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A Review and Outlook

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Review

Resilience of Natural Gas Pipeline System: A Review and Outlook

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Abstract: A natural gas pipeline system (NGPS), as a crucial energy transportation network, exhibits intricate systemic characteristics. Both uncertain disturbances and complex characteristics result in higher requirement of supply safety. The investigation into NGPS resilience addresses the constraints of pipeline integrity and reliability, centering around the vulnerability, robustness, and recovery of an NGPS. Based on a literature review and practical engineering insights, the generalized concept of NGPS resilience is elucidated. The research methodologies of NGPS resilience are classified into three types: indicator construction method, process analysis method, and complex networks method. The practical applications of NGPS resilience research are analyzed, which are based on NGPS operation safety, information safety, and market safety. The ongoing applications and detailed measures are also concluded, which can guide the researchers and engineers from NGPS resilience.

Keywords: natural gas pipeline system; system resilience; resilience evaluation; complex network theory; practical application

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1. Introduction

A natural gas pipeline system (NGPS) serves as an industrial transportation system with high complexity in both internal characteristics and external environments [1]. This complexity arises from various factors, including variable supply–demand relations [2], different kinds of disturbances and a complex NGPS topology [3]. An NGPS comprises numerous compressors, pipelines, fittings, and signal detection/transmission equipment, integrating complex processes such as gas field gathering, transportation, storage injection, and extraction [4], further increasing its physical-level complexity. Additionally, the compressibility of natural gas and continuous fluctuations in the pipes introduce slow transient and time lag characteristics [5], adding operational-level complexity. Moreover, disturbances at different levels in the pipeline network system pose potential risks, pushing NGPS safety into the unknown "deep end".

Given the inherent complexity of an NGPS, ensuring gas supply during various disturbance events becomes a challenging task. The importance lies in understanding the mechanism of characteristics changing after disturbances in NGPS, which exhibits multidimensional complexity. The core issues encompass how the system changes after disturbances and how to respond and recover effectively. While some research has been conducted on NGPS integrity [6] and reliability [5,7], it falls short in fully satisfying the safety demands of NGPS, particularly in terms of vulnerability, robustness, and recovery after a disturbance. The common assumption of normal distributions in reliability research might overlook extreme events and their consequences [8,9]. Moreover, the existing research often focuses on an individual unit or parts of the system, which can dilute evaluation results as complexity increases.

In light of these challenges, studying NGPS resilience becomes crucial. Resilience, originally proposed in 1973 [10] to explore population relationships' stability after perturbations, has evolved into a central focus in systems engineering, emphasizing a system's ability to respond and recover after a disturbance. This idea of 'resilience' has been applied rapidly across various economic, engineering, and social fields. A complex system like NGPS needs a resilience-based approach, incorporating relevant theories and methodologies.

This article analyzes research on resilience of NGPS and other systems, defining the concept of NGPS resilience. It summarizes the research methods for studying NGPS resilience and explores potential future applications for NGPS resilience.

2. Concept of NGPS Resilience

The term 'resilience' originates from the Latin word 'resiliere', which originally meant to bounce back or recover. In the context of system resilience, this concept retains its characteristic phases of disturbance and recovery, focusing on a system's ability to resist, respond, and recover from disturbances, as opposed to material resilience. The concept of resilience has been adopted in various fields, such as social systems [11], economic systems [12], healthcare systems [13], transportation systems [14], and energy systems [15]. Commonly, these applications assess the degree of performance loss, remaining capacity, and recovery of the system after disturbances, encompassing aspects of vulnerability, robustness (reliability), and resilience [16]. Within the domain of NGPS resilience, the concept comprises two main components: operational resilience of the pipeline network system and physical pipeline network resilience. Operational resilience focuses on analyzing the operational state of station dynamic equipment, while physical pipeline network resilience evaluates the pipeline network structure using indicators such as network structural integrity and connectivity.

The idea of system resilience has evolved from subjective awareness after a disturbance to a broader engineering concept and research direction, leading to the transition from qualitative understanding to quantitative evaluation. In the context of NGPS resilience, it involves multiple views, including operators, researchers, and users. As a fundamental notion for ensuring safe operation, system resilience underpins gas supply preservation. Moreover, system resilience acts as a key element for modeling and optimization in related research, characterizing the behaviors of the NGPS during disturbances. Considering different objects and perspectives, NGPS resilience embodies both an ideological cognition and a system attribute, as illustrated in Figure 1. The resilient system is the target of decider and operator, which exists in the form of ideological cognition. For NGPS operators, they can obtain the measured data at first, so the system characteristics are paid most attention. The researchers should keep a balance between deciders and operators. For the trend from qualitative to quantitative evaluation, the research on NGPS resilience needs to change the evaluation and analysis methods according to different practical engineering situations.

Indeed, the concept of 'disturbance' is crucial when discussing resilience in the context of an NGPS. Various types of disturbances can significantly impact NGPS operations, and it is essential to consider them while evaluating resilience. Common disturbances for an NGPS include natural disasters like earthquakes, landslides, and mudslides [17,18], human-caused accidents such as construction accidents and vandalism [19,20], equipment damage like compressor malfunctions and sensor malfunctions, as well as information system disturbances.

Disturbances in an NGPS can be categorized based on their nature. On one hand, they can be divided into supply–demand relationship disturbances and physical disturbances. On the other hand, disturbances can be classified based on their predictability, separating them into deterministic disturbances (e.g., seasonal variations, legal holidays) and probabilistic disturbances (e.g., disease control, fluctuations in gas prices), as shown in Figure 2.

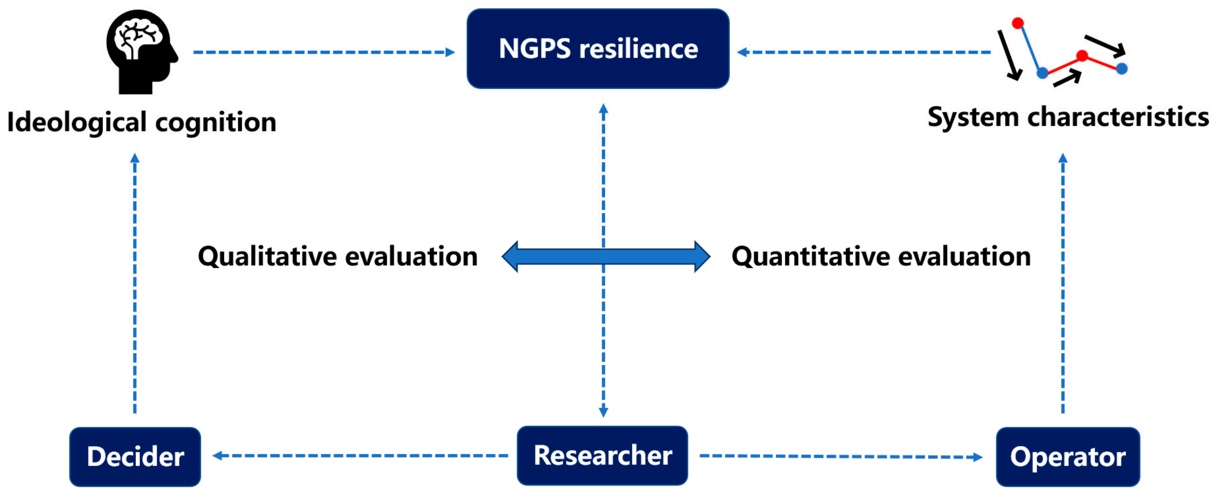

Figure 1. Connotation of NGPS resilience.

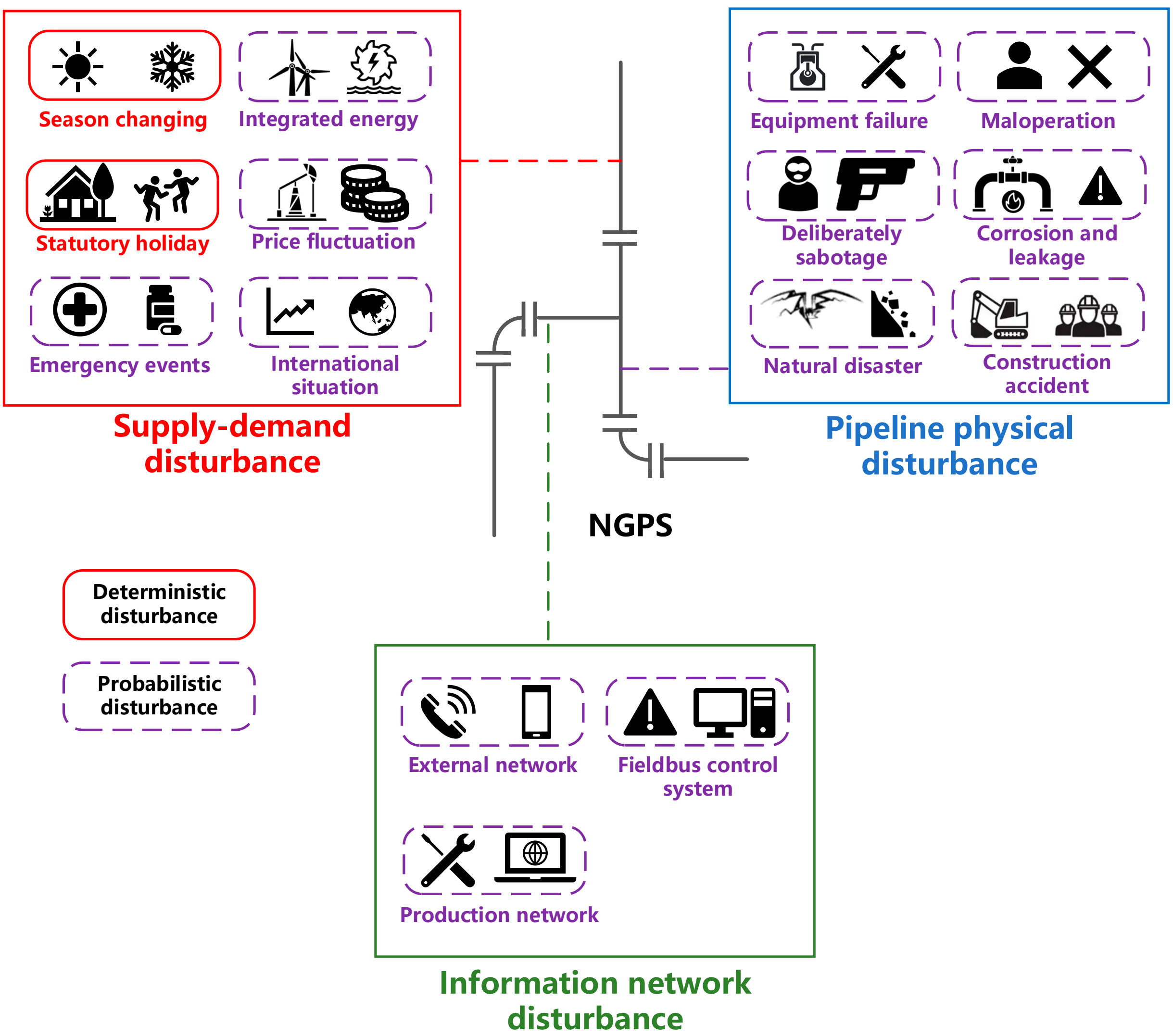

Figure 2. Categories of NGPS disturbances.

With the integration of new energy systems like wind power and photovoltaic power, uncertain fluctuations in these new energy sources also become disturbances that affect NGPS operations. Therefore, the concept of disturbance includes both the perspective of supply–demand relationship and the pipeline network entity. Combining the types of deterministic and probabilistic disturbances facilitates a comprehensive analysis of NGPS resilience. Figure 2 shows the details of the disturbance classifications. The classification of deterministic and probabilistic disturbances can guide the corresponding research and analysis methods. The classifications of supply–demand, pipeline physical, and information network disturbances determine the methods of disturbances modelling.

In summary, NGPS resilience complements the concepts of reliability and integrity, addressing their limitations both in concept and research. Conceptually, resilience fills the gap by focusing on the system's response behavior after disturbances, while in terms of research, resilience encompasses the entire process of resistance, response, and recovery. As a result, the concept of NGPS resilience extends to a broader temporal domain and scope, enhancing the understanding of pipeline system safety and providing a more comprehensive approach to supply assurance. Resilience provides a higher perspective, enabling a more holistic evaluation and management of system performance under various disturbance scenarios.

3. Research Methods of NGPS Resilience

The research methods for studying system resilience vary depending on the characteristics of the system and the specific engineering or scientific problems. While research on NGPS resilience is still in its early stages, there has been a growing interest in this area, and the methods can be categorized into three main approaches: indicator construction method, process analysis method, and complex network method, as shown in Figure 3. In detail, each kind of NGPS resilience research framework can be divided into three or four types. For the indicator construction method, the indicators are built based on the reliability-related indicator, vulnerability-related indicator, and recovery-related indicator. The process analysis method is divided into four phases according to the development processes, which are the simple integration method, temporal integration method, indirect evaluation method, and comprehensive evaluation method. Combined with the graph theory and complex network theory, the complex network method is a specialized type of resilience analysis method, including the topology analysis method, network flow method, and machine learning combined method.

3.1. Indicator Construction Method

The indicator construction method serves as the foundation for evaluating system resilience. This approach establishes the basis for quantitative resilience analysis. At present, ecosystems [21], socio-demographic systems [22], homeland security systems [23], organizational and management systems [24], power supply systems [25], and transportation systems [26] already form a more recognized resilience evaluation indicator framework. At this stage, the resilience evaluation of an NGPS is mainly based on the system gas supply capacity, and the resilience evaluation indexes are constructed from the perspectives of vulnerability, robustness, reliability, and recovery [27].

Reliability-related evaluation indexes for an NGPS are established, focusing on factors such as failure rate, maintenance rate, availability, and mean failure time. Additionally, the evaluation includes mechanical reliability, hydraulic reliability, and gas supply reliability as components of the functional reliability of the pipeline network [9]. The combination of unit reliability and network reliability is for the calculation and assessment of comprehensive reliability of the pipeline network [28]. In addition, the evaluation indexes based on the definition of the reliability can also be applied for reliability evaluation of some components, such as compressors and pipes.

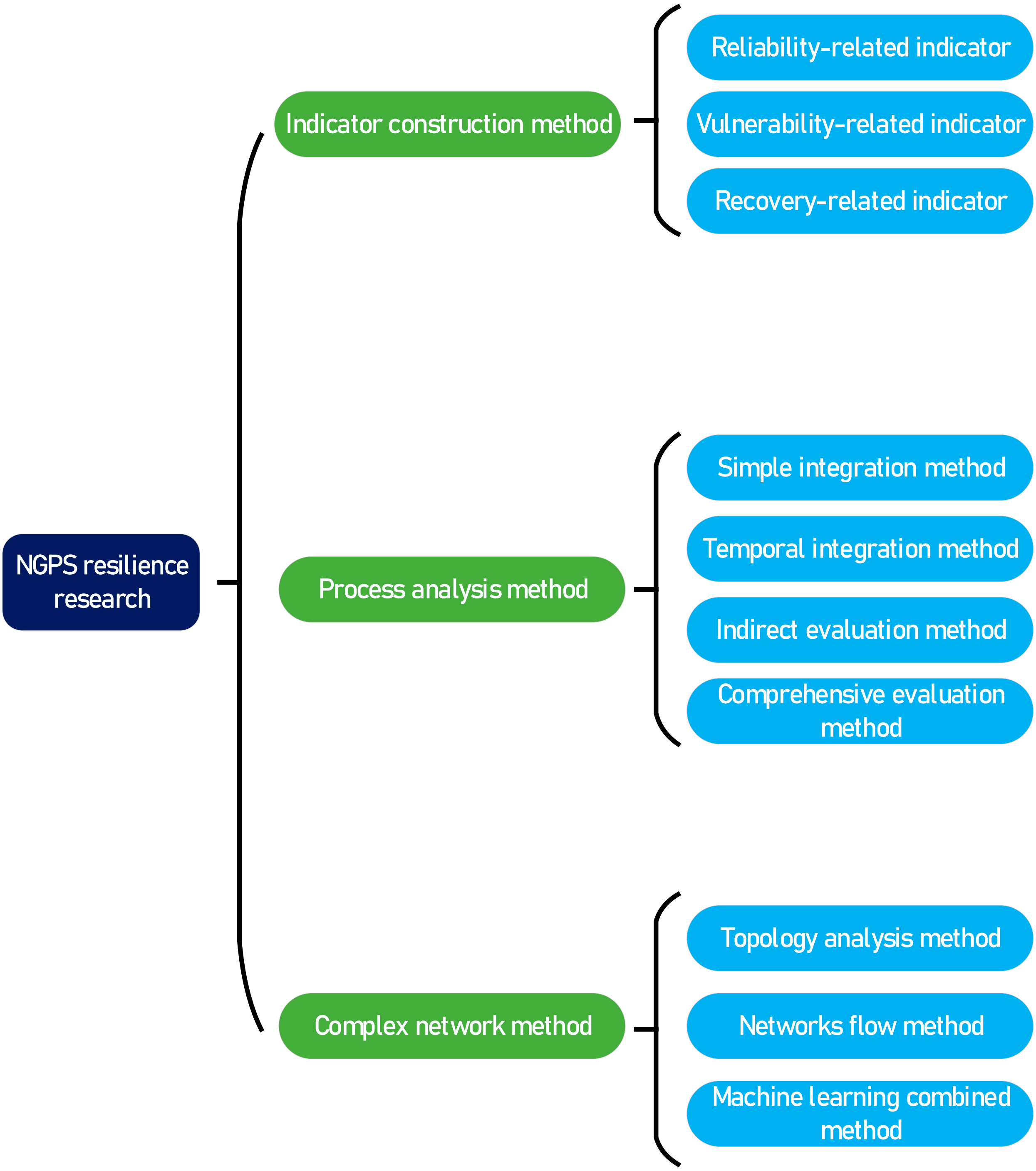

Figure 3. Categories of NGPS resilience research methods.

There are two main methods to construct vulnerability-related evaluation indicators: The first one is based on the pipeline network as a whole, qualitatively observing the changes in the pipeline network system before and after multi-scenario and multi-level disturbances, then establishing vulnerability evaluation indicators in view of the system. For example, traversing the points of the NGPS can help simulate potential disturbances and aggregate all the traversal results to construct the vulnerability evaluation indicators of the NGPS [29]. The vulnerability of the natural gas supply chain of the European Union (EU) is evaluated by studying EU member states' loss of gas supply in winter by the disruption of the one country's gas supply [30]. Moreover, vulnerability analysis of the European natural gas pipeline network combines the hydraulic element with the economic elements and uses scenario analysis for setting indicators of gas supply vulnerability [31]. Secondly, the vulnerability evaluation index is proposed from the unit interaction within the pipeline network system, combining the theory of system engineering and statistical physics, involving methods such as multi-intelligence body modelling and simulation [32–35], system conditional entropy calculation [36], and the theory of percolation [37].

The evaluation indexes of recovery are mainly based on the recovery rate and recovery time, which is one of the difficulties at the present stage of NGPS resilience research. The main methods in this area are as follows: ① Segmental Evaluation Method: The evaluation indexes are formulated in divided stages for the NGPS after a disturbance, considering the complexity of the system with multiple components being disturbed [11]. ② Network Structure Method: This method evaluates the system resilience based on the degree of network connectivity, topology of the NGPS, unit contribution, recovery rate, and other indicators [38]. ③ Management Evaluation Method: This method focuses on the system's management framework, staff training, responsibility awareness, and other aspects to construct resilience indicators [39].

In semi-quantitative evaluation, expert scoring methods are combined with hierarchical analysis or principal component analysis. This approach constructs indicators based on experts' recommendations [40] and is used in situations where historical data are limited or complex system dynamics make full quantitative evaluation difficult [41]. However, due to its subjectivity, it is less applied in NGPS resilience research, except for determining causality and variable weights in macroscopic studies of natural gas supply chains and urban gas pipeline network systems [42,43].

3.2. Process Analysis Method

The process of NGPS performance before and after disturbances is fundamental to researching system resilience, transitioning from qualitative to quantitative analysis. Resilience evaluation models for an NGPS can be classified into deterministic and probabilistic models based on the characteristics of disturbance events. Deterministic models are suitable for events with regularity, such as climate or seasonal changes, holidays, and disturbances that have already occurred. On the other hand, probabilistic models are used for unexpected events like sudden natural disasters, fluctuations in supply and demand, and pipeline corrosion. The temporal domain covered by the resilience evaluation models can be divided into preparation-included [44–46] and preparation-excluded stages [47–51]. In the preparation-included stage, the system's ability to withstand disturbances is considered, while the preparation-excluded stage only focuses on the processes after disturbances. The classification of the system resilience temporal domain has been thoroughly discussed by the Argonne National Laboratory in the United States [52]. In our opinion, the research on the resilience of NGPS, which is still in the early stage, should focus on the guidance and application of resilience to the safety and security of practical engineering.

The resilience curve (also known as the 'bathtub curve') characterizes the system's performance during the disturbance period, visually depicting the development of system resilience evaluation. As illustrated in Figure 4, the resilience curve shows the entire process of the NGPS response and recovery from the occurrence to the end of the disturbance. The degree of decline, rise, and the duration of the curve reflect the vulnerability, recovery, and robustness of the pipeline network system, respectively. Compared with the normal system resilience curve, which is in black color, the curve of resilient systems in red color shows less function loss and faster recovery. The resilience curve is a more comprehensive evaluation of the impacts of disturbances compared to traditional system function evaluations.

The development process of the resilience curve for NGPS can be summarized in four stages (Figure 5) [52]. The first stage involves considering only the decay and recovery process after the system is disturbed, often assuming an instantaneous decay and linear recovery process for simpler systems with fewer components [53] (Figure 5a). The second stage introduces standby components such as standby compressors and pipelines to improve resilience [54] (Figure 5b). The third stage transforms the assumed instantaneous degradation process into a linear process [55] (Figure 5c). Finally, in the fourth stage, factors like pipe storage gas, pressure decay in the pipe, and the characteristics of the NGPS repair process are considered, leading to a more realistic and practical engineering-oriented resilience curve [56] (Figure 5d).

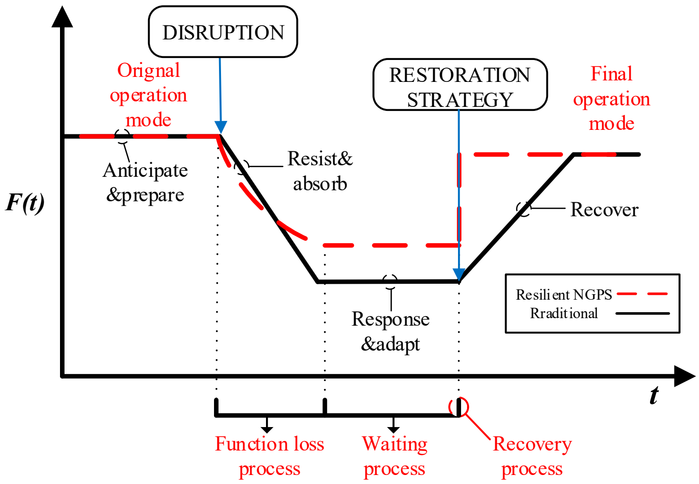

Figure 4. System resilience process.

In addition to the resilience curve, the resilience evaluation function is a crucial element in modeling NGPS resilience. The integral of the resilience curve over time holds practical engineering significance, making it a commonly used evaluation function, as shown in Table 1. Resilience evaluation functions can be classified into four categories:

(1) Simple Integration Method: This method evaluates the system function or capacity before and after disturbances without considering changes in actual production efficiency. It is suitable for modeling large and complex systems that lack degradation and recovery data, relying on ideal assumptions and simplifications to assess system resilience from the perspective of total production [57,58].
(2) Temporal Integration Approach: In this category, the production efficiency, decay rate, and recovery rate of the system are considered in the modeling [55–59]. The key is to quantitatively describe the decay and recovery processes, accounting for the reality of the system [60,61]. Linear assumption methods or key point methods are used when certain processes cannot be precisely described [62,63].
(3) Indirect Evaluation Method: This approach uses probability, economic cost, and system capacity to evaluate system resilience. It brings the resilience research closer to practical engineering and demands by using parameters based on economic and functional perspectives. The difference from other methods lies in directly evaluating system resilience using practical parameters without constructing an evaluation function [64].
(4) Comprehensive Evaluation Method: This method involves multi-dimensional model functions and can be further divided into multi-stage comprehensive evaluation and multi-indicator comprehensive evaluation. Examples include segmented evaluation considering critical time and comprehensive metrics for NGPS gas supply resilience, which incorporates temporal resilience, threshold resilience, and global resilience [56].

Each category of resilience evaluation function has its strengths and limitations, and the choice of the appropriate method depends on the specific characteristics of the systems and the objectives of the resilience analysis. The development of diverse evaluation functions enhances the accuracy and practicality of assessing NGPS resilience.

Table 1. System resilience evaluation function.

Evaluation Model Type	Calculation Function	Applied Areas	Remarks	Reference	
Simple integration method	$R = \int_{t_0}^{t_1} [100 - Q(t)]dt$	Community systems	$Q(t)$ is the ratio of function at t to the normal function; t_0 and t_1 are the starting and ending time.	Bruneau [57]	2003
	$R = \int_{t_0}^{t_1} Q(t)dt$	Medical systems	$Q(t)$ is the system function at t.	Cimellaro [58]	2010
	$R = 1 - \frac{XT}{2T*}$	Systems with linear recovery	X is the loss of function; T is the recovery period; T^* is the upper threshold of values of T.	Jin [63]	2017
	$R = \frac{\Psi(t_f)-\Psi(t_d)}{\Psi(t_0)-\Psi(t_d)}$	Network systems	$\Psi(t_0)$ is the value of system function.	Zhang [60]	2018
Temporal integration method	$R = \frac{\int_{t0}^{t1} Q(t)dt}{\int_{t0}^{t1} TP(t)dt}$	Energy systems	$TP(t)$ is the expected function of system.	Ouyang [61]	2012
	$R = \int_{t_1}^{t_6} \frac{Q(t)}{T_{\mathrm{LC}}}dt$	Infrastructure or community system	T_{LC} is the controlled period determined by communities or owners.	Cimellaro [55]	2015
	$R = \frac{\int_{t_0}^{t_1} Q(t)dt}{t_1-t_0}$	Network system under natural disasters	$Q(t)$ is the system function at t.	Reed [59]	2009
	$R = \frac{\int_{t0}^{Ta+t0} Q(t)dt}{Ta}$	Supply chain networks system	Ta is the maximum of recovery period.	Li [62]	2017
Indirect evaluation method	$Recovery = P_m \times P_d \times P_p \times (1-\rho)$	Power system	P is the corresponding probability based on Bayesian network.	Abimbola [65]	2019
	$R_r(Y,a,t,\chi) = \mathrm{R}_r^0 + \int\limits_0^t \frac{\chi b}{(1+r)^\tau} d\tau$	Offshore wind farm	R is the economic capacity; χ is the saving percentage; χb is economic reserve.	Liu [66]	2022
	$C = OC + PC + TC$	Water and energy hub	OC is the operation cost; PC is the penalty cost; TC is the transferring cost.	Ghaffarpour [67]	2018
Comprehensive evaluation method	$R_1 = \frac{\int_{t0}^{td} Q(t)dt}{\int_{t0}^{td} TF(t)dt}$ $R_2 = \frac{\int_{td}^{T} F(t)dt}{\int_{td}^{T} TF(t)dt}$ $R_3 = f(T) = 1\ (T \leq T_0)$	Multiple network systems	$F(t)$ is the system function at t; $TF(t)$ is the function needed at t.	Najarian [64]	2019
	$R_\alpha(t) = \frac{\int_{T_0}^{T} Q(t)^\alpha [Q(t)-\overline{Q}(t)\geq 0]dt}{\int_{t_0}^{T} Q^D(t)^\alpha dt}(\alpha = 0;1)$ $R_\alpha(t) = \frac{\int_{T_0}^{T} Q_P(t)^\alpha [Q_P(t)-\overline{Q}(t)\geq 0]dt}{\int_{t_0}^{T} Q_P^D(t)^\alpha dt}(\alpha = 0;1)$	Natural gas pipeline system	α is the state switch parameter; $\overline{Q}(t)$ is the minimum gas amount required; $Q_p(t)$ is the gas supply function.	Yang [56]	2023

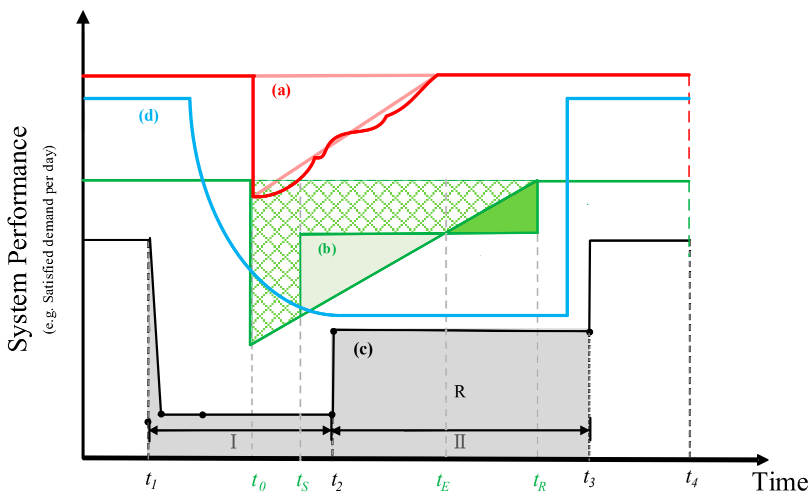

Figure 5. Examples of system resilience curves [60–63].

3.3. Complex Networks Method

In recent years, complex network theory has gained popularity and found diverse applications in various transport networks, including traffic, hydraulic, and electric power systems [68–71]. Complex network theory is highly relevant to NGPSs since they can be represented as dynamic complex networks, where pipeline structures become edges and nodes, gas flow becomes dynamic weights, and station functional parameters and pipeline transport capacity become static weights.

By incorporating complex network theory, representative algorithms such as maximum flow algorithms (e.g., Ford-Fulkerson) and shortest path algorithms (e.g., Dijkstra) are introduced into the model for pipeline network resilience analysis [72,73]. These algorithms can effectively analyze function resilience even in cases where pipeline network scheduling data are incomplete. Furthermore, the integration of complex network theory with pipeline network resilience facilitates the combination of NGPS resilience with Bayesian networks and deep learning algorithms [74,75], particularly graph neural networks [76]. This integration of machine learning and engineering system analysis, especially graph theory, has become a significant trend in the field.

Currently, the integration of machine learning and network theory is mainly focused on two major functions. Firstly, it facilitates the prediction of user load and system state parameters in NGPS [75]. Secondly, it enables the optimization of system operation, maintenance, and repair schemes [74]. This combination of advanced techniques can help enhance the resilience and efficiency of NGPS to analyze complex network behavior and make informed decisions for system operation and maintenance.

As the field of machine learning and network theory continues to be improved, we can expect further advancements in NGPS resilience research, enabling more accurate predictions, intelligent decision making, and improved overall system performance. The integration of these technologies represents an exciting direction for future developments in the field of NGPS analysis and management.

In addition, network theory provides valuable insights into the topological resilience of pipe networks, which can be understood as topology safety. Besides operational safety, supply safety, and equipment safety, topology safety is crucial for assessing the robustness of the pipeline network system. Various metrics based on network centrality, such as degree centrality, betweenness centrality, compaction centrality, and improved betweenness centrality, are proposed to analyze the topology of the pipeline network [77,78]. These metrics facilitate the traversal of nodes or edges to anticipate changes in the supply capacity of the pipeline network after perturbations and to assess changes in reliability and resilience. Furthermore, the criticality of different nodes can be evaluated based on the analysis of these metrics.

In the field of transportation, percolation theory has been applied to identify critical points in transport networks, but its application to the topological resilience of NGPS is still limited. However, the combination of complex network theory and graph theory has facilitated regional division of NGPS. Community algorithms have been integrated into the resilience evaluation of pipeline network systems, demonstrating that disturbances at specific nodes or pipe sections impact certain regional scopes according to the system's topological characteristics [56]. This is different from the power system. The above regional division is mainly based on Newman algorithm [79], Multi-Level Recursive Bisection algorithm (MLRB) [80], etc., which can further help the research on regional vulnerability and resilience.

Although complex network theory has shown promising potential for NGPS resilience research, it is still in its early stages. Current network research for pipeline network topology focuses primarily on the geometrical structure of the network, neglecting the weights of internal functional parameters and gas flow. As an NGPS is characterized by time lag due to the compressibility of natural gas, an effective combination of hydraulic calculation and complex network theory is essential for more comprehensive analyses in the future. At the same time, the optimization of an NGPS is also a crucial aspect of resilience research.

Integrating corresponding optimization theories will be a key area of research in the future. It is vital to consider users with different gas supply priorities and corresponding gas distribution regulations to ensure that the results align with practical engineering. By combining hydraulic calculations, complex network theory, and optimization techniques, researchers can develop more robust and efficient strategies to enhance the resilience and performance of an NGPS.

4. NGPS Resilience Research Application Outlook

With the development of NGPS resilience research, its engineering applications can be summarized as refining goal orientation, guiding relevant prevention and emergency response measures, and aiding engineering design and operations. There have been some technologies which bring NGPS resilience closer to engineering application. The German Institute of Economic Research has built a strategic model (GASMOD) of European gas supply [81]. The main functions include the following: identifying the main factors affecting the balance between gas supply and demand, and guiding the decision making and optimization of the gas trading market, in order to improve the gas supply resilience. The University of Cologne has developed the natural gas transmission infrastructure evaluation model (TIGER) [82], with the function of gas supply capacity analysis and gas distribution optimization, which can help enhance resilience of natural gas supply chain. The Energy Research Centre of the Netherlands developed the gas market simulation and risk evaluation model (GASTALE) for Europe [83] based on the resilience evaluation indicators to evaluate the resilience of the European gas market, in terms of gas supply risk evaluation and gas supply vulnerability analysis. The Institute for Energy of European Commission has developed the MC-GENERCIS model for risk analysis of natural gas supply systems [84], which can evaluate the system's ability to preserve supply under various supply–demand scenarios through stochastic simulations. These application examples have been tested and applied in some European countries, demonstrating the global reach and regionalized applications of NGPS resilience research. The integration of resilience evaluations into practical engineering can guide risk assessment and enhance the resilience of pipeline network systems. Based on the current stage of related research, NGPS resilience research can be applied in the following areas in the future, as depicted in Figure 6. The application areas can be concluded as operation safety (OS), information safety (IS), and market safety (MS). For operation safety, resilience research results can contribute to NGPS operation prewarning, optimization, and asset integrity management (AIM). Based on NGPS information safety, the main applications are information visualization, monitoring and prediction, and decision assistance. In addition, for market safety, NGPS resilience can help demand-side management and policy making assistance.

4.1. Application of NGPS Resilience Research in Operation Safety (OS)

The concept and methodology of NGPS resilience offer a new perspective for pipeline network system prewarning. Traditional prewarning approaches focused on preventing disturbances from occurring, but resilience thinking shifts the focus to how to cope with disturbances, minimize losses, and recover quickly and effectively. Avoiding disturbances unilaterally has proven to be inadequate, and the consequences can be more severe than anticipated [85]. In the environmental field, resilience theory has been recognized as the fourth category of prewarning methodology, emphasizing the importance of incorporating resilience principles into prewarning systems [86]. The University of Delft found that in the fight against COVID-19, the traditional early warning methodology was no longer able to adequately respond to this type of emergencies and integrate the resilience methodology into the prewarning system [87]. After the Gulf of Mexico events and the drilling rig incident at Piper Alpha, the Netherlands, Canada, and the UK have established prewarning systems incorporating system resilience to guide the economic factors responses such as stocks, before they are affected by disturbances [88]. As an expansion of traditional prewarning methods in terms of objectives and methods, NGPS resilience research can guide the prewarning of pipeline systems.

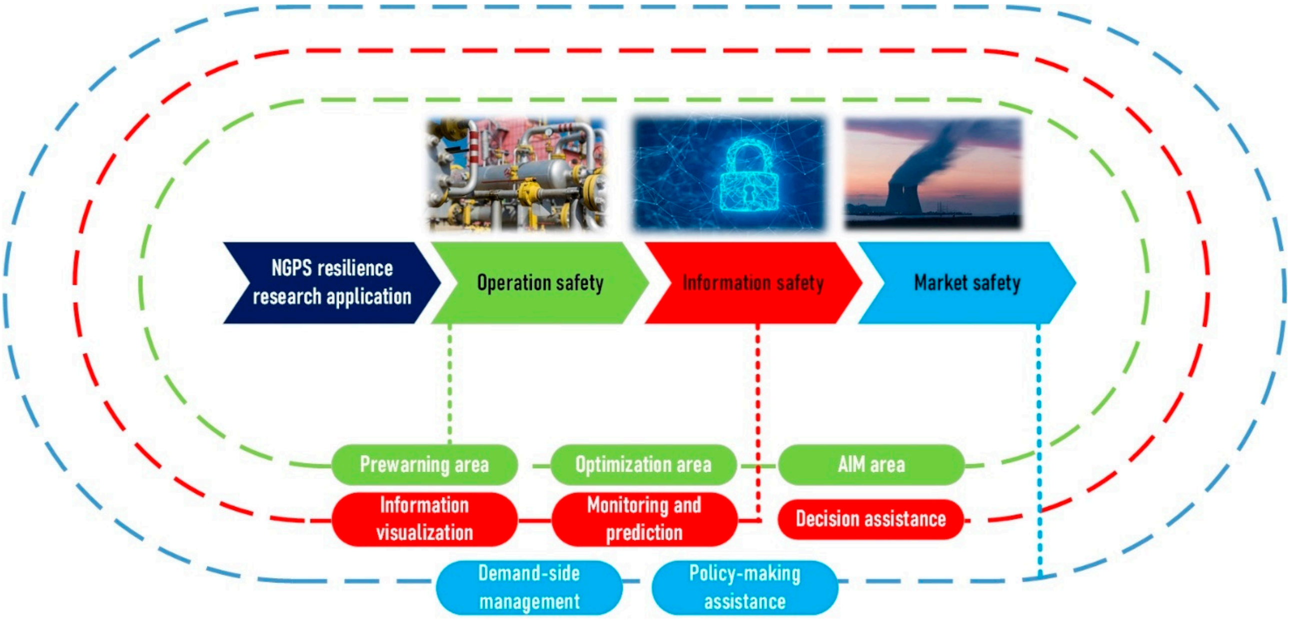

Figure 6. Examples of system resilience curves.

Compared to traditional NGPS optimizations that mostly focus on gas transmission scheduling and operational revenues, optimizations incorporating resilience concepts offer several advantages: (i) Optimization objectives are extended to include the longer temporal domain, encompassing vulnerability, robustness, and recovery optimization. This allows the results of each stage to guide each other, leading to more robust strategies [89]. (ii) Resilience thinking introduces the idea of "being prepared for danger" throughout the optimization process, helping to mitigate losses caused by neglecting uncertain disturbances [90]. (iii) Resilience evaluation indicators can complement traditional constraints, focusing on vulnerability, robustness, and recovery aspects [91]. In the EU countries, relevant resilience analyses have already been integrated into the optimal operation of various systems, such as Internet systems, geographic information systems, electric power systems, and traffic road systems, to achieve more comprehensive full-time domain optimization results.

The integration of system resilience with asset integrity management (AIM) has become more mature in the European Union, and it is now included in the engineering risk evaluation guidelines by the Joint Committee on Structural Safety. This integration has proven the development of recommended methodologies for resilience analysis, which are widely adopted in engineering practices [92].The resilience analysis method integrated with AIM evaluates system resilience through the assessment of current assets and fixed assets. One of the key advantages of this approach is its ability to quantify the resilience evaluation results from an economic perspective, which is highly relevant for enterprises. European countries like Denmark, Switzerland, and Italy have successfully combined resilience evaluation for integrated energy systems (IES) with AIM for subsystems like power transmission systems and offshore wind turbine systems. In this approach, they consider the changes in economic benefits, asset losses, and maintenance costs that may occur due to disturbances. The resilience evaluation of IES is analyzed from multiple perspectives, including management decisions, external environment, infrastructure, and economic benefits [66]. The methodology related to resilience research achieves a multidimensional assessment of system assets from the perspectives of response, resist and recovery, which can promote AIM over the full life cycle and covering uncertainty.

4.2. Application of NGPS Resilience Research in Information Safety (IS)

The first information security incident related to critical infrastructures is the Siberian pipeline explosion caused by the data acquisition and SCADA [93]. Subsequently, in 2021, a notable incident involved the hacking of the largest U.S. refined petroleum product pipeline company, resulting in the shutdown of the pipeline control system [94]. These incidents have brought the issue of information safety resilience into the spotlight. To address this, both physical and virtual resilience measures are essential. Physical resilience pertains to safeguarding typical station control equipment like controllers, HMI hosts, and SCADA servers. On the other hand, the virtual level requires implementing data protection technologies, such as firewalls and data backups. In this context, the NGPS resilience discussed in this paper is particularly relevant as it emphasizes the integration of operational safety and information safety. The core aspect lies in understanding the interconnectedness between information risk, operational risk, and supply risk. This relationship is established through computers, software, networks, and SCADA systems used for production and communication. The application of resilience research in information security has already been evident in risk identification, employing methods like HAZOP [95], FMEA [94], LOPA [96], UFoI-E [97], and STPA [98]. Moreover, for risk evaluation, approaches such as Fault Tree Identification [99] and Bayesian Networks [39] have been used. It is important to note that information disturbances differ from traditional disturbances as they simultaneously impact multiple subsystems, including operation, maintenance, and repair. Their hazards and impacts are multiply coupled. The resilience concept with full-time domain and the combination of real and virtual subsystems will further realize applications in information safety.

The application of system resilience theory in NGPS engineering has shown practical benefits and can be summarized in several key areas: ① Information Visualization Management. The combination of resilience theory allows for the display of NGPS states using multiple resilience indexes. This enables operators, managers, and government departments to carry out gas industry supervision, risk assessment, monitoring, prewarning, and decision making with better information support. ② Gas Dynamic Monitoring and Prediction. By focusing on key areas and high-risk locations, remote monitoring and automatic prewarning systems can be strengthened. This includes automatic alarms for safety anomalies, enabling timely responses to disturbances. ③ Emergency Incident-Assisted Decision Making. The resilience theory, combined with physical equipment signals, can build a knowledge base, case base, and security plan base. These tools assist managers and operators in making informed decisions during emergency incidents. In conclusion, the NGPS resilience research realizes the prewarning improvement and expansion, and provides multidimension indicators for assisting people to make decisions, containing the quantification of casualties, social impacts, and secondary and consequential disasters.

The future improvement of NGPS information safety and resilience can be achieved through the following measures: (i) SCADA systems and their corresponding basic infrastructure should be further strengthened. The safety level of SCADA, especially for internal production networks, can be improved through measures such as VLAN isolation and device isolation. (ii) Robust defense systems should be implemented to handle various types of cyber-attacks, such as virus and hack attacks. Continuous updates and improvements to the defense systems are necessary to stay ahead of potential threats. (iii) Strengthening data backup mechanisms and improving data storage methods can enhance the overall data protection of NGPS. Additional data protection equipment can be deployed to safeguard critical information. NGPS should adopt a comprehensive approach that integrates information safety and resilience. This entails considering the cross-space relation and mechanism between information risk, operational risk, and supply risk to address the multiply coupled hazards and impacts of information disturbances.

4.3. Application of NGPS Resilience Research in Market Safety (MS)

NGPS have a broad business scope encompassing production, transport, storage, and marketing, making them highly connected to the market dynamics. As supply and demand relations become more diverse, the challenges faced by pipeline systems become increasingly intricate. The application of resilience research varies depending on the scale of NGPS and the corresponding markets they operate in. At a global scale, resilience research can be utilized to study long-term development trends, especially for trend forecasting in policy development [100]. Understanding these trends is crucial for ensuring the security of the NGPS market on a global level. On a country-wide pipeline system market scale, resilience research is applied in assessing the impact of long-term factors such as national policies, market laws, and market components on the reliability of natural gas supply. For example, analyzing the potential risk of gas shortages can be accomplished by examining the characteristics of the natural gas market [101]. The vulnerability of regional gas supply can be studied based on the market environment [102], while regional gas supply security can be evaluated based on policies and market behaviors [103]. For NGPS at the regional level, researchers are particularly concerned about the impacts of short-term factors, such as demand fluctuations, contract fulfillment, and the balance between short-term supply and demand, on the stability of gas supply. For instance, a typical study focuses on the security and reliability of short-term gas supply in Colombia [104]. This study delves into the reliability and potential risks of gas supply under conditions of coupled pipeline network operation and market contracts. It simulates and analyzes the relationship between factors such as investment decisions, contract performance, and pipeline network delivery capacity.

Based on the NGPS market and user demands, improving NGPS resilience can be achieved through the implementation of flexible contracts and dynamic pricing. It has been proved that these market methods can realize the balance of gas usage fluctuations by affecting the users' decisions, so as to improve the efficiency of infrastructure and natural gas usage. Consequently, this enhances infrastructure efficiency and optimizes natural gas usage. This approach is known as demand-side management [105]. Demand-side management has also proven its significance in the power grid's production and management, often referred to as the "invisible power plant" [106]. It plays a crucial role in ensuring supply security and maximizing resource utilization. Demand-side management can be categorized based on time periods into efficiency management and demand response methods [107]. Efficiency management involves improving energy utilization efficiency through system design changes [108]. On the other hand, the demand response method aims to modify customer demand through various incentives to achieve a dynamic supply–demand balance, thereby guaranteeing the reliability of energy supply and improving resource utilization efficiency [109,110]. For the methods of demand-side management, the relationships between their impacts and timing are shown in Figure 7. These methods include both market incentives and physical incentives. The former encourages users to adjust their energy usage by changing prices, while the latter enforces adjustments by altering delivery schemes and warning signals [107]. Examples of market incentive strategies include time-of-use power price (TOU power price) [111] and dynamic price-based grid load management methods [112].

In addition, the optimization of NGPS resilience has been attracting increasing attention by combining various fields such as market, emergency, control, and environmental protection. Integrating these aspects facilitates a more comprehensive approach to enhancing the resilience of the pipeline network system. One example is the optimization of the compressor discharge system with consideration of environmental protection regulations. By aligning the system with environmental constraints, the resilience of the pipeline network can be strengthened from an environmental protection perspective [102]. The integration of NGPS resilience and environmentally sustainable development has been a growing focus in research [102,103]. Environmental concerns, such as pollution and carbon emissions, are now considered in NGPS resilience optimization research [104]. This holistic approach acknowledges the importance of environmental sustainability alongside the core aspects of flow and supply security. It is vital to consider not only technical aspects but also the broader sustainability factors, including environmental and economic dimensions [100,101]. This comprehensive view ensures that the resilience measures not only address immediate challenges but also contribute to a sustainable and robust system in the long term.

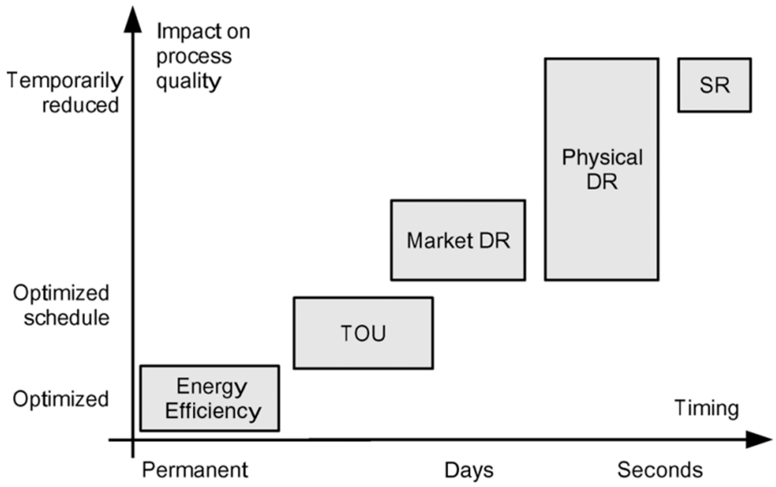

Figure 7. Categories of demand-side management methods [107].

5. Conclusions

Following the rapid development of resilience studies on power grids, water systems, integrated energy systems (IES), and urban lifeline systems, studies on NGPS resilience have been conducted to supplement the lack of reliability and integrity studies, in terms of concepts and research methodologies, which are still in the initial stage. Due to the high complexity of the pipeline network system and the corresponding disturbances, the re-search on NGPS resilience should be further developed in order to achieve the safety of gas supply, with full temporal domain and multidimensions.

(i) The concept of system resilience should be understood in terms of resilience ideas and system characteristics. For NGPS resilience research, disturbances in the broad sense are more adaptable to future trends, including but not limited to natural disasters, equipment failure, market fluctuations, and network disruptions.

(ii) Research methods for NGPS resilience can be categorized into indicator construction, process analysis, and complex network methods. The indicator construction method involves the development of quantitative indicators based on vulnerability, robustness, reliability, and recovery. Process analysis uses resilience curves as visualizations, employing different evaluation methods such as simple integration, temporal integration, indirect evaluation, and comprehensive evaluation. Complex network theory, combined with graph theory and machine learning, can further improve the efficiency of NGPS resilience analysis. It is proved that NGPS resilience research can guide system design, operation, and emergency response.

(iii) Europe and North America are leading in NGPS resilience research, developing algorithms and models for risk evaluation, performance analysis, disaster pre-warning, and recovery guidance. The future focus of NGPS resilience research could be on multidimensional safety applications, encompassing operational safety, information safety, and market safety. This involves pipeline network pre-warning, optimization, Asset Integrity Management (AIM), multi-level fault identification, risk evaluation, and demand-side management.

Developing NGPS resilience research is challenging, requiring the construction and improvement of technical, data, and theoretical bases. Accurate and effective hydraulic calculations are vital for resilience modeling, while comprehensive operation, disturbance, and market databases are crucial for system resilience analysis. Theoretical bases should involve time-lag characteristics based on line-pack and gas compressibility, especially combined with complex networks theory. In conclusion, enhancing NGPS resilience research is essential to ensure the safety and security of gas supply. By integrating multiple dimensions of safety and incorporating advanced research methods, NGPS resilience can be effectively analyzed, leading to the development of comprehensive and practical pipeline network system safety evaluation and optimization.

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