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Alternative Roof Market Analysis Based on a Hybrid Dynamic Systems Approach and Multi-criteria Decision-Making Method

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ABSTRACT

Recent advances in construction methods and sustainable development have allowed urban developers to significantly reduce urban environmental problems caused by building expansion, such as increased energy consumption, greenhouse gas emissions, and the urban heat island effect. Newer alternative roofs could be potential solutions for these urban environmental problems. However, economic and social issuesadopting have hindered the penetration of this market. This study used the systems dynamics approach to perform a comprehensive analysis of the influential factors affecting the alternative roof market, such as economic, social, legal, technical, and environmental capabilities. Then, the performance improvement scenarios were evaluated and ranked according to their relative priority based on the simulation results. The results of this case study in Iran indicate that the combined scenario of the growth of urban space according to the increase in the economic coefficient of green space can be focused on more than other scenarios. However, all the designed scenarios have made significant beneficial changes in the key variables of the system under investigation. The results show that the alternative roof market has significant growth potential solution.

Keywords

Alternative roofing, Roof market Analysis, Sustainability, System dynamics, Multi-criteria decision making.

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1. Introduction

Since the 1980s, sustainable development has been noted as a fundamental concept in the global strategy of the United Nations Organization. Sustainable development is defined as development that meets the needs of the current generation without compromising the ability of the future to meet their own needs in the form of economic, social, and environmental aspects. One of the recent issues presented as a new idea in sustainable development is sustainable architectural design. Sustainable architecture refers to buildings that have the least destructive effect on the environment and the man-made environment. In addition, sustainable architecture is effective in the sustainable cycle of the environment and the optimal function of the future (Zandiyeh and Parvardi Nejad, 2010). With the growing population, the need for construction and energy increases. However, fossil resource limitations have led to environmental concerns, including an increase in greenhouse gas emissions (GGEs) and air heat. Therefore, efforts to limit the energy consumption of buildings have led researchers to look for solutions to save energy and preserve the environment. By consuming more than 40% of total energy, buildings exert significant pressure on urban areas (Alshayeb and Chang, 2018) and play a significant role in the emission of greenhouse gases (Alirezaei et al., 2016). In addition, the rapid growth of urbanization to accommodate growing urban populations increases urban runoff and subsequent risks of flooding and water pollution. It adds to heat-related illnesses through the urban heat island effect. This phenomenon leads to increased energy consumption (Bai et al., 2017). These problems, including increased energy demand, greenhouse gas emissions, floods, and heat-related illnesses, have economic and environmental consequences for policymakers and societies (Santamouris et al., 2018). Therefore, buildings play an essential role in urban sustainability, making the urban construction industry an ideal target through which to mitigate these problems. Recent advances in construction and sustainable methods have allowed urban developers to significantly reduce the adverse impacts of buildings (Phillips et al., 2017). One of these forms of sustainable construction is the alternative roof. Alternative roof systems such as green roofs, solar roofs, and photovoltaic roofs offer an opportunity to improve urban sustainability. A green roof is a specially designed system that is installed on the roof to grow and support vegetation. In a green roof, a series of roofing layers are placed under the vegetation to create drainage and waterproof insulation and to protect the roof below it from damage caused by roots. In the solar roof, installed solar panels provide renewable energy for the building. A photovoltaic roof is a set of green roofs and solar panels that are effectively combined on the roof of a building into a single integrated system.

From its construction through operation, a building acts as a complex and dynamic system consisting of various subsystems (Thompson and Bank, 2010). They linked the obtained data to a building information model for improving the decision-making process in building design, retrofit, and operation. In addition, urban processes that are affected by buildings include construction and operations that are randomly connected (Bai et al., 2017). For example, different roof systems have different effects on the depth of annual urban runoff. In the same way, the choice of roofing system can also have a reinforcing or balancing role in the energy-saving potential of the building that may cope with the potential increase in energy demand due to population growth. Therefore, the existence of these interrelationships between the practical elements in the roofing industry has led to addressing the problem of modeling and analyzing subsystems with a systematic view and analyzing the causality between subsystems in an integrated way (Onat et al., 2014). System dynamics modeling allows the integration of these interactions, represented by feedback loops, between the subsystems that make up the building and between the building and its urban environment (Fong et al., 2009).

New systems of alternative roofs could be potential solutions for growing urban environmental problems affected by climate change. However, economic and social concerns, such as the adoption of alternative roofs, have delayed this market penetration despite its excellent growth potential. .This study comprehensively analyzes the key factors affecting the alternative roof market using the integrated system's dynamics approach with a multi-criteria decision-making method. For this purpose, key economic, social, legal, technical, and environmental aspects have been considered in the developed dynamic model.

2. Literature review

Due to the intense attention given to sustainable development in the construction industry, extensive studies have been conducted on alternative roofs in recent years. Using simulation tools, Mahmoody et al. (2012) studied and evaluated the effects of green roofs on reducing temperature and cooling the environment. They evaluated the impact of green roofs on reducing environmental temperature. The results indicate that a green roof leads to less heat transfer than a conventional one. In addition, shading and evaporative cooling plants and the role of roof layers that all perform similar insulation effectively decrease heat transfer. In another study, Vahedi et al. (2012) investigated the integration of solar photovoltaic systems and green roofs. In solar panels, efficiency and output power decrease with increasing temperature. Conversely, direct sunlight increases plant evaporation and transpiration, reducing vegetation and green roof efficiency. Therefore, vegetation on the roof cools it, increasing the panel's output and efficiency.

Additionally, the shade of panel blocks direct sunlight from hitting the plant, reducing evaporation and transpiration and promoting plant growth and development. Mohammadi et al. (2019) conducted a life cycle assessment to compare the environmental effects of green and conventional roofs and analyzed environmental concerns using simulation tools. The results indicate that the green roof, during its lifetime, has fewer environmental influences than a normal roof. Furthermore, it is addressed that in some impact groups, the environmental impacts of green roofs were more greater than those of normal roofs, and the main cause was utilizing glass fiber and polyester in its layers. Zanganeh et al. (2015) investigated the factors affecting the non-use and development of green roofs for reducing heat islands in the Mashhad metropolis using the hierarchical analysis method (AHP). The obstacles identified in the way of developing green roofs include the high cost of green roofs compared to conventional roofs, the affordability of energy, the absence of a native green roof industry and applied research, the lack of economic justification in plans for both individuals and officials and the absence of codified laws. Darvish et al. (2018) analyzed solar reflection and reflective surfaces in typical roofs as a passive solution to reduce the control of solar energy absorption and reduce the temperature and energy consumption in Ray City as a case study. The obtained results indicate that growing roof surfaces with reflective materials have a significant impact on diminishing the surface as well as the roof's surrounding air temperature. Saiz et al. (2006) reviewed the environmental benefits of green roofs and their potential for heat reduction, annual energy savings, and summer cooling loads. The main specificity of a green roof is its small solar absorptance, which leads to lower surface temperature and decreases the heat flux through the roof. The results indicated that green roofs significantly affect annual building energy consumption. Castleton et al. (2010) reviewed the current literature and highlights for evaluating the potential of green roofs to save energy. Using simulation tools, Susca et al. (2011) investigated the role of green roofs on the effects of greenhouse gases and the amount of CO_2 emissions in the air. For this purpose, the surface albedo effect is evaluated by using a climatological model. Obtained results indicate that green roofs with thermal resistance and plants' biological activity play a crucial role.

Bianchini and Hewage (2012) analyzed green roofs using Monte Carlo simulation tools with the presence of social, economic, and technical variables. The results indicate various advantages of green roofs as a sustainable alternative for urban areas and industry zones.

Costanzo et al. (2016) investigated conventional and green roofs using a simulation tool to analyze their role in reducing greenhouse gas production and energy consumption. Obtained results indicate that many variables impact green roof performance that should be considered in roof design, such as local climate conditions. Li et al. (2014) investigated the cooling capability of green roofs using the climatic composition of the region. They addressed the importance of managing moisture and surface albedo on the performance of green roofs. Morakinyo et al. (2017) conducted a parametric study on the effects of four different types of green roofs on outdoor and indoor temperatures and the amount of cooling in different climates and urban densities. Santamouris et al. (2018) analyzed the effect of green roofs on the emission of greenhouse gases in the surrounding environment under different reduction strategies. In a review study, Besir and Cuce (2018) investigated the effect of green roofs and facades on the amount and quality of GGEs and energy consumption.

Hui and Chan (2011) investigated the performance of photovoltaic roofs from the perspective of energy consumption management using energy system simulations and field measurements. Scherba et al. (2011) investigated the roof energy balance and the associated net sensible heat flux through an energy balance model for several alternative roof systems, including photovoltaic roofs. Lamnatou and Chemisana (2014) evaluated the life cycle performance of a photovoltaic roof. Alshayeb and Chang (2018) conducted an experimental and comparative analysis of different examples of photovoltaic roofs. Van Lith et al. (2018) analyzed the thermal performance of green and solar roofs according to the indoor and outdoor air and surface temperatures. Odeh (2018) also investigated the effect of roof shading caused by installing solar roofs on the thermal performance of buildings. These studies indicate the importance of developing integrated alternative roofs for optimal performance.

Yan (2009) investigated and analyzed macro strategies to increase the solar roof market in the country. Hsu (2012) also investigated the effects of government subsidies on Taiwan's solar roof market. Flynn et al. (2010) analyzed the market effect of solar renewable energy certification on solar roof adoption as a renewable energy. For this purpose, a price support mechanism based on the auction procedure for the solar portion of the target renewable portfolio standard has been adopted. The results indicate that system dynamics can be a tool for analyzing and improving sustainability plans. Kelly et al. (2020) analyzed the dynamics of alternative roofs and their effects on the urban environment in the United States. For this purpose, potential impacts of economic, social, and developmental investment issues are considered alternative roof markets. The results indicate that the alternative rood market has a substantial growth and market penetration potential. Zheng et al. (2021) investigated the role of alternative roofs in water resource management using a quantitative analytical approach.

Gonçalves and Abrahão (2023) investigated and evaluated the environmental effects of photovoltaic roofs in an integrated structure. The results indicate that the most significant positive impacts were linked to local economic development, electrical supply security, and grid decarbonization. In addition, adverse impacts were connected to original structure visibility and worker safety issues. Hekrle et al. (2023) make an economic assessment of green roofs using cost-benefit analyses. Basyouni and Mahmoud (2024) systematically reviewed green roof materials and highlighted the potential of bio-composite insulation panels. Liberalesso et al. (2023) evaluated financial subsidies for green roofs using the micro-scale analysis method. They highlighted the need to review the procedures for developing and granting public incentives at the municipal and/or macro-scale level for green roofs.

Moreover, the need to develop an efficient system for evaluating the performance of alternative roofs and analyzing their market is strongly felt, considering the comprehensive roles of economic, social, legal, technical, and environmental aspects in this decision-making environment. On the other hand, considering the dynamic and complex relationships between role-playing variables and the possibility of potential nonlinear feedback over time through the role of a set of variables, there will be a need for dynamic analysis of this complex system related to the market of alternative roofs. Therefore, this study proposes a comprehensive model for analyzing the market of alternative roofs in the metropolis of Mashhad as a real-life case study. The multi-criteria decision-making method has been integrated for evaluation planning scenarios based on the obtained simulation results.

3. Problem statement and research method

Library resources were used in this study to identify variables and relationships between them. Then, the fuzzy Delphi technique was used to confirm the identified variables and cause-and-effect relationships. The community of experts consists of experts in the field of environment and specialists of the Housing and Urban Planning Department in Razavi Khorasan Province with at least 15 years of experience related to the research problem. In analyzing the alternative roof market, numerous quantitative and qualitative factors mustbe considered. The influence of these factors on each other and their interactive relationship is inevitable despite any time delays and potential causal effects. If these delays, as well as casual loops, are not taken into account, the modeling results will deviate significantly from reality. Therefore, the dynamics of the system must be considered.

The key research question of this study is: "How can we analyze the alternative roof market using systems dynamics while considering key aspects of economics, social factors, legal issues, technical aspects, and the environment?" Consequently, this study aims to analyze the dynamics of the alternative roof market and evaluate planning scenarios for system improvement using a multi-criteria decision-making method.

The general steps of the dynamic analysis method are as follows: (1) determining the framework of the problem, including choosing the subject, identifying key variables, determining the time horizon, and providing a dynamic definition of the problem; (2) formulating a dynamic hypothesis, including creating an initial hypothesis, focusing on interpolation and mapping the model boundary diagram, cyclic root diagram, and flow state diagram; (3) formulating the simulation model, including identifying the structure and decision rules, estimating parameters, behavioral relationships, initial conditions, and conducting tests to ensure the consistency of the goal and boundary; (4) conducting the test, including comparisons with reference behaviors, limits, and sensitivity analysis; and (5) policy design and evaluation, including scenario determination, policy design, and analysis. This study analyzed scenarios for the future alternative roof market for 25 years. Figure 1 presents the overall steps of the system dynamic modeling approach in this study.

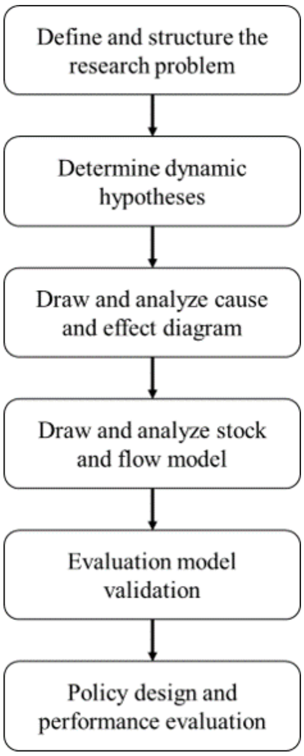

Figure 1. Modeling steps with a system dynamics approach

Various factors play a role in the analysis of the alternative roof market, such as implementation and exploitation costs, energy consumption, energy supply costs, technological factors, consumer attitudes and awareness, compatibility with other urban infrastructures, population change, and access to technology. According to the studies conducted in this field, the variables of population expansion, urban runoff, and the effect of greenhouse gases govern the dynamics of modeling subsystems. Urban runoff is the surface runoff of rainwater and landscape irrigation. Three roof options can be considered for roof market analysis: solar, green, and photovoltaic. Finally, the alternative roof market could be evaluated. The developed cause and effect diagram and stock-flow diagram are presented in Figures 2 and 3, respectively.

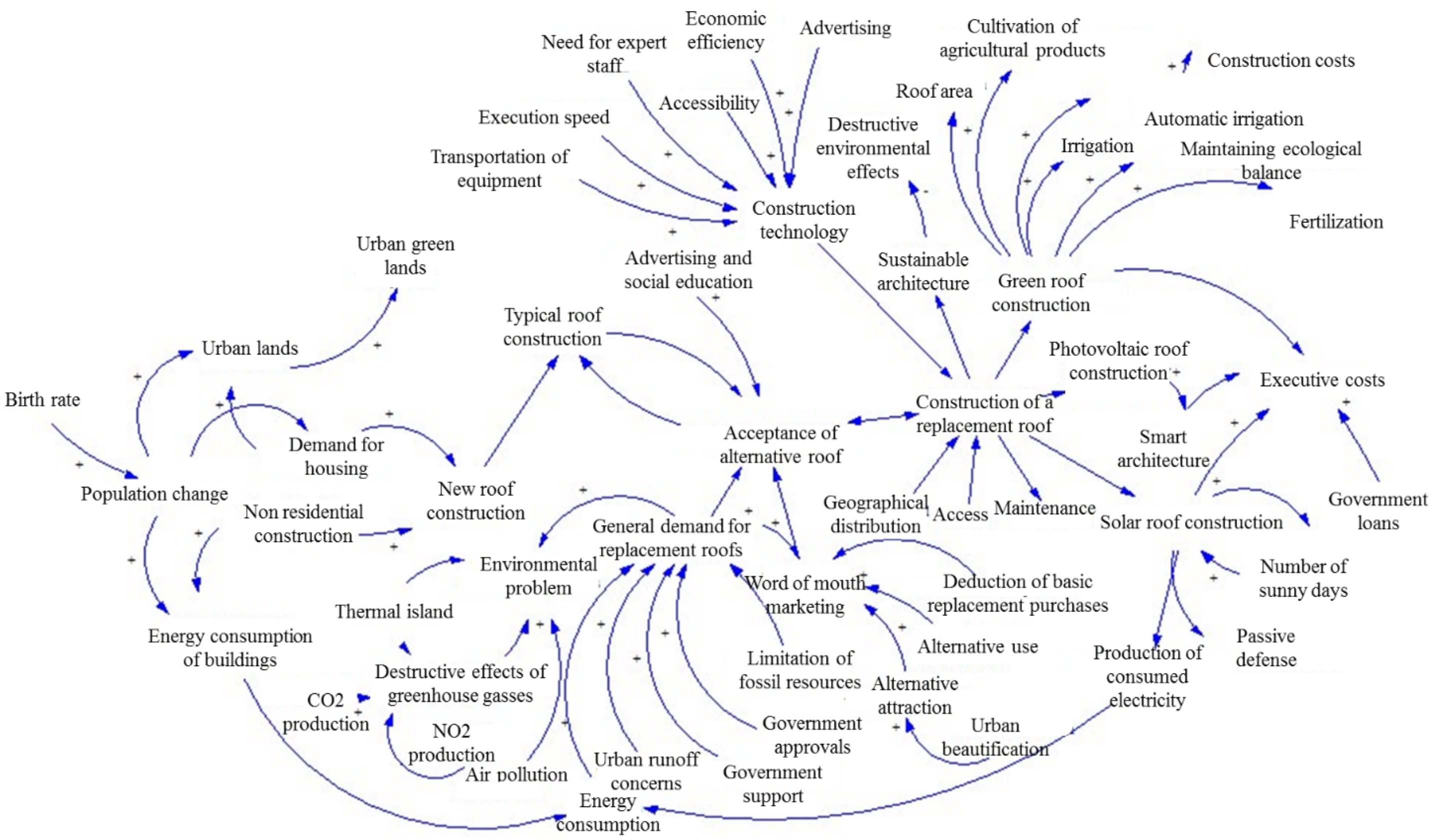

Figure 2. Proposed cause-effect diagram for alternative roof market analysis

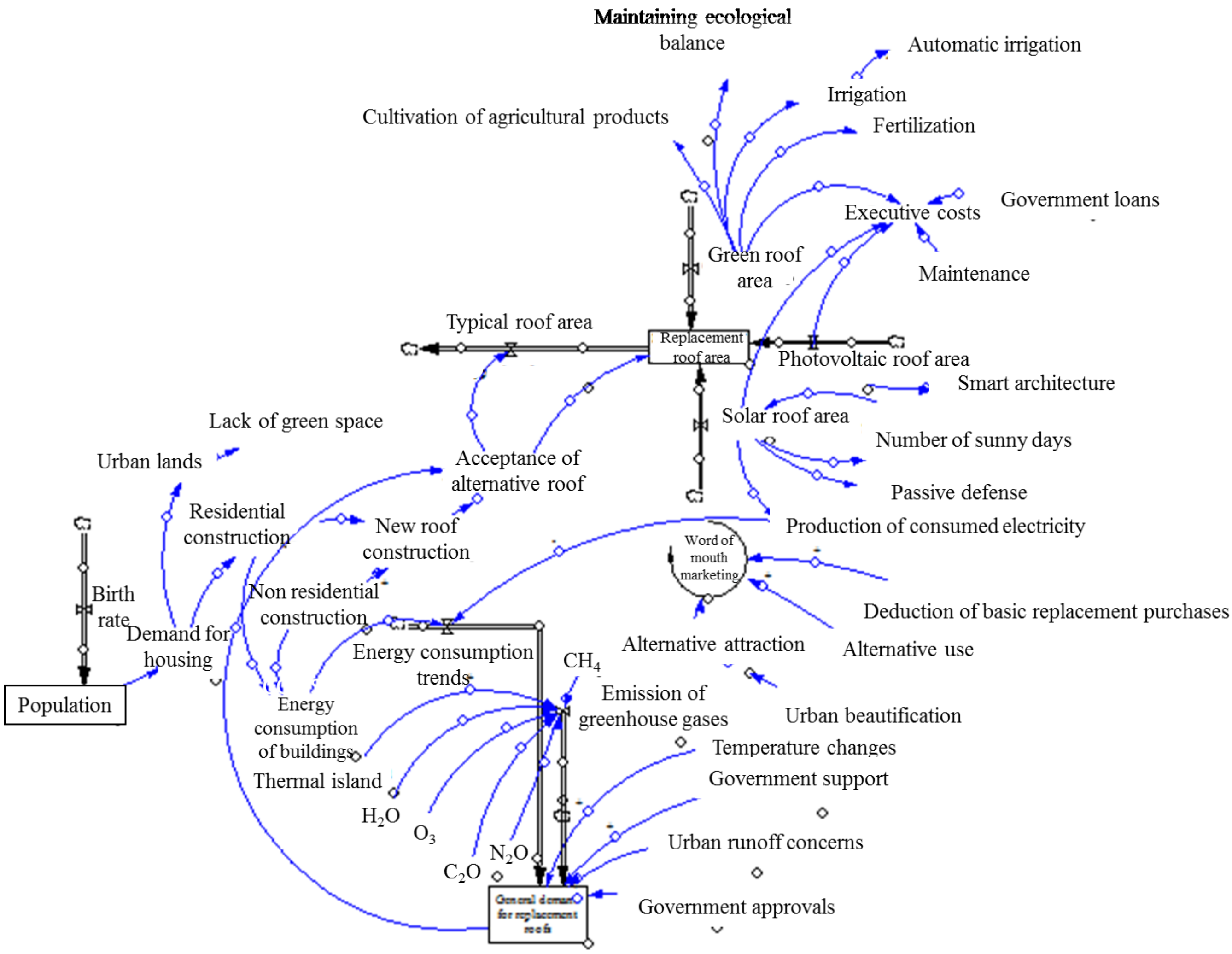

Figure 3. Proposed flow diagram for alternative roof market analysis

The amount of energy consumption of buildings is calculated in kilowatt-hours, which varies according to the area of the roof of each building. The effect of the type of roof on the amount of climate change should be regarded. The green roof with an average vegetation cover of 60 cm can reduce the heat of the air by up to ten degrees and effectively control the flow of water by up to 45 percent. With the increase in demand for new roofs the demand for roof replacements, the construction of new roofs is rising. When accepting new roofs is based on and replacing existing ones, non-standard roof options are more readily accepted. The higher the acceptance rate of alternative roofs, the lower the acceptance and construction of traditional roofs. Therefore, a negative relationship exists between the construction of alternative and normal roofs, creating a restraining effect between them. Population growth is one of the factors influencing the construction of new roofs. As the population increases, so does the demand for housing. This leads to the construction of new buildings, which leads to the expansion of urban areas and a decrease in urban green spaces. The increased demand for housing results in more residential constructions, with the size of new roofs depending on the size of the building's foundation. The increase in temperature disturbances, the heat of the ground, and the urban heat island have an effective role in replacing a new roof.

On the other hand, the speed of energy consumption is decreasing with new roofs. As a result, the demand for new roofs is increasing to reduce annual energy consumption. The roles of awareness, advertisement, and governmental support are also effective in accepting new roofs. In addition, word-of-mouth marketing promotes the attractiveness of alternative roofs. With the expansion of the population and the production of carbon dioxide, nitrogen dioxide, and other air pollutants, the volume of harmful greenhouse gases released increases, leading to an increase in environmental problems. On the other hand, the destructive effect of pollutants causes warm air to remain in the Earth's atmosphere, ultimately expanding the temperature or heat island. This cycle continues until one of the variables in this loop decreases or remains stable at a desired level.

Applied relations and their related mathematical functions are presented in Table 1.

Table 1. Applied variables and related mathematical functions in the proposed dynamic model

Variable	Formula
Advertising and social training	Cost / Number of admissions
Energy consumption	=(cost + 30) × 365
Executive costs	= Constant
Government budget	=497 million rial
Greenhouse gas (GHG) emissions	= QGHG = A × EF
Housing demand	=E(t)=H-V+H(t)+ru(t)
Maintenance	=Staff cost + equipment cost + number of breakdowns+(total maintenance time/total number of repairs)
Non-residential/Residential Construction	=Useful infrastructure = density × (total area of land × percentage of land construction)
Population	= INTEG (birth -death – migration)
Urban heat island	=ΔTu-r(max)=7.45+3.97ln(H/W)
Urban lands	Constant
Urban runoff	= Constant, 56mm

Due to ranking rank the scenarios of the alternative roof market analysis, the fuzzy TOPSIS technique is selected for ranking preferences based on their similarity to the ideal solution. The criteria weights of the decision matrix in the fuzzy TOPSIS method are calculated via the AHP (Rashidi and Cullinane, 2019). All of the applied formulas in the proposed system dynamics model are considered based on the findings of the literature and expert opinions.

The validity of the proposed system dynamics model and the obtained results are evaluated as follows:

- **Boundary Adequacy Test:** This test examines the model's behavior in the case of changing the defaults related to the model's boundary, applying the development policies of the model boundary, and so on. The first step in this test is to determine the variation range. One method uses a model boundary range chart, which summarizes the range by listing key internal and external variables and variables outside the model. Due to carry out this test, the causal diagrams of the model were provided to the experts to fix the deficiencies and provide relevant suggestions.

- **Structure verification test:** In this test, the integrated level of the model is examined to answer the question of whether the structure of the model includes the descriptive knowledge of the model system. Since this study is based on a review of the subject literature and has been widely used to complete the information from the experts' point of view, the obtained model is expected to have structural validity.
- **Dimensional consistency test:** This test uses Vensim software to determine the units of variables and their harmony with reality.

Figure 4 shows that with the increase in the demand for the construction of conventional roofs, the amount of conventional roof construction also increases, and the model's behavior is quite reasonable. When the demand for a normal roof triples, the construction of a normal roof in 2043 will reach approximately 160 square kilometers. Figure 5 shows the variable behavior of urban land area if the population variable is tripled. If the population triples, the urban land area of 1416 will reach more than 150 square kilometers.

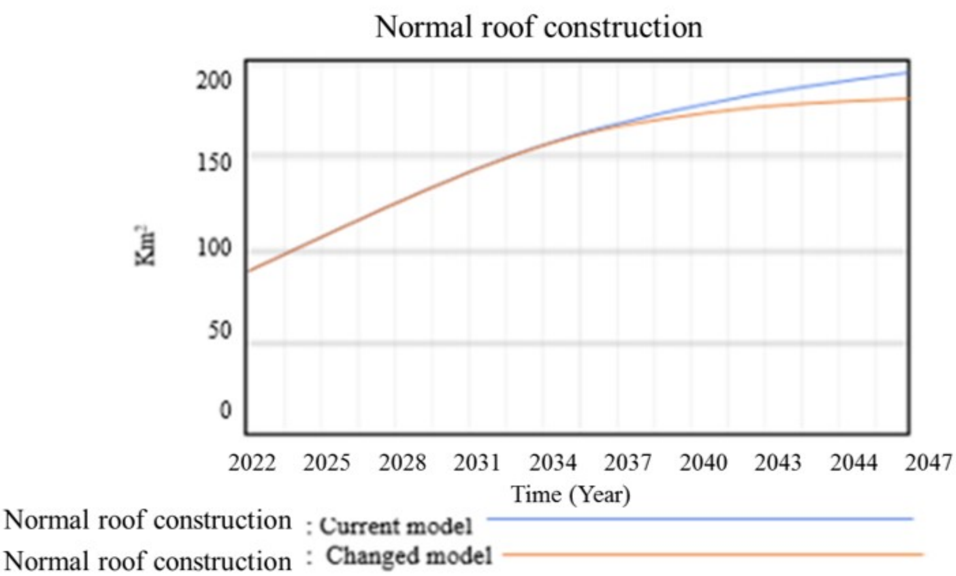

Figure 4. Comparison of normal roof construction in the main model and limit conditions of normal roof demand

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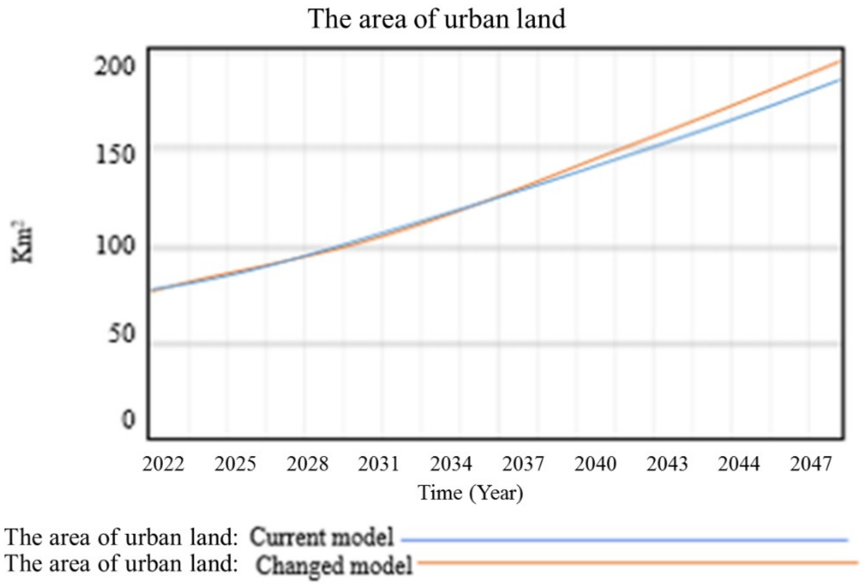
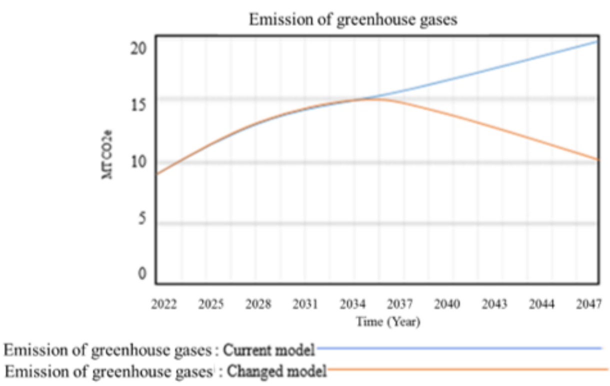
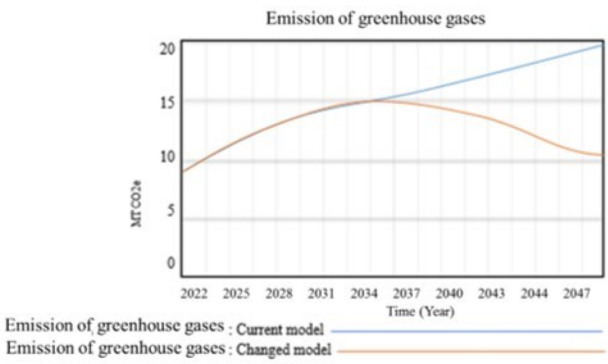


Figure 5. Comparison of the area of urban land in the main model and population limit conditions

Figure 6 shows GGEs if the amount of CO_2 and NO gas production reach half of their amount in 2047, respectively. With the reduction of half of the carbon dioxide production in 2025 and a delayed trend until 2047, GGEs will reach approximately 10 million tons of carbon dioxide equivalent. Additionally, with a 50% reduction in nitrogen oxide emissions in 2025, the amount of GGEs during its delayed process in 2022 reached 12 million tons of carbon dioxide equivalent, which is an entirely reasonable behavior of the model. Among other limit changes given in this section is the impact of building energy consumption on the overall energy consumption trend. If the energy consumption in buildings remains constant despite the increase in population, the trend of energy consumption in 2027 will continue to be constant (see Figure 7).



a: CO2 limit conditions



b: N_2O limit conditions

Figure 6. Comparison of GGEs in the main model and limit conditions

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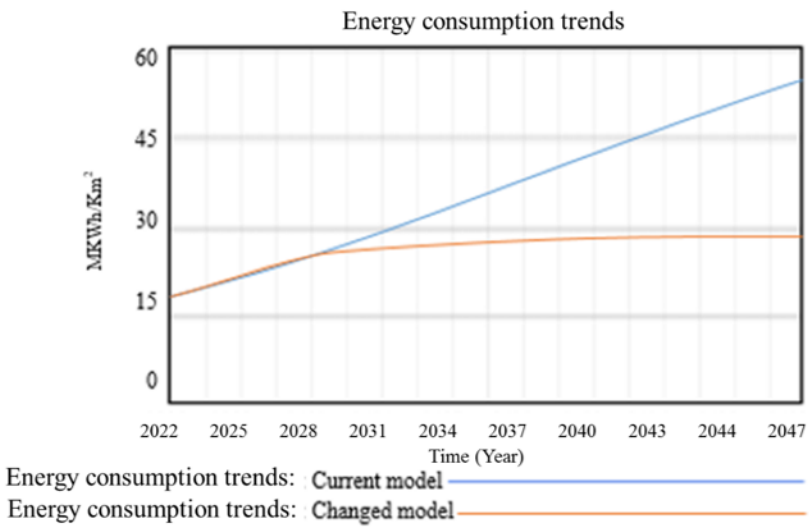
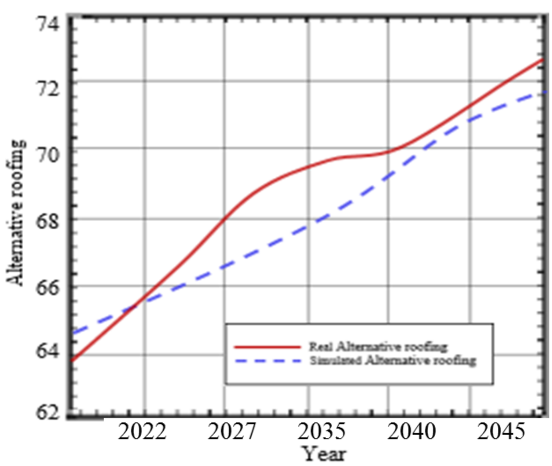


Figure 7. Comparison of the trend of energy consumption in the main model and the limiting conditions of energy consumption of buildings

- **Behavior reproducibility test:** This test aims to answer the following question: "To what extent does the model's behavior agree with the behavior observed from the real system?" (See Figure 8). Statistical methods compare the model's simulated behavior with existing reality. This test uses two coefficients of determination and the mean square error. The coefficient of determination expresses the percentage of changes in the real variable covered by the simulated variable. The mean square of the errors represents the average deviation of the simulated model from the real system. The coefficient of determination of the key variables of the model is greater than 0.8, which indicates that the model can simulate more than 80% of the changes in the main variables. According to the analysis of the values of the calculated statistical indicators, the model was evaluated regarding the reproduction of the appropriate reference behavior.



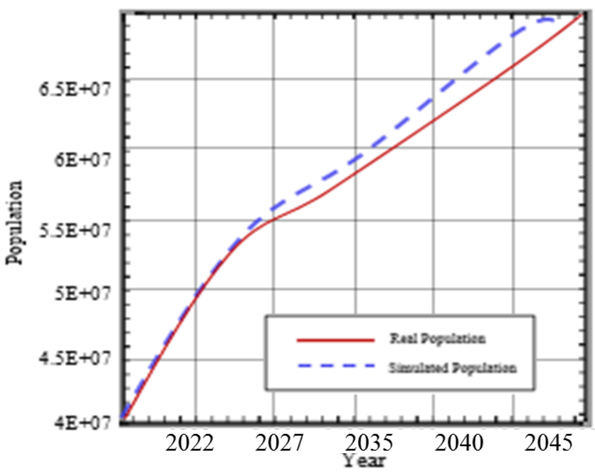


Figure 8. Reproducing the behavior of the population variables and the alternative roof demand

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4. Results analysis

According to the implementation of various tests, the model has sufficient validity and accuracy. In this section, the study model is implemented to predict the behavior of key variables. In order to simulate statistical data, this information must be obtained from the National Statistics Center of Iran. The implementation model in this study starts in 2022 and will continue for 25 years until 2047. Fixed values or model parameters were entered into the model to run in the initial year. According to the available information, in some cases, the data were entered into the model as a time series. After that, the behavior of some key variables if the current situation continues is shown in Figure 9.

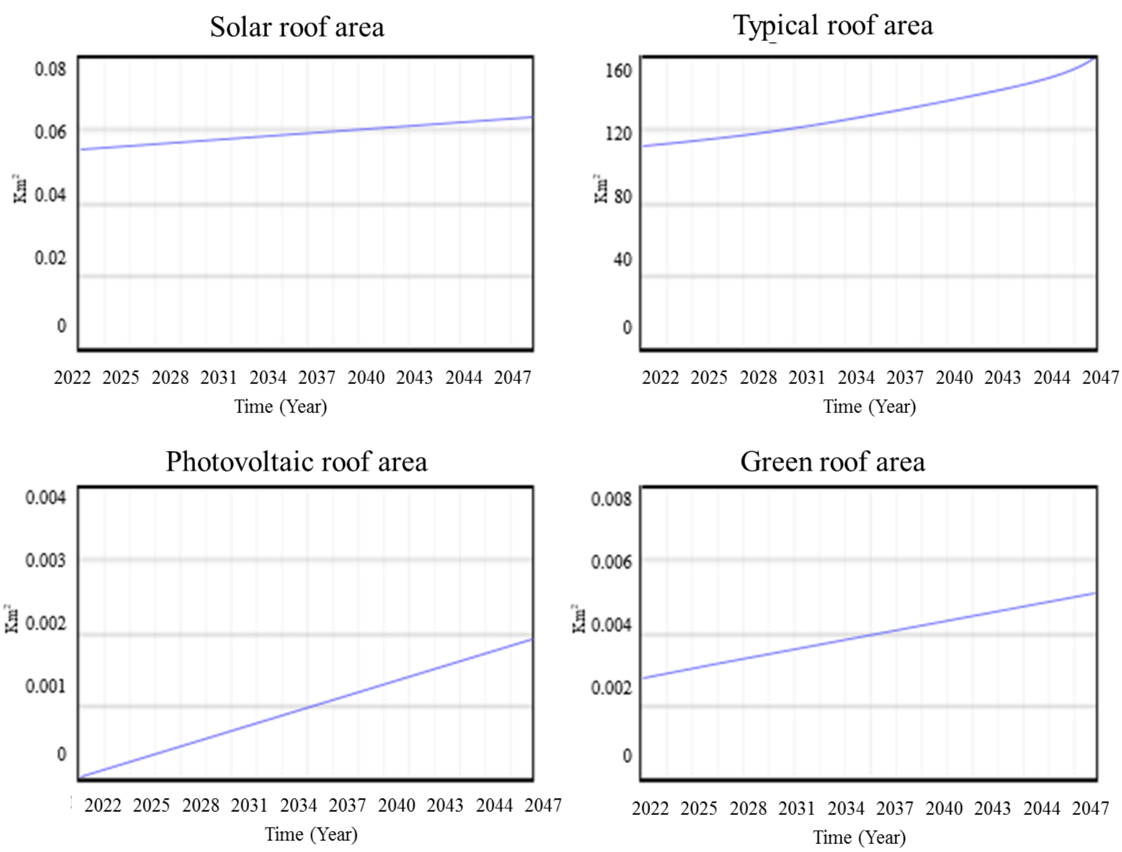

Figure 9. The behavior of some key variables after running the model

4.1. Scenario Planning

In order to analyze the proposed scenario, we changed the values of several key parameters to determine the amount of change in the key variables as performance measures. The total behavior of essential variables is analyzed under each scenario implementation. The results of these changes are shown for 2047 as the final year of the simulation planning period. The details of the scenario are given below.

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4.1.1. Scenario 1: Green roof economic technology penetration rate growth

According to the technological goals of the government regarding the expansion of technology in the field of alternative roof construction, this scenario considers the extent of the economic growth of green roofs from the perspective of technology expansion. The scenario assumes that the Mashhad municipality will increase the availability of green roofs within a favorable period by focusing on marketing activities such as increasing the green roof advertising budget and training the workforce in developing and constructing related equipment by technical and professional organizations. On the other hand, with the expansion of equipment and facilities related to the construction of green roofs, cost reduction occurs, and the government can increase accessibility by considering facilities or reducing prices specific to applicants for the construction of green roofs. Therefore, it is expected that with the training of skilled and expert personnel to become familiar with the infrastructure of green roofs with high strength and durability, the exterior design of green space, the training of environmental adaptations to the plant type in each region, access to technology, and the development of domestic technology, the penetration rate of green roof technology will increase economically. In this regard, the values of the auxiliary variables mentioned in Table 2 have been changed based on the base year value and the desired amount to investigate their effect on the model.

Table 2. Auxiliary variables input to the model under the first scenario

	Value	
Variable	**Base year rate**	**Input amount**
Advertisements	7000 (Million Rials)	75 (Billion Rials)
Specialist staff training	-	Training in the production and development of parts and equipment Green space infrastructure training with a base year of 15 to 30 years
Availability	-	Increase up to 30%
Economic efficiency (cost reduction)	Constant	Cost reduction up to 20%

4.1.2. Scenario 2: Development of urban green space in Mashhad with environmental goals

Considering the goals of Mashhad municipality based on the vertical development of green space and urban productivity regarding the efficiency of roofs in residential and nonresidential areas, the focus of this scenario is on the expansion of green space with an emphasis on reducing pollutants, providing government support, and increasing the share of marketing. The goal is that with increasing population, the amount of greenhouse gas production will increase at a slower rate. On the other hand, with the growth of building construction, the production of green

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roofs should increase the amount of urban green space. Therefore, in this regard, the per capita energy production by buildings and environmental pollutants, including greenhouse gases, were considered auxiliary variables. Additionally, marketing shares and government support, such as long-term loans, are considered (see Table 3).

Table 3. Auxiliary variables input to the model under the second scenario

Variable	Value	
	Base year rate	**Input amount**
Advertising and marketing costs	100 Million Rilas	50 Billion Rials
Government loans	120 Million Rilas	50 Billion Rials

4.1.3. Scenario 3: Easing the rules and removing obstacles to adopting alternative roofs

The purpose of developing this scenario is to focus on implementing facilitation policies for adopting and using alternative roofs. According to the protective laws to increase the attractiveness and acceptance of alternative roofs, the government can allocate protective laws, including facilitating the construction of alternative roofs, such as building permits on the condition that alternative roofs are created according to geographical conditions, reducing the costs of providing the finishing work of buildings, providing construction loans with long-term repayment, providing support laws to facilitate the maintenance costs of alternative roofs, increasing the number of requests and, as a result, increasing the acceptance and construction of alternative roofs.

4.1.4. Scenario 4: Increasing the process of clean energy production with the view of return on investment

Consistent with energy storage, this scenario is presented to produce clean energy in buildings. Mashhad Municipality can take an essential step in saving energy from fossil fuels by identifying suitable points for constructing solar roof infrastructure. By allocating funds for the construction, implementation, and maintenance of solar roofs, Mashhad Municipality will receive a return on investment in a short period. On the other hand, the amount of clean energy production will increase, which means an increase in the storage of fossil fuels. Since the construction of large solar power plants has the possibility of more significant damage, it is assumed that the implementation platform will be quickly provided with the construction of smaller solar power plants.. It will also provide the opportunity to create jobs in this field. Solar panels account for 3% of the base year's income of 25 million monthly. It is expected that with this amount of income from the construction of a 5-kilowatt solar power plant, the return on investment will occur within seven years (see Table 4).

Table 4. Auxiliary variables input to the model in the fourth scenario

	Value	
Variable	**Base year rate**	**Input amount**
Construction and implementation costs	15 Billion Rials (5 kW power plant)	80 Billion Rials (5 kW power plant)
Maintenance costs	3% of total annual income	3% of total annual income

4.1.5. Scenario 5: The growth of the economic penetration coefficient of green roofs is consistent with the approval of executive laws

The fifth scenario is introduced as a multiple and combined scenario. In this scenario, focusing on integrating scenarios 1, 3, and 4, the process of model changes was investigated. This scenario aims to facilitate the approval process related to implementing alternative roofs with economic goals. Therefore, the government can increase accessibility by providing the implementation costs of alternative roofs, increasing the expert force, attracting investors, and providing production or assembly equipment. As the practicability of alternative roofs expands, the government's protective laws also increase. This scenario can be one of the most compelling alternative roof market analysis scenarios.

4.2. Investigating performance evaluation criteria in scenarios

According to the policies proposed in this study, performance evaluation criteria were investigated based on the following variables: the area of the alternative roof, its acceptance, environmental problems such as greenhouse gases, its attractiveness, and clean energy production.

4.2.1. The area of the alternative roof

According to Figure 10, the amount of the area of the alternative roof in the base state of the model significantly differs from that in the implementation of the model scenarios. The maximum area of the replacement roof is approximately 3.7 times the minimum amount of the replacement roof in the base model. In implementing the first scenario, the number of graphs in the model increased by 2.27. The lowest amount of green roof area growth occurred by facilitating the executive rules of accepting alternative roofs and applying clean electricity production policies, which increased the area of alternative roofs by two times. Therefore, applying each of the proposed policy determines the graph's growth trend.

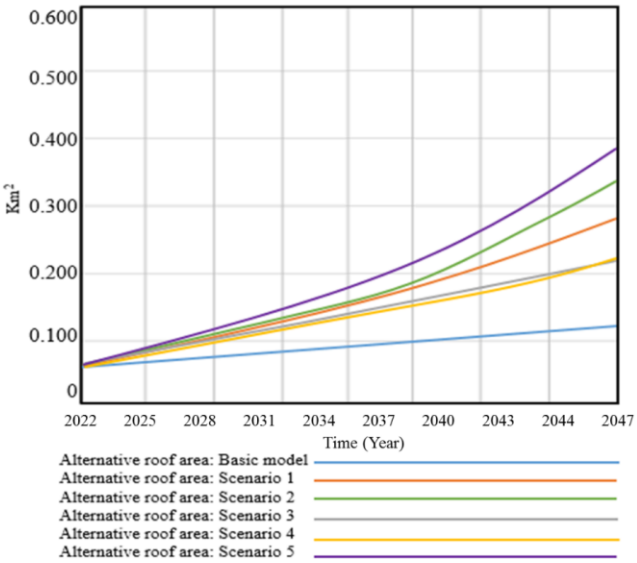

Figure 10. Comparison of alternative roof areas under different model scenarios

4.2.2. Attractiveness rate of the alternative roof

According to the graph resulting from applying the scenarios on the base model, the flow of the model shows an upward trend (see Figure 11). The distance between the maximum attraction rate of the alternative roof and the base model equals 1.1. The highest adoption rate of alternative roofs occurred in the second scenario, i.e., the increase in urban green space and the application of the combined scenario. The graph results show that green roofs have a high absorption capacity due to the design and beautification of the urban space. Due to the increase in urbanization and the increase in the temperature of cities due to industrialization, there is a greater tendency to choose plants and green covers and reduce pollutants. On the other hand, with the application of protective laws, more people are attracted to alternative roofs. Geographical location plays an essential role in choosing and accepting alternative roofs.

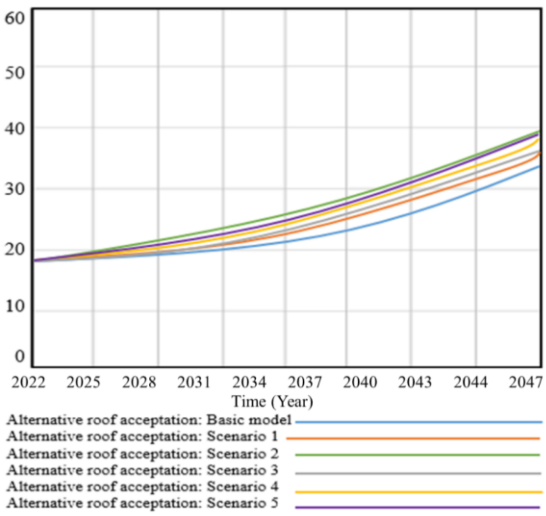

Figure 11. Alternative roof attractiveness rate under different model scenarios

4.2.3. Environmental problems

One of the most important problems of large and industrial cities is air pollution and creating heat islands. The metropolis of Mashhad is geographically located in a hot and dry region, which is one of the reasons for the increase in pollution and heat in this region. According to the graphs below, by applying the proposed policies under each scenario, we will see a future decrease in the graph of environmental concerns and GGEs (see Figures 12-13). It seems that by implementing the combined scenario, greenhouse gas production will decrease by 50% until 2047. Under the conditions of clean electricity production and reducing the share of pollution caused by fossil fuels, the amount of GGEs reaches its lowest level in 2047, approximately 25 million tons per square kilometer of the model. The downward trend of environmental concerns in the combined scenario was expected to be less steep than in the other scenarios. However, according to Figure 12, this scenario has a decreasing trend. This may be due to the long-term effect of the implementation of policy plans or the long-term efficiency of clean energy production. However, the application of each model scenario significantly reduced growth compared to the base model. Notably, the chart experiences a downward trend with a low slope, and the authorities should consider this issue.

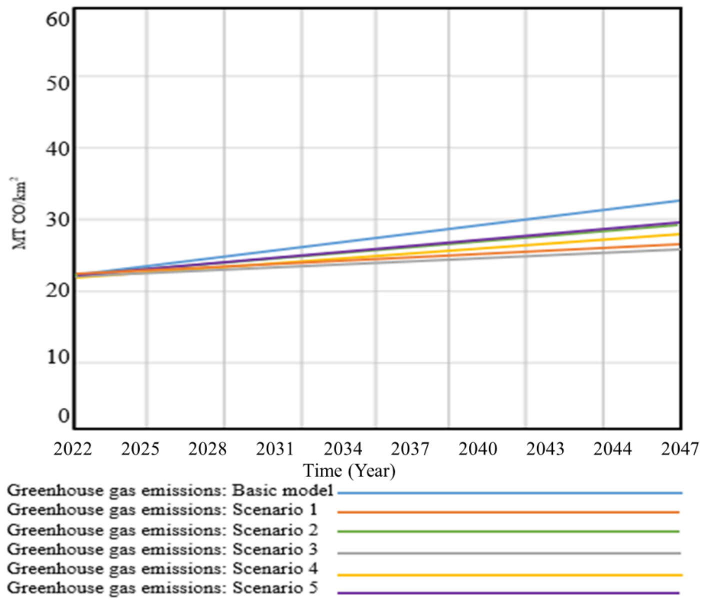

Figure 12. Emissions of greenhouse gases under different scenarios of the model

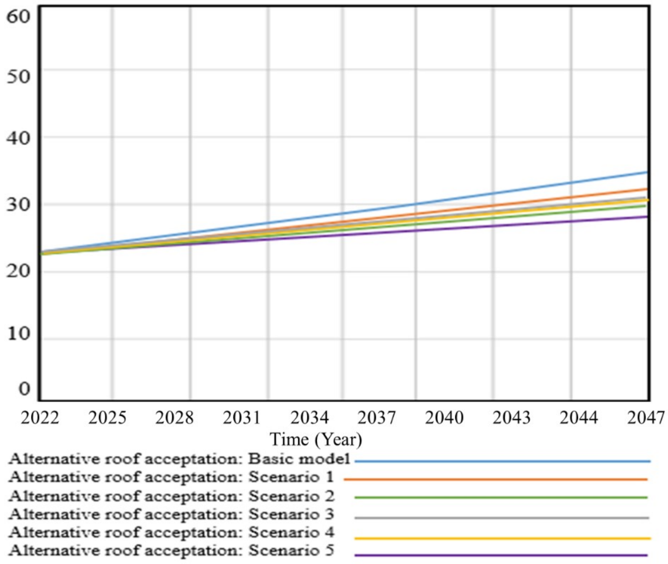

Figure 13. Environmental concerns under different model scenarios

4.2.4. Acceptance rate of alternative roofs

The acceptance and implementation of alternative roofs depend on several factors. In addition to advertising and attracting the audience to choose alternative roofs, each alternative roof's efficiency and technology level can be considered. Although advertising plays an essential role in the acceptance of a trend, forward-looking approaches such as the existence of facilities and the provision of more economical facilities have considerable power in attracting the audience. As expected, applying the combined scenario aimed at the economic penetration of green roofs from the point of view of technology aligned with clean energy production using solar and photovoltaic roofs has shown a significant growth trend in the acceptance rate of these types of alternative roofs in the model. The triple growth of the acceptance rate in the combined scenario compared to the base model shows the issue's importance. After that, using solar roofs with government facilities to produce clean electricity is a priority compared to other scenarios. This may be due to the lower annual maintenance cost of small solar power plants and the need for fewer annual repairs of photovoltaic roofs. The growth trend of accepting alternative roofs in the economic influence of green roofs from the perspective of technology and attention to urban green space will increase until 2047, with a very small difference (see Figure 15).

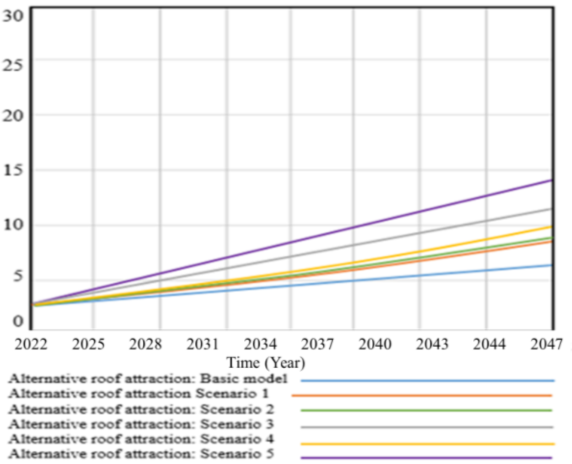

Figure 14. Acceptance of alternative roofs under different model scenarios

4.2.5. Production of clean electricity

According to the simulation results, the combined scenario has shown the most savings in energy consumption in buildings among all the presented scenarios. In the combined scenario, because solar roofs and photovoltaic roofs can meet the energy needs of buildings through solar technology and create the ability to cool buildings, the electricity consumed by buildings can be supplied from power plants. With the release of the thermal degree, it will be reduced to an acceptable level. On the other hand, by expanding the influence of green roofs by using construction technologies, they have significantly contributed to reducing energy use and cooling the environment. In fact, in the case of a green roof, this occurs by reducing the need for energy consumption and not by reducing energy consumption (such as not needing a cooling or ventilation system). According to the simulation diagrams, the trend of electricity generation in the combined scenario is up to 1.4% of that in the base model 2047.

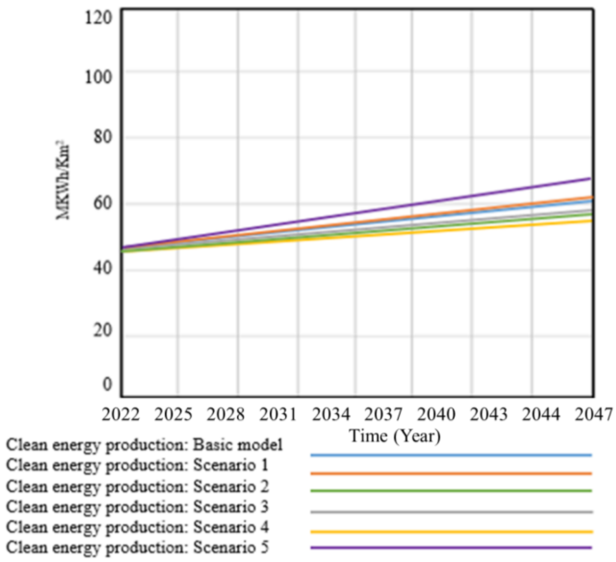

Figure 15. Clean energy production under different model scenarios

Finally, the designed scenarios were ranked using the combined method of hierarchical analysis and TOPSIS and based on the experts' opinions (see Table 5).

Table 5. Model ranking using the fuzzy TOPSIS method

CC	S^-	S^+	Scenario	Rank
0.5724	0.5277	0.3942	1	3
0.5791	0.5349	0.3888	2	2
0.4754	0.4390	0.4843	3	4
0.3179	0.2930	0.6288	4	5
0.6022	0.5584	0.3689	5	1

5. Conclusion

This study analyzed the alternative roof market via a system dynamics approach by considering extensive, influential factors and their potential cause-and-effect relationships. The results show that although the combined penetration levels of alternative roofs in the market remain marginal in almost all the simulation results, it can generally be concluded that a favorable level of demand will be created in this market. However, there is a small possibility that the trend of increasing normal roofs in the roof market will decrease dramatically. Despite the low expectation of an alternative roof market boom in the future, it is anticipated that the solar roof market will maintain its relative dominance in the alternative roof industry and have the greatest potential for future growth. Despite the considerable potential of the green roof and photovoltaic market for future growth, these markets are almost fixed in terms of investment costs and practical feasibility. Therefore, more policy support and technology development for green and photovoltaic roofs will be necessary in the future. These results are consistent with the findings of Flynn et al. (2010) and Kelly et al. (2020), which indicate the predominant share of conventional roofs in the future and the growth of the alternative roof market under the development of more supportive policies. Considering the relatively heavy green roof system, changing to lighter green roof designs or a more user-friendly design can be a more desirable option.

On the other hand, integrating light green roofs with solar and photovoltaic panels can provide many advantages concerning the roof load. Given that hybrid photovoltaic systems have more limited applications than solar roofs, contractor initiatives with green roofs can improve the performance of alternative roofs and lead to more straightforward green roofs with lower maintenance and repair costs. The results indicate that the best process for reducing runoff and the effects of greenhouse gases occurred in the combined scenarios. Since urban expansion is increasing due to the need for urban construction, it is possible to more effectively handle environmental problems by taking advantage of combined policies. Previous studies have also noticed the importance and role of integrated alternative roof systems (Hui and Chan, 2011; Scherba et al. 2011, Van Lith et al. 2018).Since the potential of alternative roofs for reducing urban runoff seems insignificant compared with conventional and solar roofs, photovoltaic roofs significantly reduce urban runoff. The solar market is vital in reducing heat islands and air temperatures in cities due to its greater penetration rate. The share of green and photovoltaic markets is more limited due to the low penetration rate. Among the alternative roofs, photovoltaic and solar systems are relatively more effective at reducing energy consumption and GGEs due to energy production and cooling load reduction. Nevertheless, development and investment in the future growth of the green roof market, especially in combination with photovoltaic roofs, are still very important for reducing energy demand and GGEs. The level of possible penetration of the green roof market in the future is facing slight growth. Still, with the addition of photovoltaic roofs, we can consider the possibility of more penetration for the green roof market, and it can be clearly said that the green roof market alone has a lower chance of penetration. Considering the technology incorporated in the green roof market and its growth and development in the future market, the need for economic and educational policies and more technology is felt.

Among the alternative roof systems in this study, photovoltaic and solar systems are relatively more effective in reducing energy consumption and greenhouse gas emissions due to energy production and cooling load reduction. Nevertheless, development and investment in the future growth of the green roof market, especially in combination with photovoltaic roofs, is still very important to reduce energy demand and greenhouse gas emissions. The results showed that the combination of green roofs and photovoltaics led to a trend of reducing annual energy consumption by 2.8 kilowatt hours per square meter, which was consistent with the findings of Jaffal et al. (2012) (1.78 kilowatt hours per square meter annually). The simulation analysis showed a reduction of 2.1 kg of carbon dioxide per square meter of greenhouse gas emissions.

Future studies should consider other operational aspects of the technology implemented in alternative roofs, such as the technology's life cycle, maintenance, repairs, and upgrading of the system in the dynamic analysis model. It is also possible to examine the effects between key variables within the system using the fuzzy mapping approach to analyze the strength of the effect.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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