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Review

The Role of Flexibility in the Integrated Operation of Low-Carbon Gas and Electricity Systems: A Review

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Abstract: The integration of gas and electricity networks has emerged as a promising approach to enhance the overall flexibility of energy systems. As the transition toward sustainable and decarbonized energy sources accelerates, the seamless coordination between electricity and gas infrastructure becomes increasingly crucial. This paper presents a comprehensive review of the state-of-the-art research and developments concerning the flexibility in the operation of low-carbon integrated gas and electricity networks (IGENs) as part of the whole system approach. Methods and solutions to provide and improve flexibility in the mentioned systems are studied and categorized. Flexibility is the system's ability to deal with changes and uncertainties in the network while maintaining an acceptable level of reliability. The presented review underscores the significance of this convergence in facilitating demand-side management, renewable energy integration, and overall system resilience. By highlighting the technical, economic, and regulatory aspects of such integration, this paper aims to guide researchers, policymakers, and industry stakeholders toward effective decision-making and the formulation of comprehensive strategies that align with the decarbonization of energy systems.

Keywords: flexibility; integrated low-carbon gas and electricity network; whole energy system; hydrogen storage; P2G; demand response program (DRP); decarbonization; linepack

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1. Introduction

Many countries have invested considerable effort in reducing carbon dioxide emissions and achieving carbon neutrality. Low-carbon economies are based on the United Nations Framework Convention on Climate Change (UNFCCC), which was adopted in Rio in 1992. In recent years, many regions around the world have prioritized developing a sustainable low-carbon economy. The European Union (EU) has played a particularly active role in developing strategies and plans for achieving a low-carbon energy system and economy. In 2024, the EU achieved a substantial milestone, with 44% of its electricity being generated from renewable sources, while ambitiously aiming for nearly complete reliance on renewables, targeting nearly 100% by 2050, as outlined in [1]. For this reason, the EU Energy Roadmap 2050 proposes extensively deploying renewable energy sources (RESs) (primarily wind and solar) as well as smart grids and sustainable economic activities. Nevertheless, other regions (e.g., China, the U.S., Japan, Brazil, etc.) are also investing considerable resources in renewables and low-carbon energy technologies [2]. China, for instance, has declared that it will become carbon neutral by 2060 [3,4]. Finland plans to achieve carbon neutrality by 2035 [5]. The goal of reaching carbon neutrality in several European countries by 2050 is mentioned in [6]. It is essential to fully utilize energy conversion technologies, such as combined heat and power (CHP), power to gas (P2G), and electric boilers (EBs), to achieve these targets and accommodate the growing RESs [7]. Over the past few years [8,9], the low-carbon integrated energy system (IES) has received much attention and has grown rapidly.

To achieve the target, reducing carbon emissions in the energy supply system is crucial [3]. Increasing the use of RESs and improving energy efficiency are the two main approaches to reducing carbon emissions. Its high energy efficiency and easy integration with renewable energies has made the IES, as an energy comprehensive utilization system, an increasingly popular option [10]. Multi-sectoral energy integration and complementation, however, make IESs more flexible [11]. IESs must adopt flexible resources to overcome this challenge and improve their flexibility. In other words, the IES requires improvement of its operational flexibility in order to facilitate carbon neutrality realization in order to enhance performance and the renewable energies share [12].

Two methods are usually used to enhance flexibility: (1) optimizing the operation while considering dynamic operating characteristics and (2) integrating flexible devices to increase the feasible operating area [13]. A combination of the operational optimization and dynamic features of the IES is used in the former (for example, the synergy of multiple time scales [14], dynamic thermal characteristics of buildings [15], demand response (DR) [16,17], and energy storage capacity of the heating supply system [18]). Reference [19] has promoted flexibility and economy by integrating the synergy on multiple time scales among the electricity, gas, and heat systems in the IES [19]. Another study was proposed to improve wind power accommodation by integrating the synergy on multiple time scales [20]. There is a significant heating pipeline in the IES, indicating a large amount of energy storage potential [21]. According to ref. [22], the heating supply network has a considerable capacity for storing energy. To manage the variability of wind energy, a combined heat and power dispatch model was developed [23]. Furthermore, operating optimization strategies frequently employ buildings' dynamic thermal features to improve flexibility. Reference [24] describes a novel optimal scheduling method that incorporates thermal comfort and inertia into a chance-constrained program. Inertia decreased the wind power penalty costs by 36.3% and daily operation costs by 6.4% [25]. Additionally, the IES also relies on DR to adjust its output [26]. Based on the price elasticity matrix [27], a DR model was built for electric and thermal loads. Following that, the IES operation costs were minimized using an optimization model that considered RESs' uncertainty [27], and according to the results, 7.86% of the total cost was saved by DR.

Efficiencies in power generation are determined by how well they can adjust to new demands arising from changes in the residual load on different timescales [2]. To balance demand and supply, operators typically rely on conventional power plants (e.g., gas- and coal-fired plants). Due to the increasing share of renewables, these plants must be able to respond not only more flexibly but also profitably. Improvements and redesigns can be made to conventional power plants to make them more flexible, as well as the definition of new operational strategies and identification of new market mechanisms [28]. Due to its maturity, lower capacity, and geographic limitations compared with DR and storage, generation flexibility will continue to be the most critical solution in the short to medium term for delivering flexibility [2]. As a result of improving the flexibility characteristics of gas- and coal-fired power plants, low-carbon electricity systems are expected to become more efficient. In recent years, there have been studies that only analyzed coal-fired plants' flexibility [29–32], while others have examined gas-fired power plants' (GFPPs') flexibility [33–35]. In some studies, the flexibility of operational processes has been compared between the two technologies, but these studies have been limited in scope [2,28,36–39].

Additionally, a handful of papers have explored the ability of conventional power generation, including both gas and coal, to support the integration of increasing RESs [40–43].

The purpose of this paper is to provide a complete and comprehensive review of the concept of flexibility in IGENs. To achieve this goal, different definitions of flexibility in different sources, the differences compared with concepts such as resilience and reliability, methods of increasing the flexibility in the network, and detailed examination of each one of the methods have been analyzed and categorized.

1.1. Difference between Flexibility and Other Related Concepts

Flexibility, as defined in this paper, is the system's ability to deal with changes and uncertainties in the network while maintaining an acceptable level of reliability [44]. In this context, one of the important and noteworthy issues mentioned below is the difference between flexibility and other similar and related terms, some of which are defined as follows.

1.1.1. Accessibility

Accessibility focuses on making the energy infrastructure and services available and usable to all stakeholders, including consumers, industries, and power producers. It ensures that the energy systems are inclusive and provide equitable access to energy resources and services for everyone [45]. The key aspects of accessibility in an IGEN include the following:

- Universal Access
- Energy Equity
- Infrastructure Development
- Information and Communication
- Regulatory Framework

1.1.2. Durability

Durability refers to the ability of the IGENs to withstand the test of time and continue to function effectively and reliably over extended periods. In this context, durability focuses on the longevity and resilience of the infrastructure and equipment used in the energy system [46].

- Infrastructure Resilience: Design and construct energy infrastructure, such as gas pipelines, power transmission lines, and power plants, to withstand environmental factors, such as extreme weather events, earthquakes, and other hazards [47].
- Equipment Reliability: Using high-quality components and materials in power generation and gas-processing equipment to reduce maintenance needs and minimize the risk of breakdowns.
- Maintenance and Upkeep: Implementing regular maintenance and inspection protocols to identify and address potential issues proactively, prolonging the lifespan of equipment and infrastructure.
- System Longevity: Planning and investing in infrastructure with a long-term perspective, taking into account future energy needs and potential technological advancements.
- Risk Management: Assessing and mitigating risks that could impact the durability of the IGENs, such as supply disruptions, market fluctuations, and geopolitical factors.

1.1.3. Resistance/Robustness/Hardening

A typhoon, for example, is a natural disaster that can be mitigated using the concept of resistance/robustness/hardening [48]. Here are the concepts we will explore:

- Resistance: Resistance refers to the capacity of energy infrastructure to withstand or resist the impact of external forces, such as natural disasters (e.g., hurricanes, earthquakes, and floods), extreme weather events, or human-induced disturbances. The goal of resistance is to minimize the damage and disruption caused by these events by making the infrastructure more durable and resilient.
- Robustness: Robustness in the context of energy infrastructure relates to the ability to maintain essential services and operations even in the face of unforeseen events or adverse conditions. A robust energy system can adapt and continue functioning efficiently under varying circumstances without significant disruptions. To achieve robustness, energy infrastructure might be designed with redundant components or alternative pathways, ensuring that the system can switch to backup mechanisms when needed.

- Hardening: Hardening involves making energy infrastructure more physically and operationally resilient to external threats or attacks. This concept is particularly relevant in the context of protecting critical energy assets from intentional harm, such as terrorist attacks or cyberattacks.

1.1.4. Maintainability and Serviceability

Maintainability and serviceability directly impact the system's ability to recover from disruptions and resume regular operation. These concepts focus on the ease and efficiency of maintenance and repair activities following a disturbance or failure. The key factors affecting maintainability include the following:

- Standardization
- Modularity
- Diagnostic Features
- Maintenance Training

A high level of maintainability means that the system can be restored to regular operation quickly after a disruption, minimizing downtime and improving overall system reliability [49,50].

1.1.5. Serviceability

Serviceability is closely related to maintainability and refers to the overall ability of the IGEN to be serviced or repaired effectively. It encompasses the entire process, from identifying the issue to completing the restoration. The key aspects of serviceability include the following:

- Repair Time: The time it takes to diagnose the problem, obtain necessary replacement parts, and complete the repairs.
- Response Time: The time it takes to respond to a disruption and initiate the restoration process.
- Spare Parts Inventory: Maintaining an appropriate inventory of spare parts, reducing the time needed to obtain replacement components.
- Skilled Workforce: Having a trained and skilled workforce capable of performing repairs efficiently.
- Emergency Preparedness: Having well-defined emergency response plans and protocols in place to handle disruptions effectively.

Higher serviceability means that the IGEN can recover from disruptions quickly, resulting in shorter restoration times and minimizing the impact on energy supply and consumers [51,52].

1.1.6. Survivability

When consumers lack full access to everyday electricity services during disruptive situations, an IGEN can provide simple power services to buyers [53]. This refers to the ability of the integrated system to continue providing essential or basic power services to consumers even in adverse conditions or during emergencies. In essence, survivability ensures that some level of energy supply remains available to meet critical needs during disruptions [54]. During natural disasters, severe weather events, or other emergencies that cause widespread power outages, survivability ensures that essential services can continue to function, providing critical support to communities and reducing the impact on public health, safety, and communication. In summary, the survivability in IGENs ensures that essential power services remain available during disruptive situations, offering support and resilience to consumers, critical facilities, and communities when the regular power supply is compromised [53].

1.1.7. Vulnerability

In terms of a situation or a technique, vulnerability describes the results of a dangerous event [55]. Ref. [56] discusses vulnerability based on the (1) hazard probability distribution, (2) feasible impact of danger, and (3) IGENs' potential.

- Hazard Probability Distribution: This aspect of vulnerability involves analyzing the probability distribution of hazardous events that could affect the IGENs. Hazards can include natural disasters (e.g., hurricanes, earthquakes, floods), human-induced incidents (e.g., cyberattacks, physical sabotage), or any other disruptive events.
- Feasible Impact of Danger: The feasible impact of danger refers to the potential consequences that could arise from the occurrence of a hazardous event. This includes the extent of the damage to infrastructure, the disruption of energy supply, the impact on consumers and industries, and the overall economic and social consequences.
- IGENs' Potential: The IGENs' potential refers to the inherent characteristics and capabilities of the IGENs to cope with hazardous events and recover from disruptions. It encompasses the system's design, infrastructure, operational protocols, emergency response plans, and the availability of backup or alternative resources [57,58].

1.2. Methodology

Our framework for presenting a comprehensive literature review of flexibility studies included five steps: (i) searching online databases and clustering information, (ii) refining citations and samples, (iii) refining abstracts, (iv) refining full-text reviews, and (v) final sorting. Identifying the papers involved searching the Web of Science database, one of the most comprehensive multidisciplinary content search platforms for academic researchers [59]. The main contributions of this paper are the following:

- A comprehensive overview of the available literature about flexibility in low-carbon gas and electricity network co-operation is presented.
- A complete and comprehensive review of the flexibility concepts and flexible technologies that create this flexibility is provided.
- A study of the modeling perspectives for IGENs is proposed, including the type of modeling for the gas flow problem (i.e., steady-state, quasi-steady-state, or dynamic gas flow).
- A comprehensive review of the available literature is presented according to the type of flexible technology used.

In this paper, our objective is to provide a definitive and up-to-date description of flexibility in the co-operation of IGENs. This effort is prompted by the evolving interplay between gas and electricity systems, a dynamic largely influenced by the increasing significance of hydrogen and low-carbon gas-fired plants in the decarbonization of the energy sector. The remainder of this paper is organized as follows. After Section 1, which has the definitions of flexibility and inflexibility and a review of the literature on the subject, the general structure of an IGEN, its coordination methods, and how flexibility is provided by IGENs are provided in Section 2. A complete review of the flexible technologies, the classification and analysis of the findings, and flexibility evaluation methods is included in Section 3. Finally, the paper's general conclusion is provided in Section 4. The logical organization of this paper is shown in Figure 1.

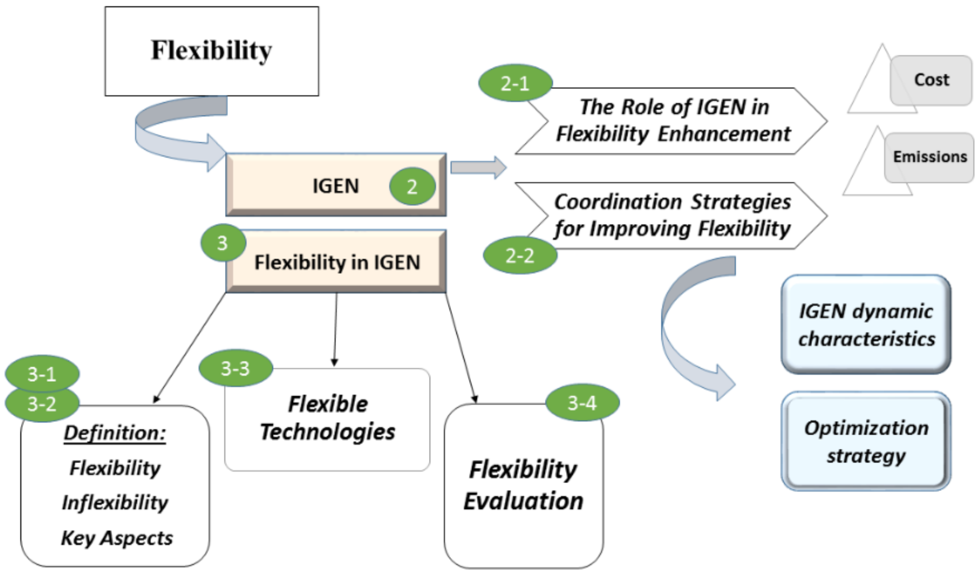

Figure 1. The logical organization in this paper.

2. Integrated Low-Carbon Gas and Electricity Networks

In recent years, extensive research has been conducted into the flexibility provided by IGENs. The concept of flexibility is defined here as the capacity of the integrated system to adjust its allocation of resources directly or indirectly to compensate for deviations in the net electricity load [60]. A growing number of stochastic production facilities are being added to electric energy systems, such as solar- and wind-based units, whose electricity generation depends on the availability of primary energy sources. These fluctuating and unpredictable energy sources present challenges to controlling, operating, and planning the grid due to the difficulty of balancing generation and demand [61]. This problem is being addressed by integrating different energy systems (e.g., electricity, gas, district heating, and transport) [62]. In fact, a system can be made more flexible and compensate for an RES's uncertain output by exploiting the interdependencies and synergies among different energy carriers.

A way to use existing infrastructure more effectively is to consider IGENs when planning and operating power plants in times of increasing energy demand and outdated infrastructure. Well-integrated infrastructure allows energy to be exchanged and exploited efficiently. Various tools based on the concept of IGENs have been developed to analyze low-carbon energy systems, which usually have multiple energy carriers. Figure 2 shows the general schematic of an IGEN.

To study the reliable operation of IGENs, it has been important to consider coordinated power and gas systems [63–65]. For instance, unreliable dispatch results resulting from wind power are determined using a distributionally robust chance-constrained model [63]. To ensure the reliable operation of IGENs, a reliability-constrained optimal reserve scheduling model is proposed in [64]. To mitigate wind power variations caused using an IGEN, [65] proposes a two-stage robust scheduling model for the reserve capacity configuration of power plants. To deal with newly observed uncertainties in RESs' output, [66] develops a multi-stage risk-averse operation model. The aim of [67] is to integrate the operation model of the local energy hub (LEH) into the stochastic dispatch of power systems, taking into account the price and RESs' uncertainty. Ref. [68] proposes a mixed-integer linear programming model for simultaneously determining LEH dispatch plans and IGEN scheduling results. System operators may encounter difficulty obtaining detailed parameters of different devices and directly controlling LEHs in practice due to the privacy concerns of multi-energy consumers [69].

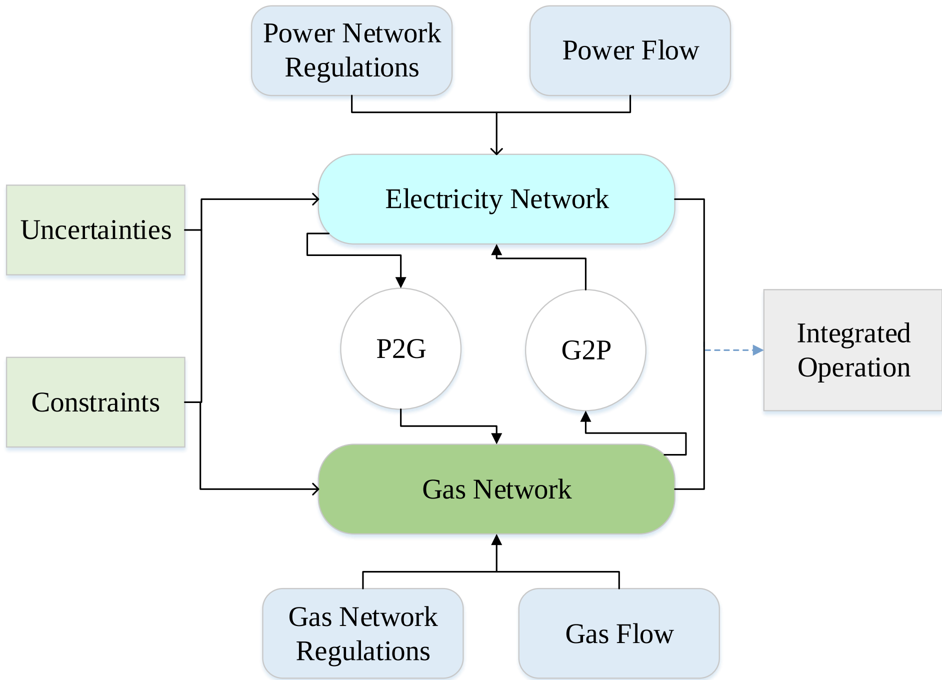

Figure 2. The general schematic of an IGEN.

2.1. The Role of IGENs in Cost Reduction and Decarbonization

Coordinating between the electricity and gas networks can lead to several benefits, including reduced operating costs and emissions. This coordination involves integrating the planning, management, and operation of both networks to optimize their interactions and efficiency. Here are some ways in which this coordination can achieve cost savings and pollution reduction (Figure 3) [66–69]:

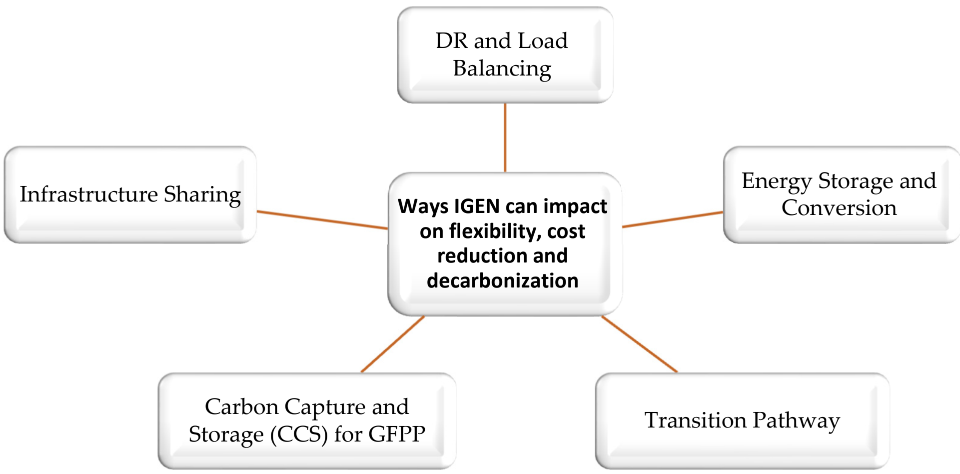

Figure 3. Impact of IGENs on flexibility, cost savings and pollution reduction.

- DR and Load Balancing: Coordinating the electricity and gas networks allows for better DR capabilities. During peak electricity demand periods, gas-based power generation can be utilized as a backup or supplement, reducing the strain on the electricity grid and avoiding the need to run expensive and polluting peaking plants. Similarly, surplus electricity can be used to power gas compressors or to produce hydrogen through electrolysis, storing energy for later use.
- Energy Storage and Conversion: Gas infrastructure can act as a form of energy storage. Excess electricity generated during off-peak periods can be used to produce hydrogen

or synthetic natural gas (SNG), which can be stored in existing gas infrastructure. Later, this stored energy can be converted back into electricity or used for other purposes, providing flexibility to the overall energy system.

- Infrastructure Sharing: Coordinating the planning and deployment of electricity and gas infrastructure can lead to shared use of certain components, reducing overall capital costs. For example, corridors for gas pipelines and electricity transmission lines can be shared, minimizing the land disruption and environmental impact.
- Carbon Capture and Storage (CCS) for GFPP: Integrated networks provide an opportunity to implement CCS technologies in gas power plants. CCS captures carbon dioxide emissions from power generation and industrial facilities and stores them underground, preventing them from entering the atmosphere. By integrating CCS with gas power plants, emissions can be significantly reduced, making GFPP a more carbon-neutral option.
- Transition Pathway: The integrated low-carbon gas and electricity network can act as a transition pathway to decarbonization. As the share of renewable electricity increases, gas-fired power plants can provide flexibility and stability to the grid during the transition phase, allowing for a smoother integration of intermittent renewable sources.

In summary, it can be said that the IGEN can enhance the resilience and flexibility of the energy system, resulting in cost savings, reduced emissions, and a cleaner, more sustainable energy landscape. However, achieving such coordination requires collaboration between energy stakeholders, policy support, and investments in smart infrastructure and technology [62].

2.2. Coordination Strategies for Improving Flexibility

As the interdependence between the electricity grid and the gas network increases, modeling and optimizing the two energy systems separately may not be practical or physically feasible. The literature about the optimal operation of IGENs features different gas flow models, optimization strategies, and approaches to dealing with uncertainties. As shown in Figure 4, IGEN modeling can be classified according to two different perspectives: IGEN dynamic characteristics and optimization strategy.

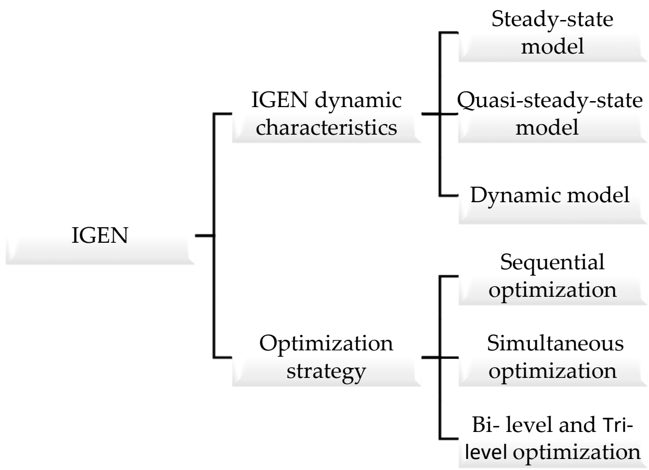

Figure 4. Classification of IGEN modeling.

2.2.1. First Category: IGEN Dynamic Characteristics

- Steady-state models: The steady-state model typically involves formulating mathematical equations that represent the power flow in the electrical system and the gas flow in the natural gas network [70–73]. The model considers the electricity and natural gas supply and demand, network topology, transmission capacities, generator characteristics, and gas pipeline constraints. In the power system context, the steady-state model usually relies on power flow equations, such as the DC or AC power flow models [63,70,71]. For the gas system, the steady-state model includes equations that describe the gas flow through pipelines, considering factors like the gas supply, pressure, and constraints on compressors and other facilities. The integration of the steady-state models for both the electrical and gas systems allows for the analysis of the energy exchange and optimization of their joint operation [72–74].

- Quasi-steady-state model: This model for an IGEN is an intermediate approach that strikes a balance between accuracy and computational efficiency [75]. This modeling technique is used to analyze the behavior and optimal operation of the combined energy networks, taking into account certain dynamic aspects while simplifying others. In a quasi-steady-state model, some components of the system, such as electricity transmission lines, are assumed to respond rapidly and are represented as steady-state elements [76]. At the same time, other components with slower response times, such as gas pipelines, are modeled with more dynamic characteristics. This enables a more realistic representation of the interactions between the electricity and gas systems, including the effects of gas flow constraints, while avoiding the computational complexity associated with fully dynamic models [77,78].
- Dynamic model: This model is a comprehensive approach that considers the time-varying behavior and interactions between the electricity and gas networks [79,80]. Unlike steady-state or quasi-steady-state models, dynamic models capture the transient responses and time delays inherent in both systems, providing a more accurate representation of their real-world dynamics. In a dynamic model, the gas flow in pipelines and the electricity flow in transmission lines are modeled with differential equations that account for various time-dependent factors, such as the inertia, time delays, and control dynamics [81,82]. This level of detail allows for a more realistic assessment of the system stability, operational constraints, and response to rapid changes in demand or supply [70,83].

2.2.2. Second Category: Optimization Strategy

- Sequential optimization strategy [81–84]: The sequential approach involves formulating two separate optimization problems for the power system and the gas system. The electricity production and transmission are optimized first, followed by determining the gas demand generated by gas-fired power plants. If P2G processes are considered, the P2G unit schedule is also determined. Subsequently, the low-carbon gas system is optimized. This sequential approach mimics current operating practices, where the two systems are optimized separately. However, it can lead to sub-optimal solutions and requires an iterative procedure to ensure consistency between the two systems.
- Simultaneous optimization strategy [75,82,85]: In contrast, simultaneous (or fully integrated) approaches aim to minimize the total cost associated with both systems using a single objective function. This means jointly optimizing the operation of the integrated system to achieve the most cost-effective and flexible solution. Simultaneous optimization provides a holistic view of the entire IGEN, allowing for better coordination between the gas and power systems [86,87].
- Bi-level and tri-level programming: Some authors have proposed bi-level programming or tri-level programming, where upper-level problems optimize the power system while lower-level problems represent the optimal gas scheduling. Within tri-level optimization, a middle tier addresses a distinct optimization challenge, influenced by the upper level and, reciprocally, impacting the lower level [88]. These formulations consider the physical and economic couplings between the two systems and are used to address specific coordination aspects of IGENs [89].

3. Flexibility in IGEN Co-Operation

3.1. Analysis of Flexibility Definitions

Flexibility in the context of an IGEN refers to the ability of the IES to adapt and respond effectively to variations in the energy supply and demand, as well as to changing operational conditions. It involves optimizing the interaction between the gas and electricity infrastructures to enhance system resilience, reliability, and efficiency. As shown in Figure 5, in an IGEN, flexibility encompasses several key aspects:

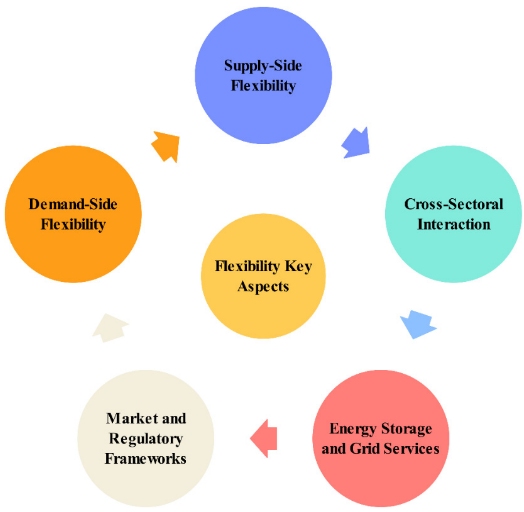

Figure 5. Key aspects of flexibility.

I. Demand-Side Flexibility: The capability of adjusting electricity and gas consumption patterns in response to changes in energy prices, availability of renewable energy, and system needs. With demand-side management techniques, such as DR, consumers can reduce consumption during high-demand periods or shift usage to off-peak hours.
II. Supply-Side Flexibility: The ability to vary energy production levels from different sources, including GFPPs, RESs, and ESSs. Flexible power generation and dispatch strategies enable the grid to dynamically balance supply and demand.
III. Cross-Sectoral Interaction: The coordination between gas and electricity networks, allowing them to support each other during peak periods and fluctuations. For instance, P2G technologies enable excess electricity to be converted into hydrogen or synthetic gas, which can be stored and later used for power generation or injected into the gas grid.
IV. Energy Storage and Grid Services: Utilizing various energy storage technologies, such as hydrogen, pumped hydro, and compressed air energy storage, to store excess energy and release it when needed. These storage systems provide grid stability and support load balancing.
V. Market and Regulatory Frameworks: Establishing flexible market mechanisms and regulatory policies that encourage the integration of gas and electricity networks. This includes facilitating energy trading, promoting fair competition, and incentivizing investments in flexible technologies.

In general, flexibility is crucial to effectively addressing demand imbalances while simultaneously ensuring a secure and sustainable energy transition. By integrating advanced technologies and smart grid solutions, IGEN systems can efficiently adapt to varying energy demands, optimize energy distribution, and seamlessly incorporate RESs, thus promoting a reliable and environmentally friendly energy landscape for the future. By embracing flexibility, gas and power systems can meet the challenges of a rapidly changing energy landscape and enhance their ability to provide consumers with a sustainable and uninterrupted electricity supply. The definition of flexibility should be based on the fact that flexibility is system-specific. Generally, systems using a variety of fuel sources (e.g., natural gas, wind, DR, and pumped storage) will be more flexible than those that exclusively use coal or nuclear power. Regulations and market rules also play an integral role in shaping the flexibility of an IGEN [44]. In summary, it can be stated that flexibility is a critical aspect of gas and power systems that allows them to adapt to changing conditions and maintain stability. Some key points about flexibility in gas and power systems are taken from [30–33,39,42,44] as follows:

1. Inherent Feature: Flexibility is a fundamental characteristic intentionally incorporated into the design and operation of gas and power systems. It recognizes the dynamic nature of electricity generation, consumption, and supply.
2. Spatial and Temporal Balancing: Gas and power systems aim to achieve a balance between electricity generation and consumption on both the spatial (geographical) and temporal (time) scales. This ensures that electricity is delivered efficiently and reliably to consumers across different locations and times.
3. Adapting to Changes: Flexibility allows the gas and power systems to respond promptly to fluctuations in the electricity demand and supply. This adaptability ensures that the system can handle variations in consumption and generation without compromising stability.
4. System Stability: Maintaining stability is crucial to avoid disruptions and blackouts in the electricity supply. Flexibility allows the system to manage sudden and substantial changes in supply or demand, ensuring continuous service without compromising reliability.
5. Cost-Effectiveness: Flexibility is not only about maintaining stability but also about doing so in a cost-effective manner. It involves optimizing the allocation of resources and ensuring that adjustments in generation and consumption are efficient and economically viable.

3.2. Signs of Inflexibility

Inflexibility can sometimes be more easily documented than flexibility [44]. In IGENs, signs of inflexibility can manifest in various ways, indicating challenges in adapting to changing energy demands and market conditions. Some common signs of inflexibility include the following:

I. Lack of Response to Demand Fluctuations: An inflexible system may struggle to adjust electricity production or gas supply to meet varying levels of demand. This could lead to either excess generation that goes to waste or insufficient supply, resulting in potential blackouts or energy shortages.

II. Difficulty in Integrating RESs: RES generation, such as solar and wind, is inherently variable. An inflexible system may face difficulties in smoothly integrating these intermittent energy sources, leading to grid instability and curtailment of renewable power when it cannot be effectively utilized.

III. Inability to Ramp Up or Down Quickly: Gas-fired power plants, often relied upon for flexibility, may face challenges in quickly ramping up or down their electricity production in response to sudden changes in demand or RES availability. This lack of responsiveness can strain the balance between electricity generation and consumption.

IV. Limited Energy Storage Capacity: Energy storage systems, crucial for managing fluctuations in RES generation, may be inadequate or not optimized in an inflexible system. This results in the inability to store excess energy during low-demand periods and discharge it during high-demand periods.

V. High Curtailment Rates: Curtailment refers to the intentional reduction or elimination of electricity generation from certain power plants, typically renewable sources, due to oversupply or grid constraints. An inflexible system may experience high curtailment rates, wasting valuable clean energy resources.

VI. Rigidity in Gas Network Management: In an integrated system, gas-fired power plants' operations are closely linked to the gas supply and demand. An inflexible gas network management could lead to gas shortages or congestion in pipelines, limiting the output of gas-fired power plants and impacting grid stability.

VII. Struggles with Demand-Response Implementation: Inflexible systems may find it challenging to implement effective demand-response programs, where consumers adjust their energy consumption based on real-time pricing or grid conditions. Limited demand-response participation can hinder load-balancing efforts.

VIII. Inefficient Use of Existing Infrastructure: An inflexible system may underutilize existing infrastructure, such as pipelines and power transmission lines, leading to inefficiencies and increased operating costs.

Addressing these signs of inflexibility requires a holistic approach, including investments in energy storage technologies, demand-response programs, improved grid management, and a diversified energy mix that incorporates a greater share of RESs. Additionally, adopting advanced technologies and fostering co-operation between the gas and power sectors can enhance the overall flexibility of IGENs. In short, the most important signs of inflexibility can be summarized in the following cases:

- Inability to balance demand and supply, which may result in load drops or frequency excursions.
- Significant curtailments in RES generation, primarily due to excess supply and transmission constraints when generation is not needed regularly or for long periods (e.g., nights, seasons) [57].
- An area balance violation, which occurs when the area power balance schedule is deviated from.

Moreover, in terms of wholesale power markets, the following can be stated:

- Negative market prices: Several types of inflexibility can be signaled by negative market prices, including conventional plants that are unable to reduce production, loads that cannot absorb excess supplies, RESs' surpluses, and limited transmission capacity to balance supply and demand over a larger area. As RESs' penetration increases, negative prices may become more prevalent in systems without renewable energy.
- Price volatility: There are several causes of price volatility, including limited transmission capacity, limited ramping, fast response, peaking supplies, and limited ability for loads to reduce demand [58].

3.3. Flexible Technologies

In addition to system operations and markets, demand-side resources and storage, generation, and transmission networks, all the elements of the integrated network can be expanded for greater flexibility. For a power system to be flexible, long- and short-term planning is required to optimize investments. Various technologies and approaches can be employed to provide flexibility in IGENs. These technologies enable the system to adapt electricity generation and consumption as needed to maintain stability and optimize overall performance. In this section, we try to review and categorize all the resources and flexible technologies that have been used in the literature and increase flexibility in the co-operation of electricity and gas networks. The classification and summary of studies based on the type of flexible technology used and year of publication in the last five years is shown in Table 1.

Table 1. Type of employed flexible technology and publication year.

Year	Flexible Technology					
	GFPP	P2G	DRP	HS	VPP	Linepack
2023, 2024	-Shahbazbegian, V et al., 2023 [90] -Wang, B et al., 2023 [91] -Rinaldi, A., 2023 [92] -Ramadhon, N. M et al., 2023 [93] -Cai, X., et al., 2023 [94]	-Ademollo, A et al., 2023 [10] -Shahbazbegian, V et al., 2023 [90] -Mizobe, K et al., 2023 [95] -Yanan, B., and Zhang, P. 2023 [96] -Qin, L et al., 2023 [97] -Xiong, J et al., 2023 [98] -Gao, H et al., 2023 [99]	-Wang, S et al., 2023 [100] -Shi, M et al., 2023 [101] -Rahimi, M et al., 2023 [102] - Nasiri, N et al., 2024 [103] -Wang, L et al., 2023 [104] -Li, L et al., 2023 [105] -Duan, J et al., 2024 [106] -Men, J., 2023 [107]	-Shahbazbegian, V et al., 2023 [90] -Moran, C et al., 2023 [108] -Walter, V et al., 2023 [109] -Wu, C et al., 2024 [110] -Schmugge, J et al., 2023 [111] -Zhang, Z et al., 2023 [112] -Niu, Y et al., 2023 [113] -Khaligh, V et al., 2023 [114] -Xu, J et al., 2023 [115] -Nasiri, N et al., 2023 [116]	-Rahimi, M et al., 2023 [102]	-Wang, S et al., 2023 [100] -Shi, M et al., 2023 [101] -Wu, C et al., 2024 [110]
2022	-Zhou, J et al., 2022 [117]	-Zhou, Y., 2022 [118] -De Corato, A et al., 2022 [119] -Zhou, J et al., 2022 [117]	-Vahedipour-Dahraie, M et al., 2022 [120]	-Zhou, Y., 2022 [118] -Yang, H et al., 2022 [121] -De Corato, A et al., 2022 [119] -Zhou, J et al., 2022 [117]	-Oladimeji, O et al., 2022 [122] -Wang, S et al., 2022 [123] -Vahedipour-Dahraie, M et al., 2022 [120]	-
2021	-Li, X., and Mulder, M., 2021 [124] -Ge, S et al., 2021 [125]	-Y. Cheng et al., 2021 [126] -Y. Tao, J et al., 2021 [127] -Chen, J et al., 2021 [128] -Jin, C et al., 2021 [129] -Li, X., and Mulder, M., 2021 [124]	-Chen, J et al., 2021 [128] -Mansouri, S et al., 2021 [130] -Gjorgievski, V et al., 2021 [131] -Ge, S et al., 2021 [125] -O'Connell, S et al., 2021 [132]	-Jin, C et al., 2021 [129] -Li, X., and Mulder, M., 2021 [124] -Rabiee, A et al., 2021 [133] -Sheha, M., 2021 [134]	-Iraklis, C et al., 2021 [135] -Ullah, Z., and Mirjat, N. H., 2021 [136]	-
2020	-Kryzia, D et al., 2020 [137] -Ameli, H et al., 2020 [138]	-Ameli, H et al., 2020 [138] -Ge, P et al., 2020 [139]	-Ameli, H et al., 2020 [138] -Heydarian-Forushani, E., and Golshan, M. E. H., 2020 [140] -Dadkhah, A et al., 2020 [141] -Mohandes, B et al., 2020 [142]	-Ge, P et al., 2020 [139]	-Yi, Z et al., 2020 [143]	-Ameli, H et al., 2020 [138]
2019	-Schwele A et al., 2019 [75] -Glensk, B., Madlener, R., 2019 [144] -Liu, J et al., 2019 [145]	-Glensk, B., and Madlener, R., 2019 [144] -Liu, J et al., 2019 [145]	-	-Teng, Y et al., 2019 [146]	-	-Schwele, A et al., 2019 [75]
2018	-Gonzalez-Salazar, M. A et al., 2018 [147] -Y. Li, et al., 2018 [148] -J.C. Liu et al., 2018 [149]	-Gonzalez-Salazar, M. A et al., 2018 [147] -J.C. Liu et al., 2018 [149]	-Y. Li, et al., 2018 [148]	-Lorestani, A., and Ardehali, M. M., 2018 [150] -J.C. Liu et al., 2018 [149]	-	-Tran, T. H et al., 2018 [151]

3.3.1. GFPP

There is a great deal of flexibility in the way GFPPs operate. In response to changes in demand or fluctuations in RES generation, they can quickly ramp up or down their electricity production. Combined Cycle Gas Turbines (CCGTs) and Open Cycle Gas Turbines (OCGTs) are widely used in integrated systems for fast and responsive power generation. GFPPs are particularly suitable for integrating intermittent RESs into a grid and supporting further penetration of clean energy due to their ability to respond quickly to changes in demand and supply. In this way, RESs' variability affects the gas demand and impacts network management. GFPPSs' power output could be limited by gas supply shortages or congestion at their nodes, and their gas consumption can vary rapidly at their nodes, affecting the security and operating costs of the two systems [147].

Furthermore, the reliance on gas-fired power plants as a flexible backup for RESs raises concerns about long-term sustainability and carbon emissions. While natural gas is considered a cleaner alternative to coal and oil in terms of greenhouse gas emissions, it still releases carbon dioxide when burned. In the context of efforts to combat climate change and transition to a low-carbon economy, the continuous operation of GFPPs may hinder the achievement of ambitious emission reduction targets [144]. To address this challenge, it becomes imperative to implement CCS technologies in conjunction with gas-fired power plants. CCS allows for the capture of carbon dioxide emissions from GFPPs and their subsequent storage underground, effectively preventing them from entering the atmosphere. By integrating CCS with gas-fired power generation, it is possible to significantly reduce the carbon footprint of these plants and align their operations with climate goals [137].

In addition to the technical challenges associated with gas-fired power plants, there are also economic and geopolitical considerations to be mindful of. The price volatility of natural gas can impact the cost-effectiveness of operating GFPPs, as fluctuations in fuel prices directly influence electricity production costs. Relying heavily on imported gas can also make a nation vulnerable to supply disruptions or price manipulations by external suppliers, leading to energy security concerns. Hence, a diversified energy mix and a comprehensive energy policy that promotes the integration of various renewables, energy storage systems, and demand-response strategies are essential for building a resilient and sustainable power system. By carefully balancing the deployment of gas-fired power plants with other RESs and incorporating innovative technologies, countries can transition toward a more secure, affordable, and environmentally friendly energy landscape [138].

3.3.2. P2G

P2G technologies convert surplus electricity into hydrogen or synthetic natural gas. This allows for the storage of excess RESs in the gas grid, which can later be used in gas-fired power plants or as a clean fuel for other applications, thereby integrating the IGENs. P2G will increase the flexibility of IGENs by reducing renewable curtailment and providing additional gas supply for the gas network [81,90,145].

As gas pipelines have storage characteristics, P2G increases the flexibility and security of IGENs, as well as improving energy efficiency, and enables environmental benefits [152]. Due to these reasons, P2G technology plays a very important role in ensuring a full-cycle power supply and converting surplus electric energy into natural gas. Enhanced flexibility of a system can be achieved by fast energy conversion and transmission of P2G [81]. An analysis of the feasibility of P2G wind power accommodation is presented in [126]. The P2G process converts excessive wind power into hydrogen and then absorbs CO_2 to produce CH_4 for IGENs' development and wind power accommodation [127,148]. Also, [128] analyses the best micro-gas turbine and P2G corporation strategy. In the references, GFPP [63,70–89,153,154] and P2G [81,90,126–128,145,148,152] are the linking components of two electricity and gas networks. In some studies, both types of linker and interface between the two networks have been used [76,81,82,89,153].

3.3.3. DRP

Demand-side management and DR enable consumers to participate in load control based on price signals. The DR mechanism includes real-time pricing, smart metering, automated load control, and time-of-use tariffs [130,131,140]. Despite its relative affordability, DR requires strict regulations regarding response times, minimum magnitudes, and the reliability of demand-side resources. DR contributes to load balancing and system flexibility by incentivizing consumers to reduce or shift their electricity usage during peak hours [100,101].

In IGENs' scheduling, DRP has attracted much attention because it smooths the fluctuation of load curves, reduces peak–valley differences, and improves the utility of both supply and demand. A further benefit of DR in IGENs is that it can reduce the net load fluctuation. Customer participation in DR is divided into two options. During peak periods when electricity prices are high, customers can reduce their electricity consumption, while they do not change their consumption patterns during other times. Another option is for customers to shift their loads from peak to off-peak periods based on the price information [131].

3.3.4. Storage Systems (Including Heat and Hydrogen Energy Storage (HES))

VRE energy produced during excess periods of VRE generation is stored by HES and discharged when required. The cost of storage is generally higher than that of DR and other flexible options [155]. They store excess electricity during low-demand periods or high renewable generation and release it during peak demand or low renewable output, effectively balancing supply and demand in the system.

- Heat storage: Wind power accommodation can be enhanced by using heat storage to decouple the electric-heat characteristics of CHP units [156]. As described in [150], heat storage, electrical energy storage, and electric heaters are used in conjunction to increase the flexibility of CHP units to accommodate wind power. However, the network of heaters responds slowly to the CHP units.
- Hydrogen energy storage: Electrolysis converts excess RESs power into hydrogen, which is stored in the HES system. A hydrogen-based gas turbine converts the stored energy into electricity during periods of high electricity demand and low wind power production [108,124,129,139,146]. Compared to other similar storage systems, the HES stores hydrogen that is either used in hydrogen-dependent industries or injected into the gas network to serve gas consumers [109,118,121,133]. A hybrid natural gas/hydrogen energy storage system (HGESS), an environmental protection energy supply system with a similar energy flow to the power grid, can store and transport energy efficiently while, on the other hand, taking full advantage of IGENs emissions [134,149]. Hydrogen storage allows for the capture and utilization of surplus energy generated from renewable sources during periods of high production and its release as needed to meet the energy demand during periods of low RES generation [117,119].

3.3.5. Virtual Power Plants (VPPs)

VPPs are software-based systems that aggregate and manage the output of multiple distributed energy resources, such as solar panels, batteries, and electric vehicles. VPPs provide a coordinated response to grid needs and can act as a flexible and decentralized resource [122,135,143]. In other words, VPPs act as intelligent energy management systems that leverage advanced algorithms and data analytics to optimize the operation of distributed energy resources and enable seamless coordination between the gas and electricity networks. By providing enhanced flexibility, VPPs contribute to the integration of renewable energy, support grid stability, and facilitate the transition toward a more sustainable and flexible IES [102,120,123,136].

3.3.6. Linepack

Another flexible feature of the gas network is the linepack that shows the amount of gas stored in gas transmission pipes, which plays a vital role in maintaining the minimum consumption pressure, stability of gas flow indicators, and management of changes in gas demand. In particular, the capabilities of the linepack increase the flexibility and reliability of the low-carbon gas system to supply gas-fired power plants and gas consumers. It has also been shown that when interruptions and random exits occur in the gas network, the linepack can be an effective tool for supplying gas loads [110]. The linepack contributes to the stability of gas flow indicators in the transmission pipelines. It acts as a buffer to balance gas supply and demand fluctuations, preventing sudden pressure drops or surges that could impact the integrity and performance of the gas network. In [75], the maximum potential of the linepack is used as a source of flexibility for power systems. The second-order complex integer formulation with McCormick release has been used to model bidirectional gas diffusion for the linepack. Reference [151] presents various models for optimal planning of the linepack by considering uncertainties such as demand fluctuations, gas shortages, and compressor failures.

Other technologies in the literature can be mentioned in relation to the following two issues:

- System operations and markets: There is a significant possibility of unlocking flexibility through system operation practices and market changes. These changes can often be achieved at lower costs than options requiring modifications to the physical power system [125]. A change in day-ahead generation scheduling practices that allows changes to be made in closer to real time allows dispatch decisions based on more accurate forecasts of both the output and demand for VREs. As a result, more precise and efficient market operations can be carried out, which reduces the need for costly reserves [91].
- Flexible transmission networks: To provide greater access to balancing resources, the power system can expand the transmission lines and interconnect them with neighboring transmission lines to have a more flexible transmission system. It has been shown that aggregating generation assets through interconnection improves flexibility and reduces net variability across the grid. Several flexible technologies and advanced management practices can be used to minimize bottlenecks in the network and optimize the utilization of transmission bandwidths, in addition to intelligent network technologies [157].

3.4. Flexibility Evaluation

The ability of an IGEN to respond and adapt to changes in demand, supply, and operating conditions is evaluated to determine the degree of flexibility of the system. The flexibility of these systems can be quantified and analyzed through various methods and metrics. A study measured power system flexibility in long-term planning by analyzing the insufficient ramping resource expectation metric reported in [158]. This study proposed a probabilistic metric that takes into account the key technical characteristics of the generation units and the current operational state of the generation units and aggregates those data to assess the system as a whole. As a result of the definition of flexibility and the physical mechanism of power systems, [159] proposed a flexibility metric for power systems. Based on their findings, the researchers developed a three-stage methodology to quantify the maximum flexibility of a district heating sector for the power grid [160]. A spatiotemporal flexibility management scheme was designed to reduce energy consumption in low-carbon power systems [161]. There have been studies to measure the flexibility in power systems, and methods to provide flexibility in those systems have been evaluated in [162].

Many studies have demonstrated that IGENs with renewable generation [163–167] and P2G can provide affordable low-carbon power and greatly increase the flexibility of planning [89,90,145,153,168–172]. Specifically, the P2G conversion process allows RESs to be converted into gas to increase the gas availability for gas turbines and the gas network.

This means that both the power systems and the gas network will be more flexible, as power systems are being converted to gas to increase the gas supply and gas networks to replenish the pipelines. A growing body of research emphasizes the importance of the flexibility of gas network infrastructure to effectively accommodate the anticipated expansion of intermittent RESs in future power grids. Furthermore, a fully integrated approach to operating gas and electricity networks was analyzed using flexible multi-directional compressor stations [87]. Using an integrated electricity/gas transmission network model, researchers quantified the gas network flexibility and discussed how gas network constraints affect electricity system operation [84,173,174]. A comprehensive overview of the technical flexibility assessment of multi-energy and distributed multi-energy systems was presented in [175], focusing on their potential to support low-carbon grids.

As a result of these studies, we are now able to understand the flexibility of power systems, gas networks, and multi-energy systems, and we can provide new insights for future research on assessing the flexibility of multi-energy systems. An integrated power–natural gas-heating energy system with P2G and gas storage was described in [176], and a framework for evaluating the flexibility of the power–natural gas-heating energy system using a multi-objective economic and environmental optimal operation strategy was presented. The linepacks of pipelines and gas storage volumes are modeled as sources of flexibility for a system, and their capability is evaluated in terms of the flexibility they provide. In [177], the authors propose a composite metric that aggregates several variables related to the flexibility of generation units through the use of normalization, weighting, and correlation analyses. There are some interdependent metrics defined in [178] that can be used to evaluate the level of flexibility available by each generation unit in real time, while in [179], a metric is proposed that also takes into account the effects of the transmission network on the level of flexibility.

In summary, by checking references [84,158,162–172], the flexibility assessment methods can be divided as follows. Figure 6 shows the flexibility assessment methods.

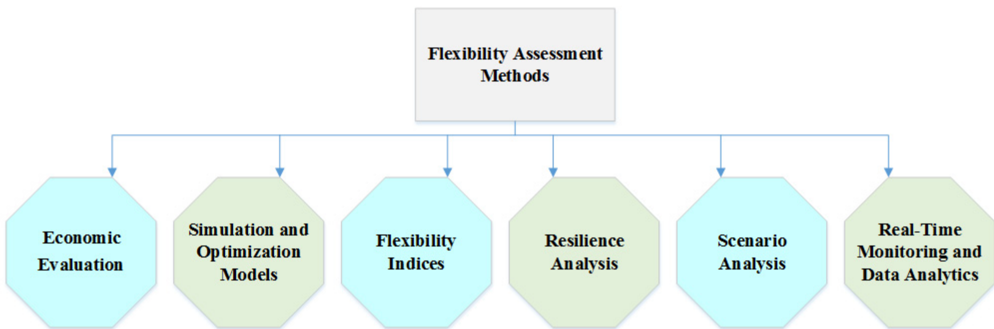

Figure 6. Types of flexibility assessment methods.

(1) Simulation and Optimization Models: These models consider factors such as the gas flow, electricity generation, demand, storage, and interconnections. Optimization techniques are applied to find the system's most efficient and flexible operation, considering various constraints and objectives.
(2) Flexibility Indices: Flexibility indices are quantitative metrics used to measure the system's ability to adjust to changes in demand and supply. These indices can be based on factors such as the ramp rates of power plants, response times of gas-fired generators, load-shifting capabilities, and storage capacities. Higher flexibility indices indicate a more responsive and adaptable system.
(3) Resilience Analysis: Resilience analysis assesses the system's ability to recover and continue operating after facing disruptions or disturbances. It evaluates how quickly the system can return to a stable state and continue supplying energy to consumers, even during unexpected events or failures.

(4) Scenario Analysis: Scenario analysis involves exploring different potential future scenarios, such as changes in demand patterns, variations in RES generation, or disruptions in the gas supply. The system's flexibility in handling different situations can be evaluated by analyzing these scenarios.
(5) Real-Time Monitoring and Data Analytics: Real-time monitoring of gas and electricity flows, demand, and supply allows for continuous system flexibility assessment. Data analytics techniques can be applied to analyze historical data and identify flexibility-related patterns and trends.
(6) Economic Evaluation: Flexibility improvements in IGENs can have economic implications. An economic evaluation can include a cost–benefit analysis, considering the costs of implementing flexible technologies and the benefits of improved system performance, reliability, and reduced operational expenses.

4. Conclusions

Flexibility in IGENs is a key concept in realizing the decarbonization goals and dealing with climate change. Flexible systems with the ability to adapt to fluctuations in energy demand and supply, while improving the efficiency and stability of the network, reduce the need for energy production during peak consumption times. Furthermore, flexibility enables the optimal use of renewable energy sources and, as a result, helps to reduce greenhouse gas emissions. It is well-recognized among researchers and practitioners that the concept of flexibility is of significant importance and has been widely discussed in the past decade. This paper has attempted to summarize the most recent updates on the subject of flexibility, providing all the information necessary about IGENs' flexibility and its relevance across various service categories.

To achieve this goal, a comprehensive and complete review of the definitions and concepts of flexibility was performed from the perspective of different authorities. In contrast to the concept of flexibility, inflexibility was also discussed. A review of the structure of IGENs and various methods of coordinating the two electricity and gas networks to achieve greater flexibility was presented. Finally, the assessment and measurement methods of flexibility in the literature were reviewed, and the technologies that provide and improve the flexibility of the network were introduced and categorized. This paper has also identified several methods and solutions for delivering and improving flexibility in integrated networks, including the use of flexible technologies and the development of new modeling perspectives. For this purpose, a complete classification and review of these technologies was conducted based on previous studies. Additionally, the importance of examining and evaluating flexibility and its relationship with network resilience and reliability has been highlighted, as well as the need to examine the topic of network flexibility from a time point of view. In contrast to the concept of flexibility, the concept of inflexibility was also introduced in this paper. Inflexibility refers to the inability or unwillingness to adapt, change, or compromise in response to different circumstances, situations, or demands. Lack of response to demand fluctuations, difficulty in integrating RESs, inability to ramp up or down quickly, limited energy storage capacity, high curtailment rates, rigidity in gas network management, struggles with demand-response implementation, and inefficient use of existing infrastructure were introduced as the signs of inflexibility. This extensive review has also demonstrated that the IGEN approach significantly contributes to improving the flexibility of energy systems. This is particularly crucial given the growing importance of low/net-zero carbon gas and gas-fired plants in the future of energy systems. These technologies are essential in mitigating the intermittency challenges posed by RES and play a vital role in the decarbonization of the energy system. The seamless coordination between electricity and gas infrastructure is increasingly crucial as the transition toward sustainable and decarbonized energy sources accelerates. Overall, this review provides a valuable resource for researchers, policymakers, and industry professionals working toward a more flexible, secure, and sustainable energy future.

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Abbreviations

IGEN	Integrated Gas and Electricity Network
UNFCCC	United Nations Framework Convention on Climate Change
EU	European Union
RESs	Renewable Energy Sources
CHP	Combined Heat and Power
P2G	Power to Gas
EB	Electric Boiler
LEH	Local Energy Hub
IES	Integrated Energy System
DR	Demand Response
DRP	Demand-Response Program
GFPPs	Gas-Fired Power Plants
CCS	Carbon Capture and Storage
SNG	Synthetic Natural Gas
CCGTs	Combined Cycle Gas Turbines
OCGT	Open Cycle Gas Turbine
HES	Hydrogen Energy Storage
HGESS	Hybrid Gas Energy Storage System
VPPs	Virtual Power Plants

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