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# Analysis on Security of Energy Networks Based on Current China's Multiple Energy Situation

Ruijin Du *, Lixin Tian, Gaogao Dong, Min Fu
Nonlinear Scientific Research Center, Faculty of Science, Jiangsu University, Zhenjiang, 212013, China
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**Abstract:** According to current China's energy situation, multiple energy resources, autonomous and non-autonomous energy region and spatial distribution feature, we study network security by using $n$ 2D lattices with multiple support-dependence relations, which are under random attack. The result suggests that lattice model becomes more robust and secure as the fraction of autonomous nodes increases. And, by decreasing the number of lattice networks, the multiple support-dependence network gets more secure. Interestingly, we find that the average supporting degree makes a significant impact on security for network composed of more than two networks, but for network composed of two networks, it has a little influence on the security. Therefore, by increasing the average supporting degree, energy network composed of more than two networks becomes more safer.

**Keywords:** energy network; energy security; multiple support-dependence

## 1 Introduction

Energy is the foundation of modern economic and social development and also an important restriction factor. Energy security has an important influence on economic security and national security. With the rapid development of China's economy, China's energy structure gradually shows features of coexistence of traditional energy structure and unconventional energy structure. Recently, the study of complex networks is a young and active area of scientific research inspired largely by the empirical study of real-world networks [1–14]. Most real networks display substantial non-trivial topological features, with patterns of connection between their elements that are neither purely regular nor purely random. Shi et al. put forward the ways to solve the contradiction between supply and demand of energy in our country by adjusting relations of China's energy supply and demand and taking a series of policies [15]. Sun et al. studied the model of energy resource supply-demand network, which was constructed to describe the actual energy resource demand-supply in China. They found that the degree of energy resource supplies enterprise can represent its market share. They also proved that this network has the characteristics of scale-free [16].

Previous works have focused on single, isolated network, where the interaction with other networks is not considered. However, real networks are often interdependent [17–27]. More Recently, Buldyrev et al. demonstrated a cascade of failures from a power network and an Internet network, which based on black out in Italy 2003. These two networks feature a bidirectional dependence such that power stations depend on communication nodes for control and communication nodes depend on power stations for their electricity supply [17]. Furthermore, Buldyrev et al. developed a theoretical framework for studying the robustness of two fully interdependent networks subject to random attack. They found that due to the dependency coupling between networks, they become extremely vulnerable to random failures and system collapse in an abrupt first order transition [17]. Parshani et al. developed mathematical framework and researched networks that are partially interdependent. They found that reducing the coupling strength could lead to a change from first order to a second order percolation transition due to random attack [18]. By mapping the targeted-attack problem in interdependent networks to the random-attack problem, Huang et al. investigated the robustness of two interdependent networks when high- or low-degree nodes are under targeted attack. They found are difficult to defend for interdependent scale-free network by using strategies such as protecting the high-degree nodes [19]. In When networks network, Quill highly praised the role of interacting networks in the study of networks, which was published in Science News [20].

*Corresponding author. *E-mail address*: gago999@126.com


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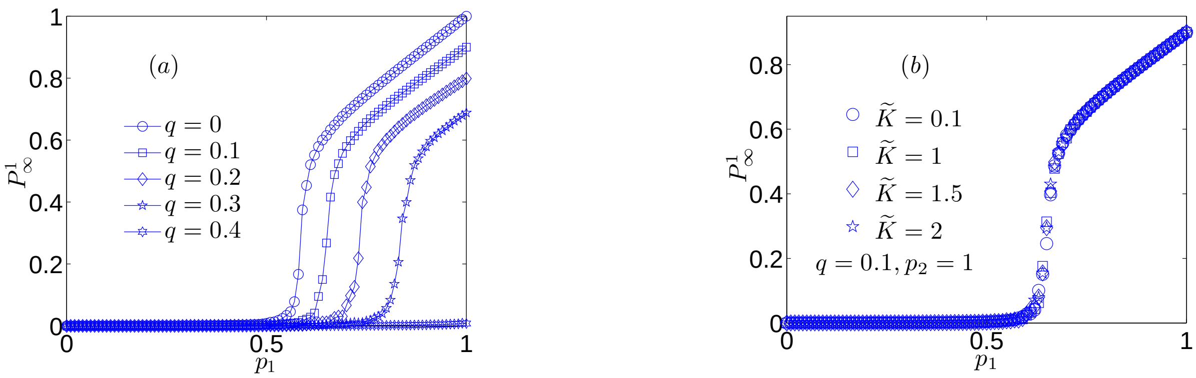


Figure 1: For two lattices with periodic boundary conditions, the fraction of giant component as a function of attacking strength for different coupling strength $q_1 = q_2 = q$ and average supporting degree $\widetilde{K}_2 = \widetilde{K}_1 = \widetilde{K}$. (a) $P^1_\infty$ as a function of $p_1$ with parameters $p_2 = 1$, $\widetilde{K} = 1$ for different coupling strengths $q$. (b) $P^1_\infty$ as a function of $p_1$ with parameters $p_2 = 1$, $q = 0.1$ for different average supporting degrees. In simulation, $L = 300$ and the results are averaged over 100 realizations.

Most previous studies of the robustness of interdependent networks focused on networks in which space restrictions are not considered [21, 22]. When China's energy situation is considered, energy networks are usually embedded either in two-dimensional or in three-dimensional space. Nodes in one network are always interdependent with nodes in other networks. Meanwhile, with the adjustment in China's energy structure, China's energy network gradually shows feature of multiple support-dependence relation, and energy security mainly focuses on the emergency capability of energy network. In this paper, we study the robustness of lattice networks embedded space with multiple support-dependence relation based on China's multiple energy situation.

## 2 Network model

China energy resource structure mainly includes conventional and non-conventional energy resources. Conventional energy resources include coal, oil and gas energy resources. Non-conventional energy resources include wind, sun, water, shale oil and shale gas and so on. 2012 statistical bulletin shows that coal output is 36.5 hundred million tons, oil output is 2.07 hundred million tons, gas output is 1072.2 hundred million stere, the consumption of water and electronic power is 8608.5 hundred million kilowatts per hour, nuclear power 973.9 hundred million kilowatts per hour, wind power 1008 hundred million kilowatts per hour. From the above data, China energy resource represents the feature of multiple energy resources coexistence. For energy consumption, "Statistical Review of World Energy" of BP company shows that in 2012, coal provided 68.5 of China's total final consumption of energy, oil 17.7, gas 4.7, water and electronic power 7.1, nuclear power 0.8 and other sources 1.2. According the IEA prediction, China energy consumption mainly depend on conventional energy, nonconventional energy have a supporting role, this will not be changed for a long time.

China energy resources have the characteristic of regional spatial distribution. The coal output diminishes from west to the east and from south to the north. About 91.8 of coal resources are mainly distributed in the north of Kunlun-Qinling-Dabie Mountains. About 81.13 of oil resources are mainly distributed in eight basins, including bohai gulf, Songliao, Tarim, Erdos, Dzungaria, Pearl River Estuary, Qaidam and East China Sea shelf. About 83.64 gas resources are mainly concentrated in Tarim, Sichuan, Erdos, East China Sea shelf, Qaidam, Songliao Qiongdongnan and bohai gulf. For non-conventional energy resources, 70 of water resources are mainly concentrated in the southwest of our country, wind resources are mainly concentrated in the northeast, the north, the northwest and the southeast coast of China. Nuclear resources are mainly concentrated in the east coast of China. Because of the constraint from regional distribution of energy, transmission distance between different regions, energy price fluctuations, regional energy production scale and efficiency, and energy consumption show the characteristics of regional autonomy and non-autonomy. For example, the West-East Power Transmission Project transmits HEP from the west to eastern China in order to cope to the spatial differences between energy production and consumption, China's East-West pipeline brings gas from the energy-rich autonomous region of Xinjiang to the booming east coast, and the shipping of power coal from the North to the South is the main way in China.

According to above features of China's energy resources, we set up a coupled network with multiple support-dependence relations to study the cascade of failures. We assume that each network of $n$ networks has two types of nodes, autonomous nodes and non-autonomous nodes. For autonomous nodes in one network, they need to be supported by nodes of other networks. On the contrary, for non-autonomous nodes, they do not need any support nodes of other networks. Furthermore, an autonomous node can function, it must (i) have at least one functional support node in other networks and (ii) must belong to the giant component of functional nodes in the network it belonging to [23, 24]. A non-autonomous node can function, it only need to satisfy condition (ii). We assume $P_A(k)$ and $P_B(k)$ are degree distributions of networks $A$ and $B$ with number of $N_A$ and $N_B$ respectively. $q_{AB}$ (or $q_{BA}$) fraction of nodes in network $B$ (or $A$) are defined as autonomous nodes. Thus, $1-q_{AB}$ (or $1-q_{BA}$) fraction of nodes in network $B$ (or $A$) are non-autonomous nodes relative to network $A$ (or $B$). The support degree $\tilde{k}_A$ (or $\tilde{k}_B$) of a node of network A (or B) denotes that the node is supported by $\tilde{k}_A$ (or $\tilde{k}_B$) nodes in network B (or A), where $\tilde{k}_A$ (or $\tilde{k}_B$) satisfies the support degree distribution $\tilde{P}^A(\tilde{k}_A)$ (or $\tilde{P}^B(\tilde{k}_B)$). When treating nodes in network $A$ at step $t$, we assume that all their supported nodes in network $B$ which are found to be functional at step $t-1$ are still functional. According to the above condition (i), nodes in network $A$, which cannot receive any support from remaining nodes of network $B$ at step 1, are firstly removed. Then, according to condition (ii), the nodes which do not belong to the giant component of network $A$, are considered to fail. All the failed nodes of network $A$ will lead to failures of supported links starting from them. Similarly, when treating nodes in network $B$ at step $t$, we assume that all their support nodes in network $A$ which are found to be functional at the current step $t$ are still functional [24]. The attack on the network of $n$ networks is represented. We assume that for one node in network $i$, there are $\widetilde{k}_{j_m i}$ support nodes of network $j_m$, the probability of having no functional support nodes in network $j_m$ at step $t$ is [24]

$$\beta_t^{j_m i} = q_{j_m i} \sum_{\widetilde{k}_{j_m i}=0}^{\infty} \widetilde{P}^{j_m i}(\widetilde{k}_{j_m i})(1 - P_{t-1}^{(j_m)})^{\widetilde{k}_{j_m i}}, \tag{1}$$

where a fraction of nodes $q_{j_m i}$ in network $i$ directly depend on nodes of network $j_m$, a fraction of nodes $P_{t-1}^{(j_m)}$ in network $j_m$ are functional nodes of network $j_m$ at step $t-1$ and $\widetilde{P}^{j_m i}(\widetilde{k}_{j_m i})$ denotes the supporting degree distribution, which follows Poisson distribution in this paper. Therefore, the remaining fraction of nodes in network $i$ at step $t$ is [24]

$$x_t^{(i)} = p_i(1 - \beta_t^{j_m i}). \tag{2}$$

Therefore, the fraction of nodes in giant component of network $i$ is

$$P_t^{(i)} = x_t^{(i)} g^{(i)}(x_t^{(i)}), \tag{3}$$

where $g^{(i)}(x_t^{(i)})$ is the fraction of nodes that belong to the giant component of the remaining nodes, which have $x_t^{(i)}$ fraction of nodes of the original network $i$. This process will continue until no further node failure in either network occurs. $x_\infty^i$ and $P_\infty^i$ denote the remaining fraction of nodes and fraction of nodes in the giant component of network $i$ at stable stage respectively.

# 3 Simulation analysis of network model

In this section, we choose square lattice $i = 1, 2, ..., n$ of linear size $L$ and $N_i = L^2$ nodes with periodic boundary conditions. For $n$ networks with multiple support-dependence relations, we choose fundamental star-like network. Network 1 is the central network, the other networks are surrounding networks. For the lattices with periodic boundary, we suppose the central network is under random attack. When the cascade of failures ends, we denote $P_\infty^1$ as the fraction of the biggest cluster. For the simplicity, we assume $q_{12} = q_{13} = ... = q_1$, $q_{21} = q_{31} = ... = q_2$, $\widetilde{K}_{2,1} = \cdots = \widetilde{K}_{n,1} = \widetilde{K}_1$, and $\widetilde{K}_{1,2} = \cdots = \widetilde{K}_{1,n} = \widetilde{K}_2$. From Fig. 1(a), we find, as the coupling strength $q$ changes, the size of giant component, the size of giant component of central network jumps from a large value to a small value and then continuously decreases to zero at $p_{1,c}$. Additionally, we observe that $p_{1,c}$ increases as $q$ increases, which means that the central network become more vulnerable as coupling strength increases. However, for two lattices with support-dependence relations, Fig. 1(b) demonstrates that the size of giant component of central network also jumps from a large value to a small value and then continuously decreases to zero as $\widetilde{K}$ changes. Furthermore, we also see that the robustness of central network is nearly invariable as average supporting degree changes, which means that for two lattices with support-dependence relations, the average supporting degree has a little influence on the robustness of central network.

In China's energy network, there exist diverse conventional energy network and non-conventional energy network, which are coupled together. Thus, understanding the robustness of spatial interdependent networks is one of the main challenges when designing resilient infrastructures. We study the robustness of five and ten lattices with support-dependence

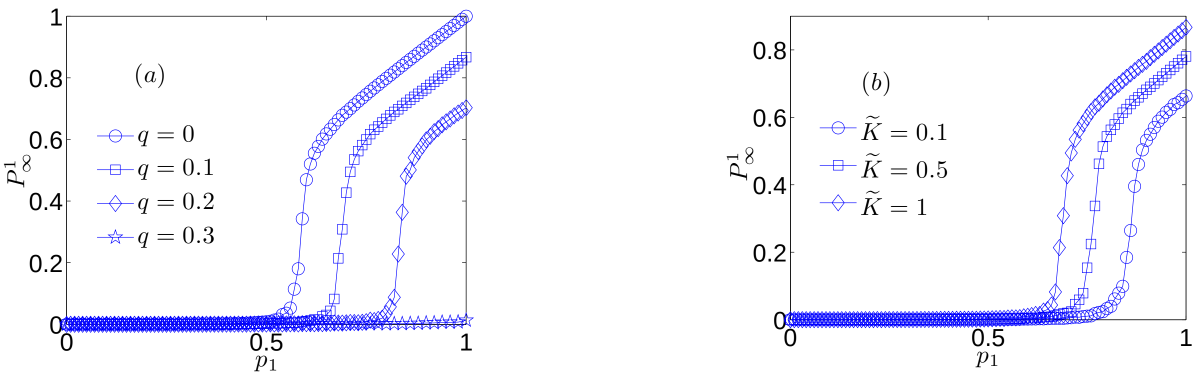


Figure 2: For five lattices with periodic boundary conditions, the fraction of giant component as a function of attacking strength for different coupling strength $q_1 = q_2 = q$ and average supporting degree $\widetilde{K}_2 = \widetilde{K}_1 = \widetilde{K}$. (a) $P^1_\infty$ as a function of $p_1$ with parameters $p_2 = 1$, $\widetilde{K} = 1$ for different coupling strengths $q$. (b) $P^1_\infty$ as a function of $p_1$ with parameters $p_2 = 1$, $q = 0.1$ for different average supporting degrees. In simulation, $L = 300$ and the results are averaged over 100 realizations.

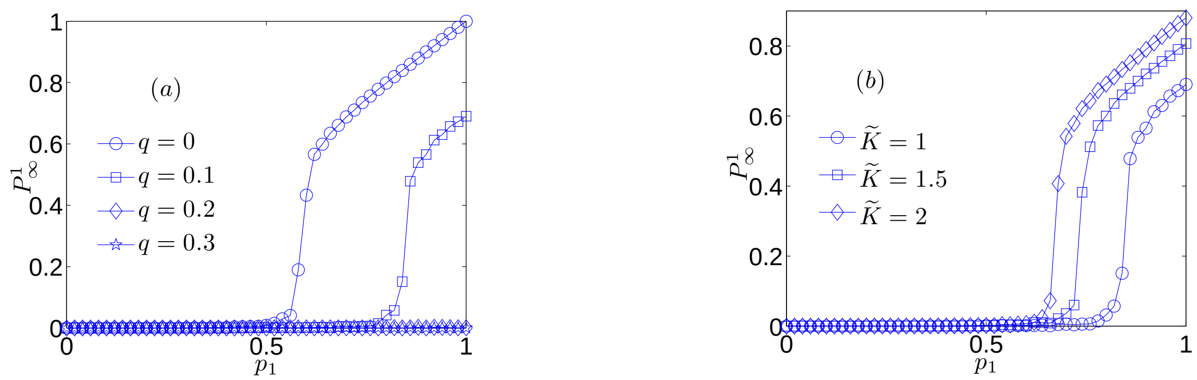


Figure 3: For ten lattices with periodic boundary conditions, the fraction of giant component as a function of attacking strength for different coupling strength $q_1 = q_2 = q$ and average supporting degree $\widetilde{K}_2 = \widetilde{K}_1 = \widetilde{K}$. (a) $P^1_\infty$ as a function of $p_1$ with parameters $p_2 = 1$, $\widetilde{K} = 1$ for different coupling strengths $q$. (b) $P^1_\infty$ as a function of $p_1$ with parameters $p_2 = 1$ , $q = 0.1$ for different average supporting degree. In simulation, $L = 300$ and the results are averaged over 100 realizations.

relations from simulation analysis. From Fig. 2(a) with 3(a), we can see that the size of giant component of central network jumps from a large value to a small value and then continuously decreases to zero. Furthermore, by comparing Fig. 2(a) with 3(a), for the same average supporting degree and coupling strength $q > 0$, as the number of networks increases, the robustness of network becomes much more vulnerable. By comparing Fig. 2(b) with Fig. 3(b), for more than two networks with support-dependence relations, as average supporting degree increases, central network becomes much more robustness, which is different from the case of two networks.

## 4 Conclusions

In this paper, based on the current China's multiple energy situation, we study the robustness of $n$ coupled lattices with support-dependence relations from simulation analysis. By defining failure mechanisms of inter- and intra- networks, we find the star-like lattice networks with boundary condition get much more robust as coupling strength or supporting average degree increases. Furthermore, the results imply that supporting average degree has no impact on two lattices with support-dependence relations, but for more than two lattices, it has key influence on the network robustness.

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