.
- *Scaling up:* Exploring strategies to scale up the implementation of sustainable rooftop solutions in cities beyond the initial case study. Considering how these strategies can be adapted to the different cities and regions with varying characteristics and challenges.
- *Integration with the smart cities:* Investigating the integration of sustainable rooftop technologies into the broader concept of smart cities. Exploring opportunities for data-driven decision-making, automation, and optimization of these technologies within urban environments.

- *Education and awareness:* Developing educational programs and awareness campaigns to inform the public about the advantages of GI solutions. Fostering a culture of sustainability and environmental responsibility within urban communities.
- *Economic analysis:* Undertaking a comprehensive economic study to assess the cost-effectiveness of applying these plans on a larger scale. Investigating financing options and incentives for individuals and businesses to invest in this area.
- *Global collaboration:* Promoting international collaboration and knowledge exchange among researchers, practitioners, and policymakers engaged in sustainable urban solutions. Drawing insights from successful initiatives in diverse regions worldwide and adapting best practices to local circumstances.

By pursuing these future works, research directions, and recommendations, it will be possible to further advance the use of sustainable technologies on rooftops in urban areas, contributing to cleaner, more sustainable, and resilient urban environments on a global scale.

References

[1] AQI Basics | AirNow.gov, (n.d.). https://www.airnow.gov/aqi/aqi-basics/ (accessed March 30, 2023).

[2] T.L. Saaty, How to make a decision: the analytic hierarchy process, Eur. J. Oper. Res. 48 (1990) 9–26.

[3] A.K. Shukla, K. Sudhakar, P. Baredar, A comprehensive review on design of building integrated photovoltaic system, Energy Build. 128 (2016) 99–110. https://doi.org/10.1016/j.enbuild.2016.06.077.

[4] C. Peng, Y. Huang, Z. Wu, Building-integrated photovoltaics (BIPV) in architectural design in China, Energy Build. 43 (2011) 3592–3598. https://doi.org/10.1016/j.enbuild.2011.09.032.

[5] Climate Change 2022: Mitigation of Climate Change, (n.d.). https://www.ipcc.ch/report/ar6/wg3/ (accessed March 30, 2023).

[6] Circular economy: definition, importance and benefits | News | European Parliament, (n.d.). https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits (accessed March 30, 2023).

[7] Y. Jia, G. Alva, G. Fang, Development and applications of photovoltaic–thermal systems: A review, Renew. Sustain. Energy Rev. 102 (2019) 249–265. https://doi.org/10.1016/j.rser.2018.12.030.

[8] Y. Tripanagnostopoulos, M. Souliotis, R. Battisti, A. Corrado, Energy, cost and LCA results of PV and hybrid PV/T solar systems, Prog. Photovolt. Res. Appl. 13 (2005) 235–250. https://doi.org/10.1002/pip.590.

[9] Solar, in: Handb. Energy, Elsevier, 2013: pp. 405–450. https://doi.org/10.1016/B978-0-08-046405-3.00010-3.

[10] H. Tributsch, Dye sensitization solar cells: a critical assessment of the learning curve, Coord. Chem. Rev. 248 (2004) 1511–1530. https://doi.org/10.1016/j.ccr.2004.05.030.

[11] G. Hammond, C. Jones, E.F. Lowrie, P. Tse, Embodied carbon, Inventory Carbon Energy ICE Version 20. (2011).

[12] Basic Information of Air Emissions Factors and Quantification | US EPA, (n.d.). https://www.epa.gov/air-emissions-factors-and-quantification/basic-information-air-emissions-factors-and-quantification (accessed March 31, 2023).

[13] A.V. Pilipenko, S.P. Petrov, Analysis of Energy Efficiency of Energy Conversion in Cogeneration Systems, IOP Conf. Ser. Earth Environ. Sci. 224 (2019) 012006. https://doi.org/10.1088/1755-1315/224/1/012006.

[14] S. Tabatabaee, A. Mahdiyar, S. Durdyev, S.R. Mohandes, S. Ismail, An assessment model of benefits, opportunities, costs, and risks of green roof installation: A multi criteria decision making approach, J. Clean. Prod. 238 (2019) 117956.

[15] T. Couture, Y. Gagnon, An analysis of feed-in tariff remuneration models: Implications for renewable energy investment, Energy Policy. 38 (2010) 955–965. https://doi.org/10.1016/j.enpol.2009.10.047.

[16] C. Good, J. Chen, Y. Dai, A.G. Hestnes, Hybrid Photovoltaic-thermal Systems in Buildings – A Review, Energy Procedia. 70 (2015) 683–690. https://doi.org/10.1016/j.egypro.2015.02.176.

[17] P. Hiltrud, B. Pierre, Urban Green-blue Grids for Sustainable and Dynamic Cities, Coop Life Delft. (2011).

[18] S. Diwania, S. Agrawal, A.S. Siddiqui, S. Singh, Photovoltaic–thermal (PV/T) technology: a comprehensive review on applications and its advancement, Int. J. Energy Environ. Eng. 11 (2020) 33–54. https://doi.org/10.1007/s40095-019-00327-y.

[19] A. Mahdiyar, S. Tabatabaee, A.N. Sadeghifam, S.R. Mohandes, A. Abdullah, M.M. Meynagh, Probabilistic private cost-benefit analysis for green roof installation: A Monte Carlo simulation approach, Urban For. Urban Green. 20 (2016) 317–327.

[20] G. Finnveden, M.Z. Hauschild, T. Ekvall, J. Guinée, R. Heijungs, S. Hellweg, A. Koehler, D. Pennington, S. Suh, Recent developments in Life Cycle Assessment, J. Environ. Manage. 91 (2009) 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018.

[21] P. Pujadas, F. Pardo-Bosch, A. Aguado-Renter, A. Aguado, MIVES multi-criteria approach for the evaluation, prioritization, and selection of public investment projects. A case study in the city of Barcelona, Land Use Policy. 64 (2017) 29–37. https://doi.org/10.1016/j.landusepol.2017.02.014.

[22] M. Mladineo, I. Veža, N. Gjeldum, Single-objective and multi-objective optimization using the HUMANT algorithm, Croat. Oper. Res. Rev. 6 (2015) 459–473. https://doi.org/10.17535/crorr.2015.0035.

[23] European Commission. Joint Research Centre., Defining zero-emission buildings: support for the revision of the Energy Performance of Buildings Directive., Publications Office, LU, 2023. https://data.europa.eu/doi/10.2760/107493 (accessed April 4, 2023).

[24] L. El Chaar, L.A. lamont, N. El Zein, Review of photovoltaic technologies, Renew. Sustain. Energy Rev. 15 (2011) 2165–2175. https://doi.org/10.1016/j.rser.2011.01.004.

[25] T.M. Sathe, A.S. Dhoble, A review on recent advancements in photovoltaic thermal techniques, Renew. Sustain. Energy Rev. 76 (2017) 645–672. https://doi.org/10.1016/j.rser.2017.03.075.

[26] E. Alakangas, Biomass and agricultural residues for energy generation, in: Fuel Flex. Energy Gener., Elsevier, 2016: pp. 59–96. https://doi.org/10.1016/B978-1-78242-378-2.00003-1.

[27] M. del M. Casanovas, J. Armengou, G. Ramos, Occupational risk index for assessment of risk in construction work by activity, J. Constr. Eng. Manag. 140 (2014) 04013035.

[28] World Health Organization (WHO), (n.d.). https://www.who.int/airpollution/ambient/pollutants/en/ (accessed October 10, 2020).

[29] S. Sakka, Sol–Gel Process and Applications, in: Handb. Adv. Ceram., Elsevier, 2013: pp. 883–910. https://doi.org/10.1016/B978-0-12-385469-8.00048-4.

[30] B. Parida, S. Iniyan, R. Goic, A review of solar photovoltaic technologies, Renew. Sustain. Energy Rev. 15 (2011) 1625–1636. https://doi.org/10.1016/j.rser.2010.11.032.

[31] E. Borgonovo, E. Plischke, Sensitivity analysis: A review of recent advances, Eur. J. Oper. Res. 248 (2016) 869–887. https://doi.org/10.1016/j.ejor.2015.06.032.

[32] M.A. Green, E.D. Dunlop, J. Hohl-Ebinger, M. Yoshita, N. Kopidakis, A.W.Y. Ho-Baillie, Solar cell efficiency tables (Version 55), Prog. Photovolt. Res. Appl. 28 (2020) 3–15. https://doi.org/10.1002/pip.3228.

[33] D.J. Watson, Comparative Physiological Studies on the Growth of Field Crops: I. Variation in Net Assimilation Rate and Leaf Area between Species and Varieties, and within and between Years, Ann. Bot. 11 (1947) 41–76. https://doi.org/10.1093/oxfordjournals.aob.a083148.

[34] U.G. Assembly, World Summit Outcome: resolution/adopted by the General Assembly, 24 October 2005, A/RES/60/1, available at: http://www. refworld. org/docid/44168a910. html …, 2005.

[35] H. Takebayashi, M. Moriyama, Background and purpose, in: Adapt. Meas. Urban Heat Isl., Elsevier, 2020: pp. 1–8. https://doi.org/10.1016/B978-0-12-817624-5.00001-4.

[36] M.W. Ulmer, N. Soeffker, D.C. Mattfeld, Value function approximation for dynamic multi-period vehicle routing, Eur. J. Oper. Res. 269 (2018) 883–899. https://doi.org/10.1016/j.ejor.2018.02.038.

[37] G. Barone, A. Buonomano, C. Forzano, A. Palombo, O. Panagopoulos, Photovoltaic thermal collectors: Experimental analysis and simulation model of an innovative low-cost water-based prototype, Energy. 179 (2019) 502–516. https://doi.org/10.1016/j.energy.2019.04.140.

[38] U.M. Declaration, Resolution adopted by the general assembly, 55/2. United Nations Millennium Declaration, Retrieved June. 4 (2000) 2015.

[39] The World Bank, (n.d.). https://www.worldbank.org/en/news/press-release/2016/09/08/air-pollution-deaths-cost-global-economy-225-billion (accessed October 10, 2020).

[40] UN climate report: It's 'now or never' to limit global warming to 1.5 degrees, UN News. (2022). https://news.un.org/en/story/2022/04/1115452 (accessed April 5, 2022).

[41] D. Maierhofer, M. Röck, M. Ruschi Mendes Saade, E. Hoxha, A. Passer, Critical life cycle assessment of the innovative passive nZEB building concept 'be 2226' in view of net-zero carbon targets, Build. Environ. 223 (2022) 109476. https://doi.org/10.1016/j.buildenv.2022.109476.

[42] Buildings – Analysis - IEA, (n.d.). https://www.iea.org/reports/buildings (accessed May 26, 2023).

[43] M.C. Catalbas, B. Kocak, B. Yenipınar, Analysis of photovoltaic-green roofs in OSTIM industrial zone, Int. J. Hydrog. Energy. 46 (2021) 14844–14856. https://doi.org/10.1016/j.ijhydene.2021.01.205.

[44] M.H. Chung, Potential analysis of a target area selection for photovoltaic-based distributed generation in cases of an existing city in Korea, Sustain. Cities Soc. 41 (2018) 341–348. https://doi.org/10.1016/j.scs.2018.05.056.

[45] P. Irga, R. Fleck, E. Wooster, F. Torpy, T. Pettit, R. Gill, J. Ball, Green Roof & Solar Array–Comparative Research Project Final Report July 2021, (2021).

[46] Y. Barwise, P. Kumar, A. Tiwari, F. Rafi-Butt, A. McNabola, S. Cole, B.C.T. Field, J. Fuller, J. Mendis, K.J. Wyles, The co-development of HedgeDATE, a public engagement and decision support tool for air pollution exposure mitigation by green infrastructure, Sustain. Cities Soc. 75 (2021) 103299. https://doi.org/10.1016/j.scs.2021.103299.

[47] D. Patra, V. Chanse, A. Rockler, S. Wilson, H. Montas, A. Shirmohammadi, P.T. Leisnham, Towards attaining green sustainability goals of cities through social transitions: Comparing stakeholders' knowledge and perceptions between two Chesapeake Bay watersheds, USA, Sustain. Cities Soc. 75 (2021) 103318. https://doi.org/10.1016/j.scs.2021.103318.

[48] P. Zambrano-Prado, J. Muñoz-Liesa, A. Josa, J. Rieradevall, R. Alamús, S. Gasso-Domingo, X. Gabarrell, Assessment of the food-water-energy nexus suitability of rooftops. A methodological remote sensing approach in an urban Mediterranean area, Sustain. Cities Soc. 75 (2021) 103287. https://doi.org/10.1016/j.scs.2021.103287.

[49] M. Thebault, V. Clivillé, L. Berrah, G. Desthieux, Multicriteria roof sorting for the integration of photovoltaic systems in urban environments, Sustain. Cities Soc. 60 (2020) 102259. https://doi.org/10.1016/j.scs.2020.102259.

[50] S. Toboso-Chavero, A. Nadal, A. Petit-Boix, O. Pons, G. Villalba, X. Gabarrell, A. Josa, J. Rieradevall, Towards Productive Cities: Environmental Assessment of the Food-Energy-Water Nexus of the Urban Roof Mosaic, J. Ind. Ecol. 23 (2019) 767–780. https://doi.org/10.1111/jiec.12829.

[51] D.S. Salvador, S. Toboso-Chavero, A. Nadal, X. Gabarrell, J. Rieradevall, R.S. da Silva, Potential of technology parks to implement Roof Mosaic in Brazil, J. Clean. Prod. 235 (2019) 166–177. https://doi.org/10.1016/j.jclepro.2019.06.214.

[52] K. Dimond, A. Webb, Sustainable roof selection: Environmental and contextual factors to be considered in choosing a vegetated roof or rooftop solar photovoltaic system, Sustain. Cities Soc. 35 (2017) 241–249. https://doi.org/10.1016/j.scs.2017.08.015.

[53] I. Josa, O. Pons, A. de la Fuente, A. Aguado, Multi-criteria decision-making model to assess the sustainability of girders and trusses: Case study for roofs of sports halls, J. Clean. Prod. 249 (2020) 119312.

[54] A. de la Fuente, M. del M. Casanovas-Rubio, O. Pons, J. Armengou, Sustainability of Column-Supported RC Slabs: Fiber Reinforcement as an Alternative, J. Constr. Eng. Manag. 145 (2019) 04019042. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001667.

[55] G. Ledesma, J. Nikolic, O. Pons-Valladares, Bottom-up model for the sustainability assessment of rooftop-farming technologies potential in schools in Quito, Ecuador, J. Clean. Prod. 274 (2020) 122993. https://doi.org/10.1016/j.jclepro.2020.122993.

[56] B. Maleki, M. d M. Casanovas Rubio, S.M.A. Hosseini, A. de la Fuente Antequera, Multi-Criteria Decision Making in the Social Sustainability Assessment of High-Rise Residential Buildings, IOP Conf. Ser. Earth Environ. Sci. 290 (2019) 012054. https://doi.org/10.1088/1755-1315/290/1/012054.

[57] S.A. Hosseini, O. Pons, A. de la Fuente, A combination of the Knapsack algorithm and MIVES for choosing optimal temporary housing site locations: A case study in Tehran, Int. J. Disaster Risk Reduct. 27 (2018) 265–277.

[58] O. Pons, A. De la Fuente, A. Aguado, The use of MIVES as a sustainability assessment MCDM method for architecture and civil engineering applications, Sustainability. 8 (2016) 460.

[59] D. Pinel, M. Korpås, K. B. Lindberg, Impact of the CO 2 factor of electricity and the external CO 2 compensation price on zero emission neighborhoods' energy system design, Build. Environ. 187 (2021) 107418. https://doi.org/10.1016/j.buildenv.2020.107418.

[60] S.S. Korsavi, Z.S. Zomorodian, M. Tahsildoost, Energy and economic performance of rooftop PV panels in the hot and dry climate of Iran, J. Clean. Prod. 174 (2018) 1204–1214. https://doi.org/10.1016/j.jclepro.2017.11.026.

[61] Y. Fu, X. Liu, Z. Yuan, Life-cycle assessment of multi-crystalline photovoltaic (PV) systems in China, J. Clean. Prod. 86 (2015) 180–190. https://doi.org/10.1016/j.jclepro.2014.07.057.

[62] F. Cucchiella, I. D'Adamo, S.C. Lenny Koh, Environmental and economic analysis of building integrated photovoltaic systems in Italian regions, J. Clean. Prod. 98 (2015) 241–252. https://doi.org/10.1016/j.jclepro.2013.10.043.

[63] F. Moran, S. Natarajan, PV in historic dwellings: The potential to reduce domestic CO2 emissions, J. Build. Eng. 3 (2015) 70–78. https://doi.org/10.1016/j.jobe.2015.06.004.

[64] M. Herrando, C.N. Markides, K. Hellgardt, A UK-based assessment of hybrid PV and solar-thermal systems for domestic heating and power: System performance, Appl. Energy. 122 (2014) 288–309. https://doi.org/10.1016/j.apenergy.2014.01.061.

[65] J. Yang, Q. Yu, P. Gong, Quantifying air pollution removal by green roofs in Chicago, Atmos. Environ. 42 (2008) 7266–7273.

[66] B.A. Currie, B. Bass, Estimates of air pollution mitigation with green plants and green roofs using the UFORE model, Urban Ecosyst. 11 (2008) 409–422.

[67] M.E. Abdalazeem, H. Hassan, T. Asawa, H. Mahmoud, Review on integrated photovoltaic-green roof solutions on urban and energy-efficient buildings in hot climate, Sustain. Cities Soc. 82 (2022) 103919. https://doi.org/10.1016/j.scs.2022.103919.

[68] K. Bao, D. Thrän, B. Schröter, Simulation and Analysis of Urban Green Roofs with Photovoltaic in the Framework of Water-Energy Nexus, in: CITIES 2050–Creating Habitats 3rd Millenn. Smart–Sustainable–Climate Neutral Proc. REAL CORP 2021 26th Int. Conf. Urban Dev. Reg. Plan. Inf. Soc., CORP–Competence Center of Urban and Regional Planning, 2021: pp. 671–680.

[69] A. Jahanfar, J. Drake, B. Gharabaghi, B. Sleep, An experimental and modeling study of evapotranspiration from integrated green roof photovoltaic systems, Ecol. Eng. 152 (2020) 105767. https://doi.org/10.1016/j.ecoleng.2020.105767.

[70] M. Ramshani, X. Li, A. Khojandi, O. Omitaomu, An agent-based approach to study the diffusion rate and the effect of policies on joint placement of photovoltaic panels and green roof under climate change uncertainty, Appl. Energy. 261 (2020) 114402. https://doi.org/10.1016/j.apenergy.2019.114402.

[71] B.Y. Schindler, L. Blaustein, R. Lotan, H. Shalom, G.J. Kadas, M. Seifan, Green roof and photovoltaic panel integration: Effects on plant and arthropod diversity and electricity production, J. Environ. Manage. 225 (2018) 288–299. https://doi.org/10.1016/j.jenvman.2018.08.017.

[72] M.S.P. Moren, A. Korjenic, Green buffer space influences on the temperature of photovoltaic modules, Energy Build. 146 (2017) 364–382. https://doi.org/10.1016/j.enbuild.2017.04.051.

[73] Chr. Lamnatou, D. Chemisana, Evaluation of photovoltaic-green and other roofing systems by means of ReCiPe and multiple life cycle–based environmental indicators, Build. Environ. 93 (2015) 376–384. https://doi.org/10.1016/j.buildenv.2015.06.031.

[74] T. Brinkhoff, The principal agglomerations of the world, Accessed Aug. 16 (2011) 2011.

[75] M. Heger, M. Sarraf, Air pollution in Tehran: health costs, sources, and policies, World Bank, 2018.

[76] Tehran Annual Air and Noise Quality Report, period of March 2020 - March 2021, Air Quality Control Company, Tehran, Iran, 2021. https://air.tehran.ir/Default.aspx?tabid=471 (accessed February 22, 2022).

[77] M.T.C. Team, SWOT Analysis, Discover New Opportunities, Manage and Eliminate Threats, Mind Tools. (2018).

[78] O. Pons, A. de la Fuente, Integrated sustainability assessment method applied to structural concrete columns, Constr. Build. Mater. 49 (2013) 882–893.

[79] O. Pons, J. Franquesa, S.M. Hosseini, Integrated value model to assess the sustainability of active learning activities and strategies in architecture lectures for large groups, Sustainability. 11 (2019) 2917.

[80] H. Zamani-Sabzi, J.P. King, C.C. Gard, S. Abudu, Statistical and analytical comparison of multi-criteria decision-making techniques under fuzzy environment, Oper. Res. Perspect. 3 (2016) 92–117. https://doi.org/10.1016/j.orp.2016.11.001.

[81] I.O. for Standardization, Environmental management: life cycle assessment; Principles and Framework, ISO, 2006.

[82] H. Lecouls, ISO 14043: Environmental management · life cycle assessment · life cycle interpretation, Int. J. Life Cycle Assess. 4 (1999) 245–245. https://doi.org/10.1007/BF02979166.

[83] O. Pons, A. Aguado, Integrated value model for sustainable assessment applied to technologies used to build schools in Catalonia, Spain, Build. Environ. 53 (2012) 49–58.

[84] S.M.A. Hosseini, O. Pons Valladares, A. de la Fuente Antequera, Sustainable building technologies for post-disaster temporary housing: integrated sustainability assessment and life cycle assessment, World Acad. Sci. Eng. Technol. 13 (2019) 244–250. https://doi.org/10.5281/zenodo.

[85] S.M.A. Hosseini, L. Farahzadi, O. Pons, Assessing the sustainability index of different post-disaster temporary housing unit configuration types, J. Build. Eng. 42 (2021) 102806. https://doi.org/10.1016/j.jobe.2021.102806.

[86] S.H. Banirazi Motlagh, O. Pons, S.M.A. Hosseini, Sustainability model to assess the suitability of green roof alternatives for urban air pollution reduction applied in Tehran, Build. Environ. 194 (2021) 107683. https://doi.org/10.1016/j.buildenv.2021.107683.

[87] S. Hamed Banirazi Motlagh, S.M.A. Hosseini, O. Pons-Valladares, Integrated value model for sustainability assessment of residential solar energy systems towards minimizing urban air pollution in Tehran, Sol. Energy. 249 (2023) 40–66. https://doi.org/10.1016/j.solener.2022.10.047.

[88] S.H. Banirazi Motlagh, O. Pons-Valladares, S.M.A. Hosseini, City-scale model to assess rooftops performance on air pollution mitigation; validation for Tehran, Build. Environ. 244 (2023) 110746. https://doi.org/10.1016/j.buildenv.2023.110746.