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Research article

A spatiotemporal analysis of personal casualty accidents in China's electric power industry

Shu Chen [a,b], Dianxue Wang [a,b], Xinkai Zhang [c], Bo Shao [a,b,*], Kunyu Cao [a], Zhi Li [d]

[a] Hubei Key Laboratory of hydropower engineering construction and management, China Three Gorges University, Yichang, Hubei, 443002, China
[b] College of Hydraulic & Environmental Engineering, China Three Gorges University, Yichang, 443002, China
[c] Shanghai Investigation, Design & Research Institute Corporation, Shanghai, 200335, China
[d] China Three Gorges Corporation, Wuhan, 430010, China

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ABSTRACT

The electric power industry in China has experienced significant growth in recent years. Despite efforts to improve safety management in the industry, accidents still occur frequently. This study aimed to analyze the personal casualty accidents in the electric power industry from 2012 to 2021. Specific methods used include descriptive analysis, principal component analysis, and Theil index model. The results indicated that fall, electric shock, and collapse were the primary types of accidents, accounting for 59.65 % of all accidents. Accidents were higher in April and August, but lower in February. While the accident rate was relatively low on Mondays, the fatality rate was higher on Mondays, Thursdays, and Fridays. Taking into account accidents, workload, and labor, we found that Ningxia, Hainan, and Guangxi exhibited subpar levels of safety management within the electric power industry. The overall difference in the number of deaths in 31 provinces was significant in 2012 and 2016. It was significantly reduced in 2021. In terms of the proportion of intraregional and interregional differences, there were significant differences in the number of accidents and fatalities between provinces in the Central China and North China regions. This study provides valuable insights for enterprises to formulate accident prevention strategies and for the government to develop relevant policies.

1. Introduction

With the continual growth of China's economy, the electricity demand is persistently increasing. In 2012, the total electricity consumption for the entire society reached 4.96 trillion kWh, and by 2021, this figure had risen by 67.34 percent to 8.3 trillion kWh. In response to the increasing demand, China's installed electric power generation capacity had reached 2.38 billion kilowatts by 2021 [1]. This vast electric power generation capacity has established a solid foundation for China's industrialization [2]. The standard operations of all industries depend heavily on supportive electricity [3]. The security and reliability of the electric power industry have become crucial conditions for social development [4]. However, accidents leading to personal casualty have occurred intermittently during electricity production and construction, including severe and exceptionally severe accidents. For instance, in June 2012, a catastrophic mudslide occurred at a hydropower facility in Sichuan, resulting in the tragic fatalities of 11 operators. The collapse of a

* Corresponding author. Hubei Key Laboratory of hydropower engineering construction and management, China Three Gorges University, Yichang, Hubei, 443002, China.

E-mail address: shaobo@ctgu.edu.cn (B. Shao).

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cooling tower construction platform at an electric power plant in Jiangxi in 2016 led to 73 deaths. Accidents can often have negative effects, leading to significant personal, social, and economic setbacks [5]. To promote safety and reduce fatal accidents in the electric power industry, it is necessary to analyze the characteristics of personal casualty accidents that occur in the electric power industry.

In recent years, extensive research has been conducted on safety accidents in the electric power industry. Categorizing accidents enables gaining insight into the factors influencing various types of accidents. Fan et al. classified 324 grid accidents according to risk factors and identified the main factors contributing to the accidents, e.g. the main risk factors for fall from height accidents were failure of safety guards, tower collapse, and quality of equipment, and they also found that unsafe human behavior was the main factor contributing to accidents involving damage to grid equipment [6]. Human factors play a crucial role in leading to accidents [7]. To reduce human unsafe behaviors in the power industry, Shi et al. developed an assessment model based on a back-propagation neural network, which determines the weights of the unsafe behaviour indicators and their non-linear relationship with the workers' unsafe behaviours, and provides the basis for preventive and curative measures [8]. DONG et al. introduced the HFACS model to the electric power industry to explore the complex relationship between human factors in electric power accidents and combined it with grey correlation analysis techniques to study electric power safety accidents. The results showed that violation of rules is closely related to the preconditions for the occurrence of unsafe behaviors, and the environment in which the operator is located and his own state are directly related to the occurrence of unsafe behaviors [9]. Accidents are usually not caused by human factors alone but by a combination of different factors [10,11]. Lu et al. used text mining technology to mine and analyze the text of personal injury and death accident reports in the power industry, and constructed a system of potential risk factors for major accidents, including human factors, physical factors and management factors, which reduces the subjectivity of potential security threats identified and judged, and lays the foundation for intelligent security management [12]. Since most of the current studies mainly focus on analyzing internal causes of accidents, few have presented spatiotemporal characteristics of accidents on the macro level. Therefore, it is imperative to analyze the spatiotemporal characteristics of personal casualty accidents in the electric power industry.

Statistical analyses are utilized to identify accident characteristics and establish a foundation for accident prevention [13]. Statistical analysis of accidents has primarily been applied to construction accidents [14,15], coal mining accidents [16], and road accidents [17]. Shao et al. and Xu et al. investigated the characteristics of fatal accidents in China's construction industry based on statistical data [14,15]. The difference between the two was that Shao et al. combined correlation coefficient analysis to explore the correlation between different factors, for example, there was a significant correlation between the type of accident and the severity of the accident [14]. Wang et al. analyzed the type, time of occurrence, location, and direct causes of major accidents in China's coal mines in 2016, and offered recommendations on the prevention and control of coal mine accidents [16]. To examine the pattern of major traffic accidents on Chinese highways, Wei et al. analyzed 802 major highway traffic accidents from 2011 to 2021 on multiple dimensions. The results showed a fluctuating downward trend in the incidence of major and major traffic accidents and the number of casualties on motorways over the past decade [17]. Several scholars used factor analysis as an auxiliary tool in studying accidents when analyzing accident statistics [18,19]. Given the different risk factors involved, it is difficult to predict accident occurrence. However, statistical analysis can reveal general patterns of accident occurrence and is widely utilized in the field of accident prevention [20], providing a valuable reference for this study.

In studies on the spatiotemporal characteristics of accidents, Feizizadeh et al. analyzed the spatiotemporal trends of urban traffic accident hotspots in Iran during the COVID-19 epidemic using the severity index and kernel density methods, and the study showed that areas with predominantly industrial lands are the hardest hit by urban traffic accidents, and that they have a higher risk of accidents [21]. Joghataei et al. evaluated the spatiotemporal trends of the burden of occupational accidents and injuries in Iran from 2011 to 2018, both at the national and local levels, and found a decreasing trend over time [22]. Wang et al. investigated the spatiotemporal characteristics of waterway accidents, both in terms of accident occurrence and accident consequences, and found that the total number of emergency events had a significant spatiotemporal distribution and that the number of fatalities and missing persons in major rivers increased sharply on June [23]. Rex et al. identified the spatial and temporal patterns of fire occurrence in Metro Manila through spatial and temporal analysis of 3506 fire accidents from 2011 to 2016, providing a reference for firefighting resource allocation and firefighting strategic planning in Metro Manila [24]. From the above studies, it becomes clear that spatiotemporal characterization of accidents can visually express their regularities in time and space. It has a guiding significance for incident prevention and provides research ideas for this study.

Previous studies have mostly focused on the study of various factors that cause accidents, with little attention paid to the temporal and spatial characteristics of electric power accidents. It is worth noting that due to the rapid development of China's electric power industry and economic situation, the characteristics of electric power accidents show differences in time. In addition, due to the different electric power development conditions in different regions and cities, the electric power accidents also differ spatially. Mining such spatial and temporal characteristics from historical data can suggest more effective control measures for power accidents. Based on this, this study took personal casualty accidents in China's electric power industry as the research object and analyzed their characteristics in time, space, and the development of spatial differences, filling a gap in the spatiotemporal analysis of accidents in the electric power industry. We started by counting the types of accidents that occurred and then used the statistical and Theil index model to examine time, space, and the development of spatial differences in accidents. In analyzing accidents spatially, we took into consideration differing generating capacities and employee numbers between provinces. To more accurately reflect safety management levels in provinces of the electric power industry, this paper integrated multiple indicators to evaluate them. By analyzing spatial and temporal characteristics of casualty accidents in the electric power industry, we can intuitively understand the temporal distribution pattern of accidents, the level of safety management in different provinces, as well as the differences between provinces in different years. This provides decision support for relevant departments in taking preventive measures and enhancing the ability and efficiency of controlling accidents in the electric power industry, thus ensuring its safe and stable development.

2. Materials and methods

2.1. Data collection

In this paper, we employed secondary data collection methods to retrieve annual nationwide data on personal casualty accidents in China's electric power industry from the official website of China's National Energy Administration (NEA) [25]. Every month, the Administration issues a bulletin on national electricity safety production, which details accidents and their descriptions in the electric power industry. The accident data spanned from January 1, 2012 to December 31, 2021 and encompassed 461 accidents involving injury and mortality across 31 Chinese provinces (excluding Hong Kong, Macau, and Taiwan).

Based on China's electric power industry standards, the types of accidents were classified as fall, electric shock, collapse, mechanical damage, struck by objects, tower fall, hoist damage, burn, drowning, poisoning, vehicle damage, explosion, mudslide, fire, roof fall, and landslide [26]. According to the Regulation on Guidelines for Reporting and Investigating Production Safety Accidents which was promulgated by Decree No. 493 of the State Council on November 3, 2018 of the People's Republic of China, accident classifications could be determined based on the number of deaths, injuries, and economic losses of an accident [27]. Let's take the ordinary accident level as an example for a brief explanation: the ordinary accident level refers to accidents that cause less than 3 deaths, less than 10 serious injuries, or less than 10 million yuan of direct economic losses. The specific criteria for the classification of accident levels are shown in Table 1.

Since accident descriptions lack standardization, crucial accident information was extracted from the raw data to obtain data that is suitable for accident analysis. For instance, the "province" was obtained from the "accident location", while "accident severity" was derived from the "number of casualties". Table 2 presents the final statistics on time, location, number of casualties, accident severity, and accident type. It is worth noting that the electricity generating capacity and the number of employees in the electric power industry in each province were obtained from the annual China Statistical Yearbook [1].

2.2. Methods

This study adopted an empirical research methodology to extract key information such as time, location, and number of accident casualties by crawling massive accident reports from relevant websites. Descriptive statistics, principal component analysis, and the Theil index method were applied to deeply analyze the temporal distribution, spatial distribution, and the development of spatial differences of accidents in China's electric power industry. Where descriptive statistical analysis is to use statistical knowledge to count the number of accidents and fatalities in three dimensions: yearly, monthly and weekly, and visualize them in bar charts; PCA is to consider the accident, power generation and labour and other factors using SPSSPRO software in the data analysis function to carry out principal component analysis research, in order to make the results of the study more intuitive, we use the ArcMap mapping tool to visualize the results of the study show; Theil index is the result of using the formula editing function in Excel to set up the model formula, and then importing the number of accidents and the number of deaths in different regions in different years, and visualizing the results through the Origin drawing tool. The specific research methodology will be detailed in the subsequent paper.

2.2.1. Descriptive analysis

Descriptive analysis is a statistical method that involves the classification and tabulation of data, as well as the use of graphs and computational generalizations to characterize it [28]. In this paper, descriptive analysis was applied to the frequency statistics of 461 personal casualty accidents that occurred in the electric power industry, analyzing them by accident type, time, and location. Histograms and pie charts were utilized to provide a visual representation of the accident type and time analyses, thereby revealing general patterns of accidents through the charts. The locations of accidents were also carefully counted to prepare for comprehensive assessments of safety management levels in the electric power industry across each province. The legend abbreviations and full titles needed for interpreting the graphs are presented in Table 3. Where ANFA was the ratio of the number of fatalities to the number of accidents; and ANFOMA was the ratio of the number of fatalities to the number of accidents caused by ordinary and major accidents.

2.2.2. Principal component analysis

Principal Component Analysis (PCA) is a method that uses the idea of reducing the dimensionality of data and retaining the most important information in order to better understand and analyze the inherent structure and patterns of the data [29]. In this study, Information on personal casualty accidents, power generation, and labor in the electric power industry was extracted from raw data. Then, we employed principal component analysis to determine the contribution rate and eigenvectors of each component and identified those components with a cumulative contribution rate of over 85 % as statistically significant principal components. The eigenvector coefficients a_{ij} and evaluation index x_j were multiplied and added to derive the principal component f_i, as shown in

Table 1
Classification of the accident level in China.

Accident Level	Ordinary	Major	Severe	Extraordinarily Severe
Deaths	$[0,3)$	$[3,10)$	$[10,30)$	≥ 30
Number of Injured	$[0,10)$	$[10,50)$	$[50,100)$	≥ 100
Economic Loss (million yuan)	$[0,10)$	$[10,50)$	$[50,100)$	≥ 100

Table 2
Data on personal casualties in the electric power industry.

Number	Date	Province	Deaths	Number of injured	Accident level	Type of accident
1	2012.01.06	Zhejiang	3	0	Major	Collapse
2	2012.02.07	Inner Mongolia	2	0	Ordinary	Fire
3	2012.02.27	Yunnan	1	0	Ordinary	Electric shock
⋮	⋮	⋮	⋮	⋮	⋮	⋮
459	2021.11.09	Fujian	1	0	Ordinary	Struck by object
460	2021.11.12	Shanxi	1	0	Ordinary	Mechanical damage
461	2021.12.29	Guangdong	1	0	Ordinary	Mechanical damage

Table 3
Abbreviations and full titles.

Abbreviation	Full title
NA	Number of Accidents
NDA	Number of Deaths in Accidents
NIA	Number of Injuries in Accidents
ANFA	Average Number of Fatalities per Accident
ANFOMA	Average Number of Fatalities per Ordinary and Major Accident

equation (1). Based on the contribution rate b_i of each principal component, we obtained the weighted superposition of principal components f_i to determine the final evaluation value of safety management levels in each province of the electric power industry. The specific mathematical expression is displayed in equation (2).

$$f_i = \sum_{j=1}^{n} a_{ij} x_j (i = 1, \dots, m) \tag{1}$$

$$F = \sum_{i=1}^{m} b_i f_i \Big/ \sum_{i=1}^{m} b_i \tag{2}$$

Where n is the number of evaluation indicators; m is the number of eligible principal components.

2.2.3. *Theil index model*

As the main method that can quantitatively show the trend of differences within and between groups and the extent to which differences between two groups contribute to overall differences, the Theil index method has been widely used in regional development [30], and in the analysis of spatial differences in carbon emission [31]. The number of deaths in accidents and the number of accidents were representative indicators used by the Ministry of Emergency Management to reflect the level of safety production [32]. Therefore, this paper chooses the number of accidents and the number of deaths as the research objects to explore the spatial variation of personal casualty accidents in China's electric power industry. The country's 31 provinces are divided into six regions based on the way the jurisdiction of the six regional energy regulators is divided [33]. The specific division is shown in Table 4. By calculating the total difference T_i in region i, we can obtain the intra-regional difference T_{WR}. Adding the intra-regional difference T_{WR} to the inter-regional difference T_{BR}, we can obtain the national total difference T. The specific expressions are shown in (3) to (6).

$$T_i = \frac{1}{n_i} \sum_{j=1}^{n_i} \frac{y_{ij}}{\overline{y}} \log \frac{y_{ij}}{\overline{y_i}} \tag{3}$$

$$T_{BR} = \frac{1}{n} \sum_{i=1}^{m} n_i \frac{\overline{y_i}}{\overline{y}} \log \frac{\overline{y_i}}{\overline{y}} \tag{4}$$

Table 4
Regional division.

Region	Province
South China region	Guangdong, Guangxi, Yunnan, Guizhou, Hainan
North China region	Beijing, Tianjin, Hebei, Inner Mongolia, Shanxi
Northeast China region	Heilongjiang, Jilin, Liaoning
Northwest China region	Shaanxi, Qinghai, Ningxia, Gansu, Xinjiang
East China region	Shanghai, Jiangsu, Zhejiang, Anhui, Shandong, Fujian
Central China region	Henan, Hubei, Chongqing, Jiangxi, Hunan, Sichuan, Tibet

$$T_{WR} = \sum_{i=1}^{m} \frac{n_i \overline{y_i}}{n \overline{y}} T_i \tag{5}$$

$$T = T_{BR} + T_{WR} \tag{6}$$

where m is the number of regions; n_i is the number of provinces included in the region i; y_{ij} is the value of the indicator for province j in the region i, $\overline{y}$ is the average value of the indicator for all provinces in the country; $\overline{y_i}$ is the average of the indicators for all provinces in the region i.

3. Result

3.1. Type of accidents

Statistical analysis of different types of accidents can provide a basis for taking targeted prevention and control measures.Since the average number of fatalities per accidents (ANFA) was used, this section provided standard deviation of accident fatalities (SDAF) in addition to NA, NDA, and NIA data, which are shown in Table 5.

As shown in Table 5, the number of accidents and the number of deaths are higher for the two types of accidents: fall and electric shock, but the Average number of fatalities per accidents (ANFA) is 1.11 and 1.08, respectively, which is lower than other accidents. This indicates that falls and electric shocks mostly cause single fatalities. The collapse resulted in the highest number of deaths, amounting to 166 fatalities. The ANFA was calculated to be 3.53, indicating group death and injuries phenomenon is obvious in the collapse accident, the accident is more dangerous. To reduce and prevent the collapse accidents, the safety management department should do a good job in the investigation and design of construction, and strengthen the review of construction programs and the inspection of construction quality. The ANFA in mudslide accidents is the highest at 13.2. During electricity production and construction activities, workers should always pay attention to the influence of extreme weather conditions and carry out good geological surveys. In addition, the number of accidents and fatalities caused by poisoning, explosion and landslide is low, but the ANFA is more than 2, which needs to be taken more seriously when operating.

To gain a better understanding of the magnitude of the hazards of the various types of accidents, we have analyzed the percentage of accidents of each type among major or higher level accidents. As shown in Fig. 1, the incidence of collapse accidents is highest among major and above grade accidents. In addition, the proportion of tower fall accidents is also relatively high. The two types of accident, collapse and tower fall, together accounted for 53.5 %. Therefore, while preventing collapse accidents, workers should also carry out timely investigation of hidden hazards in towers to prevent tower fall accidents. Although accidents involving struck by object, hoisting damage, and burn may not result in major accidents, they should still be given high priority due to the potential threat they pose to personnel safety.

3.2. Time distribution of accidents

After sorting out the accident it was found that out of a total of 461 accidents, only 4 were classified as major or extraordinarily major. They resulted in 133 fatalities, which accounts for 18.14 % of the total number of fatalities. This indicates that these two levels of accidents are infrequent but have a significant impact on the results. Therefore, this paper considered the Average number of fatalities per ordinary and major accident (ANFOMA) to study the characteristics of the time distribution of personal casualty accidents in China's electric power industry. The annual, monthly and weekly characteristics of accidents are shown in Fig. 2.

3.2.1. Accident distribution by year

As illustrated in Fig. 2(a), there were occasional fluctuations in the frequency of accidents between 2012 and 2021, but overall, a downward trend was observed. Specifically, the number of accidents decreased from 52 in 2012 to 35 in 2021. Moreover, the number of accidents hit its lowest point during the 12th Five-Year Plan period (2011–2015) in 2015, which could be attributed to reduced work intensity. An analysis of the annual growth rate of electric power generation revealed that the national growth rate in 2015 was the lowest in that period, standing at approximately 2.93 % [1]. The number of accidents decreased significantly in 2018 compared to

Table 5
Distribution of casualties by type.

Type	NA	NDA	NIA	ANFA	SDAF	Type	NA	NDA	NIA	ANFA	SDAF
Fall	119	132	7	1.11	0.45	Burn	9	6	20	0.67	0.71
Electric shock	116	125	12	1.08	0.42	Vehicle damage	7	7	0	1.00	0.00
Mechanical damage	48	61	3	1.27	0.98	Explosion	6	13	6	2.17	1.17
Collapse	47	166	29	3.53	10.47	Mudslide	5	66	1	13.20	12.82
Struck by object	34	38	1	1.12	0.33	Fire	4	6	0	1.50	0.58
Tower fall	33	58	6	1.76	1.03	Other	2	2	0	1.00	0.00
Hoist damage	10	12	0	1.20	0.42	Roof fall	1	2	0	2.00	0.00
Drowning	10	16	0	1.60	1.35	Landslide	1	4	1	4.00	0.00
Poisoning	9	18	5	2.00	1.30	–	–	–	–	–	–

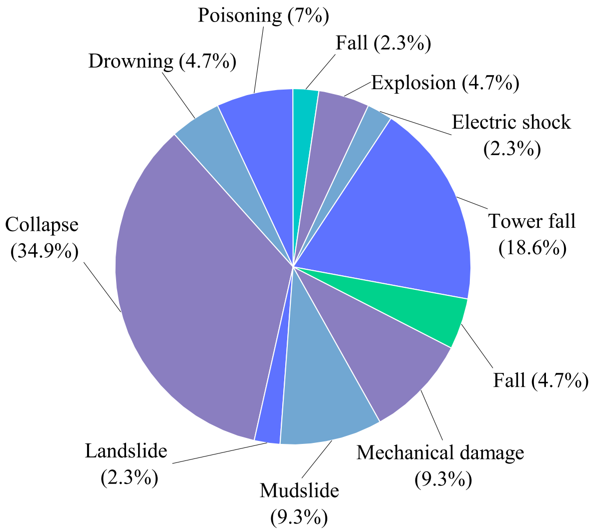
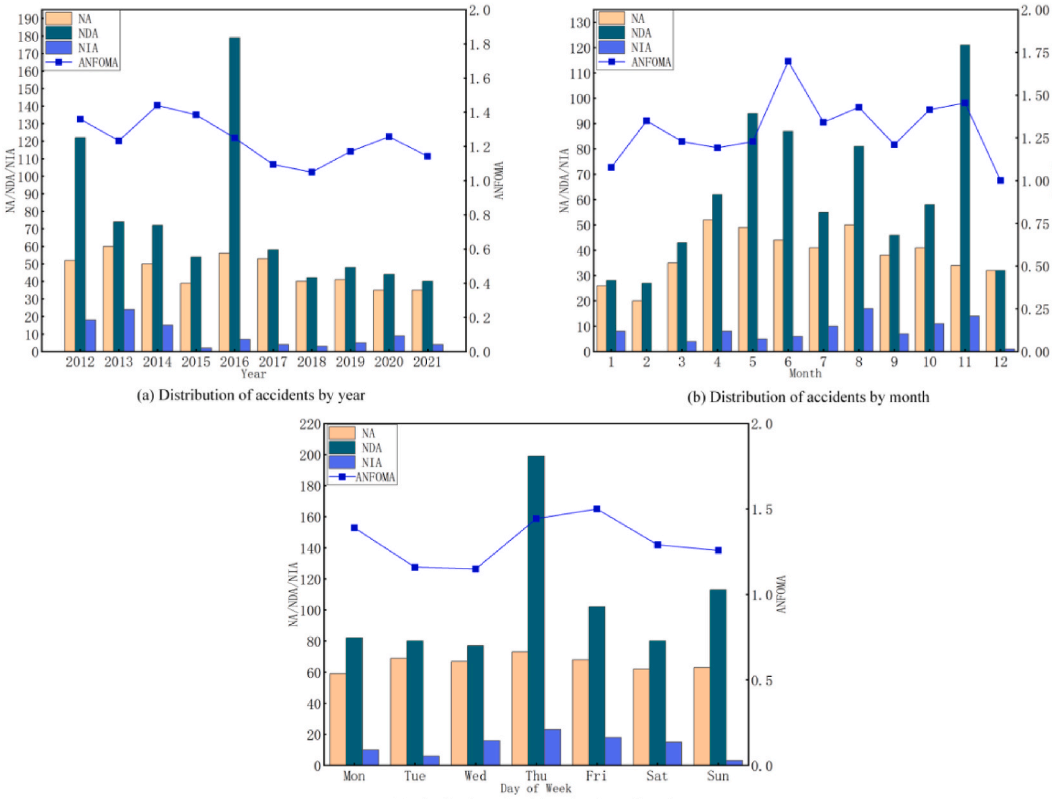


Fig. 1. Percentage of accidents of each type among major or higher level accidents.



(a) Distribution of accidents by year

(b) Distribution of accidents by month

(c) Distribution of accidents by days of week

Fig. 2. Time distribution of accidents.

previous years, probably due to the high priority given to electricity safety after the National Energy Administration released the Action Plan for Safe Production of Electricity (2018–2020) [34]. Especially, since the enactment of the Three-Year National Action Plan for Specialized Work Safety Improvements in 2020 [35], the frequency of accidents significantly decreased in 2020 and 2021, reaching a decade low.

As a result of four natural disasters in 2012 and an exceptionally severe accident in Jiangxi in 2016. Therefore, the number of deaths is much higher than the number of accidents. In contrast, the gap between fatalities and accidents was relatively minor in the remaining years. The ANFOMA for the period spanning 2012 to 2021 exhibited a fluctuating trend, with an overall decline. It decreased from 1.36 in 2012 to 1.14 in 2021, reflecting a decrease of 19.3 %. This indirectly reflected the improvement of employees' safety awareness as well as the improvement of the enterprise's safety management level. The ANFOMA in 2014 was the highest of the last 10 years at 1.44, indicating a higher accident hazard in that year compared to other years. In 2018, the ANFOMA was the lowest of the past 10 years, measuring at 1.05. This suggests that most accidents in that year resulted in the death of a single person and were classified as ordinary accidents. From the trend of ANFOMA by year, it was easy to see that since 2014, ANFOMA has shown a decreasing trend year by year, but rebounded in 2019 and continued to rise in 2020, which may be related to the outbreak of the novel coronavirus epidemic. Although the number of accidents decreased during the outbreak as many companies stopped work and production, the average casualty rate per accident increased due to psychological factors such as panic among the employees on duty. In 2021, with the outbreak under control, the ANFOMA again showed a decreasing trend.

3.2.2. Accident distribution by month

In this subsection, we conducted a monthly statistic of accident occurrences spanning from January 1, 2012, to December 31, 2021. Taking January as an example, the number of accidents(NA) in that month is the aggregate sum of accidents recorded each January from 2012 to 2021.

As illustrated in Fig. 2(b), accidents follow an "M" shape trend in China's electric power industry, with lower frequency at the beginning and end of the year, and higher frequency in April and August. Notably, the number of accidents and fatalities in February is typically the lowest of the year, which could be attributed to the Chinese New Year holiday. This national celebration is tremendously significant in China, where workers have a holiday of about two weeks. However, the ANFOMA of 1.35 in February was the highest of the quarter. Therefore, there is an urgent need to pay attention to changes in employee safety awareness before and after the holidays, strengthen safety education and guidance, and prevent mass casualties.

Accidents and fatalities gradually increased in March as companies returned to work and production after the Chinese New Year holiday. Accident frequency typically peaks at 52 in April, necessitating a heightened focus on employee safety training during the peak period of resumption of work and production. Since 2002, the Ministry of Emergency Management of China has conducted a "Safety Production Month" activity every June [36], which promotes employee's attention to occupational safety during the month and reduces the occurrence of accidents in June to a certain extent. However, the highest ANFOMA in June suggests the need for robust investigation of high-risk hazards alongside effective safety education and publicity efforts in the electric power industry. After the "Safety Production Month" activities in June, employees tend to exhibit improved awareness and safety practices, leading to reduced accident frequency in July.

In August, 50 accidents with 81 fatalities occurred, including 70 fatalities from ordinary and major accidents, indicating a clear rebound in accident frequency. Analysis of the raw data revealed five natural disasters, including mudslides and landslide. On one hand, China tends to experience more rainfall in summer, which heightens the risk of natural disasters such as mudslides and landslides. On the other hand, the high-temperature environment often leads to exhaustion and impatience among workers, both of which increase the likelihood of accidents [37]. Consequently, summer production activities should prioritize worker safety, avoid fatigue, be alert to meteorological conditions, and have contingency plans in place for accidents related to flooding, landslides, and mudslides.

3.2.3. Accident distribution by days of week

In this subsection, we conducted a weekly analysis of the accident occurrences for each day of the week from January 1, 2012, to December 31, 2021. Using Monday as an illustration, the number of accidents(NA) on Mondays is the aggregate sum of accidents recorded each Monday throughout the statistical period from 2012 to 2021.

Fig. 2(c) shows the distribution of casualties in the electric power industry for each day of the week. As can be seen, there is an inverted "V" trend in the number of accidents. Although some studies have found a clear "Monday effect" (highest number of accidents on Mondays of the week) for accidents in the construction industry [38], this paper found that this is not the case for accidents in the electric power industry. Antonio et al. suggested that the reason for the "Monday effect" in the construction industry is that some accidents that occur over the weekend are reported on Mondays in order to receive more compensation from insurance companies. However, this is unlikely to be the case in China's electric power industry due to the state's stringent regulation of electricity safety. In fact, the state has established six main regulatory bureaus and twelve provincial regulatory bureaus since 2013 to enhance electricity regulation [33]. Furthermore, the majority of enterprises operating in the electric power industry are state-owned, which means regulators are typically the first to be informed about any accidents that occur. The number of accidents in the electric power industry is lower on Mondays than on any other day of the week. This may be because workers are in a better physical and mental state to face their work after a weekend break, which reduces the number of accidents. The ANFOMA is higher on Mondays, Thursdays and Fridays, indicating that these days are more prone to serious accidents. This is around the holiday weekend, so management must pay particular attention to identifying high-risk hazards at this time to reduce the likelihood of serious accidents.

3.3. Spatial distribution of accidents

3.3.1. Indices

Provinces vary considerably in terms of electricity generation capacity and the number of people employed in the electric Power Industry. To accurately assess the level of electrical safety management in different provinces, it is essential to comprehensively consider factors such as accidents, power generation, and labor. The selection of appropriate indicators is crucial to ensuring the validity and accuracy of performance evaluations for electrical safety management. To minimize the impact of severe accidents, this study excludes 4 extremely serious incidents of the 461 personal casualty accidents in the electric power industry. The resulting indicator system consists of both absolute and relative indicators. Absolute indicators include the number of accidents (X1), the number of deaths (X2), and major accidents (X3), while relative indicators include the death rate per 10 billion kWh (X4), death rate per 100,000 employees (X5), and percentage of major accidents (X6) [19]. The number of accidents, the number of deaths, and major accidents are intuitive indicators that reflect the performance of electrical safety management and serve as the foundation for other indices. The percentage of major accidents highlights the potential for serious accidents to occur. In line with the Chinese government's workplace safety requirements, the million-tonne death rate is a crucial indicator for evaluating safety in the coal mining industry [39]. Similarly, the 10 billion kilowatt-hour fatality rate describes the relationship between the number of fatalities and workload in the electric power industry, while the death rate per 100,000 workers is a recommended occupational fatality indicator by the Chinese government [39].

3.3.2. Security management performance assessment

When conducting PCA, it is essential to ensure a robust correlation among the original variables. Hence, the chosen indicators were first normalized and made dimensionless. The SPSS data analysis software was utilized to carry out KMO and Bartlett's tests on the raw data. The test results show that the KMO sampling adequacy test displayed a value of 0.554, surpassing the 0.500 threshold, and Bartlett's spherical test registered a Sig value of 0.000, lower than the significance level of 0.05. This finding indicates that the sample data satisfied the prerequisites of PCA. Then, PCA was performed on the data using SPSSPRO to ascertain the characteristic root and factor contribution. The obtained results are tabulated in Table 6.

The eigenvalues associated with the initial three principal components listed in the table are all greater than 1 and collectively contain 93.044 % (exceeding 85 %) of the total influence of all factors. For evaluation purposes, these three principal components have been selected as comprehensive indices. By rotating the loadings matrix, the corresponding factor component matrix shown in Table 7 can be obtained.

A safety management composite score is calculated for the 31 regions using equations (1) and (2). As all the selected evaluation indicators are inverse, a higher score denotes a worse level of safety management in the electric power industry, emphasizing the need for increased attention towards safety issues in the production process. Fig. 3 depicts the safety management composite scores in each province, revealing significant variations in the safety management level of the electric power industry among different provinces. Provinces with lower safety management levels comprise Ningxia, Hainan, Guangxi, Sichuan, Yunnan, and so on, whereas provinces with higher safety management levels include Beijing, Tianjin, Shandong, and others.

According to Fig. 3, Ningxia has the worst level of security management in the electric power industry. This may be attributed to Ningxia's economic development and living environment. Regarding economic development, Ningxia is currently ranked 29th out of 31 provinces in China, indicating a relatively low level. As for the living environment, Ningxia's climate is characterized by aridity, substantial daily temperature fluctuations, severe land desertification and being one of the most water-scarce provinces in China. Such adverse circumstances may lead to the problem of brain drain [40], thereby contributing to looser production process management and an increased likelihood of safety accidents [41]. Fig. 3 also shows that Beijing has the highest level of safety management in the electric power industry, which may be because Beijing, as the capital of China, pays more attention to production safety. Moreover, from 2012 to 2021, there were four severe and extraordinarily severe accidents, including two in Sichuan, one in Jiangxi, and one in Fujian. Therefore, relevant authorities must also pay attention to these provinces to prevent severe and extraordinarily severe accidents.

3.4. Spatial and temporal differences

3.4.1. Evolution of the overall differences in China

Since 1953, the Chinese government has been formulating development plans every five years to guide social development, including energy development plans. These plans encompass the development of the electric power industry [42]. Therefore, this section analyses the overall national difference from different periods. Fig. 4 shows the results of measuring the overall difference in the NA and NDA between 31 provinces using the Theil index model. Examining the figure, it can be seen that, apart from the significant fluctuation in the Theil Index of the NDA in 2016, the trend of the Theil Index of both the NA and the NDA remains relatively consistent in other years. Taking into account the statistical data and the shift in the center of gravity of the number of accidents, we have analyzed the changing pattern of the overall difference in the number of accidents and fatalities between 31 provinces. Fig. 5 shows the shift in the center of gravity of the number of accidents.

Table 6
Eigenvalues and contributions.

Element	Eigenvalue	Contribution rate (%)	Cumulative contribution rate (%)
f_1	2.80	46.63	46.63
f_2	1.71	28.47	75.10
f_3	1.10	17.95	93.04
f_4	0.30	4.97	98.01
f_5	0.10	1.68	99.69
f_6	0.02	0.31	100.00

Table 7
Factor loading coefficients.

Index	f_1	f_2	f_3
X_1	0.82	0.15	−0.54
X_2	0.77	−0.53	0.26
X_3	0.92	0.02	−0.37
X_4	0.37	0.67	0.55
X_5	0.55	0.68	0.27
X_6	0.51	−0.70	0.46

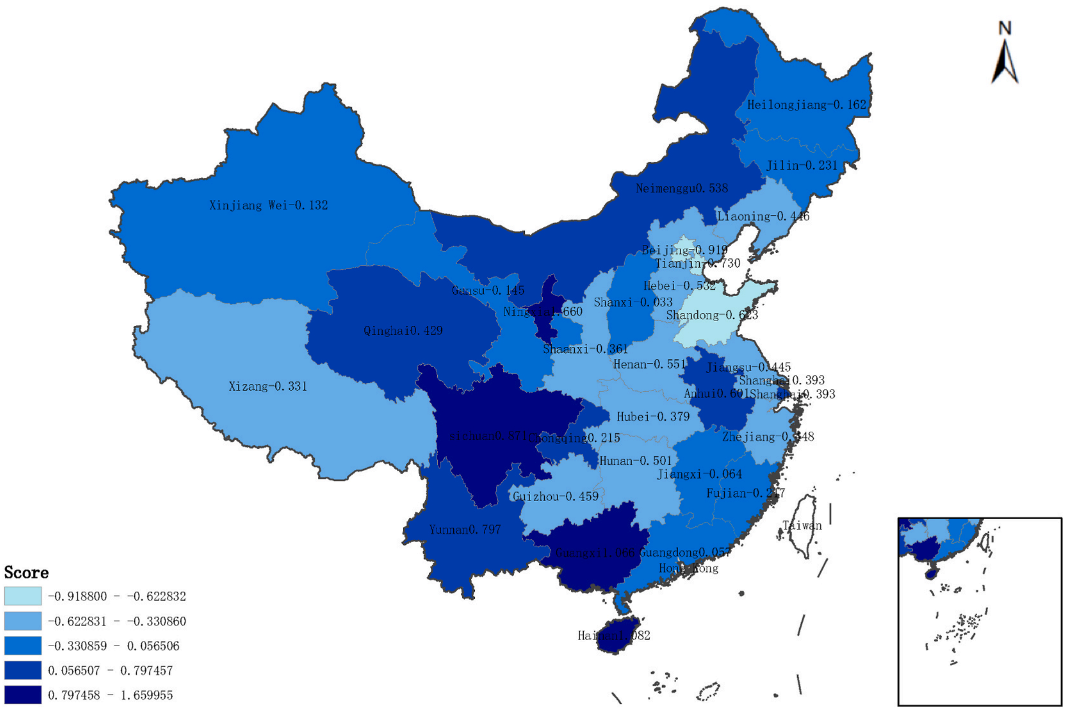


Fig. 3. Accident evaluation scores for 31 provinces in China.

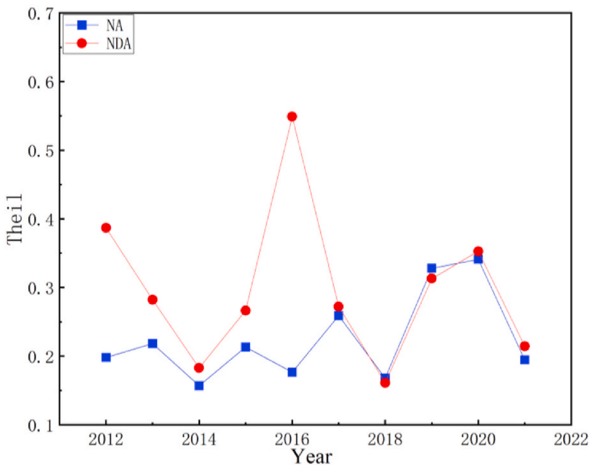


Fig. 4. Overall difference Theil index for 31 provinces.

During the 12th Five-Year Plan period from 2012 to 2015, the change in the Theil index of the NA was relatively stable and below 0.25. The overall downward trend in the Theil index of the NDA indicates a narrowing of the overall difference in fatalities between provinces. As can be seen in Fig. 5, the spatial focus of accidents has shifted eastwards over this period, with a more pronounced shift in 2014. The main reason for this is that the number of accidents in the Central China region, represented by Sichuan, and in the Northwest China region, represented by Xinjiang, decreased more significantly, and electricity production safety situation improved significantly.

During the 13th Five-Year Plan period, from 2016 to 2020, there were significant fluctuations in the Theil index of the NDA. Specifically, in 2016, the Theil index of the NDA exceeded 0.5 due to an exceptionally severe accident that occurred in Jiangxi. Notably, from 2019 to 2020, there was a significant northward shift in the center of gravity of accidents, accompanied by a notable increase in the Theil indexes of the NA and NDA. This increase is mainly due to Inner Mongolia, located in northern China, which experienced a significant rise in the number of accidents and fatalities. As a result, the overall difference in both the number of accidents and fatalities between provinces increased. One possible reason for the significant increase in accidents in Inner Mongolia is the significant increase in electric power generation between 2019 and 2020, which creates additional challenges and pressures for operational safety.

2021 marked the opening year of the 14th Five-Year Plan and the second year of Three-Year National Action Plan for Specialized Work Safety Improvements [35]. During the year, the Theil index of the NA and NDA decreased sharply. This indicates a narrowing of differences between provinces in terms of both the number of accidents and the number of deaths, as well as a marked improvement in the overall level of safety management across the country. Changes in the Theil index indicate a change in the spatial distribution pattern of the frequency of accidents and the level of damage in the provinces.

3.4.2. Evolution of interregional differences

Fig. 6 displays the Theil index of the difference in the NA and NDA between 6 regions. Except for 2012 and 2016, the trend of the Theil index of the NA and NDA remained largely consistent. This is because, in 2012, three natural disasters occurred in the Central China region, resulting in the deaths of 31 individuals. Moreover, in 2016, an exceptionally severe accident occurred in Jiangxi, resulting in 73 fatalities. The occurrence of such accidents resulted in considerable differences in accident fatalities between the Central China region and the rest of the regions. After 2019, the Theil index of the NA and NDA has exhibited a decreasing trend to varying degrees. This might be attributed to different regions placing greater emphasis on work safety in the electric power industry following the release of the Three-Year National Action Plan for Specialized Work Safety Improvements in 2020. This has led to a reduction in interregional differences in the number of accidents and fatalities.

3.4.3. Composition of overall national difference

Based on the fact that the Theil index has the property of being compositionally decomposable, we can decompose the overall national differences into interregional and intraregional differences. The exact composition of the differences is shown in Fig. 7.

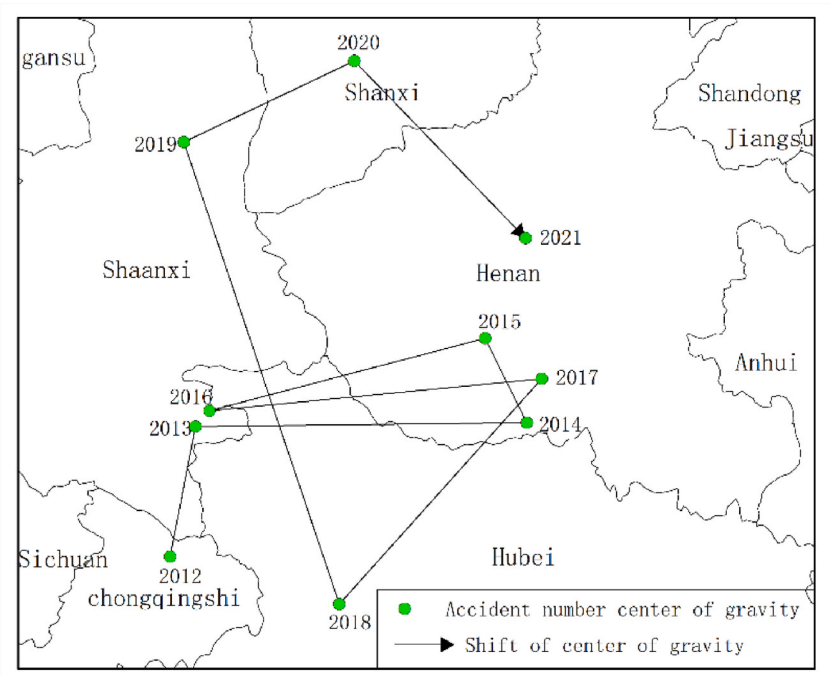


Fig. 5. Shift in the center of gravity of accidents.

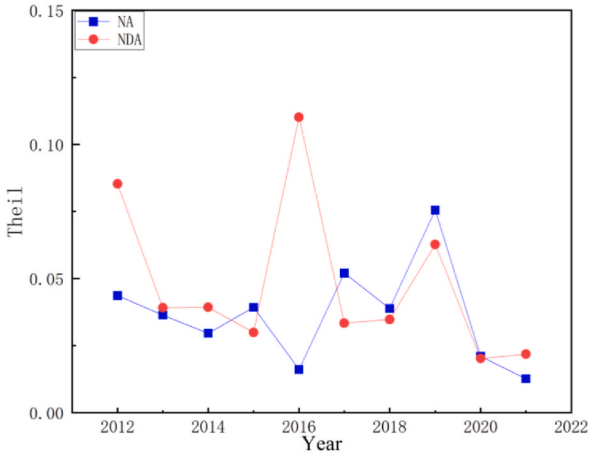


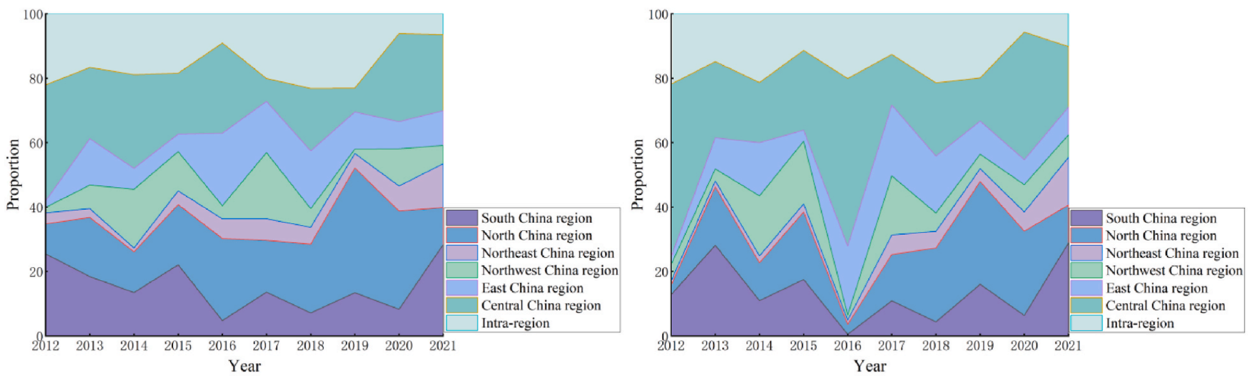
Fig. 6. Development of interregional differences.

1) The number of accidents.

Fig. 7(a) shows the intraregional and interregional differences in the number of accidents as a percentage of the overall national differences. Upon analysis, it is evident that intraregional differences dominate. Specifically, the differences in the number of accidents between provinces in the Northeast China region are relatively small. In 2021, intraregional differences in the South China region accounted for a more significant portion of the overall difference. This is primarily attributed to the notable surge in accident frequency in Guangdong, leading to a considerable difference in the number of accidents between Guangdong and the other provinces in the region. Furthermore, the proportion of intraregional differences in the overall national differences for the Central and North China regions fluctuates from year to year but remains relatively high, indicating that the number of accidents varies considerably between provinces in these two regions. Upon examining the raw data, it is clear that the number of accidents in Sichuan in the Central China region is consistently higher than the regional average, except in 2014 and 2015. Meanwhile, the number of accidents in Inner Mongolia in the North China region is higher than the regional average every year, especially in 2019 and 2020. This might be related to the scale of electricity generation in Sichuan and Inner Mongolia. Both provinces are major electricity generation provinces in China, and a higher workload may increase the risk of accidents. As such, regulators should strengthen safety supervision of the electric power industry in Sichuan and Inner Mongolia.

2) The number of deaths.

Fig. 7(b) shows the intraregional and interregional differences in the number of deaths as a percentage of the overall national differences. Overall, intraregional differences dominate, and the proportion of intraregional differences has increased in the last two years, suggesting that intraregional differences have further increased their influence on overall national differences. In terms of the share of each region, the intraregional differences in the Central China region accounted for a larger share each year but were particularly prominent in 2012, 2016, and 2019. This is mainly due to two severe mudslide accidents in Sichuan in 2012, an exceptionally severe collapse accident in Jiangxi in 2016, and a major poisoning accident in Hunan in 2020, which led to significant



(a) Theil index decomposition of the number of accidents

(b) Theil index decomposition of accident fatalities

Fig. 7. Theil index decomposition of accidents.

differences in the number of deaths between provinces in Central China region. Since 2016, the proportion of intraregional differences has been larger in the North China region. In particular, the proportion reached 31.89 % in 2019. This is mainly due to the sharp increase in deaths in Inner Mongolia in that year, making the difference with other provinces more obvious.

4. Discussion

The healthy and stable development of the electric power industry is crucial to ensuring the country's economic prosperity. However, differences in national development plans over time have led to different levels of national emphasis on certain industries, which in turn affects the allocation of resources across provinces and regions. For example, in China, municipalities and southeastern coastal cities usually receive better policy support, while other regions may face the challenge of insufficient resources [43]. National policies and regional development characteristics have led to differences in power sector development across provinces. As a result, the safety situation of the power industry in each province also shows different degrees of differences. To further explore the development of China's power industry, we conducted a spatiotemporal characterization of personal injury and fatality accidents that occurred in China's power industry during the period 2012–2021. This analysis provided a clearer picture of the performance of different provinces and regions in terms of safety production in the power industry, as well as possible development trends and problems.

In this study, descriptive analyses revealed the frequency of various accident types and the temporal distribution of accidents in China's electric power industry. From the frequency statistics of accident types, falls, electric shocks, and collapses are frequent accident types, which should be given high attention. And although mudslides and landslides occur less frequently, they are more destructive, so geological surveys should be done in the process of electricity production and construction. Regarding the temporal distribution of accidents, the number of accidents year by year shows an overall decreasing trend. Especially after the government introduced the production safety policy [34], the frequency of accidents decreased significantly, showing the impact of macro policies on the electric power industry's safety. The high-temperature environment in summer is more prone to personal casualty accidents, which is also reflected in the construction industry accidents [19]. In addition, the electric power industry also shows a high number of accidents during the peak months of resumption of work and production. Although some studies have shown that the "Monday effect" of accidents in the construction industry in Spain may be because accidents occurring on weekends are reported on Mondays [38], this effect does not exist in China's electric power industry due to the country's strong regulation of electric power safety. According to the theory of accident causation, accidents are the result of two major factors, namely, unsafe human behavior and unsafe state of things [44]. Therefore, it is necessary to do a good job of employee safety training and education as well as regular hidden danger investigations.

Using PCA, the level of safety management in the electric power industry in 31 provinces was assessed by taking into account accidents, workload, and labor. The overall score of each province shows that Beijing has the best safety management level, thanks to the high importance the state attaches to the capital city "Beijing". On the contrary, Ningxia has the worst safety management level, which may be due to the relatively harsh living environment and the backward economic development of Ningxia, which makes it difficult to attract skilled managers and technicians [40]. In contrast, the level of safety management in the electric power industry in Tibet, which has the worst economy in China and the highest altitude, is higher than in Ningxia. This can be explained by the intensity of electric power production activities. Ningxia's average annual power generation over the last decade was 142.887 billion kWh, compared to Tibet's 5.9 billion kWh. The more intense the production activity, the more safety problems may be exposed.

We explored the overall national difference and the difference between the six regions by the Theil index model. Both the overall national and interregional differences in the number of accidents and fatalities showed a significant reduction in 2021. This might be because, after the national emphasis on safety [35], all provinces were paying more attention to the issue of electricity safety. In terms of the proportion of intraregional and interregional differences in the overall differences, there are significant differences in the number of accidents and fatalities between provinces in the Central and North China regions. This is mainly due to the higher number of accidents and fatalities in Sichuan and Inner Mongolia, where high workloads increase uncertainty in the production process and thus the likelihood of fatalities and injuries. To promote the improvement of the overall production safety level of the national electric power industry, each regulatory region should take into account its own actual situation, rational allocation of resources, and strengthen the supervision of the provinces with high accident and casualty rate.

Based on the above analyses, the following recommendations are made to Chinese electric power companies: firstly, develop a practical safety training and hazard detection system, and conduct regular employee safety training and hazard detection, especially during the peak months of resumption of work and production; secondly, when working in the summer, companies should do a better job of reassuring employees about high temperatures and avoiding fatiguing them. For example, in hot weather enterprises provide drinking ice water and sunshade rooms or tents for employees to cool down and avoid the summer heat; increase the frequency and length of employee breaks to reduce the risk of heatstroke and fatigue; and strictly implement the high-temperature subsidies and benefits to stabilize the high-temperature mood of employees; Lastly, companies should not only carry out safety campaigns in June as required by the government but should consider carrying out such campaigns more frequently. For the Chinese government, practical policies to attract talent should be formulated and strengthen its support for economically backward regions, especially Ningxia and Hainan. There should also be a focus on safety activities in provinces with large power generation capacity, particularly Sichuan and Inner Mongolia.

5. Limitation and future research

This study may have the following limitations: firstly, governmental rules such as punishments and other limitations makes companies to sensor some of accidents because the insurance and health matters, which may result in less comprehensive statistics from the official NEA website. Secondly, the data source used in this study is from the NEA website and is secondary data, which we have not been able to take into account in our research as we have not been able to verify the stability of the data in the website.

The object of this paper in analyzing the temporal, spatial and spatial differences is the 461 personal injury and fatality accidents that occurred in Chinese electric power enterprises from 2012 to 2021, and it does not analyze the temporal and spatial analyses for specific accident types. Considering the differences in regions and climates, the types of accidents that may be caused may also vary. Future research could explore the spatial and temporal characteristics of different accident types by considering accident types in more detail.

6. Conclusion

Electricity production and construction activities are prone to personal casualty accidents. This study attempts to analyze the patterns and characteristics of personal casualty accidents in China's electric power industry in time and space through a survey of personal injury and death accidents in China's electric power industry from 2012 to 2021, using descriptive statistical analyses, PCA, and Theil index model, to comprehensively evaluate the level of safety management in each province, and to explore the trend of spatial differences in accidents. The main research conclusions are as follows.

(1) The distribution of the types of personal casualty accidents in China 's power industry has certain clustering characteristics. Electric shock and fall are the main types of accidents, and the accidents caused by the two account for 50.98 % of the total. In addition, the collapse and tower fall often lead to more than larger accidents, accounting for 53.52 % of the larger accidents.
(2) In terms of the annual distribution of accidents, the effect of production safety control has been obvious in recent years, with the number of accidents and casualties dropping significantly. The number of accidents decreased from 52 in 2012 to 35 in 2021, while the number of fatalities decreased from 122 in 2012 to 40 in 2021; the peak period for resumption of work and production and the hot summer months tend to cause more accidents, while weekly holidays and festivals are more likely to lead to more serious accidents.
(3) From the perspective of regional safety management level, Ningxia, Hainan, Guangxi and other places have lower management level, and it is urgent to pay strict attention to production safety to protect the life and property of employees. In the past two years, the overall difference in the number of accidents and fatalities between regions showed a decreasing trend, but central and northern China regulatory regions compared to other regulatory regions within the overall difference in the number of accidents and fatalities is larger, which has a certain relationship with its intraregional power generation in Sichuan and Inner Mongolia.

In summary, there are large differences in time and space between personal casualty accidents in China's power industry. Overall, the safety situation has improved significantly over time; spatially, although there are no clear regional characteristics, provinces with a lower level of safety management also have a relatively lower level of economic development. Due to the number of accidents and fatalities in some electric power regulatory regions are concentrated in one province within the region, making the overall difference in the number of accidents and fatalities within the region, which is not conducive to the enhancement of the overall level of safety in the whole country. Enterprises and related departments should formulate appropriate policies for different time periods and regions to better improve the safety level of electric power production. The conclusions of the study can provide a scientific basis for improving the safety management and control of the electric power industry in various regions.

Ethics declarations

Review and/or approval by an ethics committee was not needed for this study because informed consent was not required for this study. After all, all data were derived from an open database.

Data availability statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Shu Chen: Methodology, Formal analysis, Conceptualization. **Dianxue Wang:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **Xinkai Zhang:** Resources, Project administration, Investigation. **Bo Shao:** Writing – review & editing, Supervision, Methodology. **Kunyu Cao:** Visualization, Supervision, Software. **Zhi Li:** Visualization, Supervision.

Declaration of competing interest

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

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