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Assessing the Vulnerability of Geographical Regions to Potential Infrastructure Risks in the Energy Sector Through the Lens of Passive Defense

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Research Article

Abstract

In modern times, the significance of energy sector infrastructures has significantly increased as they play a crucial role in catering to the needs of society. Ensuring land security entails prioritizing the protection of infrastructures against attacks and threats. One crucial aspect of this security provision involves evaluating the vulnerabilities of these infrastructures based on their location, which is the main focus of this research. The aim is to assess the susceptibility of the energy infrastructure in the Yazd province and determine the capacity of the territory to withstand such vulnerabilities. To achieve this, the descriptive-analytical approach was employed along with the utilization of network analysis techniques and Arc GIS software. The findings indicate that when considering passive defense, the arrangement of infrastructure in the province was not appropriately designed. In Yazd province, the central region is at a higher risk compared to the surrounding areas, resulting in over 55% of the energy network infrastructure being situated in this highly vulnerable zone. Additionally, 18% of the infrastructure also falls within this high-risk area. The significance of passive defense measures is particularly emphasized in the province.

Keywords: Vulnerability, Spatial Vulnerability, Energy Infrastructure, Passive Defense, Yazd Province

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1. Introduction

Infrastructure protection, specifically the safeguarding of critical infrastructure, has gained significant importance in recent times (Abedi, Gaudard, and Romerio, 2018: 2; Huang, Liou, and Chuang, 2014: 66). The economic prosperity and the quality of life of a particular area rely heavily on the consistent and trustworthy functioning of its infrastructure (Ouyang, 2014: 44). These essential structures are likened to the lifelines that are crucial for the sustenance of urbanization in the modern world (Sultani, Mousavi, and Zali, 2016: 97). There are certain infrastructures in different societies that can cause significant harm to security, economy, and society at both regional and national levels if they are damaged or fail. Various countries have varying lists of their vital and sensitive infrastructure, encompassing communication infrastructure systems, electricity, gas and oil systems, banking and financial operations, transportation, water supply systems, government services, and emergency services (Ouyang, 2014: 44). Examining various infrastructures and their categorization demonstrates that energy infrastructures possess greater significance and play a more substantial role compared to other infrastructures.

The growing demand for and reliance on energy, coupled with the comparatively slower development of energy infrastructure in comparison to other types of infrastructure, significantly heightens the significance of energy infrastructures (Abedi et al., 2018: 3). Moreover, any potential harm to energy infrastructures holds much greater importance as they serve as a crucial lifeline and a central hub of activity and vitality in every region (Farji Melai, Zahedi, and Hosseini Amini, 2014: 199). According to Razaviyan, Alian, and Rostami (2017: 32), these infrastructures now face a higher likelihood of risks and an increased vulnerability to threats. In simpler terms, if these infrastructures are damaged, it can not only disrupt the equilibrium of urban and regional systems but also pose significant challenges for the society residing in that area, ultimately creating a crisis (Sarmi and Hosseini Amini, 2013: 56). Vulnerability is a term used to indicate the magnitude and level of potential harm resulting from an infrastructure crisis. It encompasses different forms, and location vulnerability, being one of those forms, involves identifying vulnerable areas and regions as a means of assessing the consequential destruction of infrastructure. Due to the significance of a region's energy infrastructure and the objective of understanding and evaluating its vulnerability, it is regarded as a suitable approach for conducting scientific and well-thought-out planning. The main objective of the present study is to evaluate and examine the vulnerability of energy infrastructures in the province of Yazd. Initially, it seeks to identify the spatial vulnerability of these infrastructures, and subsequently, it investigates the potential risks associated with them. Furthermore, given its strategic positioning and placement within the country's strategic depth, Yazd province holds significant importance as one of the country's vital provinces. It possesses vital infrastructures in diverse sectors owing to its unique location, including energy-efficient infrastructures. These infrastructures can serve as the driving force behind industrial activities and densely populated areas, while also playing a crucial role in bolstering national security and amplifying their impact. The current study aims to address the following questions considering the vulnerability of the energy infrastructure in this region.

1. From an energy infrastructure standpoint, how susceptible is Yazd province to spatial vulnerability?

2. What is the extent of harm and potential dangers posed by threats to the energy infrastructure in Yazd province?

2. Literature Review

2.1. Spatial Damage and Vulnerability

Despite vulnerability being a widely discussed concept in academic literature concerning passive defense, various scientific disciplines have interpreted and employed it differently, encompassing areas like social, organizational, economic, environmental, geographical, and territorial aspects, as well as physical and systematic elements (Dolan, Walliman, Amouzad, and Ogden, 2017: 744; Kundak, 2013: 196).

Vulnerability is commonly described as the potential for harm or negative impact (Cutter, 1996: 531). It entails the extent and magnitude of damage within a factor or group of factors caused by the presence of any event or phenomenon (M. Little, Paul, Jordens, and Sayers, 2000: 495). Another definition of vulnerability is the inadequate ability of society to confront dangers and uncertainties, which is influenced by the position of individuals and groups within the physical and social environment (Clark et al., 1998: 59).

Generally, vulnerability can be defined as the extent of harm that a specific element is exposed to, typically represented on a scale ranging from zero (indicating no harm) to one (representing complete damage and destruction). Vulnerability, it should be noted, is not a fixed occurrence. Instead, it is an ever-changing process that alters the likelihood and extent of harm caused by destructive elements, subsequently impacting them (Ghafory-Ashtiany, 2005: 2). Concerning this matter, spatial vulnerability pertains to the extent of discrepancies in the infrastructure location's capacity when impacted by threats. It is determined by geographic characteristics, indicators, and passive defense measures (Seydin et al., 2016: 336). Hence, the vulnerability of infrastructures in terms of spatial aspect can be determined by assessing the ability of geographical regions to withstand threats to infrastructure. Building upon this concept, the present study aims to measure and assess the spatial vulnerability of energy infrastructures on a regional scale.

2.2. Vulnerability Process Approaches

Numerous attempts have been undertaken to create models and techniques in order to examine infrastructure systems and their susceptibility. In terms of classifying the methods and models utilized in the realm of infrastructure vulnerability assessment, Johansson and Jonsson (2008) have divided them into two overarching groups: empirical and predictive approaches. The objective of empirical methods is to enhance awareness and comprehension of the infrastructure and its interactions by analyzing previous occurrences. Indeed, the objective of these practical methods frequently involves identifying patterns that could potentially be associated with political choices. One instance of this method is its ability to assess the trends in outcomes for a particular community or the effects of failures on other infrastructures (Johansson and Hassel, 2008: 16). Various studies by McDaniels, Chang, Peterson, Mikawoz, and Reed (2007), Zimmerman & Restrepo (2006), and Restrepo et al. (Restrepo, Simonoff, and Zimmerman, 2006) have provided practical examples of these experimental approaches (McDaniels, Chang, Peterson, Mikawoz, and Reed, 2007: 175), along with other related observations. However, typically, predictive methods focus on modeling and simulating infrastructure, particularly its interactions, which can lead to significant disruptions across various sectors of infrastructure. Numerous models have been utilized in diverse research studies within this discipline, including economic-computational models (Haimes and Jiang, 2001: 1). To simulate the behavior of infrastructures during different threats, there are various models and methods available. These include ecosystem dynamic models (Min, et al., 2007: 57), agent-based models (Brown, Beyeler, and Barton, 2004: 108), network-based modeling (Apostolakis and Lemon, 2005: 361), and other similar approaches (Huang et al., 2014: 66). However, the difficulties in comprehending, organizing, categorizing, and representing these systems remain significant, and the current endeavors in this domain have not yet undergone the stages of development (Little, 2002: 110). However, there is a common factor in using and implementing these models. Studies that employ predictive methodologies focus on assessing the effects of infrastructure and its interactions through various models and viewpoints. It is important to note that there is no all-encompassing and universally applicable model for assessing infrastructure vulnerability. The choice of approach depends on the specific nature of the infrastructure being examined, the extent of analysis, and the geographical area under scrutiny. In some cases, conventional methods, such as experimental or predictive approaches, may be employed depending on the nature of the problem being investigated.

3. Research Methodology

The choice of research method typically depends on the nature of the subject and the objectives of each study. Considering these factors, the present research falls under the category of applied research in terms of its goal and is classified as descriptive-analytical research in regards to its methodology. The literature and theoretical foundations section of this study obtained the necessary information through the library and document method. This method primarily relies on utilizing books, both domestic and foreign scientific articles, reports, and other relevant sources. The following stage involved extracting the location data using the infrastructure database of the country. This study focuses on analyzing the infrastructure of Yazd province, specifically the electricity transmission network, power generation facilities, electric substations, gas transmission lines, gas pressure regulation stations, oil transmission lines, oil product transmission lines, as well as oil and gas storage facilities and gas stations, in terms of energy infrastructure.

The following step involves assessing the significance of each infrastructure component in relation to another infrastructure component. Hence, once the criteria relationship is established through the Dimetal model, we proceed to the phase of comparing infrastructure elements on a binary scale. This comparison was accomplished utilizing the network analysis process model, in which every infrastructure element of Yazd province was evaluated based on a specialized questionnaire compiled by experts and professionals. However, the key concern in this comparison lies in the evaluation standard, commonly known as the control criterion, within the model for analyzing networks. To accomplish this, understanding the roles of each infrastructure, classifying them appropriately, and precisely determining their scopes are crucial. Determining the desired outcome in this matter aids in categorizing and establishing priorities for the infrastructure, which is undeniably crucial in defining benchmarks for this objective. Factors such as strategic-political significance, economic significance, social significance, and defense significance can serve as appropriate indicators to assess the importance of each infrastructure. In this particular study, the questionnaire was developed by taking into account a set of criteria including strategic-political significance, economic importance, social importance, and defense significance.

The evaluator team was chosen based on their possession of expertise and being experts. They were selected from two communities, the passive defense organization and the academic community, who were well-versed in the concepts of passive defense, threat, infrastructure, and infrastructure vulnerability. A total of 34 questionnaires were obtained after distributing 50 initial questionnaires. Following the initial monitoring conducted to address the significant difference and lack of rationality, and the exclusion of two collected questionnaires, the analysis process proceeded with 32 questionnaires that were deemed valid. The statistical population of respondents in this study comprised nine individuals from the expert community of the non-active defense organization and 23 individuals from the academic community.

Once the calculations in the network analysis process model are finished, the subsequent phase involves creating maps and information layers for every infrastructure component. This task is accomplished within the ArcGIS environment, where the final coefficients obtained from the network analysis process are applied to individual layers. Ultimately, the vulnerability map of the province is produced.

4. The Scope of the Study

Yazd province, situated in the central region of the Iranian plateau, holds significant strategic importance due to its location at the heart of the country and its proximity to the provinces of Fars, Kerman, Isfahan, and Khorasan. It is considered a key focal point and plays a crucial role in the country's strategic positioning. This province is divided politically and consists of 10 cities. The largest city in terms of size is Ardakan, which covers approximately 23 thousand square kilometers. On the other hand, the smallest city is Maybod, spanning about 1200 square kilometers. As per the 2015 census, the population of the province is estimated to be around 1138533 individuals (Yazd Governorate, 2016: 15). Additionally, Figure 1 displays the energy infrastructure of Yazd province.

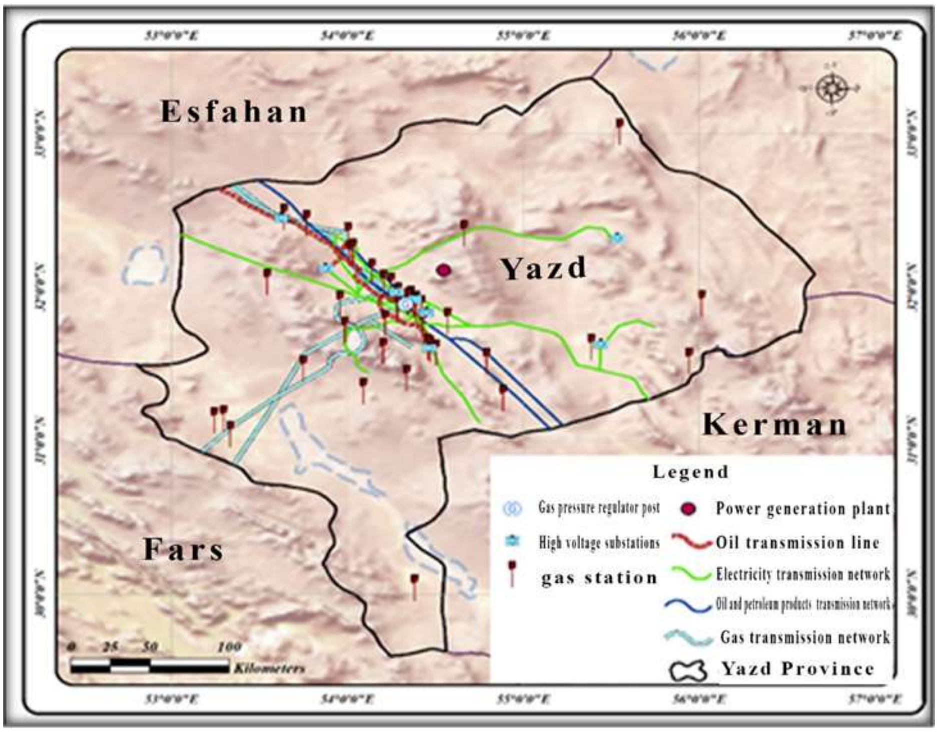


Fig 1 Energy infrastructures of Yazd province

5. Analysis

5.1. Analysis of the Attractiveness and Importance of the Infrastructures

Measuring the vulnerability of infrastructures and understanding their impact on the region is a crucial aspect when it comes to planning and implementing passive defense measures (Bernaffer et al., 2013: 163). Therefore, it is crucial to give importance to the infrastructures and evaluate their vulnerability to adversaries when carrying out this task. Multiple methods can be suggested and employed to accomplish this objective. In this study, the network analysis process model has been utilized to obtain more practical and effective outcomes. Subsequently, the practical execution of this model will be elaborated upon.

After establishing the framework of infrastructural components, experts conducted a thorough evaluation of each infrastructural element's effectiveness through pairwise comparisons. Now it is necessary to ascertain the nature of the relationship between these elements. To begin, we employ the DEMATEL model's table. The objective at this point is to assess the infrastructures in pairs and individually, taking into account their cause-and-effect relationship. Put simply, all the infrastructure components need to be compared individually regarding their effectiveness. This ensures that each element is considered both as an independent and dependent variable in the matrix. Experts and specialists in the field performed the assessment and analysis, assigning points ranging from 0 to 5 based on the relationship between the infrastructures. The score of 5 for an infrastructure element, considered as an independent variable, significantly affects another element, considered as a dependent variable, while the influence of the independent element gradually diminishes towards a score of zero. The least impact is represented by the number 1 in this range, while the number zero indicates no impact between the two elements. This process completes the comparison matrix of infrastructure elements. It is important to highlight that the matrix has a diameter of zero.

The matrix is completed by evaluating all infrastructure elements together, as shown in Fig 2. Once the questionnaires are distributed and collected, the results are calculated for each questionnaire. These results are then inputted into Excel software, and subsequently the average score of all the questionnaires needs to be calculated. In the following stage, the highest number of columns (43) and the highest number of rows (46) are identified by calculating the total of rows and columns in the average matrix. Subsequently, all the numbers in the average matrix are divided by the smaller number (43). The resulting matrix is then utilized in MATLAB software for further computations using equation 1 (refer to Fig 2).

$$T = D(I * D)^{-1} \qquad \text{Eq. 1.}$$

T: the matrix anticipated for subsequent examination.

D: The matrix derived from the mean viewpoints of professionals.

I: identity matrix (a matrix with a diagonal of 1 and all other elements being zero).

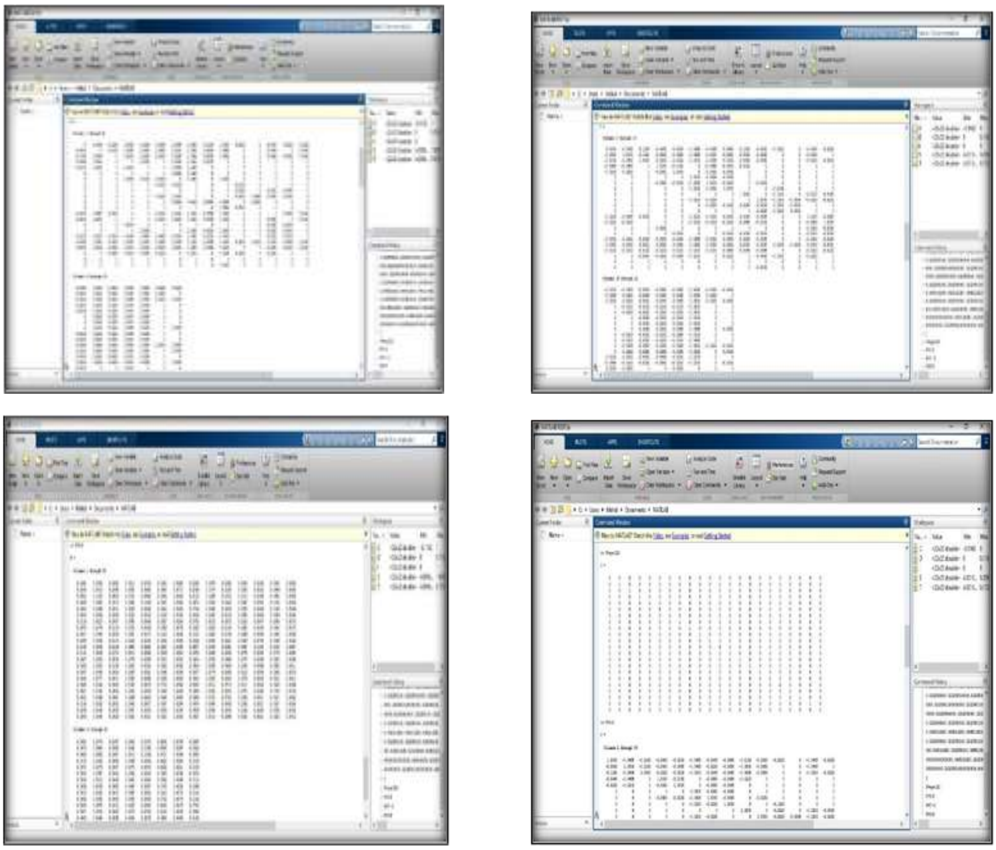


Fig 2 Steps to calculate the relationship between infrastructure elements in MATLAB software

Afterwards, the matrix obtained from the calculation in MATLAB software (Fig 2) is transferred to Excel software. Next, the entire matrix is averaged. In the final step, each cell of the matrix with a value greater than the average is replaced with the number 1 using the If operator. Conversely, any cell with a value lower than the average is replaced with the number zero in the matrix. Through the resulting matrix that contains values of zero and one, the linkages and interconnections among infrastructures are identified. Subsequently, this matrix aids in mapping out the relationships between infrastructure components in the network analysis model. The binary comparison process is then initiated within the network analysis model. Table 1 displays the outcomes of this computation. Hence, when examining the overlap between rows and columns, a value of 1 indicates that the element in the row of the matrix impacts the infrastructure element in the column. Conversely, if the value at this intersection is zero, it signifies that the row element does not affect the infrastructure element of the column, but the opposite scenario is feasible. In the case of the power transmission network, it impacts the power generation plant with a significance of 1, however, there is no connection between the power transmission network and bridges, with a significance of 0. The analysis extends to other elements of infrastructure and ultimately involves assessing interactions between infrastructures as one-way relations, bilateral relations, or no relations.

Table 1 The matrix resulting from the results of Dimtel's model

	Electricity transmission network	Power generation plant	High voltage substations	Gas transmission network	Gas pressure regulator post	Oil and petroleum products transmission lines	Oil and gas warehouse	gas station
Electricity transmission network	0	1	1	1	1	1	1	1
Power generation plant	1	0	1	1	1	1	1	1
High voltage substations	1	1	0	1	1	1	1	1
Gas transmission network	1	1	0	0	1	0	1	1
Gas pressure regulator post	0	0	0	1	0	0	1	1
Oil and petroleum products transmission lines	0	0	0	0	0	0	1	1
Oil and gas warehouse	0	0	0	1	1	1	0	1

Gas station	0	0	0	0	0	0	0	0

Once the final matrix has been computed to ascertain the correlation and infrastructure interactions, the subsequent stage involves implementing these connections to the components and alternatives. This task has been accomplished using the Super Decisions software.

In this stage, the clusters' comparison matrices and the interdependencies of infrastructure elements are constructed and their suitability is monitored. The evaluation of infrastructure elements using a 9-point quantitative scale based on total hours, following the same sequence as the hierarchical analysis process, was carried out by experts and professionals and then inputted into the software.

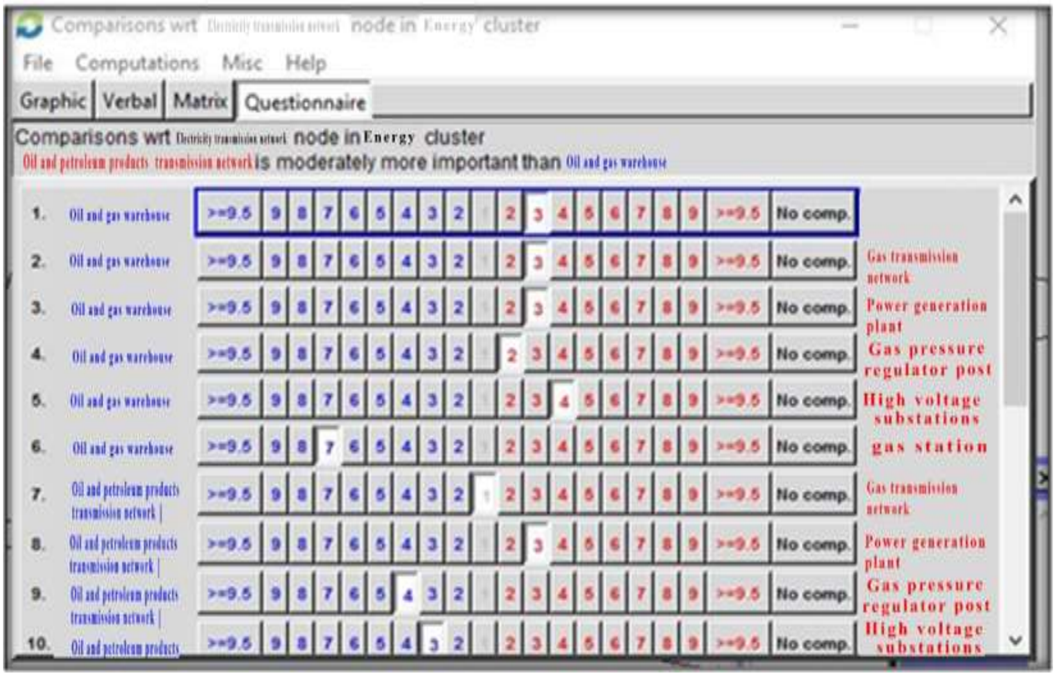


Fig 3 Evaluation matrix and binary comparison of infrastructural elements

The final stage in the process model of network analysis is the super matrix. The super matrix is a composite of individual matrices arranged together and merged in order to determine the ultimate importance and desirability of each infrastructure component. Considering that all comparative matrices are calculated in the unweighted supermatrix structure and their compatibility is also controlled, the ununweighted supermatrix is calculated as the first stage of calculations (Fig 4). The current task involves the conversion of the unweighted supermatrix into a weighted supermatrix, which should have column elements summing up to 1, as illustrated in Fig 5. This transformation requires multiplying the unweighted supermatrix with the cluster matrix, as the latter represents the impact of each cluster and infrastructure element. The subsequent task involves computing the limit supermatrix (Fig 6). In essence, the aim of maximizing the balanced super matrix is to ascertain the enduringly comparative influence of each infrastructure component on one another.

Super Decisions Main Window: Untitled.sdmod: Unweighted Super Matrix

Cluster / Node / Labels		Energy							
		Oil and gas warehouse	Oil and petroleum products transmission network	Electricity transmission network	Gas transmission network	Power generation plant	Gas pressure regulator post	High voltage substations	gas station
Energy	Oil and gas warehouse	0.000000	0.833333	0.063015	0.187908	0.156480	0.296575	0.085945	0.000000
	Oil and petroleum products transmission network	0.400305	0.000000	0.198335	0.000000	0.190656	0.000000	0.169475	0.000000
	Electricity transmission network	0.000000	0.000000	0.000000	0.227240	0.263629	0.000000	0.199151	0.000000
	Gas transmission network	0.385282	0.000000	0.112225	0.000000	0.130961	0.644980	0.225911	0.000000
	Power generation plant	0.000000	0.000000	0.364343	0.453170	0.000000	0.000000	0.209387	0.000000
	Gas pressure regulator post	0.164126	0.000000	0.081449	0.098619	0.070865	0.000000	0.082893	0.000000
	High voltage substations	0.000000	0.000000	0.162537	0.000000	0.163514	0.000000	0.000000	0.000000
	gas station	0.050286	0.166667	0.018097	0.033062	0.023895	0.058445	0.027238	0.000000

Done

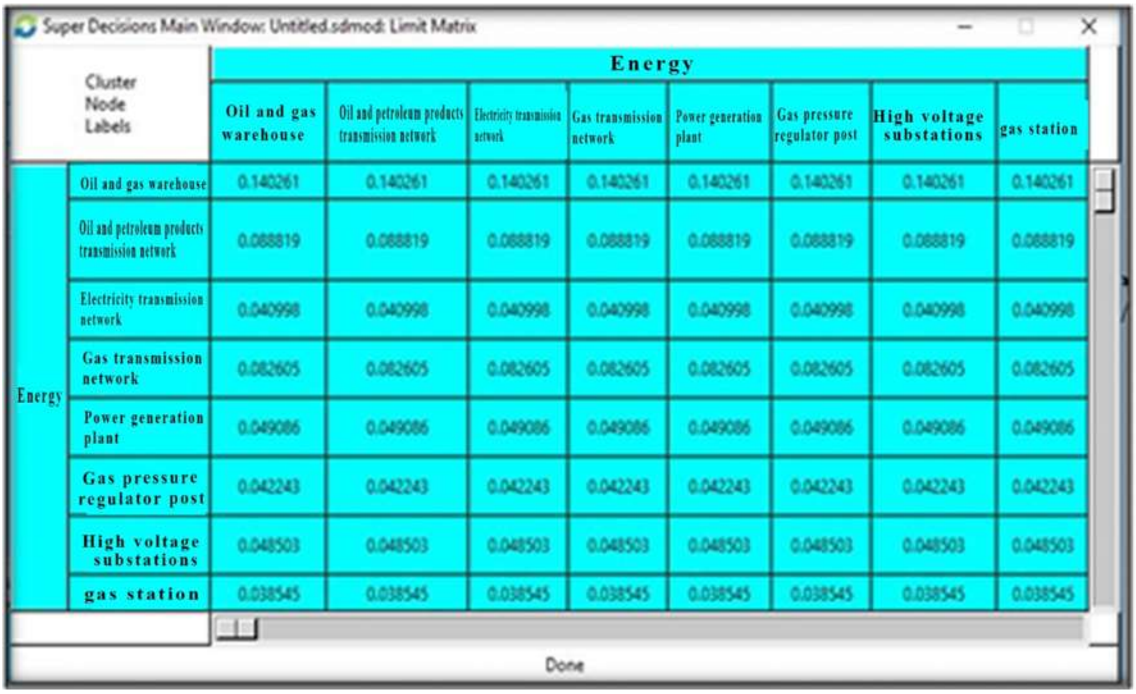
Fig 4 Unweighted super matrix

Super Decisions Main Window: Untitled.sdmod: Weighted Super Matrix

Cluster / Node / Labels		Energy							
		Oil and gas warehouse	Oil and petroleum products transmission network	Electricity transmission network	Gas transmission network	Power generation plant	Gas pressure regulator post	High voltage substations	gas station
Energy	Oil and gas warehouse	0.000000	0.833333	0.030103	0.094193	0.074751	0.175469	0.041056	0.000000
	Oil and petroleum products transmission network	0.236840	0.000000	0.094746	0.000000	0.091077	0.000000	0.080959	0.000000
	Electricity transmission network	0.000000	0.000000	0.000000	0.113909	0.125937	0.000000	0.095136	0.000000
	Gas transmission network	0.227952	0.000000	0.053610	0.000000	0.062561	0.381601	0.107919	0.000000
	Power generation plant	0.000000	0.000000	0.174049	0.227160	0.000000	0.000000	0.100025	0.000000
	Gas pressure regulator post	0.097105	0.000000	0.038909	0.049435	0.033853	0.000000	0.039599	0.000000
	High voltage substations	0.000000	0.000000	0.077645	0.000000	0.078111	0.000000	0.000000	0.000000
	gas station	0.029752	0.166667	0.008645	0.016573	0.011415	0.034579	0.013012	0.000000

Done

Fig 5 Weighted super matrix



Super Decisions Main Window: Untitled.sdmod: Limit Matrix

Cluster Node Labels		Energy							
		Oil and gas warehouse	Oil and petroleum products transmission network	Electricity transmission network	Gas transmission network	Power generation plant	Gas pressure regulator post	High voltage substations	gas station
Energy	Oil and gas warehouse	0.140261	0.140261	0.140261	0.140261	0.140261	0.140261	0.140261	0.140261
	Oil and petroleum products transmission network	0.088819	0.088819	0.088819	0.088819	0.088819	0.088819	0.088819	0.088819
	Electricity transmission network	0.040998	0.040998	0.040998	0.040998	0.040998	0.040998	0.040998	0.040998
	Gas transmission network	0.082605	0.082605	0.082605	0.082605	0.082605	0.082605	0.082605	0.082605
	Power generation plant	0.049086	0.049086	0.049086	0.049086	0.049086	0.049086	0.049086	0.049086
	Gas pressure regulator post	0.042243	0.042243	0.042243	0.042243	0.042243	0.042243	0.042243	0.042243
	High voltage substations	0.048503	0.048503	0.048503	0.048503	0.048503	0.048503	0.048503	0.048503
	gas station	0.038545	0.038545	0.038545	0.038545	0.038545	0.038545	0.038545	0.038545

Done

Fig 6 Limit super matrix

To ascertain the ultimate value and coefficient of clusters and infrastructure elements, the final step involves computing the outcomes of the cluster matrix and standardizing the coefficient of infrastructure elements within the limit super matrix.

After performing the calculations, the matrix coefficients of the clusters are normalized with the coefficients of the supermatrix. Consequently, the significance of the infrastructure in delivering services to the people and other infrastructures, as well as its appeal, is individually evaluated for each infrastructure element. The ultimate outcome is presented in Table 2. The significance of the gas transmission network is evident, with a value of 0.1003, while the transmission lines for oil and petroleum products have a slightly lower score of 0.0988. Similarly, oil and gas storages are also of relatively lesser importance, with a score of 0.0985. Lastly, gas stations hold the least significance among all energy infrastructures in the province, scoring 0.0485.

Table 2 The weight of infrastructure elements of Yazd province in terms of importance and attractiveness

Infrastructures	Normalized coefficients by clusters	Final weight
Gas transmission network	0.2831	0.1003
Oil and petroleum products transmission lines	0.2641	0.0988
Oil and gas warehouse	0.2613	0.0985
Power generation plant	0.2500	0.0926
Electricity transmission network	0.2320	0.0885
Electric high voltage post	0.2051	0.0694
Gas pressure regulator post	0.1988	0.0673
Gas station	0.1556	0.0485

5.2. Evaluation of the Vulnerability of the Energy Network

The vulnerability of the infrastructure in Yazd province is being assessed, including the electricity transmission network, power generation plant, high voltage substation, gas transmission network, gas pressure regulation substation, oil transmission lines, and oil and gas storage facilities, as well as gas stations. The Yazd province meets its electricity needs by generating power in its active power plants, such as the Yazd power plant and Tabas city power plants in Khorasan province, as well as through the national electricity network. The integrated electricity system, which encompasses electricity generation, transmission, and distribution, is a vast and intricate national and regional infrastructure. Its convenient production conditions, rapid transferability, and adaptability to other energy sources have attracted significant interest and attention from people. Furthermore, the significant expenses associated with investing in building and setting up production, transmission, and distribution infrastructure, as well as the costs of repair and maintenance, are compounded by the essential reliance of daily human activities on electricity. This dependence underscores the critical need for uninterrupted electricity supply during natural disasters, wartime conditions, and terrorist attacks. Based on the information from Fig 7 and Fig 9, the central areas of the province, which include Maybod, Yazd, Ashkazar, and to some extent Bafaq and Ardakan, are comparatively more at risk in terms of electricity distribution network and high voltage substations. Additionally, Fig 8 indicates that the central region of the province is more susceptible, taking into account the power plant's location.

Another crucial aspect of the energy infrastructure in Yazd province is the gas and oil infrastructure. Pipelines are a practical and cost-effective method for transporting hazardous and flammable materials like natural gas, crude oil, and its by-products, which cannot be transported via land or railway. In the Yazd province, the pipeline network is growing to accommodate the rising demand for oil and gas. This expansion necessitates the development of safe facilities and operations. Additionally, the presence of combustible materials in the transmission networks poses a natural risk of explosion and fire in the event of failure or leakage. Incidents such as fires, explosions, pollution, and financial losses can result from pipeline-related issues. These incidents can have widespread impacts on society and are attractive targets for sabotage. It is clear that pipeline incidents affect various aspects of production, including labor, equipment, and the environment. On one side, the economic impact of wasting valuable materials in our products or raw materials is undesirable, while on the other side, it results in significant costs for replacing damaged equipment, repairing and replacing pipelines, and cleaning up the environment, which companies have to bear.

As mentioned before, Yazd province does not have its own gas sources and relies on the national network for natural gas supply. As a result, the central and western areas of the province are at a higher risk due to this dependency. Additionally, as the gas reaches the consumption points, it must go through pressure reduction and measurement systems. Therefore, pressure regulation posts are crucial infrastructure. Fig 11 illustrates the vulnerability of the province in terms of gas pressure regulation posts and oil and gas storage.

Furthermore, despite the absence of oil refineries in Yazd province, the region's demand for oil and its products is met through two transmission lines. These lines supply oil and oil products to various cities in the province, including Mehriz, Yazd, Ashkazar, Meibod, and Ardakan, as depicted in Fig 14. Gasoline and diesel pumps are crucial infrastructures in every province and region, providing essential services to society. As depicted in Fig 13, the concentration of infrastructure in Yazd province is greater in the central areas, primarily because of the higher population density and the presence of the north-south corridor. Consequently, the central parts of the province are more vulnerable from this perspective.

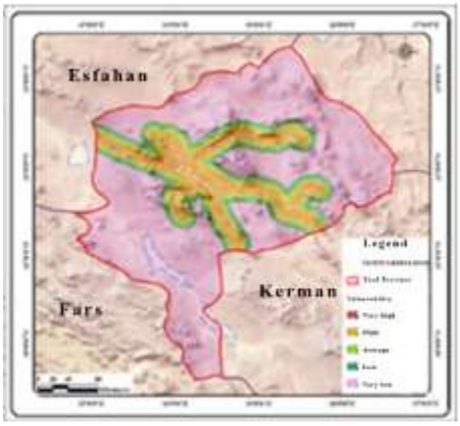


Fig 7 Vulnerability zoning map of electricity transmission network of Yazd province

Fig 8 Vulnerability zoning map of Yazd province power plant

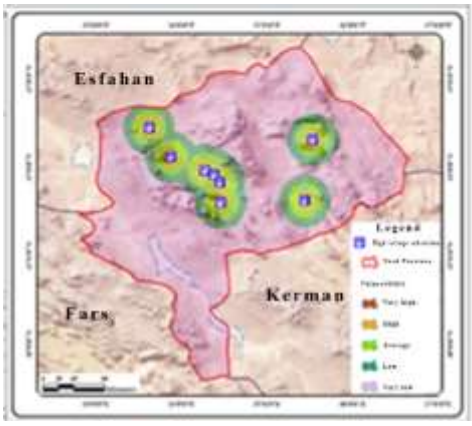


Fig 9 Vulnerability zoning map of high voltage substations in Yazd province

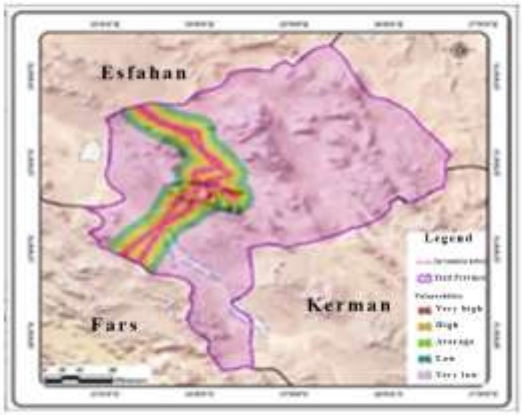


Fig 10 Vulnerability zoning map of gas transmission network in Yazd province

Fig 11 Vulnerability zoning map of oil and gas storage in Yazd province

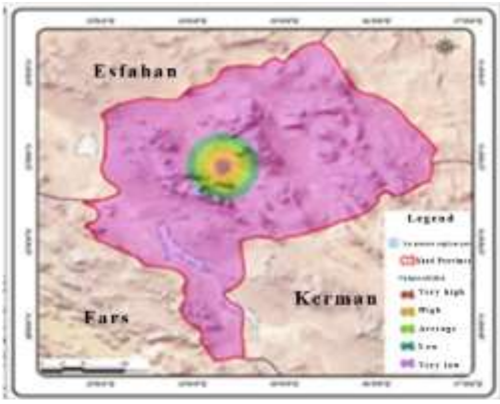


Fig 12 Vulnerability zoning map of gas pressure regulation station in Yazd province

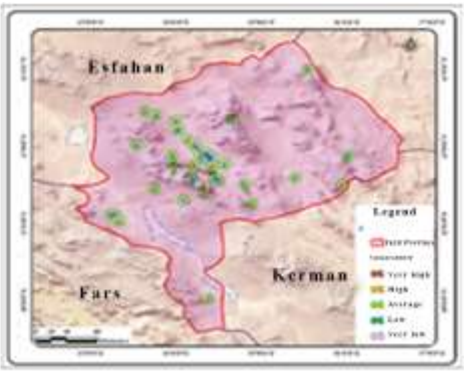


Fig 13 Vulnerability zoning map of fueling centers (petrol, gas and diesel pumps) in Yazd province

Fig 14 Vulnerability zoning map of oil and oil products transmission network in Yazd province

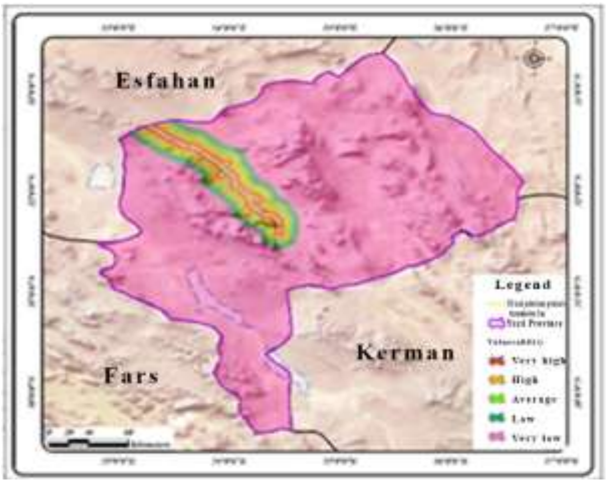
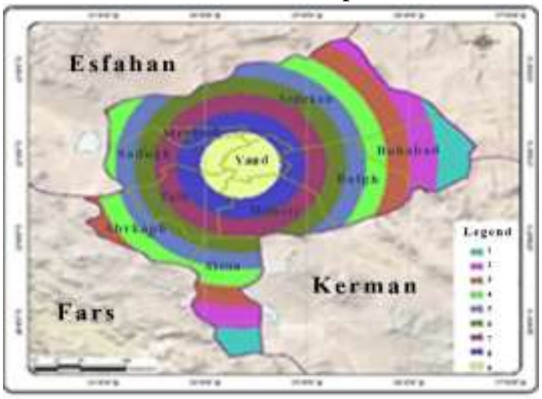
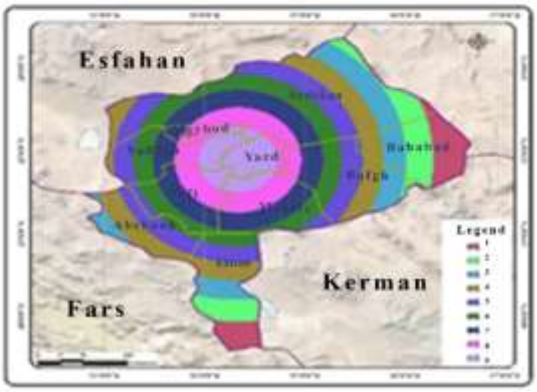


Fig 15 Vulnerability zoning map of oil and oil products transmission network in Yazd province

After reassessing the vulnerability of each infrastructure, the vulnerability of the energy infrastructure sector in Yazd province was ultimately determined using overlapping functions, as depicted in Fig 16. The central area of the province exhibits higher vulnerability attributed to the concentration and density of energy infrastructures, while the vulnerability decreases as we move towards the outskirts of the province, as illustrated in Fig 17.





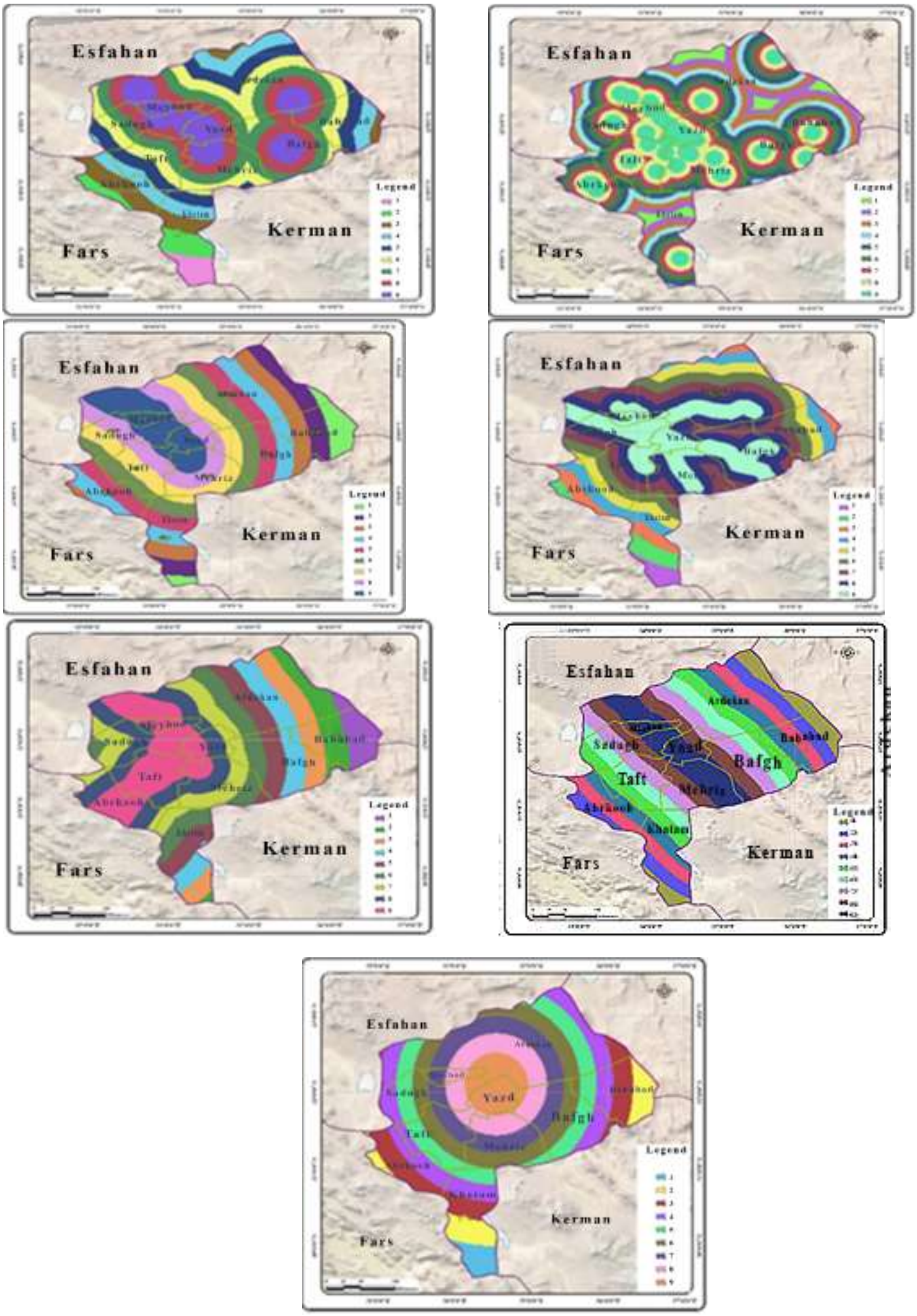


Fig 16 Reclassification maps of the vulnerability of the infrastructure of the energy network of Yazd province

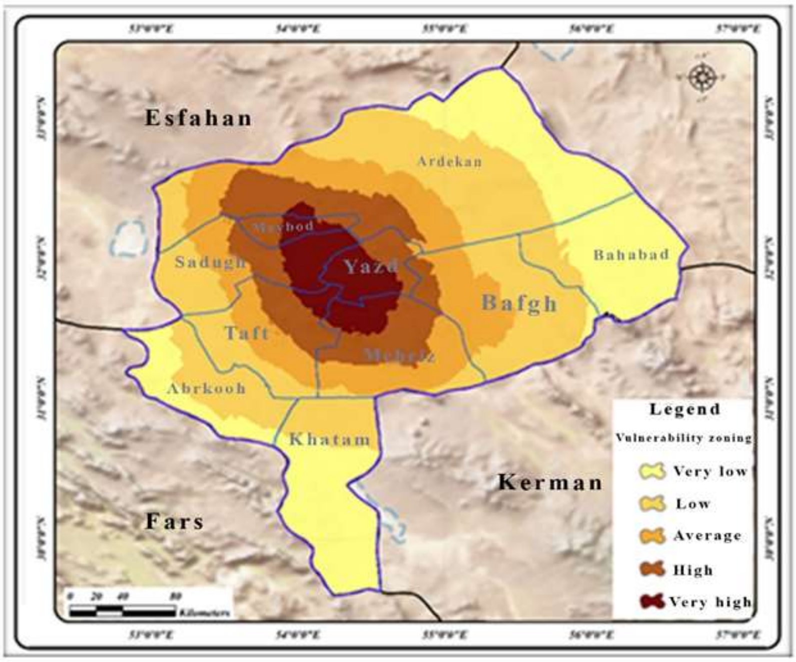


Fig 17 Vulnerability zoning map of energy network infrastructure of Yazd province

Based on the data in Table 3 and Fig 18, when analyzing the vulnerability of energy network infrastructure at the city level, it is evident that Yazd and Meibod are highly vulnerable, followed by Mehriz and Sedek, while Bahabad, Khatam, and Abarkoh exhibit lower vulnerability. This is attributed to the concentration of critical infrastructures in the central part of the province and in the cities of Yazd and Meybod.

Table 3 Vulnerability status of Yazd province in terms of energy network infrastructure by city

City	Pixel count	Min	Max	Average	Standard deviation	Mean	Total	Vulnerability
Abarkoh	2233	3.000	6.000	4.565	0.671	5.000	10194.000	Low
Ardekan	9805	2.000	9.000	5.664	1.634	6.000	55533.000	Average
Bafgh	3516	4.000	8.000	6.187	0.935	6.000	21752.000	Average
Bahabad	2811	1.000	6.000	3.229	1.094	3.000	9076.000	Low
Taft	2433	5.000	9.000	7.010	1.038	7.000	17056.000	High
Khatam	3363	1.000	6.000	3.607	1.300	3.000	12129.000	Low
Sadugh (Akezar)	2374	4.000	9.000	7.202	1.389	7.000	17098.000	High
Mehriz	2811	6.000	9.000	7.579	0.857	8.000	21305.000	High
Meybod	511	8.000	9.000	8.405	0.491	8.000	4295.000	High
Yazd	1040	7.000	9.000	8.567	0.549	9.000	8910.000	High

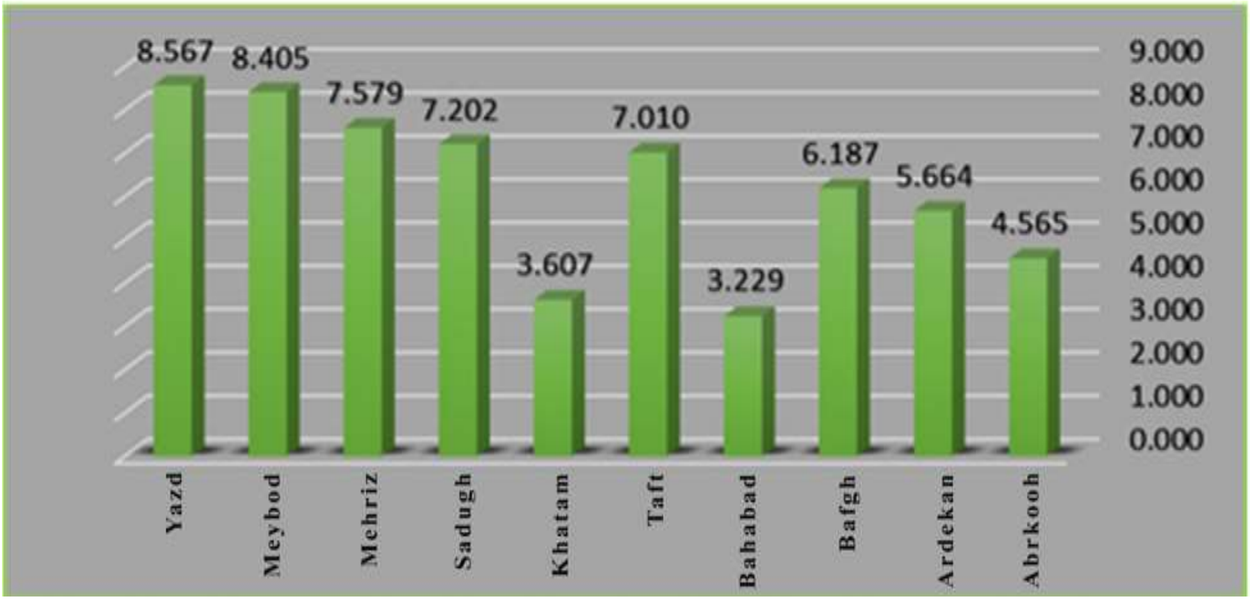


Fig 18 Average vulnerability graph of the cities of Yazd province in terms of energy network infrastructure

5.3. Assessing the Location of Energy Network Infrastructure in Vulnerable Areas

Following the assessment and analysis of the susceptibility of the energy network in Yazd province, the examination of infrastructure placement within each vulnerable zone represented in Fig 19 indicates that over half (55%) of the energy network infrastructure in Yazd province is in an extremely vulnerable zone. Additionally, 18% of the infrastructures are situated in an area characterized by a high level of vulnerability. In the meantime, both the Yazd combined cycle power plant and the oil and gas storage facilities in the province, which are considered critical infrastructure, are situated in highly susceptible areas. Each energy sector infrastructure and its position in vulnerable regions are illustrated individually in Fig 20.

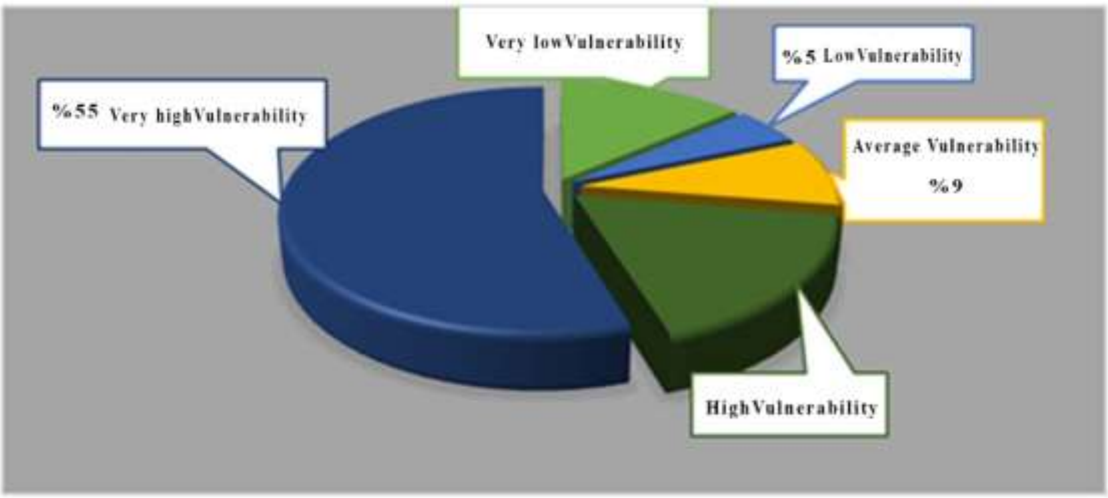


Fig 19 Diagram of the deployment status of Yazd province's energy network infrastructure in vulnerable areas

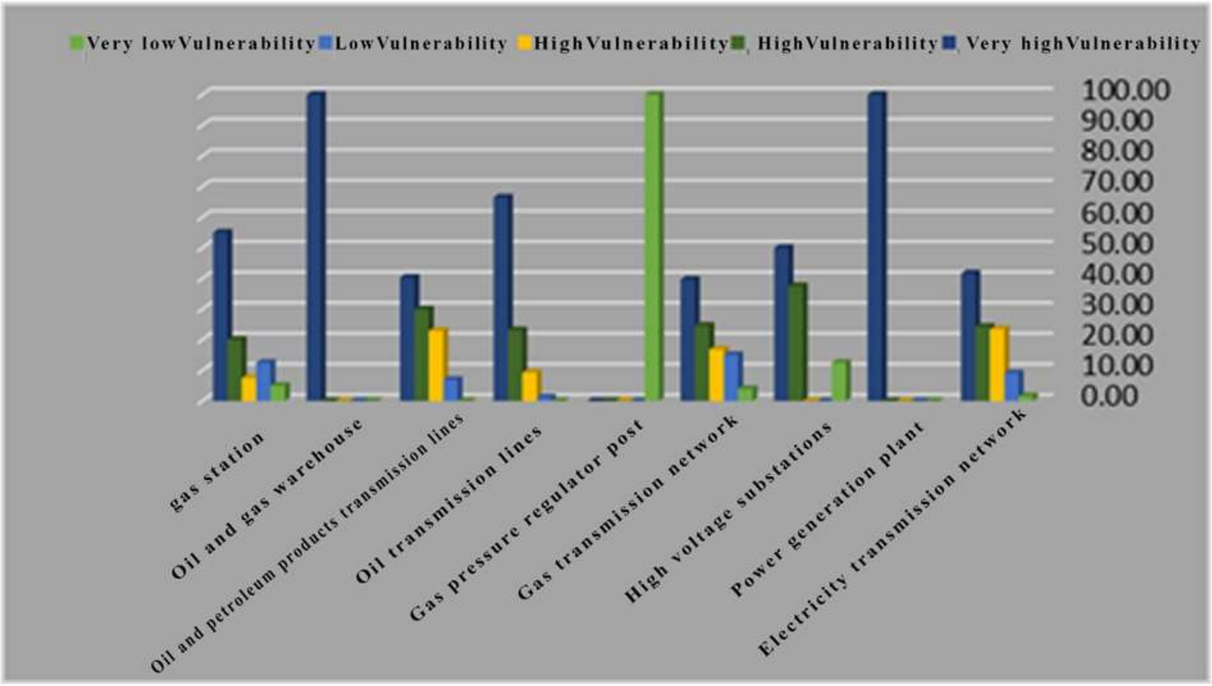


Fig 20 Distribution diagram of Yazd province's energy network infrastructure in the five vulnerability zones

6. Conclusion

Today, the significant importance of passive defense is closely associated with security at various levels, including local, regional, and national, due to its strong potential to enhance both the well-being of communities and their essential facilities and supports. According to this perspective, if a website or organization fails to adhere to the principles of passive defense, it becomes susceptible to risks. The level of vulnerability is directly proportional to the extent to which these principles are disregarded. Given the possible dangers posed to Iran and its important infrastructures within the region, it is crucial to prioritize the issue of passive defense for critical, sensitive, and vital facilities. This wise approach not only reduces costs but also prevents erroneous decision-making. Additionally, it enhances the efficiency and performance of these centers and avoids unnecessary depletion of resources, capital, and time. Vulnerability assessment is a comprehensive evaluation of the effectiveness of infrastructures and systems when confronted with potential risks. Its goal is to identify weaknesses in infrastructure and implement corrective measures to minimize their impact. It is important to note that achieving absolute vulnerability-free conditions is merely a theoretical possibility as stability cannot be guaranteed in the real world. Therefore, vulnerability assessment serves as a means to evaluate and quantify situations that can be monitored.

Vulnerability assessment is a comprehensive analysis of the effectiveness of infrastructures and systems when confronted with potential risks. Its objective is to identify weaknesses in infrastructure and implement corrective strategies to mitigate risks. It is important to acknowledge that achieving zero vulnerability is theoretically impossible. Absolute stability does not exist in the real world. Rather, vulnerability assessment allows for the evaluation and quantification of situations that can be monitored. The research in question initiated an assessment of the vulnerability of the infrastructure within this specific province.

According to the research findings, the gas transmission network, with a value of 0.1003, along with the transmission lines for oil and petroleum products, with a score of 0.0988, and the oil and gas storages, with a score of 0.0985, hold the greatest weight and significance. Conversely, gas stations, with a score of 0.0485, are considered the least important. These infrastructures have demonstrated increased importance in comparison to other energy facilities within the province. According to experts, energy-related infrastructures, such as fossil and electric energy, hold greater significance in line with the country's resources and society's energy requirements. The susceptibility of the energy network's infrastructure, coupled with the increasing concentration of crucial infrastructures in the central area of the province and the cities of Yazd and Meibod, indicates a high vulnerability for Yazd, Meibod, and Mehriz, while Bahabad and Khatam fall within the spectrum of vulnerability. Thus, the findings indicate that the central region of Yazd province is at a higher risk due to the presence and concentration of energy infrastructure. Conversely, as we move towards the outskirts of the province, the susceptibility of the infrastructure decreases. Consequently, these findings validate the notion that the principle of dispersing infrastructure, which is a crucial aspect of passive defense in Yazd province, has been overlooked and neglected. As a result, this disregard has amplified the spatial vulnerability of the province.

Furthermore, the way in which people in Yazd province are distributed, both in urban and rural areas, highlights the significance of implementing effective strategies to ensure the safety of energy infrastructure. It is crucial to take necessary measures to prevent any harm to individuals and minimize potential casualties or injuries.

Reducing susceptibility and danger while ensuring consistent security involves adhering to systematic and practical approaches. While the primary focus of ongoing research is predominantly on the research methodology, recognizing the significance of implementing procedures based on the outcomes can lead to more favorable impacts and achievements. It appears essential to develop an all-inclusive plan for managing infrastructure at the national and provincial levels, taking into account passive defense principles. This plan should serve as a foundational document.

The principle of dispersion is a fundamental aspect of passive defense. It is crucial to prioritize this principle in order to ensure the safety of Yazd's critical and sensitive infrastructures. Particularly, considering the dispersion of certain infrastructures away from the central area of the province can effectively decrease the susceptibility of this region to potential threats. In the present circumstances, taking into account the significant expenses involved in relocating certain vital infrastructures in accordance with the dispersion principle, it may not seem practically justified. However, implementing alternative passive defense principles is warranted from a security, strategic, economic, social, and environmental standpoint. Furthermore, it is advisable to:

Using the principle of strengthening and fortification in critical and sensitive infrastructures, especially in the central part of the province;

Utilizing domestically developed technology, we employ efficient and secure advanced warning systems.

Physical protection and physical barriers are implemented to restrict and hinder unauthorized access to critical and sensitive infrastructures, such as the national gas network, transmission network for oil and petroleum products, and the high voltage electricity network within the province.

One way to ensure a backup system in case of infrastructure malfunction, particularly concerning electricity which plays a crucial role in society, is through parallelization and implementation of specific measures.

Ensuring the sufficient storage and provision of safe and reliable raw materials is crucial for the uninterrupted functioning of essential infrastructure systems and components in Yazd province.

Ultimately, it is anticipated that vulnerability can be diminished and harm can be prevented through the implementation of specialized training programs and workshops for managers, employees, and particularly crisis management leaders and provincial supply council heads. These initiatives aim to enhance the knowledge and skills of managers involved in sensitive and critical infrastructures.

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