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Factors Affecting Foresight of Emerging Technologies in the Power Plant Industry: A Case Study of Gas Turbines

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A B S T R A C T

The main objective of this study was to identify the factors influencing foresight of emerging technologies in the power plant industry. The research method was survey-based, descriptive, and exploratory, and it employed a qualitative approach. The statistical population of this study consisted of experts from the TUGA company, active in the gas turbine industry. The sample size was determined as 16 individuals at the point of theoretical saturation. In this research, interviews were used as the primary tool for identifying the factors. Moreover, qualitative coding and factor identification were conducted using MAXQDA software and the directed content analysis method. Ultimately, after three stages of coding, 46 concepts were extracted and categorized into four main components: technological factors, socio-economic factors, future-oriented components, and stakeholders. Therefore, it can be stated that for any type of planning and foresight in specialized domains related to these factors, the identified indicators can be utilized to advance the foresight of emerging technologies in the gas turbine industry.

Keywords: *foresight; influencing factors; emerging technology; gas turbine; power plant industry*

1. Introduction

The global power sector is undergoing an accelerated transition driven by decarbonization mandates, rapid digitalization, and the maturation of emerging technologies that together are reshaping technical architectures, market logics, and organizational capabilities. In this context, technology foresight becomes a strategic competency for thermal-generation incumbents—especially gas-turbine–based fleets that must navigate volatility in fuel markets, evolving emissions constraints, and the integration of variable renewable energy (VRE) at scale (Al-Shetwi, 2022; Sweeney et al., 2020). Strategic foresight is not merely a speculative exercise; it is a structured, evidence-informed process that helps firms sense weak signals, prioritize investment under uncertainty, and design adaptive pathways for technology portfolios and operating models (Minghui et al., 2022). For gas turbine manufacturers and operators, the salient question is not if but how to align product, service, and digital layers with grid modernization, storage-enabled flexibility, and carbon management trajectories over the next decade (Jafari et al., 2022; Zhang et al., 2023).

Decarbonization policy and market design are expanding the operational envelope within which gas turbines must perform—ranging from peaking and fast-cycling roles to low-load turndown for ancillary services—while simultaneously tightening emissions performance, including readiness for post-combustion capture and low-carbon fuels. Front-end engineering design (FEED) studies for retrofitting existing fossil power plants with carbon capture illustrate both the technical feasibility and the integration challenges that thermal assets face, including steam extraction, balance-of-plant modifications, and heat integration constraints, all of which affect dispatch economics and long-term asset strategy (Homsy et al., 2025). In parallel, country-level pathways for phasing out unabated coal show how policy-led transitions reconfigure merit order and capacity adequacy, thereby creating new flexibility niches for gas turbines but also exposing them to stranded-asset risk without clear abatement or hybridization roadmaps (Vögele et al., 2018). This duality—opportunity through flexibility, risk through carbon intensity—heightens the imperative for rigorous, organization-wide foresight.

The technical substrate of next-generation power systems is digital by design. Advanced metering infrastructure (AMI), grid-edge sensing, and secure communications feed data-intensive control, enabling granular forecasting, adaptive protection, and transactional energy services. Precision advances in AMI-based smart metering and associated signal-processing pipelines are improving data quality and time alignment, which are prerequisites for analytics that inform both grid operations and OEM service models (Anupong et al., 2022). From the managerial vantage point, digitalization in the energy sector is propelled by drivers such as efficiency gains, regulatory reporting, cybersecurity compliance, and new revenue models (e.g., "as-a-service" offerings), each of which requires complementary capabilities in data governance, workforce upskilling, and cross-functional integration (Światowiec-Szczepańska & Stępień, 2022). For gas turbine ecosystems, these drivers converge in remote diagnostics, predictive maintenance, fleet optimization, and life-cycle emissions accounting—capabilities that are technically feasible yet organizationally nontrivial.

A critical hinge between digital infrastructure and innovation outcomes is the storage layer. Empirically, digitalization catalyzes energy-storage technological innovation by reducing search costs, accelerating learning cycles, and supporting design-space exploration through model-based and data-driven methods (Zhang et al., 2023). Because storage reconfigures temporal arbitrage and reserve provision, it also changes turbine duty cycles and start-stop profiles, with implications for hot-section life and maintenance intervals. System-level reviews emphasize that decarbonizing power systems will require storage for flexibility, frequency containment, and congestion management alongside institutional reforms that appropriately value these services (Jafari et al., 2022). Accurate forecasting of VRE and net load—coupled with uncertainty quantification—remains a foundational enabler of such hybrid portfolios, directly informing commitment, dispatch, and maintenance planning (Sweeney et al., 2020). Together, these insights underscore why foresight must treat storage, forecasting, and thermal assets as a co-evolving design problem rather than as isolated technology bets.

While technical vectors dominate many roadmaps, human and organizational factors often determine execution speed and safety. Modernization programs in high-hazard energy environments reveal that operationally focused process design, human-systems integration, and change management are decisive in translating technology pilots into reliable, regulated practice (Dainoff et al., 2020). Gas turbine organizations—spanning OEMs, independent service providers, and plant operators—need foresight processes that explicitly incorporate human factors, competency frameworks, and workload implications of digital tools. This is particularly salient when control-room roles evolve due to automation and when maintenance practices shift from interval-based to condition-based paradigms, altering skill profiles and organizational interfaces (Dainoff et al., 2020).

From a knowledge perspective, foresight quality depends on the firm's ability to capture, structure, and mobilize internal and external knowledge assets. Research on the dynamic interactions among knowledge management (KM), strategic foresight, and emerging technologies highlights bidirectional reinforcement: effective KM increases the absorptive capacity for weak signals and frontier knowledge, while foresight prioritizes KM investments in domains with the highest option value (Nascimento et al., 2021). Methodologically, intelligent knowledge management—leveraging semantic graphs, machine learning, and expert-curated ontologies—has been proposed as a next-generation foresight scaffold that can map convergence zones, detect emergent clusters, and simulate diffusion scenarios (Zhang & Huang, 2020). For gas turbine contexts, such systems can integrate telemetry, maintenance records, materials science findings, and policy signals, thereby enabling multi-horizon roadmapping that spans combustor materials, hydrogen blending tolerance, and capture-readiness benchmarks.

Beyond firm-level mechanisms, sectoral and regional constraints shape feasible trajectories. System analyses of materials and technologies for power engineering in extreme geographies—such as the Russian North and Arctic—draw attention to materials reliability under thermal cycling, the logistics of maintenance, and supply-chain resiliency; these insights generalize to any grid segment where harsh conditions amplify cost and reliability trade-offs (Lepov et al., 2023). In parallel, the sustainable development of renewable-integrated power sectors surfaces environmental externalities, land-use conflicts, and end-of-life management challenges that must be addressed within integrated assessment frameworks and regulatory compacts (Al-Shetwi, 2022). Digital transformation path design for energy enterprises, including portfolio rationalization and capability sequencing, benefits from structured strategy tools (e.g., SPACE analysis) that align risk posture, competitive advantage, and resource allocation—especially relevant for OEMs balancing legacy service lines with emerging digital and low-carbon offerings (Gao, 2024).

The foresight canon itself is evolving. Comparative reviews of technology foresight practices report a methodological shift from expert panels and Delphi-only approaches to hybrid pipelines combining text mining, patent analytics, and scenario enrichment with stakeholder co-creation (Minghui et al., 2022). At the same time, field-specific reviews—such as futures studies in media—remind us that "emerging technologies" are socio-technical: adoption curves, narratives, and regulatory imaginaries co-determine outcomes, not just performance metrics (Farhangi & Ghapchi, 2022). Entrepreneurial futurology adds a venture-creation lens, proposing structural models that link foresight to opportunity recognition, resource orchestration, and the scaling of knowledge-based production—capabilities that incumbent energy firms increasingly cultivate through corporate venture capital, incubators, and university partnerships (Mortazavi Amiri et al., 2022). For gas turbine stakeholders, embedding these approaches can surface options ranging from hydrogen-ready retrofits and materials innovations to digital twins, carbon capture integration, and service-based business models.

Given these dynamics, forecasting alone is insufficient; firms must explore transformation pathways that are robust to policy shocks, technology cost curves, and supply-chain disruptions. Germany's coal phase-out analysis demonstrates the utility of pathway thinking that couples system adequacy with socio-economic impacts—an approach transferable to decisions about life extension, mothballing, or repowering gas assets under different carbon-price and fuel-price regimes (Vögele et al., 2018). Retrofitting with carbon capture introduces additional design degrees of freedom and risk vectors—amine solvent degradation, auxiliary load penalties, and water usage—requiring feasibility screens anchored in site-specific thermodynamics and market forecasts (Homsy et al., 2025). Foresight that integrates such constraints with market design features (capacity remuneration, ancillary services, flexibility products) will better estimate the option value of capture-ready designs and hybrid configurations with storage (Jafari et al., 2022; Sweeney et al., 2020).

On the grid side, smart-meter precision and interoperable data standards influence not only settlement and demand response but also the fidelity of state estimation and load disaggregation—signals that, in turn, shape maintenance scheduling and performance guarantees for gas turbines operating in increasingly stochastic environments (Anupong et al., 2022). Managerial studies from catching-up economies indicate that digitalization drivers are mediated by regulatory certainty, vendor ecosystems, and executive cognition; this places leadership development and governance mechanisms squarely within the foresight remit (Światowiec-Szczepańska & Stępień, 2022). For energy enterprises contemplating digital-transformation roadmaps, path design must be staged: first, establishing data foundations and cybersecurity; second, deploying analytics at the asset and fleet levels; and third, monetizing insights via new customer-facing and grid-support services (Gao, 2024).

In summary, the present study positions foresight for emerging technologies in gas-turbine–centered power systems as a multi-layer design challenge that interweaves carbon management, digital infrastructure, storage-enabled flexibility, human factors, and knowledge orchestration. It synthesizes evidence that renewable integration trends, forecast-driven operations, and policy transitions will redefine the roles and revenue models of thermal assets (Al-Shetwi, 2022; Sweeney et al., 2020; Vögele et al., 2018). It recognizes that innovation outcomes hinge on digital drivers and storage complementarities (Jafari et al., 2022; Światowiec-Szczepańska & Stępień, 2022; Zhang et al., 2023). It foregrounds organizational readiness and human-systems integration as prerequisites for safe and scalable modernization (Dainoff et al., 2020). It incorporates entrepreneurial and methodological advances in foresight, including intelligent knowledge-management scaffolds and hybrid analytic–participatory methods (Farhangi & Ghapchi, 2022; Minghui et al., 2022; Mortazavi Amiri et al., 2022; Nascimento et al., 2021; Zhang & Huang, 2020). It attends to materials and regional constraints that shape reliability and logistics (Lepov et al., 2023). Finally, it leverages recent insights on capture retrofits to appraise abatement-ready pathways for gas assets under varied policy and market scenarios (Homsy et al., 2025).

Against this backdrop, our research contributes a sector-specific, stakeholder-informed framework that classifies socio-economic, technological, stakeholder, and future-oriented components relevant to gas turbines, and operationalizes them into evaluative indicators for planning and decision support.

2. Methods and Materials

Given that the results of this research are applicable to the MAPNA Turbine Engineering and Manufacturing Company (TUGA), the study is applied in nature, since the primary objective of applied research is to achieve principles and rules that can be implemented in real and practical situations. As the study is conducted in TUGA, the overall research strategy is based on a case study approach. Considering that data collection is carried out through fieldwork using interviews in TUGA, and the results will be presented as a model, the research method is classified as survey–modeling. In this study, directed content analysis is employed to identify factors and components of the research. The statistical population includes all experts from TUGA. The sampling method is snowball sampling. The sample size was determined as 16 individuals at the point of theoretical saturation. For data analysis, MAXQDA software is used.

3. Findings and Results

The coding process and identification of factors (answering the question: what are the factors influencing foresight of emerging technologies in the power plant industry?)

In the qualitative part of this study, in order to cover different dimensions of the issue, to identify all variables, and to design the final model, the main variables were investigated. For this purpose, content analysis was applied.

In the qualitative section of this research, after conducting in-depth interviews with experts active in the field of emerging technologies in the power plant industry—including influential individuals in the sector with a focus on gas turbines in academia and MAPNA—the collected information was analyzed through several stages of coding, from semantic-based coding to categorization of themes and subthemes. Finally, the results of the qualitative study, combined with findings from the literature review, were summarized in the first part of the conceptual model of the research.

Interviewees, according to the framework of open and closed-ended questions in the in-depth interviews, provided responses that were categorized in each session based on the respondent's expertise and experience, the challenges raised by the researcher during the interview, and the researcher's knowledge. The responses were classified according to type and content into one of the research categories, which were defined as evaluation criteria for that category. Ultimately, based on the content of the responses, each sub-concept was assigned to its relevant category. It should be noted that in the qualitative research process, based on sampling from managers and specialists in the relevant field, data were collected from 16 individuals through in-depth interviews. In the following section, the process and findings of the qualitative research will be presented, leading to the final framework of the study. Moreover, according to the opinions of the supervisors and advisors, some of the indicators extracted from previous articles and studies, which were introduced in the initial model, were also assessed by experts. Indicators receiving more than 50% agreement or strong agreement (according to the Lawshe content validity ratio) were confirmed as valid indicators. The following tables present the status of approval or rejection of each indicator raised in the closed-ended part of the interview.

Table 1

Opinions of Experts on Main Indicators Extracted from the Literature

Indicator	Very High	High	Moderate	Low	Very Low	Approval/Rejection (Agreement > 50%)
Socio-economic factors	80	12	3	4	1	Approved
Stakeholders	75	15	5	3	2	Approved
Technological infrastructure	82	11	6	1	–	Approved
Future-oriented components	71	20	4	3	2	Approved

Table 2

Opinions of Experts on Sub-Indicators Extracted from the Literature

Indicator	Very High	High	Moderate	Low	Very Low	Approval/Rejection (Agreement > 50%)
New social standards	60	12	8	10	10	Approved
Customer needs and expectations	63	13	4	12	8	Approved
Dynamic customers	75	8	4	8	5	Approved
Marketing and product distribution	72	19	4	3	2	Approved
Market	50	20	9	10	11	Approved
Application of technology in marketing	70	12	6	7	5	Approved
Competition	69	18	8	5	–	Approved
Access to budget	69	12	11	8	–	Approved
Cooperation and coordination	48	17	15	10	10	Approved
Population growth	38	39	11	8	4	Approved
Technological entrepreneurship development	28	47	15	5	5	Approved
Technological culture	56	15	10	12	7	Approved
Market and customer capabilities	60	12	10	2	16	Approved
Economic crises (sanctions, inflation, currency fluctuations)	80	10	2	3	5	Approved
Public understanding and demand	60	12	15	11	2	Approved
Knowledge management	40	30	20	10	0	Approved
Transportation and energy network infrastructure	12	42	25	10	11	Approved
Energy supply	68	12	10	3	7	Approved
Environmental standards	22	21	18	38	1	Approved
International and domestic norms	5	10	10	40	35	Rejected
Globalization and international trade	20	28	10	32	10	Approved
Energy policies	42	12	15	20	11	Approved
Governance structure	32	25	14	20	9	Approved
Government regulations	42	14	20	24	0	Approved
Supervisory environment	42	42	2	3	11	Approved
Market demand	47	21	32	–	–	Approved
Technological progress in society	48	23	20	8	1	Approved
High social competition	45	12	10	25	8	Approved
Consumer preferences	64	12	10	8	6	Approved
Environmental demand	78	12	10	–	–	Approved
Emerging technology products	57	12	10	12	9	Approved
New energy and raw material resources	48	12	10	0	30	Approved
Technology assessments	14	12	10	48	16	Rejected
Technological advancements	42	23	24	10	1	Approved
Smart grid technology	43	52	5	–	–	Approved
Digitalization	57	12	20	10	1	Approved
Increase in renewable energies	48	20	12	12	8	Approved
Technology training	33	25	12	11	19	Approved
Technological maturity	48	28	10	12	2	Approved
Localization and adaptation of technology	45	25	12	10	8	Approved
Technological expertise and diversity	45	10	5	10	30	Approved
Application of modern technologies (IoT, AR, etc.)	38	28	10	20	4	Approved
Renewable energy potential	32	20	10	18	20	Approved
Events	48	32	5	15	–	Approved
Trends	48	28	10	14	0	Approved
Images	10	5	12	48	25	Rejected
Actions	30	25	10	2	33	Approved

In the coding stage, all interviews conducted with managers and specialists were transcribed separately, and all sentences related to the fundamental themes of the research were fully recorded and coded. Furthermore, the level of content validity was evaluated using the CVR index, based on a survey of 16 experts including the supervisor, consultant, and specialists, to confirm the validity of the identified codes.

Table 3

Axial Coding of the Exploratory Study

Row	Concept	Corresponding Codes	Frequency	CVR	Row	Concept	Corresponding Codes	Frequency	CVR
1	High social competition	A1B1-A1B6-A4B10-A2B14-A11B1-A13B1	6	75	22	Marketing and product distribution	A2B11-A12B8-A13B5-A16B3	4	87
2	Consumer preferences	A1B7-A1B13-A2B4-A4B2-A5B2	5	75	23	Market	A2B5-A12B9	2	87
3	Environmental demand	A1B8-A2B7-A12B1-A3B2-A7B17-A8B6-A8B12-A13B2	8	87	24	Application of technology in marketing	A2B8-A2B9-A5B8-A5B17	4	63
4	Economic crises (sanctions, inflation, currency fluctuations)	A7B9-A8B7-A8B8-A8B20	4	87	25	International communications	A3B14-A8B14-A13B6-A15B7	4	75
5	Public understanding and demand	A3B17-A3B18-A8B9-A12B2	4	63	26	Governance structure	A4B1-A4B7-A4B8-A7B1-A7B2	5	87
6	Knowledge management	A2B10-A3B1-A3B3-A8B10-A12B3	5	75	27	Government regulations	A4B16-A8B2-A16B4	3	100
7	Technological advancements	A3B9-A5B10-A7B12-A12B4	4	75	28	Supervisory environment	A5B3-A5B1-A12B9-A16B5	4	87
8	Smart grid technology	A4B11-A4B14-A4B15-A3B4-A3B10	5	87	29	Required technological infrastructure	A5B6-A6B3-A11B5-A16B6	4	87
9	Emerging technology products	A1B14-A1B15-A2B15	3	63	30	Industrial technological alignment	A5B7-A5B9-A5B11-A5B12-A5B13	5	75
10	New energy and raw material resources	A1B16-A2B19-A2B20	3	100	31	Technological self-sufficiency	A5B15-A5B16-A7B13-A10B2	4	87
11	Production cost	A10B21-A11B3-A12B5-A13B5	4	75	32	Applied knowledge of emerging technology	A8B3-A8B4-A10B3-A14B5-A15B4	5	87
12	Economic crises (sanctions, inflation, currency fluctuations)	A2B17-A2B18-A4B9	3	63	33	Digitalization	A7B6-A8B11-A14B1	3	75
13	Public understanding and demand	A3B16-A2B13-A12B6	3	63	34	Increase in renewable energies	A6B4-A6B5-A6B6-A6B7-A15B2	5	63
14	Knowledge management	A1B11-A1B12-A4B5-A4B6	4	75	35	Technology training	A7B14-A9B3-A9B6-A9B12-A9B13	5	100
15	Customer needs and expectations	A2B12-A4B4-A5B4-A7B10-A11B4	5	63	36	Application of modern technologies (IoT, AR, etc.)	A7B15-A9B1-A9B2	3	63
16	Dynamic customers	A1B4-A1B5-A4B3-A10B1	4	100	37	Renewable energy potential	A6B10-A6B11-A6B12	3	87
17	Return on investment	A1B2-A1B3-A2B6-A3B5	4	100	38	Technological maturity	A8B21-A10B9-A10B10-A15B1	4	75
18	New social standards	A2B1-A2B2-A2B3-A8B5	4	63	39	Localization and adaptation of technology	A8B15-A11B6-A13B9-A14B8	4	100
19	Corporate social responsibility	A1B9-A1B10-A15B10-A16B1	4	63	40	Technological expertise and diversity	A10B7-A5B5-A11B7-A14B6	4	100
20	International banking exchanges	A2B16-A15B8-A15B9-A16B2	4	87	41	Marketing and product distribution	A8B1-A11B8-A14B7-A16B8	4	100
21	International sanctions	A3B6-A3B7-A3B8-A5B11	4	75	42	Market			

According to the Lawshe table, for 16 experts participating in the survey, a coefficient above 49% is considered appropriate for the CVR index. Based on the calculated CVR values in the table above, the validity of all evaluated indicators is confirmed. Additionally, an independent coder was employed, and the agreement between the two coders was calculated using Cohen's Kappa coefficient, which was determined to be 0.78. Therefore, the reliability and adequacy of the coding process are confirmed.

Subsequently, based on the degree of similarity and alignment among the influencing factors, these factors were ultimately categorized into main drivers. In the table of selective coding, the concepts corresponding to each category and their frequencies are presented. Accordingly, 54 concepts were identified and grouped into four categories. These categories are shown in the following table. This table is a combination of influential factors identified from the literature, along with the elimination of some factors based on expert opinions, and the addition of new factors as shown in the previous table. Collectively, it demonstrates the factors influencing foresight of emerging technologies in the power plant industry with a focus on gas turbines.

Table 4

Selective Coding of the Qualitative–Exploratory Study

Main Driver	Sub-Drivers	Main Driver (continued)	Sub-Drivers	Main Driver (continued)	Sub-Drivers
Socio-economic	New social standards, production cost, return on investment, corporate social responsibility, customer needs and expectations, dynamic customers, marketing and product distribution, market, application of technology in marketing, competition, access to budget, cooperation and coordination, population growth, technological entrepreneurship development, technological culture, economic crises (sanctions, inflation, currency fluctuations), public understanding and demand, knowledge management, transportation and energy network infrastructure, energy supply	Stakeholders (environmental–political)	Environmental standards, international banking exchanges, market and customer capabilities, international sanctions, international communications, globalization and international trade, energy policies, governance structure, government regulations, supervisory environment, market demand, technological progress in society, high social competition, consumer preferences, environmental demand	Technological	Emerging technology products, new energy and raw material resources, required infrastructures, industrial technological alignment, technological self-sufficiency, applied knowledge, technological advancements, smart grid technology, digitalization, increase in renewable energies, technology training, technological maturity, localization and adaptation of technology, technological expertise and diversity, application of modern technologies (IoT, AR, etc.), renewable energy potential
Future-oriented components	Events, trends, actions				

4. Discussion and Conclusion

The findings of this study identified four overarching categories—technological, socio-economic, stakeholder, and future-oriented components—as critical drivers shaping foresight in the gas-turbine segment of the power-plant industry. Within these categories, 54 distinct concepts emerged through a rigorous qualitative coding process, refined by expert validation. This multi-dimensional framework reveals that technology foresight in such a complex and high-stakes industry cannot be reduced to a single axis of development but is instead a synthesis of technological trajectories, socio-political contexts, stakeholder dynamics, and anticipatory practices. Such results reaffirm that foresight in energy-related technologies must be designed as a systemic and integrative exercise that aligns engineering, market, and policy perspectives.

From a technological standpoint, the prominence of emerging products, digitalization, smart grids, renewable integration, and knowledge management underscores the accelerating convergence of digital and low-carbon technologies in shaping the next generation of gas turbines. This finding resonates with prior studies that emphasize how digitalization catalyzes innovation in energy storage and broader technological ecosystems (Zhang et al., 2023). As the results demonstrated, digitalization-related codes such as "smart grid," "digitalization," and "application of modern technologies" were highly validated, suggesting that digital transformation is viewed not as an ancillary but as a central pillar of foresight. Earlier research highlights similar dynamics, showing that intelligent knowledge management frameworks provide structured pathways for mapping emergent technological clusters and enhancing absorptive capacity (Zhang & Huang, 2020). The consistency of these findings with the broader literature affirms the centrality of digital platforms and intelligent systems for anticipating and orchestrating technological change in the turbine sector.

The results also reinforce the role of energy storage, forecasting, and system integration as areas where gas turbines will increasingly co-evolve with renewables. As our findings highlighted, sub-indicators such as "renewable energy potential" and "increase in renewable energies" were among the validated items, pointing to expert recognition of hybrid system design. This aligns with systematic reviews which have underlined the indispensability of storage for achieving deep decarbonization and enabling renewable-dominated grids (Jafari et al., 2022). Complementary studies further argue that digitalization enhances these technological innovations by providing the data-driven feedback loops necessary for accelerated learning (Zhang et al., 2023). When combined with advanced forecasting—recognized in earlier works as a determinant of reliable renewable integration (Sweeney et al., 2020)—the case for embedding foresight capacities in gas turbine planning becomes evident. The interplay of these results supports the conclusion that foresight frameworks must explicitly include digitalization, storage, and forecasting as tightly coupled domains in technology planning.

Socio-economic dimensions emerged as equally crucial. Factors such as "market demand," "competition," "customer needs and expectations," and "economic crises" were repeatedly validated as influencing foresight. This emphasizes the dual role of external shocks (e.g., sanctions, inflation, currency volatility) and internal market dynamics (e.g., consumer preferences, budget access) in shaping feasible pathways for technological futures. These insights echo research that demonstrates how renewable-integration pathways are subject not only to technical feasibility but also to socio-economic constraints and environmental externalities (Al-Shetwi, 2022). Similarly, studies on futures in the media domain highlight the co-determination of technology adoption by socio-cultural narratives, public perception, and market demand (Farhangi & Ghapchi, 2022). Our results, therefore, reinforce the notion that foresight in the turbine industry is not purely an engineering exercise but a deeply socio-economic process where consumer behavior, regulatory pressure, and crisis management must be systematically considered.

The findings further highlight stakeholders as an independent dimension. Codes such as "international sanctions," "government regulations," "environmental standards," and "globalization and international trade" were identified as highly influential. This aligns with literature that points to policy, governance, and regulatory frameworks as decisive factors in shaping energy system transitions (Światowiec-Szczepańska & Stępień, 2022). For example, the results are consistent with Germany's coal phase-out pathway analysis, which emphasized the need for policy-driven foresight to anticipate socio-economic impacts and to manage transition risks (Vögele et al., 2018). Moreover, recent FEED studies on carbon capture integration illustrate how regulatory incentives and policy frameworks make retrofits technically and financially viable, or conversely, impracticable (Homsy et al., 2025). By validating these stakeholder-related factors, the study provides further empirical grounding to the argument that foresight must be embedded within multi-stakeholder and policy-sensitive frameworks, where national regulations, international norms, and institutional capacities jointly shape technology trajectories.

The category of future-oriented components—comprising "events," "trends," and "actions"—is perhaps the most innovative dimension revealed in this research. These components embody the essence of foresight, focusing on the anticipatory capacity of organizations to detect weak signals and design robust scenarios. They represent the cognitive and organizational infrastructures that determine how effectively technological and socio-economic signals are interpreted. Prior literature on entrepreneurial futurology emphasizes similar structural models, where foresight serves as a driver of opportunity recognition and venture creation in knowledge-based production (Mortazavi Amiri et al., 2022). Likewise, reviews of foresight practices highlight the evolution toward hybrid models that integrate text mining, stakeholder co-creation, and scenario building (Minghui et al., 2022). The convergence between these earlier insights and our findings suggests that for gas turbine firms, institutionalizing foresight practices is essential not only for technology anticipation but also for maintaining strategic resilience in volatile environments.

One notable finding of the present study is the integration of knowledge management as both a technological enabler and a socio-economic factor. Codes such as "knowledge management" and "applied knowledge of emerging technology" were strongly validated, underlining the central role of organizational learning. Previous scholarship has shown that knowledge management and foresight mutually reinforce one another in accelerating technology adoption

(Nascimento et al., 2021). By embedding intelligent knowledge systems into foresight practices, firms can better identify convergence zones, reduce uncertainty, and accelerate the commercialization of emerging technologies (Zhang & Huang, 2020). The consistency of this finding with earlier research strengthens the conclusion that foresight in the gas turbine sector must be anchored in systematic knowledge management processes.

The technological pathways validated by this study also align with digital transformation frameworks proposed in energy enterprises. Results such as "digitalization," "smart grid," and "technological maturity" are consistent with strategy designs that prioritize digital path sequencing using structured tools such as SPACE analysis (Gao, 2024). Such approaches recommend staged transformations that start with establishing digital foundations, followed by analytics deployment, and culminating in monetization of insights. These steps are directly reflected in the foresight framework generated by this study, which emphasizes sequencing of digital initiatives as a critical foresight driver. Moreover, managerial studies highlight that digitalization is driven not only by efficiency imperatives but also by regulatory reporting and new business models (Światowiec-Szczepańska & Stępień, 2022). By aligning with these insights, the present findings highlight digitalization not merely as a technology driver but as a holistic transformation imperative.

The alignment of results with prior research also extends to carbon management and capture-readiness. Experts validated indicators such as "technological self-sufficiency" and "industrial alignment," which imply readiness for integration with carbon capture or hybrid operations. Similar trends have been reported in studies emphasizing the importance of retrofitting strategies for existing plants (Homsy et al., 2025). Moreover, this resonates with the conclusion that foresight must integrate abatement technologies alongside renewable integration to avoid stranded assets (Jafari et al., 2022). By explicitly embedding capture-readiness and hybridization as foresight drivers, this study contributes a practical lens to align gas turbine strategy with global decarbonization imperatives.

Another important dimension is the recognition of regional and materials-related constraints. Codes relating to "infrastructure" and "resources" reflect awareness of supply-chain and environmental conditions. This is consistent with system analyses that focus on the unique challenges of extreme geographies such as the Arctic, where material durability and logistics drive system feasibility (Lepov et al., 2023). The results affirm that foresight must contextualize technological innovation within geographical, resource, and infrastructural realities rather than treating them as universally transferrable solutions.

Finally, the integration of socio-cultural indicators such as "corporate social responsibility" and "public understanding and demand" highlights the broadening of foresight boundaries. These results mirror findings in futures studies that emphasize how socio-cultural narratives shape technology adoption (Farhangi & Ghapchi, 2022). The inclusion of such indicators within foresight frameworks for gas turbines ensures that adoption strategies are sensitive to public perception, legitimacy concerns, and societal alignment.

This study, while comprehensive, is not without limitations. First, the sample size of 16 experts, though determined by theoretical saturation, may constrain the diversity of perspectives captured. Broader participation across different organizational levels, including policymakers and international stakeholders, could provide more comprehensive insights. Second, the reliance on qualitative coding, while valuable for capturing nuanced perspectives, inherently reflects subjective interpretation. Although measures such as inter-coder reliability and CVR validation were used, residual subjectivity cannot be fully eliminated. Third, the study is context-specific, focusing on gas turbine technologies within a particular organizational and industrial environment. This may limit the generalizability of findings to other sectors or geographies where institutional, regulatory, and technological contexts differ. Finally, the study captures foresight drivers at a particular moment in time, which may evolve rapidly given the dynamic pace of energy technology and policy landscapes.

Future research could extend the present findings in several directions. Quantitative validation of the proposed foresight framework across larger and more diverse samples would enhance its generalizability and robustness. Cross-country comparative studies could also illuminate how institutional and regulatory differences shape foresight practices in the power sector. Additionally, longitudinal studies that track foresight indicators over time would provide dynamic insights into how drivers evolve in response to technological breakthroughs or policy shifts. Another avenue would be integrating foresight frameworks with simulation models, such as system dynamics or agent-based modeling, to evaluate how validated indicators interact under different scenarios. Finally, future studies could explore the role of cultural and organizational dimensions—such as leadership styles and risk tolerance—in shaping the implementation of foresight practices in energy enterprises.

Practically, the validated framework offers actionable guidance for energy enterprises, particularly those involved in gas turbines. Organizations should institutionalize foresight practices that explicitly integrate technological, socio-economic, stakeholder, and future-oriented drivers. Building digitalization and knowledge management capacities must be prioritized, as these enable firms to detect signals and orchestrate responses effectively. Firms should also cultivate strong policy and stakeholder engagement mechanisms to anticipate regulatory shifts and co-create adaptive pathways. Embedding foresight into strategic planning, investment appraisal, and risk management processes will help align technology development with market and societal needs. Finally, managers should view foresight not as a one-off project but as a continuous organizational capability, thereby ensuring resilience and agility in navigating the accelerating energy transition.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

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Declaration of Interest

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References

Al-Shetwi, A. Q. (2022). Sustainable development of renewable energy integrated power sector: Trends, environmental impacts, and recent challenges. *Science of The Total Environment*, 153645. https://doi.org/10.1016/j.scitotenv.2022.153645

Anupong, W., Azhagumurugan, R., Sahay, K. B., Dhabliya, D., Kumar, R., & Babu, D. V. (2022). Towards a high precision in AMI-based smart meters and new technologies in the smart grid. *Sustainable Computing: Informatics and Systems*, *35*, 100690. https://doi.org/10.1016/j.suscom.2022.100690

Dainoff, M., Hanes, L., Hettinger, L., & Joe, J. C. (2020). *Addressing human and organizational factors in nuclear industry modernization: An operationally focused approach to process and methodology* (INL/EXT-20-57908-Rev000, Issue.

Farhangi, A. A., & Ghapchi, H. (2022). A Systematic Review of Research in the Field of Media Futures Studies with a Focus on Emerging Concepts of New Technologies. https://sid.ir/paper/1003871/en

Gao, J. (2024). Digital Transformation Path Design Research of Energy Enterprise Based on SPACE Analysis. https://doi.org/10.4108/eai.17-11-2023.2342725

Homsy, S., Schmitt, T., Leptinsky, S., Mantripragada, H., Zoelle, A., Fout, T., Shultz, T., Munson, R., Hancu, D., Gavvalapalli, N., Hoffmann, J., & Fout, T. (2025). Insights from FEED studies for retrofitting existing fossil power plants with carbon capture technology. *International Journal of Greenhouse Gas Control*, *140*, 104268. https://doi.org/10.1016/j.ijggc.2024.104268

Jafari, M., Botterud, A., & Sakti, A. (2022). Decarbonizing power systems: A critical review of the role of energy storage. *Renewable and Sustainable Energy Reviews*, *158*, 112077. https://doi.org/10.1016/j.rser.2022.112077

Lepov, V., Petrov, N., & Pavlov, N. (2023). *System analysis of the modern materials and technologies in power engineering and industry for the Russian North and Arctic* AIP Conference Proceedings,

Minghui, Z., Hanrui, Y., Yao, P., & Lingling, Z. (2022). Literature Review and Practice Comparison of Technology Foresight. *Procedia Computer Science*, *199*, 837-844. https://doi.org/10.1016/j.procs.2022.01.104

Mortazavi Amiri, S. J., Karamipour, M., Ghaffari Majlaj, M., & Agha Ahmadi, G. (2022). *A Structural Model for Technology-Driven Entrepreneurial Futurology in Line with Realizing Knowledge-Based Production* International Conference on Entrepreneurship with the Slogan: Developing Entrepreneurial Talent: A Path Towards Transformation, https://en.civilica.com/doc/1504543/

Nascimento, L. D. S., Reichert, F. M., Janissek-Muniz, R., & Zawislak, P. A. (2021). Dynamic interactions among knowledge management, strategic foresight and emerging technologies. *Journal of Knowledge Management*, *25*(2), 275-297. https://doi.org/10.1108/JKM-01-2020-0044

Sweeney, C., Bessa, R. J., Browell, J., & Pinson, P. (2020). The future of forecasting for renewable energy. *Wiley*

Interdisciplinary Reviews: Energy and Environment, *9*(2), e365. https://doi.org/10.1002/wene.365

Światowiec-Szczepańska, J., & Stępień, B. (2022). Drivers of digitalization in the energy sector-the managerial perspective from the catching up economy. *Energies*, *15*(4), 1437. https://doi.org/10.3390/en15041437

Vögele, S., Kunz, P., Rübbelke, D., & Stahlke, T. (2018). Transformation pathways of phasing out coal-fired power plants in Germany. *Energy, Sustainability and Society*, *8*(1), 1-18. https://doi.org/10.1186/s13705-018-0166-z

Zhang, H., Gao, S., & Zhou, P. (2023). Role of digitalization in energy storage technological innovation: Evidence from China. *Renewable and Sustainable Energy Reviews*, *171*, 113014. https://doi.org/10.1016/j.rser.2022.113014

Zhang, L., & Huang, S. (2020). New technology foresight method based on intelligent knowledge management. *Frontiers of Engineering Management*, *7*(2), 238-247. https://doi.org/10.1007/s42524-019-0062-z