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Analysis of urban form indicator for optimizing renewable energy use in coastal cities based on professional perspectives and COPRAS method: A case study of Tonekabon

Farshad Rafipour [a] , Maryam Khastou [a,*], Vahid Bigdeli Rad [a]

[a] *Department of Urban Planning, Qazvin Branch, Islamic Azad University, Qazvin, Iran.*

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Abstract

Population growth and high energy consumption in buildings have prompted a need for urban space, infrastructure, and transportation networks to incorporate environmental protection measures and mitigate related challenges. This has led to the integration of renewable energy considerations into urban planning and design, necessitating changes in the physical and spatial layout of cities. The interrelationships among various components and form parameters of urban blocks—such as density, orientation, building facades, transportation access, climate, and land use—are increasingly important, especially in coastal cities. Additionally, the adoption of new technologies is gaining emphasis in contemporary society. The purpose of this study is to analyze and examine the indicators of urban form that influence the effective use of renewable energies in coastal cities, with a specific focus on Tonekabon. Information was gathered through documentary research, surveys, field observations, and library studies. Using content analysis, the study highlights the importance and role of each urban form component suitable for coastal areas and their impact on renewable energy efficiency. It also reviews the intellectual foundations and various research efforts related to urban form and energy, while identifying challenges faced by researchers in this domain. Employing a two-way analysis of variance (ANOVA) method and complex proportional assessment (COPRAS), the study evaluates the effectiveness of different urban form indicators on the efficiency of solar, wind, and sea wave energies, prioritizing them accordingly. The central research question addresses which type of renewable energy is most effective in coastal cities, particularly in Tonekabon. Findings indicate that a thorough assessment of urban form and climate indicators reveals solar energy as the most efficient, followed by wind and sea wave energies.

Keywords: Urban form; Renewable energies; Solar energy; Content analysis; Two-way ANOVA; COPRAS.

1. Introduction

Cities are major energy consumers worldwide, accounting for a significant portion of energy expenses and contributing to harmful greenhouse gas emissions. According to the United Nations Human Settlements Programme (UN-Habitat), cities utilize 78% of the world's energy and generate over 60% of greenhouse gases (Moghadam 2017). However, with the efficient use of resources, tools, and technologies, it is possible to assess their level of sustainability through various existing components and indicators (Qaraei, Azadeh et al. 2020). The International Renewable Energy Agency (IRENA) emphasizes the importance of addressing issues such as wind energy, ocean energy, biomass, waste-to-energy conversion, solar photovoltaic systems, geothermal energy, and decarbonization (IRENA 2020). A thorough understanding of the relationship between urban form and energy consumption is essential for developing policies aimed at mitigating climate change, particularly at the city level. This understanding can inform effective strategies in this area (Shoja, Pourjafar et al. 2019). Energy requirements differ based on climate, energy technologies, and urban form, indicating that a city's layout significantly influences its energy consumption (Ahmadian 2021). Thus, it is crucial to investigate the dimensions, components, and indicators of urban form and how they relate to the components and indicators of renewable energy, drawing on the insights of scholars and experts to identify existing challenges. In light of advancements in technology and the political commitment of both developed and developing nations, as well as a growing focus on resilience amid the energy crisis and environmental degradation, assessing the potential for renewable energy use across various climates has become a key indicator of energy policies, developments, and regulations. Consequently, urban form and planning have increasingly aimed to minimize reliance on fossil fuels, lower carbon and ecological footprints, reduce greenhouse gas emissions, and promote the use of renewable energy sources (Li, Jing et al. 2021). The purpose of this study is to analyze and examine the indicators of urban form that influence the effective use of renewable energies in coastal cities, with a specific focus on Tonekabon. By examining existing renewable energy solutions, along with insights from previous studies and international experiences, it becomes evident that coastal cities, as ecological areas, can optimize the use of renewable energies such as hydro, wind, and solar power. However, the geographical characteristics of coastal cities influence the application of these energy sources, which must align with the city's

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* Corresponding Author Email: khastou@qiau.ac.ir

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layout and economic conditions. In the specific context of Tonekabon, challenges and advantages regarding the efficiency of renewable energy sources have been identified through a review of existing research. Each energy type can impact the city, but factors such as climate, topography, economic parameters, and available technologies suggest that solar energy presents the most viable option. Regarding marine wave energy, several challenges need addressing, including insufficient knowledge, economic feasibility, wind and wave power density, the absence of waves in certain areas, potential loss of natural landscapes in favor of industrial scenery along the Caspian coast, threats to marine ecosystems, and inadequate energy supply to meet peak demand. For wind energy efficiency, issues such as low wind speeds and power density, the presence of dense forests, failure to meet minimum threshold conditions, shifts in urban spatial organization due to economic pressures, and challenges concerning visual aesthetics and high costs significantly hinder its potential. Thus, this article aims to identify the challenges linking urban form components to renewable energy efficiency and seeks to determine which type of energy is most effective for optimizing renewable energy use in coastal cities, particularly focusing on Tonekabon.

2. Research Background

In "Clean Energy in Australia," Ellison underscores the strategic implementation of solar energy as a vital response to the energy demands intensified by geopolitical events, particularly the Russian invasion. In 2023, Australia experienced a significant surge in solar energy adoption, with the installation of 337,498 solar systems. While the overarching policy has predominantly focused on large-scale solar projects, there have been noteworthy advancements in small-scale applications as well. These initiatives utilize a successful strategy aimed at lowering solar installation costs for consumers. Ellison examines five major projects in Queensland that collectively generate 800 megawatts, including a standout project with a remarkable capacity of 400 megawatts. The site selection for these facilities considers land availability and its constraints, thereby enhancing the agricultural sector's competitiveness in adopting solar technology compared to hybrid energy solutions. The financing structures established for these projects have also played a crucial role in their feasibility. Additionally, the response from various Australian states to these initiatives has been robust, bolstered by proactive federal and state policies. These measures have energized the solar sector and improved the efficiency of wind energy operations, leading to a 3.6% increase in wind farm developments and an impressive 28.5% growth in solar cell efficiency. This momentum indicates a significant commitment to advancing renewable energy technologies across the nation (Ellison 2022) . In the article titled "Review of Form Parameters of Urban Blocks Affecting Energy Consumption and Solar Energy Absorption," Sanayian et al. emphasize the importance of enhancing building energy efficiency through the integrated use of active and passive solar design strategies. These strategies aim to reduce energy consumption, improve equipment efficiency, and harness renewable energy to convert it into thermal energy. The authors investigated energy consumption in buildings from the perspective of passive design at the urban block level. Their methodology involved analyzing key parameters affecting energy consumption, the impact of form parameters on passive solar design, and the utilization of energy simulation software. By examining factors such as urban density, building facade orientation, and the layout of buildings and streets, they assessed how form variables and courtyard orientation influence the thermal performance of buildings. The review highlighted that many studies focus on the effects of urban block shape, accessibility, and the thermal behavior of nearby structures. However, it was noted that analyzing the influence of neighboring units on a building's thermal performance is quite challenging due to the complexity of simultaneously evaluating all the relevant parameters. Ultimately, the findings suggest that form parameters significantly impact passive solar design in both buildings and urban blocks, playing a crucial role in energy optimization during the early stages of the design process (Sanaiiean 2020). In the article titled "Analysis of Radiation Climate Resilience in the Climate Design of Mazandaran Coastal Cities: A Case Study of Noor Coastal City," Khalidi et al. concluded that the most effective buildings are those that harmonize with the local climate. They found that such buildings can achieve up to 93 percent climate resilience by utilizing local architectural materials, ensuring appropriate orientation, and incorporating windows and openings in all directions, along with a height above ground level. These design features contribute to climatic comfort and lower energy consumption for residents. The key findings include the following: 1. To optimize solar energy efficiency in coastal cities, it is essential for a building's facade to face south. 2. Although the southeast and southwest facades receive more consistent radiation throughout the year, they tend to be colder in winter compared to the south facades. 3. The east and west facades, while warmer in summer, are also colder in winter than the south and southeast facades. Additionally, the color of the building's facade plays a significant role in climate resilience, affecting thermal stress levels (Khalidi 2021). In their doctoral dissertation, guided by Manouchehr Tabibiyan, Shoja et al. explore "the relationship between urban form and energy" in an article titled "Meta-Analysis of the Relationship between Urban form and Energy: A Review of Approaches, Methods, Scales, and Variables." Their study involves extracting data from various documentary sources and analyzing scholarly opinions across seven general categories: 1) Urban form (focusing on the building sector or relevant indicators, especially density) and energy; 2) Urban form (emphasizing land use) and energy; 3) Urban form (considering the transportation sector) and energy; 4) Urban form (a combination of building and transportation sectors) and energy; 5) Urban form about climate change, heat islands, climatic comfort, and sustainability; 6) Urban form and thermal loads; 7) Urban form along with energy management, energy planning, and policies. The findings suggest that the relationship between urban form and energy holds the potential for an integrated and dynamic perspective that transcends single-disciplinary approaches, scales, and methods (Shojaa 2018). In a study titled "Efficient Solar Cells in Rainy Conditions," published in the journal ACS Nano, Li Yu and colleagues introduced an innovative approach to solar cells designed for coastal and rainy cities. They highlighted a solar cell capable of harnessing energy from raindrops during wet weather, in addition to capturing solar energy on sunny days, demonstrating high efficiency even in rainy conditions. This technology integrates a triboelectric nanogenerator featuring a molybdenum trioxide electrode, which exhibits excellent energy conversion efficiency from raindrops, with a perovskite solar cell through shared electrodes. The resulting solar cell is engineered for optimal energy efficiency from both raindrop impact and solar energy utilization. This development represents a significant strategy for enhancing complementary energy distribution in the future. The research addresses the challenge of utilizing renewable energy in rainy urban areas and aims to bridge the existing knowledge gap. Moreover, these panels can be conveniently installed and operated as thin films across various parts of a building (Liu 2021). The International Renewable Energy Agency in Cities, in its publication "Increasing Renewable Resources in Cities," discusses emerging technologies designed to maximize the potential of solar energy, particularly in buildings featuring innovative architectures. These technologies seek to transform solar cells into functional building materials that generate electricity, rather than relying on traditional electricity generators. Currently, integrated solar cell technology has garnered significant attention in this realm, and this approach is increasingly being incorporated into the planning and policy-making processes of numerous countries (IRENA 2020). In his doctoral thesis, supervised by his advisor, titled "Locating Wind Power Plant Deployment Areas Based on Spatial Assessment of Environmental Factors in Mazandaran Province," Bayram Vand concluded that certain regions of Mazandaran Province are more suitable for the construction of wind power plants. Specifically, the western areas of Noor County, the northern parts of Savadkouh County, Sari Neka, Beheshahr, the central strip of Babol County, and the central and northern regions of Amol County exhibit greater suitability compared to other areas in the province. Conversely, while the land in all counties leading to the Alborz highlands (southern part) possesses favorable climate conditions and optimal sub-indicators for wind power plant construction, it is not recommended due to the high-density ridges and land cover in these regions. Additionally, the northern parts and coastal areas of the province, except the Amirabad coastal area, are also deemed unsuitable for power plant establishment, as they fail to meet the minimum threshold conditions of the technical wind criteria required for operating wind turbines (Bayramvand 2022). In a study conducted by Bayram Vand et al., titled "Analysis of Wind Power Characteristics and the Effect of Topography on It with the Approach of Renewable Energy Production in Mazandaran Cities," the impact of topography on wind variables—such as wind speed, continuity, and wind power density—was evaluated. The researchers explored the relationship between altitude and slope indices about these factors. Their findings revealed a Pearson correlation coefficient of 0.677 between wind speed and altitude above sea level, indicating a strong positive correlation at a 95% confidence level. This suggests that as the altitude of meteorological stations in the province increases, wind speed at a height of 10 meters above ground also rises. Additionally, the study assessed the correlation coefficients of wind speed, the continuity of wind hours with speeds exceeding 3 meters per second, and wind power density against the slope index. With P-value values greater than 0.05, it was determined that none of the wind variables showed any correlation with the slope index. Consequently, changes in slope values do not significantly affect wind variables, and their correlation cannot be established. Finally, the researchers concluded that the highest wind speeds are found in the southern regions of Noor. In contrast, the plains and coastal areas of Mazandaran province—particularly the counties of Joibar, Babolsar, Mahmoudabad, Sari, Ghaemshahr, North Savadkouh, Babol, Amol, the western regions of Ramsar, Tonekabon, and the eastern parts of Behshahr and Neka—exhibit the lowest average annual wind speeds (Bayramvand 2022). In an article titled "Wind Energy Potential Measurement to Determine the Optimal Location for the Construction of Wind Turbines in Mazandaran Province," Ghobadi highlighted that the spatial diversity of the stations studied, along with their proximity to the Caspian Sea and the Alborz Mountain Range, leads to variations in airflow direction throughout different seasons at coastal, plain, and foothill stations. These factors result in fluctuations in the prevailing wind direction across Mazandaran Province. To estimate the potential energy that can be harnessed from wind flow in the region, Ghobadi conducted calculations based on four years of wind direction and speed data. Utilizing data collected every three hours from five meteorological synoptic stations at a height of 10 meters, the characteristics of wind speed and direction were analyzed. The parameters of the Weibull probability distribution functions were determined, followed by calculations of the wind potential and power density at the stations in the province. The findings indicate that the Balade Noor station experienced the highest average wind speed and power, reaching 150 watts per square meter during the warm months of June and July, with power levels exceeding 300 watts per square meter. In early spring, this value drops to around 200 watts per square meter, classifying it as a medium class (2) in the wind power classification system (Ghobadi 2020). In their article titled "Sea Wave Energy: A Review of Current Technologies and Perspectives," Courteau et al. discuss the various technologies and devices designed to harness sea wave energy. They note that wave energy represents a dynamic field of research, with numerous concepts and technologies currently under proposal and development. A significant challenge facing these technologies is the cost associated with their development, highlighting the crucial role of government support in this area. The primary objective of this research is to introduce new technologies capable of generating electrical energy from renewable sources, particularly effective in urban settings. These technologies are especially utilized in regions with favorable climatic and morphological conditions for capturing sea wave energy. This review systematically lists several wave energy converter power plants and examines their years of operation, ultimately providing insights into the average operational status of these plants and their impact on urban landscape(s (Curto and Franzitta 2021.

3. Theoretical Framework

3.1. Urban Form

Urban form refers to the physical layout and design of a city, encompassing aspects such as density, street configuration, urban blocks, parcels, buildings, transportation, employment, and overall urban form. It is shaped by a multitude of factors, including economic, regional, and a blend of political and legal influences, reflecting the prevailing social and economic structure of urban society (Safirova and Gillingham 2007). The spatial arrangement of urban functions within an area significantly impacts urban energy consumption (Chen and Li 2011). Urban form is the outcome of various forces acting over time, which can be either spatial and physical or non-spatial. It possesses a three-dimensional characteristic, manifested not only on the surface but also in volume. Each urban indicator within a city cell has its distinct form, and their combinations give rise to a specific urban form (Porjafar 2014). Lynch defines urban form as the spatial pattern of large, stationary, and permanent physical indicators in a city. The creation of urban form results from the convergence of numerous concepts and components within the city structure, including street patterns, block sizes and shapes, street design, and lot layouts. Urban form can influence a city’s trajectory toward sustainability or unsustainability, driven by various economic, social, and environmental factors (Lynch 1995).

3.2. Indicators of urban form

In "Urban Morphology," Oliveira, explores city texture, natural context, and the interplay of urban form indicators like streets, city blocks, and buildings. These indicators combine uniquely to create identifiable textures in cities. The natural context, including land elevation, soil quality, climate, and landscape, shapes the urban habitat, influencing everything from initial street layouts to building materials. Streets serve as stable, democratic spaces within cities, playing a key role in their ongoing transformation and stability. The relationship between street orientation and plot positioning impacts urban development, distinguishing public from private spaces. Buildings—ordinary and exceptional—are primary urban indicators, differentiated by use, form, height, and their relationship with surrounding streets. The design and materials of buildings also affect energy consumption patterns (Oliveira 2019). A summary of urban form components is presented in Table 1.

Table 1
summarizes the components and indicators of urban form based on a review of global literature.

References	Components And Parts
(Lynch 1984)	The distribution of individuals participating in an activity, the flows of people, goods, and information, and the physical characteristics that shape space in ways relevant to those activities.
(Anderson 1996)	Spatial patterns of human activities over a specific period include land use density and the design of transportation infrastructure.
(Kropf 1996)	An artifact is a form that belongs to a specific historical period, resulting from activities conducted during that time and designed to accommodate them.
(Ibrahim 1997)	The physical layout of land use, population distribution, and communication networks.
(Banister 1997)	Includes the components of density, open space, compactness, and population. The text includes the concepts of density, open space, compactness, and population.
(Smith 1999)	various aspects of urban planning, including land use patterns, transportation infrastructure, water and energy systems, and the physical design of developments.
(Stead and Marshall 2001)	The following indicators are important to consider: 1. Distance of residence from the city center 2. Size of settlements 3. Variety of land uses 4. Availability of local facilities and amenities 5. Development density 6. Proximity to transportation networks 7. Access to residential parking 8. Type of road network 9. Type of neighborhood unit
(Wheeler 2003)	The pattern of streets, plots, blocks, and land use features The arrangement of streets, plots, blocks, and land use features.

(Song and Knaap 2004)	Design of streets and circulation systems, land use mix, accessibility, pedestrian accessThe design of streets and circulation systems, along with a mix of land uses, should prioritize accessibility and ensure pedestrian access.
(Alberti 2005)	Showing the effects of human actions on the environment inside and outside the city demonstrating the impact of human actions on the environment, both within the city and in surrounding areas.
(Williams, Keszthelyi et al. 2005)	Factors to consider include density, size, topography, and the layout of the road network.
(Tsai 2005)	Metropolis: factors such as concrete size, density, uneven distribution, centrality, and continuity.
(Grimm, Foster et al. 2008)	The connection between a city and its surrounding areas.
(Bramley and Power 2009)	Housing type and height, percentage allocated to each use, density, distance from the city center, and access to gardens.
(Jenks and Jones 2009)	Size, shape, scale, density, land use, construction types, urban block layout, and distribution of green space.
(Habib 2000)	Comprising artificial, natural, and human factors, including concepts such as city size, city layout, physical structure, and environmental integration.
(Pakzad 2006)	It encompasses all-natural indicators that humans can potentially interact with, as well as all factual information related to the urban environment. This includes the functional, economic, social, communicative, and physical aspects of a city. It goes beyond just the visual representation of a space, highlighting the significance of the activities and uses that arise from these indicators.
(Golkar 2002)	Physical form system, urban landscape system, spatial structure system, user system, and movement and access system.
(Daneshpur 2013)	Incorporating natural spatial codes, physical spatial codes, artificial factors, non-spatial codes, and human factors.
(Ali 2013)	The interaction between residential and non-residential urban activities and their patterns in the built environment.
(پورلیما و همکاران، 1398)	The layout of a city is shaped by all its visible indicators, both natural and man-made. It serves as the spatial and formal representation of the activities of the urban community. This three-dimensional essence is reflected not only in the surface but also in the volume of the city.
(Monjazi 2023) (Zanganeh 2024) (Colak 2020)	Population density, access to wasteland and abandoned lands, average plot size, and building density.
(Tavakoli 2022) (Karami 2021) (Li 2021)	Proximity to industries, building density, distance from rivers and the sea, access to communication networks, and distance from farms and orchards.

3.3. Urban form and Energy Consumption

City layout has both direct and indirect effects on energy consumption and the attainment of sustainable development (Ewing and Rong 2008, Liu and Shen 2011). Understanding the relationship between urban form and energy usage can help in developing more effective strategies in this area.

Today, cities serve as the economic engines of our planet, housing 55 percent of the world's population and contributing to 80 percent of global Gross Domestic Product (GDP). The United Nation Department of Economic and social Affairs (UN-DESA) biased on the Intergovernmental Panel on Climate Change (IPCC) reports that cities are responsible for 71 to 76 percent of global energy-related carbon dioxide emissions. The use of fossil fuels and other greenhouse gases has led to severe air pollution problems in over 80 percent of cities worldwide, resulting in approximately seven million premature deaths each year from diseases such as lung cancer, stroke, and asthma (WHO 2018). With an expected influx of 2.5 billion people into urban areas over the next three decades, today's decisions regarding the construction of sustainable energy systems will significantly impact our collective future. It is essential to find innovative ways to power the growing urban population while transforming existing systems. Renewable energy can play a vital role in reshaping urban energy infrastructures. Moreover, the variety and maturity of technology applications in cities, along with existing modeling tools, can help identify viable options and develop sustainable energy strategies, revealing untapped opportunities for locally available renewable energy (UN-DESA 2018). Renewable energy systems—incorporating enabling technologies, digital innovations, and smart energy management—are increasingly being deployed in and around cities globally. This trend is anticipated to continue with the emergence of innovative business models such as “energy as a service,” aggregators, electricity trading, social ownership models, and urban energy payments (IRENA 2019). Currently, urban development decisions, climate change, and the impact of urban structure on city climates have not received adequate attention. Thus, it is crucial for officials and experts in this field to focus on planning and policymaking that make cities resilient to climate change, particularly concerning urban heat islands (Song and Leng 2020, Ahmadian 2021). Efforts to develop effective climate-friendly energy infrastructure strategies, along with forward-looking actions and investment decisions, should enhance our understanding of renewable energies. These efforts influence both the amount and type of energy demand as well as the potential for renewable energy production, ultimately affecting the relationship between energy and urban form and density. Therefore, it is essential that the urban built environment aligns with climatic conditions (Morganti and Coch Roura 2012).

3.4. Solar power

Solar energy is a renewable energy source and one of the primary sources of energy supply in our solar system. It is produced from the heat and light generated by the sun. The amount of solar energy radiation varies in different regions of the world, with the highest levels found in the solar belt. Iran is also located in one of these high-radiation areas (Kalaiselvan and Purushothaman 2016). Because solar energy is completely clean and free from pollution, it is considered a very affordable energy source (Gašparović 2019). The phenomenon that generates electricity from light radiation without the use of mechanical devices is known as the photovoltaic phenomenon. Any system that harnesses this phenomenon is referred to as a photovoltaic system (Hassan and Jaszczur 2017). These systems operate by converting sunlight directly into electrical energy through solar panels. Photovoltaic systems are among the most widely used types of renewable energy. To date, various photovoltaic systems with differing capacities have been installed and commissioned around the world (Sahragard and Arianejad 2016).

3.5. Wind power

Wind is generated by the pressure gradient resulting from the uneven solar radiation on the Earth's surface. Like other renewable energy sources, wind energy is geographically abundant, dispersed, and decentralized, making it almost always available. Over the years, it has been demonstrated that wind energy can be converted into mechanical or electrical energy for practical use. Additionally, the cost of energy produced from wind is lower than that of fossil fuels. Therefore, by harnessing more of the wind energy potential for electricity generation and other related applications, we can reduce our reliance on fossil fuels)Razjoyan 2018(. Wind is a form of solar energy, resulting from the movement of air, and a portion of the solar radiation that reaches the atmosphere is consistently converted into wind energy (Nasrollahi 2014). As one of the types of renewable energy, wind energy has long captured human interest, and there has always been a desire to utilize this resource. Wind power plants are favored sources of energy due to their low electricity generation costs and environmental benefits, and their development has significantly increased in recent years (Noorollahi 2011). In our country, due to its large size and diverse topography, assessing the wind energy potential of all regions and creating a comprehensive wind energy atlas requires considerable time and financial investment. Therefore, it is essential to evaluate the wind energy potential of various geographical areas, either independently or regionally, to identify suitable locations for constructing wind power plants (Boroumand 2004).

3.6. The wave power

Wave power consists of both potential and kinetic energy. Potential energy arises from the difference in height between the crests and troughs of waves, while kinetic energy is generated by the movement of water particles as waves pass. In seas and oceans, wave energy is produced by the wind blowing across the water's surface. This mechanical energy from the wind is created by the uneven absorption of infrared and visible light from the sun. It is stored as gravitational potential energy in seawater and is released as kinetic energy (waves) shortly thereafter (Larry 2012). The total wave energy available on Earth is estimated to be around 2,500 gigawatts, which is comparable to the total amount of solar energy (Raitpishe 2014). As a renewable resource, wave energy can generally be produced more consistently than wind energy. The energy extracted from waves is quickly replenished through interactions with the ocean surface. Wave energy is characterized as irregular, oscillating, and low-frequency. To be integrated into the power grid, it must be converted to a 60 Hz frequency. The primary driver of wave energy is the wind's effect on the sea surface. Wind itself is a unique form of solar energy, and as a clean and renewable resource, it has the potential to significantly contribute to meeting the world's increasing energy demands (Dardizadeh 2014).

3.7. Indicators of urban form with a focus on improving renewable energy efficiency

Table 2, illustrates the components of urban form with a focus on renewable energy efficiency. It is structured in three layers: the first layer outlines dimensions, the second layer presents criteria, and the third layer lists indicators. Numerous scholars and researchers have evaluated the relationship between these components and renewable energy consumption. This article aims to address existing knowledge gaps and prioritize renewable energy sources that can be utilized in coastal cities, specifically Tonekabon City, by carefully analyzing the current research and identifying present challenges.

3.8. Identifying a case study

The city of Tonekabon is situated at the end of the alluvial cone formed by the Cheshme-Kileh River, adjacent to the southern shores of the Caspian Sea. Its geographical coordinates are approximately between 36 degrees 48 minutes and 36 degrees 50 minutes north latitude, and 50 degrees 51 minutes to 50 degrees 54 minutes and 30 seconds east longitude. The Cheshme-Kileh River and the Caspian Sea are crucial to the formation, growth, and expansion of Tonekabon. This coastal city lies in the western part of Mazandaran Province, along the Rasht-Chalus Road. It is bordered to the north by the Caspian Sea, to the east by Chalus County, to the south by Qazvin County, and to the west by Ramsar County. According to the latest administrative divisions in 2016, Tonekabon County covers an area of 2,140 square kilometers (figure 1).

Table 2
Components of urban form highlighting the importance of renewable energy efficiency

Type	Scale	Indicator
Spatial structure and form of the city	Granulation of parts	Average plot area, Block spacing, Compression and occupancy area Building height, Radiation angle
	Mass and space organization	
	Orientation of building blocks	
	The pattern of placement of building blocks	
	Density	Building density percentage, Population density rate
Architecture of buildings	Number of floors	Building height, Amount of shading from buildings
	Optimal orientation of building facades	Radiation direction angle, Wall direction angle
	Building materials	Type of materials
	Facade	Facade material, color, and shape (concave, convex, flat)
	Openings	Opening direction, and Optimal percentage of openings to the building facade
Communication network	Access to the communication network	Road accessibility
	Access to wasteland and open spaces	Access to wasteland and open spaces
	Degree of confinement	Ratio of road width to wall height
	Length of streets and passages	The angle of the main facade of the buildings
Natural factors	Shape of the Earth	Slope size, Slope direction, Topography
	Height	Altitude above sea level
	Vegetation	Scattering of green spaces and vegetation
	Sea waves	Wave density, power, speed, and energy
Climate	Temperature	Radiation intensity and direction
	Humidity	Humidity percentage
	Sunny hours	Sunshine hours coefficients
	Rainfall	Precipitation rate
	Cloudy days	Number of cloudy days
	Wind	Wind direction, speed, and density

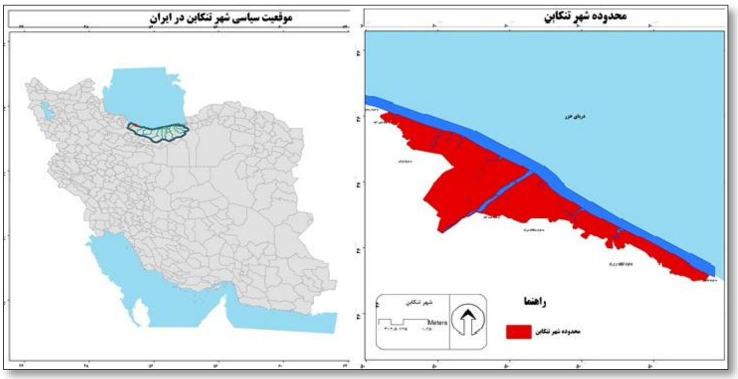

Fig. 1. Location of tonekabon city

3.9. The coastal city of Tonekabon is utilizing renewable solar, wind, and sea wave energies

By examining the available energy resources and utilizing the findings of researchers as well as the experiences of various countries in renewable energy efficiency, it becomes clear that the importance of utilizing hydro, wind, and solar energy in coastal cities should be prioritized. Given that coastal cities are often considered ecological, the approach to harnessing these energy sources must be adapted to fit the unique geographical, economic, and structural characteristics of each city.

Taking Tonekabon, a coastal city in Mazandaran province, as a case study, we find that, based on existing research and experiences, the impact of renewable energy varies. However, considering the climatic, topographic, economic, and technological factors, it can be concluded that Tonekabon has significant potential for solar energy efficiency. According to the data from the World Solar Atlas, the average daily solar irradiation in Tonekabon is approximately 4 kWh/m², amounting to about 1460 kWh/m² per year. This suggests that the city has a greater capacity for solar energy utilization than might have been expected.

On the other hand, the potential for marine energy efficiency faces several challenges, including a lack of sufficient knowledge and economic considerations. Factors such as average wind speeds, wave and wind power density, the unavailability of consistent waves, and the potential negative impact on natural scenery and the marine ecosystem complicate matters. Additionally, there are concerns about energy supply meeting maximum demand in the study area.

When it comes to wind energy efficiency, challenges persist due to low wind speeds and power density, dense vegetation, and insufficient technical criteria to meet minimum thresholds. Significant economic concerns, along with issues relating to urban planning—such as high-rise buildings that disrupt the city's spatial organization and do not align with the needs of local residents—further diminish the effectiveness of wind energy in Tonekabon. These factors collectively underscore the complexities and challenges involved in optimizing renewable energy in this coastal city.

4. Research Method

The research is based on the Saunders model, incorporating a positivist philosophy. It employs a deductive approach and an applied strategy, utilizing mixed research methods that combine quantitative and qualitative data. Data collection techniques include questionnaires (attached), interviews and observations to gather diverse opinions from various professional groups, as well as documentary and library studies. The statistical population consisted of 50 individuals, and based on the Cochran formula, the sample size was determined to be 48 people, which included experts in municipalities, environmental science, urban planning, and geography with a focus on climate and energy. This study aims to extract components of urban form that influence the effective utilization of renewable energies and to identify methods for employing these energies in coastal cities. To achieve this, a content analysis method— a qualitative research approach used for identifying, analyzing, and interpreting semantic patterns within qualitative data (Ghaedi Mohammad Reza 2016)—was utilized. After reviewing the opinions of researchers on the relationship between urban form parameters and the utilization of renewable energies, the study determined components based on their dimensions, criteria, and indicators. Additionally, it evaluated processes and existing challenges that have been overlooked. Two-way variance analysis was employed to compare the significance of each indicator in relation to solar, wind, and wave renewable energies, allowing for the selection of the most effective option. Finally, the effectiveness and efficiency of each renewable energy source were assessed, and their prioritization was established.

5. Findings

5.1. Examining the challenges of urban form components in effectively utilizing renewable energy in coastal cities, with a focus on a case study

This study utilizes content analysis, a qualitative research method that identifies, analyzes, and interprets semantic patterns in qualitative data. It aims to uncover meanings, priorities, attitudes, understanding, and organization (Ghaedi Mohammad Reza 2016). The research introduces the dimensions, criteria, and indicators of urban form and examines the role each plays in the efficiency of renewable energy sources such as solar, wind, and ocean wave energy. Furthermore, it discusses related studies and evaluates existing knowledge gaps, particularly in coastal cities, with a focus on the coastal city of Tonekabon (Table 3).

Table 3
Challenges of urban form components in utilizing renewable energies in coastal cities effectively

Type	Scale	Indicator	Conducted research	Knowledge gaps and challenges
Spatial structure and form of the city	Granulation of parts	Average plot area Block spacing Compression and occupancy area Building height Radiation angle	Solar technologies are fully integrated into the roof, walls and windows. Increasing building dimensions and site coverage leads to increased solar energy potential (Lee 2016). Paying attention to density and design of urban morphology and placement of buildings for maximum access to sunlight (Hachem 2013). The shape and orientation of urban blocks have a significant impact on the amount of sunlight available (Kanters 2012). Building shape plays an important role in the access of sunlight to urban fabric and buildings (Kämpf and Robinson 2010). Connecting street furniture to solar energy—like benches, bus shelters, and streetlights—demonstrates how we can rethink everyday infrastructure to utilize solar power. These installations serve practical purposes while also functioning as distributed energy sources, which helps alleviate the pressure on the centralized electricity grid (Kämpf and Robinson 2010).	There is a lack of definitive and generalizable insights regarding the impact of increasing or decreasing density on energy consumption. Other dimensions of density are often overlooked, with an emphasis primarily on accessibility and the building sector. There are minimal studies addressing this issue in coastal cities, particularly considering their temperate, humid, and mountainous climates. - In recent years, there has been a lack of overarching plans for development and construction. - Integrated and comprehensive models for analyzing the energy sector in cities and buildings are lacking. - Spatial limitations restrict the installation of solar power plants in residential and urban areas. - There is a deficiency in management and smart systems. - The potential of biomaterials and their combined use has received insufficient attention. - A significant knowledge gap exists between research, industry, and policy, which needs to be addressed through qualitative collaboration among various stakeholders.
	Mass and space organization			
	Orientation of building blocks			
	The pattern of placement of building blocks			
	Density	Building density percentage Population density rate		
Architecture of buildings	Number of floors	Building height Amount of shading from buildings	The effective use of solar energy in tall buildings is influenced by the geometric shapes of the buildings and the type of solar cells used (Shirinbakhsh 2024). The height and area of a roof significantly affect the amount of solar energy harvested per unit area (Shirinbakhsh 2024).	

Type	Scale	Indicator	Conducted research	Knowledge gaps and challenges
	Optimal orientation of building facades	Radiation direction angle Wall direction angle	Access to natural light on the facade and the building's orientation are critical factors for capturing solar energy (Alterman 2018). The design of the roof and the building's orientation significantly affect the amount of solar energy absorbed .(Shirinbakhsh 2024) Focus on the design of bioclimatic facades by Kämpf & Robinson.	Research on the solar energy efficiency of high-rise buildings has been inadequate, resulting in conflicting opinions among researchers regarding the potential for achieving performance standards in high-rise residential structures. In Iran, particularly in suburban areas, there are very few studies that explore the impact of building orientation on energy consumption and the identification of optimal orientations. Additionally, there is a lack of focus on parametric designs that incorporate energy-efficient criteria and guidelines for optimizing sunlight exposure and integrating solar panels on facades in coastal cities. There is also insufficient attention to bioclimatic design principles, as well as to aspects such as building orientation, the appropriate placement of openings, and the facilitation of airflow between building blocks in the design process.
	Building materials	Type of materials	Access to daylight on the facade and the direction of the building are factors in receiving solar energy. Residential blocks exhibit the highest energy absorption in their roofs and facades. The energy capacity of a structure influences the efficiency of solar energy systems, making building materials essential (CleanEnergyCounci 2024). The role of insulation is a crucial factor to consider when selecting building materials for solar energy use (CleanEnergyCounci 2024). Utilizing biomaterials like timber, bamboo, straw, or hemp that absorb carbon during their growth and applying them in the construction sector helps minimize pollution and energy usage (Kyllmann 2024).	
	Facade	Facade material		
		Facade color		
		Facade shape (concave, convex, flat)		
	Openings	Opening direction		
		Optimal percentage of openings to the building facade		
Communication network	Access to the communication network	Road accessibility	The openness at ground level significantly influences thermal comfort. Utilizing street shape as a design factor can enhance energy performance in neighborhood units (Gupta 2012). Street width significantly affects sunlight access, while street orientation affects it the least (Gupta 2012). Streets and access networks are shaped by the arrangement of blocks (or masses) within each other. This component relates to the orientation of the blocks and how they are positioned next to one another. Additionally, the alignment of pathways is influenced by the same orientation of these blocks (Gupta 2012). Incorporating brightly colored reflective materials on the roof or facade of the building, integrating photovoltaics into the structure, and using environmentally friendly materials such as cement, ceramics, timber, brick, aluminum, and glass (CleanEnergyCounci 2024). Solar roads use the pavement surface as a platform for photovoltaic cells, turning roads into energy-generating assets. This method addresses the challenge of limited space while also enhancing the sustainability of urban transportation systems.	-Linear growth of coastal cities, particularly the coastal city of Tonekabon. -Insufficient consideration of how the orientation of plots along the roads impacts development. -Spatial constraints affecting urban planning. -Limited studies exploring the relationship between population density and the road and transportation network.
	Access to wasteland and open spaces	Access to wasteland and open spaces		
	Degree of confinement	Ratio of road width to wall height		
	Length of streets and passages	The angle of the main facade of the buildings		

Type	Scale	Indicator	Conducted research	Knowledge gaps and challenges
Natural factors	Shape of the Earth	Slope size	The leaves of a tree serve as a barrier to wind flow. Green spaces can alter the direction of wind as it interacts with buildings. Utilizing windbreaks can enhance indoor ventilation. Additionally, creating open areas within windbreaks forms wind channels that can boost wind speed by as much as 20 percent (Watson 2008). Wave energy in the seas and oceans is generated by the wind blowing across the water's surface. The mechanical energy from the wind is produced due to the uneven absorption of infrared heat and visible light from the sun. This energy is stored in the seawater as gravitational potential energy, which is released as kinetic energy in the form of waves after a short period of time (Larry 2012). Wave energy is primarily generated by the wind's effect on the surface of the sea. Wind is a unique form of solar energy, and as a clean and renewable resource, it can play a significant role in addressing the world's increasing energy demands (Dardizadeh 2014) Wave energy is influenced by wave height, speed, length, and water density during their period. While most wave technologies are designed for deployment near the ocean surface, they can be utilized in nearshore, offshore, and far- offshore locations based on resource availability (Qanbari 1996). The amount of energy transferred by waves depends on two main factors: how fast the wind is blowing and how far the wind interacts with the water surface. Wave power is quantified in kilowatts per meter. This measurement indicates the energy transferred along a 1-meter stretch that is parallel to the direction of the waves (Seyof Jahromi and Souri 2016) Waves are formed when wind transfers energy to the ocean's surface. The amount of energy transferred depends on how fast the wind blows and how far it travels over the water. Waves contain potential energy from the weight of the displaced water and kinetic energy from the movement of water particles. This stored energy is lost over time due to friction and turbulence, with the rate of loss influenced by wave characteristics and water depth. Large waves in deep water retain their energy longer, making wave systems complex, as they can be influenced by both nearby winds and distant storms that occurred previously (Marovati 1384).	The power of waves in deep ocean locations is 3 to 8 times stronger than that of waves near the coast. However, building and managing the site, as well as transmitting electricity to the shore, can be very costly. Additionally, equipment related to reclamation can pose a danger to ships, as it may be undetectable by the naked eye or even on radar. The western and coastal belt, along with the flat areas of Mazandaran Province, experience weak wind conditions, which necessitate the installation of wind turbines at a minimum. Furthermore, there is a concern regarding the loss of natural scenery, as industrial development in the seas can harm the marine ecosystem and disrupt the distribution and life of marine organisms close to the coast. It is also important to note that wave energy is not available in all areas.
		Slope direction		
		Topography		
	Height	Altitude above sea level		
	Vegetation	Scattering of green spaces and vegetation		
	Sea waves	Wave density Wave power Wave speed Wave energy		

Type	Scale	Indicator	Conducted research	Knowledge gaps and challenges
Climate	Temperature	Radiation intensity and direction	Wind energy is a renewable energy source that has gained popularity due to its cost-effectiveness and environmental benefits. Wind power plants have proliferated in recent years (Noorollahi 2011). When designing buildings in windy areas, the windward facade should avoid sharp corners and instead have a convex shape, allowing wind to flow around the structure (Kasmaii 1385). A narrower windward facade reduces maximum air pressure and internal air speed, especially when aligned perpendicular to the wind. Arranging buildings in a checkerboard pattern helps create more uniform air flow (Kasmaii 1385). Interior air flow is influenced by window frames, protrusions, and shutters. Window frames typically direct air upward, while hinged and pivot frames can channel air into living spaces. Protrusions above windows create pressure differences that enhance air flow. In coastal cities, roof protrusions help prevent rain and guide wind into buildings (Kasmaii 1385). Trees can act as windbreaks, redirecting wind flow and improving ventilation within buildings. Open spaces created by windbreaks can also form channels that increase wind speed by up to 20% (Watson 2008).	-There is a lack of focus on effective designs and the adoption of new solar technologies that are suitable for the local climate, along with insufficient investment in this area. -The western and coastal winds in the plain areas of Mazandaran province are inconsistent, resulting in weak wind conditions. -In building design, insufficient attention has been given to the airflow pathways and the spacing between buildings, which are important for moisture removal. -The low percentage of wind and the low wind power density in the study area make it challenging to install wind turbines for electricity generation. -Wind projects located in areas with inadequate wind resources, such as the study area, are not financially viable. -Wind turbines generate noise, alter the visual landscape, and can be quite loud. -Ideal locations for wind farms are often remote, presenting significant challenges for transporting electricity to urban areas. -The study area is characterized by high-density forests, making the construction of wind power plants inadvisable.
	Humidity	Humidity percentage		
	Sunny hours	Sunshine hours coefficients		
	Rainfall	Precipitation rate		
	Cloudy days	Number of cloudy days		
	Wind	Wind direction		
		Wind speed		
		Wind density		

5.2. Examining the productivity, both in terms of effectiveness and efficiency, of different renewable energy sources in coastal cities, with a focus on a specific case study

This section investigates the effectiveness and efficiency of three types of energy in coastal cities employing the COPRAS method. To identify the most effective and efficient renewable energy sources based on the specific conditions of the case study, various indicators were assessed. To validate the results of evaluating the effective efficiency of renewable energy methods in coastal cities, the indicators were first weighted using the ANP technique. Following this, a decision-making matrix was created, normalized, and both positive and negative values were calculated. The final prioritization of effective efficiency methods for renewable energy in coastal cities, with a focus on Tonekabon, was then analyzed (Table 4, 5, 6).

5.3. A two-way analysis of variance on the relationship between the urban form index and renewable energy sources

After conducting the content analyses described in the previous section, we examined the relationship between urban form indicators and renewable energy using a two-way analysis of variance across thirty indicators. Additionally, we assessed the semantic differences between these components and renewable energies. Our comparison revealed that solar energy is prioritized higher in terms of efficiency compared to wind and wave energy. All first thirty indicators show a significant difference (P-value < 0.001) between solar energy, waves, and wind (Figure 2, Figure 3 Figure 4).

Table 4
Decision Matrix Normalization

Indicators	Weight of criteria	Solar	Wave	Wind
Capital cost and economic savings	0/22	0/084	0/036	0/060
Ease of use (accessibility)	0/18	0/124	0/041	0/055
Uniqueness of operating facilities	0/1	0/050	0/019	0/031
Energy production rate and efficiency	0/19	0/067	0/048	0/076
Environmental impacts	0/15	0/079	0/026	0/044
Maintenance cost	0/16	0/070	0/030	0/060

Table 5
Calculating positive values Sj+ and negative values Sj-

Sj+	**0/404**	**0/170**	**0/266**	**0/840**
Sj-	0/070	0/030	0/060	0/160
1/Sj-	14/286	33/333	16/667	64/286

Table 6
Focusing on enhancing renewable energy efficiency in coastal urban areas.

Solar	Wave	Wind
0/439	0/253	0/308

Fig. 2. Two-Way ANOVA Analysis of Ten Different Indicators

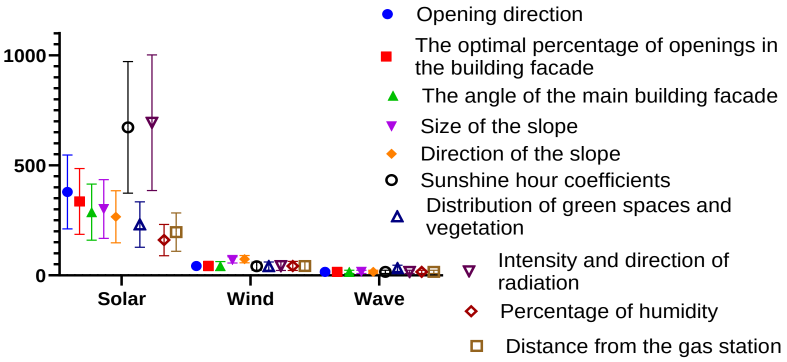

Fig. 3. Two-Way ANOVA Analysis of Ten Different Indicators

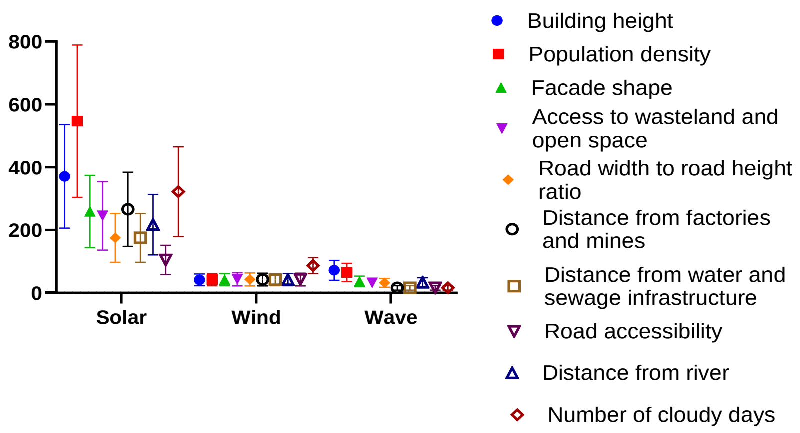

Fig. 4. Two-Way ANOVA Analysis of Ten Different Indicators

In relation to the indicators for wave and wind energy, particularly focusing on wind and wave indicators, the analysis shows a significant difference (P-value < 0.001) among the sources of energy: wave energy, solar energy, and wind energy. Notably, wave energy emerges as the preferred option, aside from considerations like distance from the fault and the amount of precipitation, as illustrated in the graph above (Figure 5).

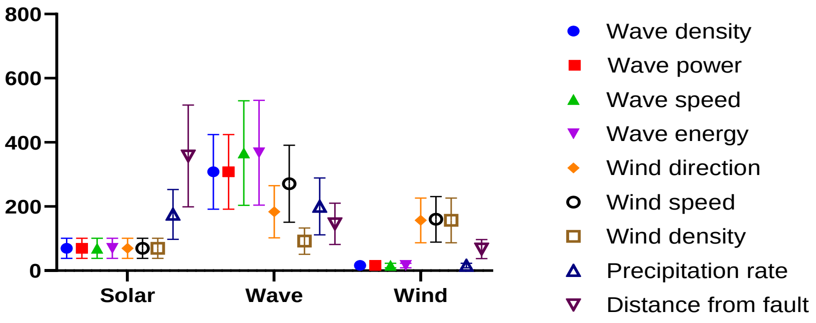

Fig. 5. Two-Way ANOVA Analysis of Ten Different Indicators

Despite a significant increase in the solar column, the large range of data changes results in a P-value of 0.0195 when comparing the sun and the wind, indicating low significance (*). In contrast, although there has been a notable increase in wind compared to waves, the large variability in data means that no statistically significant difference has been reported for wind and waves (Figure 6).

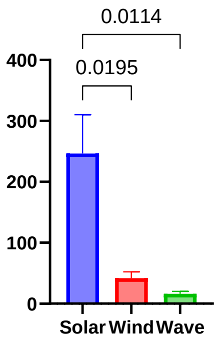

Fig. 6. compares the efficiency of different renewable energy sources based on their priority

6. Discussion

The challenges between urban form and renewable energy in coastal cities are complex and multifaceted. A review of opinions from researchers and relevant scientific literature reveals several critical issues that must be addressed. Firstly, the impact of population density on energy consumption is not straightforward; generalizable conclusions are elusive. There is often an emphasis on accessibility and the building sector, while other dimensions of density receive less attention. Additionally, research specific to coastal cities—where climates are temperate, humid, and mountainous—is relatively sparse. One major challenge is the absence of integrated models for analyzing energy consumption in urban environments and buildings. Spatial constraints hinder the installation of solar power systems in residential and urban areas. There is also a notable lack of management and smart systems, as well as insufficient emphasis on biomaterials and their potential combined uses. Research on the energy efficiency of high-rise buildings concerning solar energy is limited, and there is a divergence of opinions among scholars regarding the feasibility of meeting performance standards for these structures. Furthermore, there exists a knowledge gap between academic research, industry practices, and policy formulation, highlighting the need for collaborative efforts among various stakeholders. Spatial limitations are compounded by the fact that the energy potential of waves in deep ocean locations significantly surpasses that of waves near the shore, making electricity transmission from offshore sources to the coast costly. Moreover, difficulties such as inconsistent westerly winds and weak wind conditions in areas like Mazandaran province, coupled with the degradation of natural landscapes due to industrial installations, disrupt local marine ecosystems and alter the habitat of coastal organisms. Wave energy is not available uniformly across all regions, and there is a lack of focus on effective design strategies and innovative solar technologies that align with local climatic conditions. Research has highlighted the importance of considering building orientation and its effect on energy consumption, particularly in coastal areas, to determine optimal positions for energy efficiency. In conclusion, although various challenges exist regarding energy in coastal cities, utilizing the latest advancements in photovoltaic technology suited to specific climatic conditions, alongside learning from successful experiences in other countries, suggests that solar energy has the potential to be the most effective renewable energy source in these environments. The following summarizes the key issues and gaps in research regarding energy consumption and sustainable design in coastal cities, particularly focusing on Tonekabon (Table 1).

The analysis of the effectiveness and efficiency of various renewable energy sources in coastal cities highlights key factors such as capital costs and economic savings, which are prioritized. Important indicators also include energy production and efficiency, environmental impacts, and maintenance requirements. To ensure success, it is essential to focus on economic justification and to enhance public awareness, participation, and understanding. Based on the evaluation of the relevant indicators and scores, solar energy emerges as the most efficient and effective option, scoring 0.439. Wind energy follows in second place with a score of 0.308, while wave energy ranks third with a score of 0.253 in the case study (Figure 7).

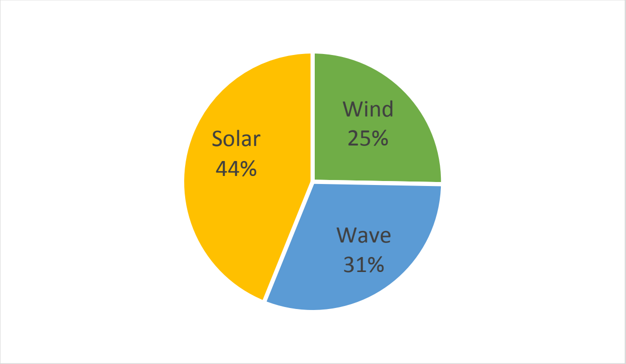

Fig. 7. Prioritizing renewable energy sources according to their effectiveness and efficiency.

The indicators presented in Figures 2, 3, 4, 5, and 6 were analyzed using a two-way ANOVA. This analysis allowed us to evaluate the semantic differences among these components and renewable energy sources. Our findings indicate that solar energy is regarded as more efficient than both wind and wave energy.

7. Conclusion

In this article, researchers investigated the dimensions, criteria, and indicators related to urban form and its impact on the efficiency of renewable energy sources. They examined existing literature to identify knowledge gaps and challenges that have not been adequately addressed, along with potential resolutions. A total of 41 indicators were extracted from the components of urban form, and their effects on the efficiency and effectiveness of renewable energies were evaluated through statistical analyses, specifically two-way analysis of variance. The findings indicated that solar energy leads in efficiency, followed by wind and wave energies. The article emphasizes the importance of fostering self-confidence and policy-making in the development of renewable energies, leveraging existing potentials and capacities. It highlights the need to support knowledge-based companies, invest in solar cell production, and enhance the country's self-sufficiency. Additionally, it advocates for private sector involvement and raising public awareness regarding participation in renewable energy initiatives. The existence of management and intelligent systems, along with the creation of integrated models to analyze renewable energy use in cities and buildings, is crucial, especially considering spatial limitations. The article suggests the necessity of engaging in effective designs, adopting new solar technologies, and increasing research collaboration between industry and policy sectors related to energy and design. These areas demand increased attention and cooperation among stakeholders to advance the efficiency of renewable energies.

8. Suggestions

Suggestions for enhancing renewable energy development and efficiency, particularly in coastal cities, include:

1. Foster self-confidence and policy-making that aligns with the country's renewable energy potential and capabilities.

2. Focus on knowledge-based companies and invest in increasing the nation's scientific expertise in solar cell production to achieve self-sufficiency.

3. Consider urban form indicators and climatic conditions, alongside innovative technologies for solar panel integration, to boost local energy use and reduce reliance on fossil fuels, emphasizing the critical need for investments in this sector.

4. Encourage private sector participation and raise public awareness to promote collective involvement in renewable energy initiatives.

5. Advocate for government investments that can lower the burden on infrastructure investments.

6. Expand distribution networks in Tonekabon city, taking into account vulnerable areas and their positive influence on urban development and property value.

7. Plan the construction of solar power plants in Tonekabon near transportation routes to minimize transportation and facility costs.

8. Optimize land use by carefully considering existing agricultural areas, forests, wetlands, and undeveloped lands for renewable energy projects.

9. Enhance research on urban density, accessibility, and the building sector, with a focus on improving studies relevant to coastal cities.

10. Implement intelligent management systems and develop integrated models that analyze renewable energy use in urban environments while acknowledging spatial constraints.

11. Increase research efforts to establish performance standards for high-rise residential buildings, prioritizing the effective use of renewable energy.

12. Pay more attention to innovative designs and the adoption of new solar technologies tailored to local climates, along with investing in such initiatives.

13. Promote collaborative, high-quality research in the energy and design sectors, engaging various stakeholders to advance industry and policy development.

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