

Comparative Vulnerability Assessment of Transportation and Energy Infrastructure to Future Maximum Temperature Increase in Fars Province, Iran: A GIS-Based Climate Risk Approach

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Abstract— Rising temperatures associated with climate change are expected to impose increasing pressure on critical infrastructure systems, particularly in arid and semi-arid regions. This study evaluates the potential impacts of future maximum temperature (Tmax) increases on transportation and energy infrastructure in Fars Province, Iran, under the SSP5-8.5 climate scenario for the period 2071–2100. The research adopts a GIS-based climate risk assessment framework to compare the relative vulnerability of transportation infrastructure, including roads, railways, bridges, airports, and railway stations, with energy infrastructure, including power plants, transmission networks, and gas networks. Future Tmax projections are spatially integrated with infrastructure distribution data to identify areas of elevated exposure and vulnerability. The analysis focuses on comparing the spatial patterns and intensity of temperature-related risks between the two infrastructure sectors rather than on climate projections themselves. The results are expected to reveal significant differences in sectoral vulnerability, with infrastructure components characterized by extensive spatial coverage and high operational sensitivity exhibiting greater exposure to future warming. The findings provide a basis for prioritizing adaptation measures, improving infrastructure resilience, and supporting climate-informed planning and management in regions facing increasing thermal stress.

Keywords— Climate Change, Maximum Temperature, Infrastructure Vulnerability, GIS-Based Assessment, Fars Province.

I. INTRODUCTION

Climate change has intensified the frequency, duration, and magnitude of extreme heat events across many regions of the world, making rising temperatures one of the most critical environmental challenges affecting infrastructure systems (Calvin et al., 2023).

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Transportation and energy systems are among the most important components of critical infrastructure because they support economic activities, public services, and regional development (da Silva et al., 2025). These infrastructure systems are increasingly exposed to climate-related hazards, including rising temperatures, which can affect their performance, reliability, and long-term functionality (Sharmin et al., 2026). In the transportation sector, high temperatures can damage road pavements, deform railway tracks, and reduce the operational efficiency of airport facilities (Liu et al., 2023). In the energy sector, increasing temperatures may reduce power plant efficiency, increase electricity transmission losses, and place additional stress on energy networks (Rahbari et al., 2023). These different responses suggest that transportation and energy infrastructure may not experience the same level of vulnerability under future warming conditions (Alblooshi et al., 2026).

Several studies have evaluated the impacts of climate change on transportation or energy infrastructure under future climate conditions (Bari et al., 2024; Climate, 2018; Pantoja Porro et al., 2025). Most previous studies have focused on individual infrastructure sectors or specific infrastructure assets rather than comparing multiple sectors within the same assessment framework (Haghighi et al., 2025; Koks et al., 2019; Nemry & Demirel, 2012). In addition, relatively few studies have combined projected maximum temperature with GIS-based spatial analysis to evaluate infrastructure vulnerability at the regional scale (Kho et al., 2025). This limitation is particularly evident in arid and semi-arid regions such as Iran, where future warming may impose considerable pressure on critical infrastructure systems (Salimi & Al-Ghamdi, 2020). Therefore, a comparative assessment of transportation and energy infrastructure vulnerability under future warming conditions can provide valuable information for climate adaptation and infrastructure planning.

This study presents a GIS-based comparative assessment of transportation and energy infrastructure vulnerability under future maximum temperature conditions. The analysis focuses

on Fars Province and evaluates infrastructure exposure under the SSP5-8.5 climate scenario for the late twenty-first century (2071–2100). Unlike previous studies that primarily examine individual infrastructure sectors, this research compares the relative vulnerability of transportation and energy infrastructure within a unified spatial assessment framework (Reference). The findings are expected to support infrastructure prioritization and climate adaptation planning by identifying the sector that is more vulnerable to future warming. The present study aims to compare the vulnerability of transportation and energy infrastructure to future maximum temperature increases in Fars Province. Using GIS-based spatial analysis, projected maximum temperature under the SSP5-8.5 scenario for the period 2071–2100 is integrated with the spatial distribution of major infrastructure assets. The study addresses the following research question: Which infrastructure sector, transportation or energy, is more vulnerable to future warming? Answering this question can support climate-informed infrastructure planning and the prioritization of adaptation measures.

II. METHODOLOGY

This study employed a GIS-based analytical framework to comparatively assess the vulnerability of transportation and energy infrastructure to projected maximum temperature increases under future climate conditions. Unlike conventional climate projection studies, the proposed framework does not aim to evaluate climate change itself but focuses on identifying which infrastructure sector is more vulnerable to future warming. The analysis integrates projected maximum temperature, infrastructure characteristics, and spatial exposure within a unified GIS environment to support climate-informed infrastructure planning.

The methodology consists of four main stages. First, a geospatial database of transportation and energy infrastructure assets was compiled and organized within a GIS environment. Second, projected maximum temperature (T_{max}) under the SSP5-8.5 scenario for the late twenty-first century (2071–2100) was processed and incorporated as the climatic hazard layer. Third, infrastructure importance and vulnerability indices were assigned based on the functional characteristics of individual infrastructure assets and their expected sensitivity to high-temperature conditions. Finally, the climatic hazard layer and infrastructure datasets were integrated through a semi-quantitative GIS-based risk assessment framework to generate spatial risk maps and enable a comparative evaluation of transportation and energy infrastructure vulnerability.

Spatial analyses were performed within the GIS environment, while additional data processing, map preparation, and analytical procedures were implemented using Python scripts to ensure computational consistency and reproducibility. The resulting risk maps provide a regional-scale assessment of infrastructure vulnerability under projected future warming and identify spatial hotspots where

critical infrastructure assets coincide with areas experiencing higher maximum temperatures.

The first stage of the analysis involved the development of a geospatial database containing the selected transportation and energy infrastructure assets within Fars Province. Establishing a unified spatial database enables the integration of infrastructure information with projected climate data and provides the basis for spatial vulnerability assessment.

Infrastructure datasets were collected from official national organizations responsible for transportation and energy management. The transportation sector included road networks, railway lines, bridges, airports, and railway stations, while the energy sector comprised power plants, electricity transmission networks, and gas transmission networks. Because these datasets were obtained from different organizations and provided in various formats, all spatial layers were harmonized, quality-checked, and converted into a common GIS database before analysis.

The climatic dataset consisted of projected annual maximum temperature (T_{max}) under the SSP5-8.5 scenario for the late twenty-first century (2071–2100). The temperature raster was prepared at approximately 1 km spatial resolution and projected into the same coordinate system as the infrastructure database to ensure spatial consistency during overlay analysis.

Following data preparation, all infrastructure layers were organized according to infrastructure type and converted into standardized geospatial formats suitable for spatial analysis. Linear infrastructure assets, including roads, railways, transmission lines, and gas networks, were preserved as polyline layers, whereas airports, railway stations, bridges, and power plants were represented as point features. This standardized geospatial database formed the basis for the subsequent vulnerability assessment and GIS-based risk analysis.

The importance of critical infrastructure is commonly determined according to its role in maintaining essential societal functions, including transportation services, energy supply, economic activities, and public safety (Forzieri et al., 2018). Infrastructure disruption may lead to cascading consequences that extend beyond the affected asset and influence the performance of interconnected systems. Therefore, evaluating infrastructure importance is a fundamental step in climate risk assessment (Koks et al., 2019).

In this study, an impact-based classification approach was adopted to assign infrastructure importance according to the functional role and regional significance of each infrastructure type. Infrastructure assets providing wider regional services or supporting essential public functions were assigned higher importance values than assets with more localized functions. The importance index used in this study is presented in Table 1 (Pescaroli & Alexander, 2018).

The vulnerability of infrastructure represents the degree to which an infrastructure asset is likely to be adversely affected by a given climatic hazard. Since this study focuses on

projected increases in maximum temperature, vulnerability was evaluated based on the expected sensitivity of each infrastructure type to prolonged exposure to high-temperature conditions. Infrastructure systems directly influenced by thermal stress, material degradation, or temperature-related operational limitations were assigned higher vulnerability scores than systems with limited sensitivity (Birkmann et al., 2013).

TABLE 1. INFRASTRUCTURE IMPORTANCE INDEX (HAWCHAR ET AL., 2020)

Infrastructure Importance Level	Importance Index (I)
Local	1
Regional	2
National	3
Vital National / International	4

Following this approach, infrastructure importance (I) and vulnerability (V) indices were assigned using standardized four-level classification schemes. These indices enable the integration of infrastructure characteristics with projected climatic conditions within the GIS-based risk assessment framework. The importance index is presented in Table 1, while the vulnerability index is summarized in Table 2 (Hawchar et al., 2020).

TABLE II. VULNERABILITY INDEX (HAWCHAR ET AL., 2020)

Level of relationship between climate hazard and infrastructure system	Vulnerability Index (V)
No relationship	0
Low	1
Moderate	2
High	3

Projected increases in maximum temperature represent one of the most important climate hazards affecting the long-term performance of critical infrastructure. Prolonged exposure to high temperatures may accelerate material deterioration, reduce structural performance, increase maintenance requirements, and disrupt the operation of infrastructure systems (Kho et al., 2025). The magnitude of these impacts varies among infrastructure types according to their physical characteristics, operational functions, and sensitivity to thermal stress (Kopiika et al., 2025).

Based on the projected maximum temperature dataset, infrastructure assets were evaluated according to their expected exposure to future warming conditions. The assessment does not quantify the physical damage of individual infrastructure components; instead, it provides a relative comparison of infrastructure vulnerability using standardized importance and vulnerability indices integrated within a GIS environment. Transportation infrastructure considered in this study includes road networks, railway lines,

bridges, airports, and railway stations. The energy sector comprises power plants, electricity transmission networks, and gas transmission networks. Each infrastructure type was assigned an importance index and a vulnerability index according to its functional significance and expected sensitivity to high-temperature conditions. The adopted classification is summarized in Table 3 (Hawchar et al., 2020).

TABLE III. LIST OF CRITICAL INFRASTRUCTURE ASSETS IN THE TRANSPORTATION AND ENERGY SECTORS (HAWCHAR ET AL., 2020)

Sector	Assets		Importance Index (I)	Vulnerability Index (V)
Transport	Airports	Government-owned international airports	4	3
	Railway stations	Large railway stations	2	1
		Small railway stations	3	1
	Railway network	Railway lines	2	3
	Road network	National roads	1	3
		Regional roads	3	3
	Bridges	Railway bridges	3	3
		National road bridges	2	3
		Regional road bridges	3	3
	Energy	Power plants	Large power plants (capacity > 100 MW)	3
Small power plants (capacity < 100 MW)			3	3
Gas network		High-pressure gas network	3	1
		Medium-pressure gas network	4	1
		Low-pressure gas network	3	1

The assigned importance and vulnerability indices were subsequently combined with the projected maximum temperature layer during the GIS analysis. This integration enables the spatial comparison of infrastructure vulnerability and supports the identification of areas where highly important infrastructure assets coincide with regions projected to experience greater future warming.

To evaluate the spatial distribution of infrastructure vulnerability under future warming conditions, projected maximum temperature ($T_{\max}$) was integrated with the infrastructure database using a GIS-based analytical framework. The projected $T_{\max}$ raster was overlaid with the spatial distribution of transportation and energy infrastructure to identify locations where critical assets are expected to experience greater thermal exposure during the 2071–2100 period under the SSP5-8.5 scenario.

The analysis was conducted using a grid-based approach to enable a consistent comparison of infrastructure vulnerability across the study area. The study region was divided into regular grid cells, and the amount of infrastructure located within each cell was calculated according to infrastructure type. Linear infrastructure, including roads, railways, electricity transmission lines, and gas transmission networks, was quantified using total length within each grid cell, whereas discrete infrastructure assets such as airports, railway stations, bridges, and power plants were quantified using feature counts.

The relative contribution of each infrastructure type within every grid cell was weighted according to its infrastructure importance (I) and vulnerability (V) indices. This weighting procedure enables infrastructure assets with higher functional significance and greater sensitivity to thermal stress to contribute more strongly to the overall infrastructure measurement. The resulting weighted infrastructure measurement index represents the spatial concentration of infrastructure potentially affected by future maximum temperature.

According to the IPCC risk framework, climate-related risk emerges from the interaction of climatic hazards, infrastructure vulnerability, and exposure (Smith et al., 2014). In the present study, projected maximum temperature ($T_{\max}$) is considered the climatic hazard, whereas the spatial distribution and characteristics of transportation and energy infrastructure represent the exposure and vulnerability components. To integrate these factors within a unified GIS environment, a weighted infrastructure measurement index was calculated for each grid cell based on the importance and vulnerability assigned to individual infrastructure assets:

$$M_{th}^{(g)} = \sum_{a=1}^{n_a} (I_a \cdot V_{a,th}) \cdot m_a^{(g)} \quad (1)$$

where $M_{th}^{(g)}$ is the weighted infrastructure measurement within grid cell g , I_a denotes the importance index of infrastructure type a , $V_{a,th}$ represents the vulnerability index of infrastructure type a with respect to the investigated thermal

hazard, and $m_a^{(g)}$ corresponds to the infrastructure measurement within grid cell g , expressed as the total length for linear infrastructure or the number of facilities for point-based infrastructure.

To allow comparison of infrastructure vulnerability across the study area, the weighted infrastructure measurements were normalized as follows:

$$R_{th}^{(g)} = \frac{M_{th}^{(g)} - M_{th}^{\min}}{M_{th}^{\max} - M_{th}^{\min}} \in [0,1] \quad (1)$$

where $M_{th}^{\min}$ and $M_{th}^{\max}$ denote the minimum and maximum values of the weighted infrastructure measurement among all grid cells, respectively. The resulting normalized index $R_{th}^{(g)}$ expresses the relative spatial distribution of infrastructure vulnerability, with larger values indicating a greater concentration of highly important and thermally sensitive infrastructure (Hawchar et al., 2020).

The normalized infrastructure risk index was subsequently combined with the projected maximum temperature layer to generate regional risk maps. Areas characterized by high infrastructure concentration and elevated projected maximum temperatures were identified as relative thermal-risk hotspots. Rather than estimating absolute physical damage, the proposed framework provides a comparative assessment of infrastructure vulnerability. The resulting maps enable a spatial comparison of the relative vulnerability of transportation and energy infrastructure, supporting the identification of priority areas for climate adaptation and infrastructure planning.

III. RESULTS

The results are presented in a stepwise manner to illustrate the spatial characteristics of projected maximum temperature and their implications for infrastructure vulnerability. The analysis begins with the spatial distribution of $T_{\max}$ under the SSP5-8.5 scenario for the period 2071–2100, followed by the GIS-based assessment of transportation and energy infrastructure risk. Finally, the relative vulnerability of the two infrastructure sectors is evaluated based on the derived risk maps and summary statistics.

As shown in Fig. 1, the projected spatial distribution of maximum temperature ($T_{\max}$) under the SSP5-8.5 scenario exhibits a distinct spatial gradient across Fars Province. Higher $T_{\max}$ values are predominantly concentrated in the northern, northeastern, and parts of the central regions, whereas comparatively lower values occur in the southern and southwestern areas. This non-uniform distribution indicates that future thermal exposure is expected to vary considerably across the province rather than occurring uniformly. Consequently, infrastructure located within the northern portion of the study area is expected to experience greater thermal loading than assets situated in the southern regions. Although Fig. 1 identifies the spatial pattern of the climatic hazard, it does not represent infrastructure vulnerability

directly. The relative risk depends on the spatial coincidence of projected T_{max} with infrastructure distribution, importance, and vulnerability, which is examined in the following sections.

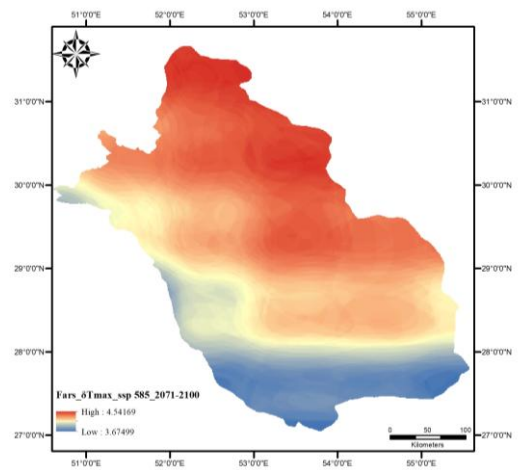


Fig.1. Projected spatial distribution of maximum temperature (T_{max}) in Fars Province under the SSP5-8.5 scenario for the period 2071–2100

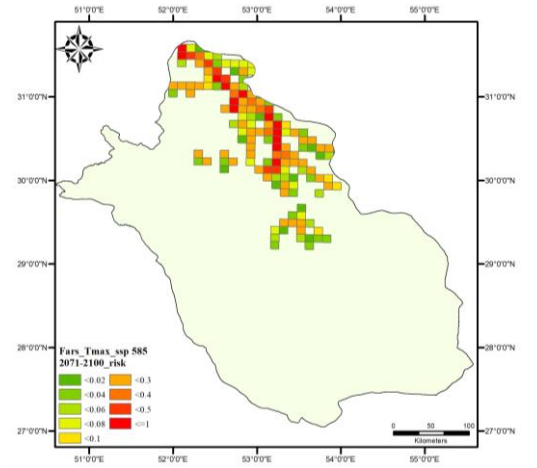


Fig. 2. Spatial distribution of infrastructure risk associated with projected maximum temperature (T_{max}) in Fars Province under the SSP5-8.5 scenario for the period 2071–2100

TABLE IV. SPATIAL ASSESSMENT OF INFRASTRUCTURE RISK ASSOCIATED WITH PROJECTED MAXIMUM TEMPERATURE (T_{MAX}) IN FARS PROVINCE UNDER THE SSP5-8.5 SCENARIO FOR THE PERIOD 2071–2100.

Infrastructure Type	Unit	Total Infrastructure	Climate Risk Distribution	Relative Share of Risk Classes (%)
Transportation Bridges	No.	3,854	Increased Risk: 296 No Significant Change: 3,558	Increased Risk: 7.68% No Significant Change: 92.32%
Airports	No.	7	No Significant Change: 7	No Significant Change: 100%
Oil and Gas Transmission Networks	km	2,343.15	Increased Risk: 460.17 km No Significant Change: 1,882.98 km	Increased Risk: 19.64% No Significant Change: 80.36%
Electricity Transmission Lines	km	2,333.86	Increased Risk: 483.34 km No Significant Change: 1,850.51 km	Increased Risk: 20.71% No Significant Change: 79.29%
Power Supply Facilities	No.	7	Increased Risk: 1 No Significant Change: 6	Increased Risk: 14.29% No Significant Change: 85.71%
Railway Stations	No.	7	Increased Risk: 6 No Significant Change: 1	Increased Risk: 85.71% No Significant Change: 14.29%
Railway Network	km	399.70	Increased Risk: 290.52 km No Significant Change: 109.17 km	Increased Risk: 72.69% No Significant Change: 27.31%
Road Network	km	6,115.41	Increased Risk: 983.12 km No Significant Change: 5,132.29 km	Increased Risk: 16.08% No Significant Change: 83.92%

Table 4 summarizes the proportion of selected transportation and energy infrastructure located within areas projected to experience increased maximum temperature under the SSP5-8.5 scenario during 2071–2100. The results reveal substantial differences in vulnerability among infrastructure types, indicating that future warming is expected to affect infrastructure systems unevenly.

Within the transportation sector, railway infrastructure exhibits the highest level of exposure to projected thermal risk. Approximately 72.69% of the railway network and 85.71% of railway stations are located within areas characterized by increased maximum temperature. In comparison, only 16.08% of the road network and 7.68% of transportation bridges fall within the increased-risk category, while none of the airport facilities are projected to experience significant changes in thermal risk. The energy sector shows a more moderate level of projected exposure. Approximately 20.71% of electricity transmission lines and 19.64% of oil and gas transmission networks are located within areas of increased thermal risk. Similarly, only one of the seven power supply facilities (14.29%) is situated within the projected high-risk zone. A comparison between the two infrastructure sectors suggests that transportation infrastructure is generally more vulnerable to future maximum temperature than energy infrastructure. This difference is primarily driven by the extensive exposure of railway assets, which are concentrated within regions projected to experience greater warming. In contrast, the spatial distribution of energy infrastructure appears to be less closely aligned with the identified thermal-risk hotspots. These findings highlight the importance of prioritizing adaptation strategies for transportation corridors, particularly railway infrastructure, while maintaining targeted resilience measures for critical energy transmission systems.

IV. DISCUSSION

The results demonstrate that projected increases in maximum temperature under the SSP5-8.5 scenario are not spatially uniform across Fars Province. Instead, areas of elevated thermal risk are concentrated within specific regions, resulting in considerable differences in the vulnerability of critical infrastructure. This spatial heterogeneity indicates that future climate impacts on infrastructure systems are strongly influenced by local geographic conditions and the spatial configuration of infrastructure assets. Similar spatially differentiated climate responses have been reported in previous regional climate studies, emphasizing the need for location-specific climate risk assessments (Calvin et al., 2023; Lelieveld et al., 2012).

A comparison of infrastructure sectors indicates that transportation infrastructure, particularly railway networks, is more vulnerable to future warming than energy infrastructure. The higher exposure of railway assets is mainly associated with their linear configuration and extensive spatial distribution, which increase the probability of intersecting areas projected to experience elevated maximum temperatures. Similar observations have been reported in previous studies, which identified linear infrastructure systems

as among the most climate-sensitive components because of their network continuity, large spatial extent, and dependence on local environmental conditions (Hallegatte et al., 2019; Papilloud & Keiler, 2021).

From a practical perspective, the generated GIS-based risk maps provide a useful screening tool for identifying infrastructure assets that may require priority adaptation measures under future warming conditions. Such spatial information can support infrastructure managers and decision-makers in prioritizing maintenance programs, improving resource allocation, and incorporating climate considerations into long-term infrastructure planning. Although the proposed framework does not replace detailed engineering assessments, it provides an efficient regional-scale approach for identifying vulnerability hotspots and supporting climate-resilient infrastructure management (De Moel et al., 2015).

The present study is subject to several limitations. The results depend on the uncertainty associated with future climate projections and the spatial resolution of the climatic datasets. Moreover, the adopted semi-quantitative framework provides a relative assessment of infrastructure vulnerability rather than a direct estimation of physical damage. Nevertheless, the proposed approach offers a practical basis for comparing the relative vulnerability of different infrastructure sectors and identifying priority areas for future adaptation planning (Hawkins & Sutton, 2009).

V. CONCLUSION

This study presented a GIS-based framework to assess the relative vulnerability of transportation and energy infrastructure to projected maximum temperature under the SSP5-8.5 climate scenario for the period 2071–2100 in Fars Province, Iran. By integrating projected Tmax data with spatial information on critical infrastructure, the proposed approach identified areas where future warming is expected to coincide with infrastructure systems of higher importance and vulnerability. The results revealed a distinct spatial pattern of thermal risk across the province. High-risk areas were primarily concentrated in the northern and north-central regions, while comparatively lower risk levels were observed elsewhere. The quantitative assessment further demonstrated that transportation infrastructure, particularly railway networks and railway stations, is more vulnerable to projected future warming than energy infrastructure. In contrast, airports and most power supply facilities showed relatively limited exposure to increased thermal risk. The proposed framework provides a practical regional-scale tool for identifying infrastructure vulnerability hotspots and supporting climate-informed infrastructure planning. The resulting risk maps can assist planners and decision-makers in prioritizing adaptation measures, improving resource allocation, and enhancing the long-term resilience of critical infrastructure systems under future climate conditions.

Future studies may extend the proposed framework by incorporating additional climate hazards, multiple emission scenarios, and engineering-based vulnerability indicators to

provide a more comprehensive assessment of climate-related infrastructure risk

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