Humanities & Social Sciences Communications

ARTICLE

https://doi.org/10.1057/s41599-025-05019-z OPEN

Check for updates

Multi-dimensional policy decision-making model based on the quantum probability: the case of Korea's nuclear power plant policy

Seunghwan Myeong [1✉], Jae Woo Lee [2], Jaehyun Bae [3] & Chang Hee Cho [2]

Implementing a digital government is a more rational and transparent decision. However, many complex real-practice policies, such as nuclear energy, pensions, climate change, and aging societies, may require more nuanced and multi-dimensional perspectives. This study critiques the schools of deterministic perspectives and examines alternative frameworks grounded in quantum probability theories and multi-dimensional decision-making models. It further examines policy transparency and its interaction with policy values. Through an empirical case study of Korea's nuclear power policy, the study demonstrates the transformative potential of a quantum-informed approach in policy-making. Our findings emphasize incorporating interaction, correction, and recalibration processes to improve policy effectiveness. In this respect, this study proposes a multi-dimensional policy-making model based on quantum probability. Inspiring a new era in policy-making, this quantum probability model proposes the integration of norms, institutions, technology, and contextual variables.

[1] Department of Public Administration, Inha University, Incheon, Korea. [2] Department of Physics, Inha University, Incheon, Korea. [3] Department of Industrial Security Governance, Inha University, Incheon, Korea. ✉email: shmyeong@inha.ac.kr

Introduction

As we move from the era of digital transformation to an era characterized by quantum probability, we should re-evaluate the policy-making frameworks that are based on classical probability theory. The limitations of digital-era policy models in addressing today's multifaceted governance challenges are becoming increasingly apparent, despite their ability to provide fast and accurate analysis using binary operations. Quantum probability, for example, can better incorporate uncertainty. It can account for multiple potential outcomes simultaneously. It can adapt to changing stakeholder dynamics. It can adjust probabilities in real time. It can probe and navigate complex policy environments by providing a more contextual and nuanced understanding of the interplay of different factors (Leung, 2005).

There is now an urgent need for a more flexible, multifaceted policy model based on quantum probability. This goes beyond linear causality and probabilistic reasoning. This model must reflect the various variables, environments, and human perceptions and behaviors latent in the internal and external environments that are variously connected to society. In particular, power is distributed in the era of governance, where governments, companies, and citizens operate national affairs as cooperative partners. Several evaluation indicators have reached their limits. These include traditional tools such as preliminary feasibility analysis, cost-benefit analysis, discounting and qualitative indicators such as desirability, feasibility and effectiveness. Despite their widespread use, these indicators often fail to capture the multi-dimensional nature of stakeholders' preferences and the contextual dynamics in policy environments (Moynihan and Soss, 2014; Capano and Howlett, 2024; Arias-Yurisch et al. 2024). In particular, they are often rooted in linear, rationalist frameworks that overlook real-world policy implementation's interdependent and feedback-driven nature (Peters, 1996; Orlikowski, 1995).

Therefore, it is necessary to review and seek alternatives to the existing policy process based on new social phenomena and policy environment in the digital transformation era, future demand forecasting, alternative analysis and selection, and evaluation. In contrast to traditional approaches, quantum probability theory suggests a framework for understanding policy decisions as probabilistic rather than deterministic. It also considers the inherent uncertainties in governance (Howlett and Ramesh, 2023). This study investigates how much quantum principles, including superposition and entanglement, can increase policy transparency and responsiveness. It particularly examines Korea's nuclear power plant policy as a pilot case for the applicability of this framework. Quantum probability may provide a contextual alternative to deterministic approaches, providing a robust model that captures governance uncertainties, dynamic stakeholder interactions, and complex contexts more effectively (Zahariadis, 2007; Schelling, 1960; Pelopidas, 2017).

Limitations and alternatives to the deterministic approach

Research on digital government (e-government) has relied heavily on deterministic frameworks since the emergence of the information society that assumes technological advancements inherently lead to predictable and beneficial societal outcomes (March and Simon, 1958). Terms such as "knowledge society," "intelligent society," "smart society," and "intelligent information society" have proliferated, typically emphasizing linear relationships between technological innovation and social progress (Walther et al. 2006; Castells, 2000; Nam and Pardo, 2011; Myeong, 2023). In spite of their contributions, these paradigms often neglect critical dimensions such as the adaptability of the institutions, the political context, and stakeholder interactions (Capano and Howlett, 2024; Howlett and Ramesh, 2023). As a consequence, these paradigms have shown notable limitations. However, they were widely used, especially regarding their explanatory power in complex governance issues characterized by uncertainty, non-linear dynamics, and diverse stakeholder interactions (Zahariadis, 2007; Ingold, 2011).

Specifically, the "smart society" and "intelligent society" paradigms emphasize streamlined information flows and ICT-driven analysis techniques. However, they fail to address the dynamic interplay between technological systems and human decision-making. Such models underestimate how institutional inertia, social behaviors, cognitive biases, and political dynamics complicate the implementation and sustainability of technological solutions (Orlikowski, 1995; Myeong, 2006; Moynihan and Soss, 2014).

For this reason, this exploratory study introduces an alternative quantum probability-based framework that explicitly addresses these shortcomings by incorporating concepts like superposition (multiple simultaneous stakeholder preferences), entanglement (interconnected policy dynamics across sectors), and interference effects (unexpected shifts in preferences due to context changes). The proposed multi-dimensional quantum model transcends deterministic paradigms by better capturing complex, context-dependent, and dynamic interactions among governance elements. This quantum approach offers theoretical progress and practical analytical tools for more nuanced and responsive governance strategies.

Limitations of the deterministic perspective. Although widely used in policy analysis, the deterministic approach has noticeable limitations. First, it assumes that technological progress automatically brings about predictable social changes, neglecting the role of institutional structures and social behavior (March and Simon, 1958). Second, it fails to look at non-linear and interdependent decision-making processes, as illustrated in the Multiple Streams Theory (Zahariadis, 2007) and the Advocacy Coalition Framework (Ingold, 2011). Third, deterministic models inadequately address policy interactions, feedback mechanisms, and recalibration processes, which are crucial for adaptive governance (Capano and Howlett, 2024; Howlett and Ramesh, 2023).

Technological determinism presupposes that technological advancement is the primary driver of social change. This view has been critiqued for oversimplifying the nuanced relationship between technology, institutions, and societal behavior (Markus and Robey, 1988; Walther et al. 2006; Castells, 2000). These deterministic perspectives often ignore institutional inertia and the socially constructed nature of policy design and implementation (Howlett and Ramesh, 2023; Myeong, 2006). As such, the belief that digital innovations automatically improve governance outcomes is increasingly questioned (Capano and Howlett, 2024).

We propose a quantum-inspired approach that considers governance structures dynamic and probabilistic to address these shortcomings. Quantum probability accounts for stakeholders' evolving preferences and interactions, unlike classical probability models, which assume fixed variables (Busemeyer and Bruza, 2012).

The problem with bounded rationality. Classical rationality assumes fixed preferences and perfect information, assumptions rarely met in public decision-making (Simon, 1955; March, 1997). Bounded rationality models improved this by reflecting on heuristic behavior under cognitive limitations (Gigerenzer and Todd, 1999). However, these models still operate within deterministic probability logics. In contrast, quantum probability theory (QP) provides context-sensitive reasoning, cognitive interference, and superposition of preferences (Busemeyer and Bruza, 2012; Pothos and Busemeyer, 2013). This shift offers novel insight into cognitive inconsistency, preference reversals, and policy opinion volatility. In this context, "generative perspective" and "quantum perspective" can be an alternative to overcoming the limitations of conventional deterministic thinking.

An alternative approach is a generative perspective, which views the hypothetical relationship between antecedents and outcomes in two ways: deviation theory (or causal determinism) and process theory (or generativity) (Marcus and Robey 1988, 586) and, more recently, quantum theory.

Variance theory or causal determinism. This theory suggests that clear causal laws predict and explain cause and effect. Technological and social structure determinist approaches to the information society fall under deviation theory. The former considers information technology to be causing changes in organizations and institutions. At the same time, the latter see digital technologies as being selected according to the information needs of organizations, cultures, and nations. Nevertheless, they are the same in that they see effects caused by technological or social events.

Generative or process theory. The generative perspective views cause and effect as unclear or interactive. Here, the application of information technology continues to change the interrelationship between information technology and human beings, organizations, and society. This iterative process leads to changes in organizations and society that differ from the initial intention. Therefore, it denies causal determinism. Changes in organizations and society occur initially through the planned introduction and application of information technology by humans, organizations, and society.

Nevertheless, existing institutional, social, and normative conditions slow the pace of change or bring about new aspects of change. Moreover, organizations, societies, and countries seek innovations and find more appropriate ICTs through this iterative learning process (Orlikowski, 1995).

Quantum theory (QT) as non-determinism. Quantum theory includes several concepts used to describe the "states" of particles. The most important of these are superposition and entanglement. Superposition is the idea that a particle can have multiple states simultaneously, while entanglement is the idea that two particles can affect each other, even if they are far apart. Memory, reasoning, and categorization research traditions have long been studied independently in cognitive science. Recent developments, however, have begun to blur the lines between these cognitive processes, particularly in reasoning and categorization. Traditionally, reasoning has been associated with logical and probabilistic rules, while categorization has focused on similarity-based processes. Nevertheless, there is growing recognition that similar cognitive mechanisms may underlie these distinct processes (Oaksford and Chater, 1994; Pothos, 2010; Griffiths and Schroeter 2020; Vantaggiato and Lubell, 2022)).

One promising theoretical framework that bridges the gap between reasoning and categorization is applying QP theory to cognitive modeling. At the beginning of the 20th century, classical physics could not explain the phenomena of light and the microscopic world. To illustrate this, a new physical system, quantum mechanics, emerged to describe the atomic and molecular world. QP theory provides a geometric approach to probability, representing events or questions as subspaces in a multi-dimensional Hilbert space. This theoretical framework provides a potential way to understand probabilistic reasoning and similarity processes in cognitive tasks (Tversky and Kahneman, 1983; Pothos et al. 2013).

This study discusses the concept of a multi-dimensional decision-making model based on the principles of quantum theory, using the "multidimensionality of policy issues in the policy process" as an example. In other words, this study explores how QP theory can be applied to cognitive processes, such as reasoning and categorization, to reveal the underlying cognitive mechanisms.

Theoretical foundations: QP theory

Quantum theory provides essential governance concepts such as superposition (multiple simultaneous stakeholder preferences), entanglement (interconnected policy decisions), and interference effects (context-driven preference shifts), enabling complex and dynamic policy modeling (Pothos and Busemeyer, 2013; Busemeyer et al. 2011).

Geometric representations in Hilbert space. In QP theory, cognitive possibilities or events are represented as subspaces within a multi-dimensional Hilbert space. Cognitive states are represented as state vectors. Probabilities are calculated by projecting state vectors onto relevant subspaces and computing the square of the projection's length. This geometric approach facilitates modeling complex cognitive processes involving multiple dimensions (Tversky and Kahneman, 1983; Pothos et al. 2013).

Incompatibility and interference. QP theory emphasizes incompatibility, where incompatible possibilities cannot simultaneously have definite truth values. Knowing one possibility with certainty renders another uncertain, reflecting interference between events. It differs from classical probability theory, which allows joint probability distributions for all alternatives. Interference provides insight into cognitive processes such as decision-making and reasoning, highlighting inherent incompatibility considerations (Busemeyer et al. 2011; Griffiths and Schroeter, 2020).

Superposition and entanglement. Superposition and entanglement are core quantum mechanics principles relevant to cognitive modeling. Superposition represents a quantum system's ability to exist simultaneously in multiple states. Similarly, cognitive states can represent multiple possibilities simultaneously. Entanglement reflects intrinsic dependencies between distinct cognitive dimensions or mental states (Bruza et al. 2009; Busemeyer et al. 2011; Griffiths and Schroeter, 2020).

Quantum cognition model: linking reasoning and categorization. Quantum cognitive models, grounded in QP theory, propose that reasoning and categorization share cognitive mechanisms. These models capture context, interference, and order effects in cognitive tasks, challenging traditional classical logic and probabilistic reasoning. The quantum reasoning model suggests cognitive reasoning processes resemble quantum wave functions, applying the "information maximization principle" rather than traditional deductive logic (Oaksford and Chater, 1994; Pothos et al. 2013). Quantum categorization models extend prototype and exemplar theories, suggesting that similarity judgments involve projecting cognitive states onto subspaces to measure similarity. These models explain cognitive phenomena like triangle inequality violations and order effects in similarity assessments (Pothos et al. 2013).

Table 1 Logical structure.

	Deviation theory (variance theory)	Course theory (process theory)	Quantum theory (Quantum theory)
Role of time	None (at one point in time)	Time on a continuum	Concurrency (list of events) (Simultaneous existence of past, present, and future)
Definition	ACause is a necessary and sufficient condition for an effect.	The cause is just a requirement of the process; Opportunities and events play a crucial role	Uncertainty of results Probabilistically inferring outcomes (locations) only from observations
Assumptions	Necessary and sufficient conditions always result in an outcome	(even if certain conditions are met). Results do not necessarily appear.	(even if certain conditions are met). Results are not guaranteed but can be calculated probabilistically.
Logical structure	If X, then Y; if more X, then more Y.	If it is not X, then it is not Y, but if it is more X, it is not more Y.	If it is not X, then it is not Y, but if it is more X, then it is more Y, probabilistically.

Source: Marcus and Robey, 1988: 590 reprinted.

Table 2 Conditions for securing policy transparency and their relationship with values.

Values	Role of bureaucrat	Role of citizen	Conditions for transparency	Engagement types	Expected backfires
Efficiency	Provider (adjustor)	Consumer (consumer)	. Fast . Accurate knowledge & information	Select (choice)	. Quasi-optimization under non-market economies
Effectiveness	Responder (reactor)	Customer (client)	. Active interaction	Conversations (dialogue)	. Information asymmetry
Responsiveness	Moderator	Active participant	. Engagement mechanisms Settling	intervention	. Fragmentation
Two-sided value (Quantum value) = [efficiency, effectiveness, responsiveness] + new value expression	Observers (observer)	Active watchers (active surveillant)	. Constant communication . Close data-information sharing . Recognize interactions between internal and external environmental factors	Immersion (immersion)	.AI, Machine Learning Overdependence .Simulation dependencies

Table 3 Distribution of respondents by affiliation.

Category of respondents	Number of respondents
Undergraduate students	31 (22.30%)
Members of KAPAE	23 (16.55%)
Government officials	79 (56.83%)
General public	6 (4.32%)

Quantum probability model

Quantum reasoning challenges classical logic, applying an "information maximization principle" instead of traditional inductive reasoning. Cognitive state vectors represent hypotheses or information relevant to a task. Quantum reasoning captures phenomena like conjunction errors, reflecting unexpected cognitive outcomes during decision-making (Busemeyer et al. 2011).

Quantum classification model. Quantum categorization incorporates QP theory to model similarity judgments through projections of cognitive state vectors. The squared length of projections measures similarity, addressing cognitive inconsistencies observed in classification tasks (Pothos et al. 2013).

Ambiguity in quantum decision models. Quantum decision models differ from classical fuzzy logic in interpreting ambiguity through quantum states and superposition. The quantum measurement process is decision-making, linking cognitive states with outcome probabilities (Oaksford and Chater, 1994).

Governance applications. Quantum theory introduces governance-applicable concepts: superposition (simultaneous stakeholder preferences), entanglement (dependencies between policy dimensions), and interference (context-driven shifts in preferences). These concepts enhance the modeling of complex governance scenarios (Moynihan and Soss, 2014).

Challenges and future directions. Quantum decision models provide valuable insights into decision-making processes. However, they also confront challenges, including clarifying empirical validity and exploring neural underpinnings. Further research should focus on applying these models broadly across cognitive science, psychology, economics, and policy-making contexts (Busemeyer et al. 2011; Griffiths and Schroeter, 2020).

Quantum approach to policy transparency

Transparency in policy-making relates to efficiency, effectiveness, and responsiveness. Efficient transparency involves accurate and quick dissemination of information, while effective transparency requires active stakeholder dialog. Responsive transparency emphasizes mediation and active participation from stakeholders, necessitating clear governance mechanisms (Tables 1–3).

Table 4 Distribution of the respondents according to the age group.

Age group of respondents	Number of respondents by age group
20 s	32 (23.02%)
30 s	15 (10.79%)
40 s	37 (26.62%)
50 s	46 (33.09%)
60 s	7 (5.04%)
Not respond	2 (1.44%)

Transparency conditions and stakeholder engagement. Policy transparency and stakeholder roles can be categorized into rational-market, responsive, and participatory governance models. Rational-market transparency emphasizes clarity and efficiency but risks "democracy without politics." Responsive transparency involves active dialogue to reduce stakeholder expectation gaps, and participatory transparency requires co-production, potentially leading to information asymmetry or exclusivity issues among stakeholders. Table 4 categorizes the relationship between policy transparency and related values and the roles, conditions, and types of participation of bureaucrats and citizens in securing policy transparency. It is an analytical distinction, and there may be mixed or exceptional cases in practice.

The first situation can be characterized as a rational or market model approach. The problem is that there is a significant non-market economy in the public sector, and the circumstances and patterns of individual choice of specific consumer goods are different from the circumstances and patterns of choice in policy-making for public goods and public services. Nevertheless, suppose the impersonality and simplicity of ICTs are emphasized, and administrative transparency is pursued through streamlined administrative transparency and technical-bureaucratic expertise. In that case, it will likely lead to depoliticization, meaning "democracy without politics" (Montin and Elander, 1995). Therefore, participation and policy transparency will likely be high if clear performance management principles and market-economic competition are met.

The second situation is a model that requires policy transparency to reduce the difference in expectations between internal and external groups regarding organizational goals. It is a stretch governance model, as responding flexibly through dialogue channels with citizens and external stakeholders is important. In this case, bureaucrats who want to provide active services and citizens willing and able to take an interest in and participate in government policies with a more mature sense of citizenship are the conditions for maintaining a high level of policy transparency.

The third situation corresponds to the participatory governance model, in which bureaucrats and citizens act as co-producers of policy. In order to achieve this level of policy transparency and to ensure that citizens are fully involved in the policy-making process, participatory mechanisms need to be put in place. In addition, citizens should always be politically interested and actively engaged, giving them a certain stake in the process centered on user group leaders. In this case, however, the government and bureaucrats should strive to promote citizen autonomy and leadership and have the ability to mediate various interests. Therefore, if these conditions are met, the distance between bureaucrats and citizens may become more distant and irreconcilable, and the possibility of social information inequality through the exclusive participation and stake exercise of some specific groups can be included.

Dualistic transparency: from control to governance. Conventional discussions of transparency often emphasize control mechanisms. However, considering contextual and interference effects, governance frameworks require transparency to balance the interactions between governments, markets, and civil society. This dualistic transparency framework facilitates more comprehensive and realistic governance models, which are essential in the digital age (Montin and Elander, 1995).

Policy transparency is instrumental in achieving responsible government by resolving or alleviating information asymmetries between masters and subjects, administrative insiders, and outsiders. In this view, transparency is critical from a policy perspective of control and governance. Therefore, quantum theory's integration into decision-making and governance offers nuanced insights into cognitive mechanisms underpinning complex policy scenarios, providing a robust analytical framework for future policy modeling and transparency practices.

Quantum-informed models may significantly enhance transparency by emphasizing dynamic recalibration, ongoing stakeholder engagement, and adaptive governance, overcoming limitations found in deterministic models (Howlett and Ramesh, 2023; Moynihan and Soss, 2014). At a more operational level, the following hypothetical questions can be posed.

To what extent will the public trust the transparency of the policy process?

What are the levels and expectations of transparency when transparency is linked to economic efficiency or rationality, which emphasizes customer preferences and choices; effectiveness, which emphasizes achieving policy goals; responsiveness; and feasibility, which emphasizes the positions and preferences of various stakeholders?

Empirical test based on quantum probability model

Rationale for selecting Korea's nuclear power plant policy. Korea's nuclear power plant policy was chosen as a case study due to its distinctive blend of complexity, uncertainty, political polarization, and dynamic stakeholder interactions. The nuclear policy in South Korea presents a fascinating scenario for applying quantum probability theory. It showcases how conflicting preferences co-exist (superposition) and how changes in political context or informational environment lead to unexpected shifts in stakeholder interests and positions (interference effects). The history of nuclear policy debates in Korea, marked by strong ideological polarization and significant transitions across different administrations, adds an intriguing layer to the study (Kim, 2023). This political oscillation provides a unique context for examining the concept of quantum entanglement, where policy decisions in one area or timeframe influence others.

Additionally, Korea's geopolitical location, particularly its proximity and relationship with North Korea, intensifies the importance and sensitivity of nuclear energy policy decisions, embedding them within broader national security and international diplomatic considerations. Thus, Korea's nuclear policy context is ideal for investigating how policy transparency, responsiveness, and effectiveness can be understood and potentially enhanced through quantum-informed frameworks[1].

Methodology and data collection. This study employs a two-wave survey methodology meticulously designed to capture shifts and stability in stakeholders' policy preferences over time. Respondents were classified by nuclear policy knowledge and political orientation, revealing that political biases significantly influenced policy preferences, supporting earlier findings on policy overreaction and blame avoidance (Maor, 2014; Weaver, 2018). The two-wave design, specifically tailored for testing quantum probability theory, allows for the examination of how initial opinions (quantum states of superposition) evolve and stabilize (collapse) through repeated measurement and interaction (quantum entanglement)[2].

The survey, conducted from 17 November to 23 December 2023, garnered a high response rate of 99.29% with a diverse group of 139 respondents out of 140 samples. This diverse group included undergraduate students enrolled in e-government courses (31 respondents), members of the Korean Association for Policy Analysis and Evaluation (KAPAE; 23 respondents), local government officials (79 respondents), and members of the general public (6 respondents). The participants judged 16 distinct nuclear policy scenarios, resulting in 17,792 observations (139 participants × 128 judgments each). Responses were analyzed individually to capture significant variations across demographics and stakeholder categories. We explained the purpose and method of the survey for nuclear power plant issues through emails, social media, and classes taking the university's E-government class. We asked the participants to respond, emphasizing the importance of the survey in Korea's nuclear policy[3].

Survey questionnaire and analytical approach. The participants judged the extent to which they believed nuclear policies based on the following policy values: 'the safety of a nuclear power plant' (S), 'the informativeness about a nuclear power plant' (I), 'the economics of a nuclear power plant' (E), and 'the feasibility of a nuclear power plant' (F). In future studies, policy effectiveness beyond safety would be expanded to include economic viability, energy security, and social acceptability[4].

Each dimension was operationalized through contextually relevant scenarios, allowing you, the participants, to express nuanced opinions reflecting your policy preferences[5]. The survey's two rounds were intentionally designed to measure potential interference effects, with identical scenarios presented in different orders to observe how contextual shifts influenced your preference expression. Data analysis employed chi-square tests of independence to evaluate the significance of observed opinion changes between survey rounds, highlighting the quantum concepts of superposition and entanglement. Results indicated statistically significant correlations between initial and subsequent responses, confirming the suitability of the quantum probability approach in capturing complex, dynamic opinion formation processes[6].

Of the 139 respondents, 32 (23.02%), 15 (10.79%), 37 (26.62%), 46 (33.09%), and seven (5.04%) were in their 20 s, 30 s, 40 s, 50 s, and 60 s, respectively; two (1.44%) did not report their age.

Notably, the study found that many participants maintained their initial opinions even after a second round of questioning, suggesting a phenomenon analogous to a "collapsed state" in quantum terms, where the act of measurement (re-questioning) solidifies their stance. Younger participants were more likely to keep their initial stance unchanged, whereas older participants tended to change their opinions over iterations gradually.

One hundred and 39 people participated in the survey: 24 stated they had 'no interest in nuclear power plants at all'; 64 indicated they could understand the topic 'if provided with explanatory materials'; five felt they could comprehend 'related materials even without explanations'; one claimed to have 'expert-level knowledge'; and 45 expressed their interest was 'of a political nature.' While we report the expert and near-expert responses for demographic completeness, it's important to note that these groups ($n = 5$) were rigorously excluded from all chi-square and inferential analyses due to their small size. Their inclusion in descriptive statistics allows us to illustrate the variation in knowledge-level-based opinion patterns, but does not influence empirical generalizations. Their responses were used exclusively to observe contrastive opinion formation trends and validate context-sensitivity hypotheses central to quantum-based modeling.

In summary, this study effectively demonstrates the practical application and theoretical utility of quantum probability models in policy analysis. By explicitly examining Korea's nuclear policy context's unique suitability and clearly outlining the two-wave survey design's methodological rationale, this research can significantly enhance our understanding of nuclear policy dynamics and contribute to developing more effective policy frameworks.

Before the survey, survey participants were in a state of quantum superposition regarding the original question and existed in a social environment and a state of quantum entanglement. The survey process corresponds to measurements, causing the quantum state of each survey participant to collapse, forming their individual opinions. After the survey concludes, the participants enter a new social quantum entanglement state. The participants act autonomously, reinforcing or diminishing the probability of specific views in their quantum states. The entanglement between their opinion quantum state and the quantum environment results in a collapsed state with altered quantum states in the second survey round, leading them to express their views.

Each participant judges 16 different nuclear policies. One stimulus type contains eight examples that favor the expansion of nuclear power plants, and another includes eight policy values that oppose the expansion of nuclear power plants. Each participant judges each nuclear policy value in eight contexts with two attributes and four combinations of two attributes presented in different orders.

For example, one context is SI, where the participants respond to a question about whether a nuclear policy is safe and informative by choosing one of YY, YN, NY, or NN (e.g., YN means yes if they think it is safe and no if they believe it is informative). Thus, each participant answers 16 (PT) × 8 (context) = 128 questions. These answers are presented in a randomized order across participants. This results in 139 participants X 128 judgments per person = 17,792 observations. Significant individual differences and all subsequent analyses are made at the personal level of the study.

The survey consists of questions from two rounds. The first round includes IS, SE, EF, and FI, while the second round comprises questions IF, FE, ES, and SI. Each question presents two reasons for supporting (or opposing) nuclear power plants and asks the respondents to choose the one they consider more important. The respondents can select both examples, just one or neither. The questions in the second round are a reverse order restructuring of those in the first round. Therefore, questions IS and SI, SE and ES, EF and FE, and FI and IF are identical in terms of the examples provided but differ in the order of presentation.

Based on the matching results, the following provides the response rates for opinions favoring increasing the share of nuclear power plants. The notation for the safety and economics of a nuclear power plant is SE. This notation is used in the table below: 0 is coded as NN, 1 is coded as NY, 2 is coded as YN, and 3 is coded as YY (Tables 5–8).

The chi-square test of independence was used to test the significance of the differences in the responses between the first and second rounds of surveys. The chi-square test is a statistical method used to determine if two categorical variables are correlated or independent of each other (Nevill et al. 2002).

The formula for calculating the chi-square (χ^2) statistic is

$$X^2 = \sum \frac{(O_i - E_i)^2}{E_i}$$

O_i: the observed frequency in each category or cell.

Table 5 Response rate for the opinions in favoring the expansion of nuclear power plants.

	NN	NY	YN	YY
Round1				
IS	0.021	0.5	0.271	0.208
SE	0	0.396	0.333	0.271
EF	0.042	0.188	0.688	0.083
FI	0.042	0.375	0.5	0.083
Round2				
SI	0.104	0.479	0.25	0.167
ES	0.083	0.417	0.313	0.188
FE	0.083	0.208	0.688	0.021
IF	0.083	0.271	0.563	0.083

Table 6 Response rate for the opinions opposing the expansion of nuclear power plants.

	NN	NY	YN	YY
Round1				
IS	0.044	0.637	0.253	0.066
SE	0.066	0.791	0.099	0.044
EF	0.143	0.418	0.407	0.033
FI	0.099	0.286	0.560	0.055
Round2				
SI	0.088	0.615	0.375	0.099
ES	0.066	0.813	0.055	0.066
FE	0.187	0.363	0.418	0.033
IF	0.110	0.231	0.626	0.033

E_i: the expected frequency in each category or cell, calculated based on the hypothesis being tested.

The correlation between two categorical variables can be determined through the p value obtained from a chi-square test. A p value of 0.05 or less indicates a significant correlation between the variables. R 4.3.2 was used for the chi-square independence test.

In conclusion, the two categorical variables are not independent but significantly correlated. This result confirmed that the entanglement between the participant's opinion quantum state and the quantum environment results in a collapsed state with altered quantum states in the second round, leading them to express their opinions (Fig. 1).

Findings and discussion

Propensity to transition. This study measured the number of times an answer transition occurred in the data, where 4 is when all four opinions change and 0 is when none change. Figure 2 presents the distribution of the transitions, with blue for those in favor of expanding nuclear power and red for those against it.

The number of cases where the opinions did not change was the highest and decreased as the number of transitions increased to 1, 2, and 3. The number of cases in which the opinions changed altogether was surprisingly high. Opinions on nuclear power were not significantly affected by the number of transitions (Figs. 3–6).

Analysis of question 1 (level of knowledge for nuclear power plants). Next, this study looked at the number of transitions based on the answers to "1. How knowledgeable do you think you are about nuclear power plants?" The number of transitions was checked based on the answer to "1." Due to the small sample size, those with "expert-level knowledge" and those who answered "I could understand if I looked at relevant materials without commentary" were excluded.

Table 7 *P* values for the responses favoring the expansion of nuclear power plants.

Question number	*P* value
IS & SI	8.2×10^{-9}
SE & ES	8.2×10^{-9}
EF &FE	1.3×10^{-3}
FI & IF	1.2×10^{-4}

Table 8 *P* values for the responses opposing the expansion of nuclear power plants.

Question number	*P* value
IS & SI	1.4×10^{-12}
SE & ES	2.2×10^{-16}
EF & FE	2.2×10^{-16}
FI & IF	2.2×10^{-16}

Most notably, the frequency rankings were reversed when a transition was 0 (no change of opinion) and 4 (change of opinion). Those who answered "politically interested" were more likely not to change their opinions, while those who changed all of their opinions were most likely to answer "not interested at all." Interestingly, very few who answered "politically interested" had a transition of 1.

Analysis result by age group. This time, the people who transitioned were classified according to age.

Older people were believed to be more conservative and less likely to change their minds, but the results were the opposite. Younger people were less likely to change their opinions, and older people were more likely to change their opinions gradually. It is worth considering whether this is because younger people are less likely to change their opinions, or whether they answered the same because they thought the second survey was the same as the first.

When broken down according to age, the older the respondent, the more opposed they were to expanding nuclear power, except those in their 30 s who favored it.

Those in their 30 s, 50 s, and 60 s were the most knowledgeable and interested in nuclear power issues. Nevertheless, it is interesting that people in their 30 s, 50 s, and 60 s had opposed opinions on nuclear power expansion. The in-betweeners, those in their 40 s, were most likely to say they were "politically interested," but they were also the most likely to be uninterested. The 20 s were more likely to say "not at all interested" but were also more likely to say "politically interested." The percentage of people interested in politics was similar across generations. In contrast, the percentage of people not interested in politics increased with age. This statistic shows the difference between Korean feminists in their 20 s, men in their 20 s, the anti-dictatorship movement generation of the 1980s, and the 21st-century SNS generation in their 30 s.

The lower transition rates among younger participants may reflect cognitive anchoring effects and digital-native exposure to curated media (Sharot et al. 2010; Tversky and Kahneman, 1983). Younger individuals are more influenced by ideological consistency, particularly on issues like climate change (Griffiths, 2003). Generational political research in Korea further suggests that individuals in their 20 s and 30 s demonstrate strong ideological convictions, influencing their rigidity in policy perspectives (Kim, 2023; Chung, 2020). In contrast, older participants, often exposed to broader historical policy shifts, may exhibit more deliberative

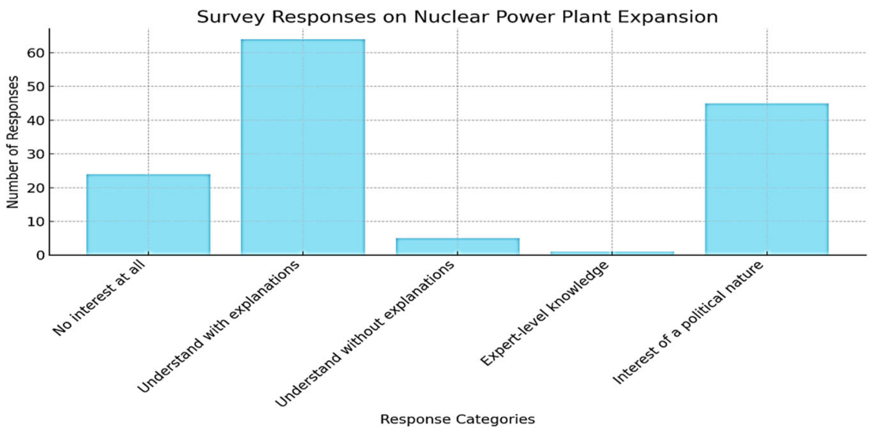

Fig. 1 Opinions on nuclear power plant expansion.

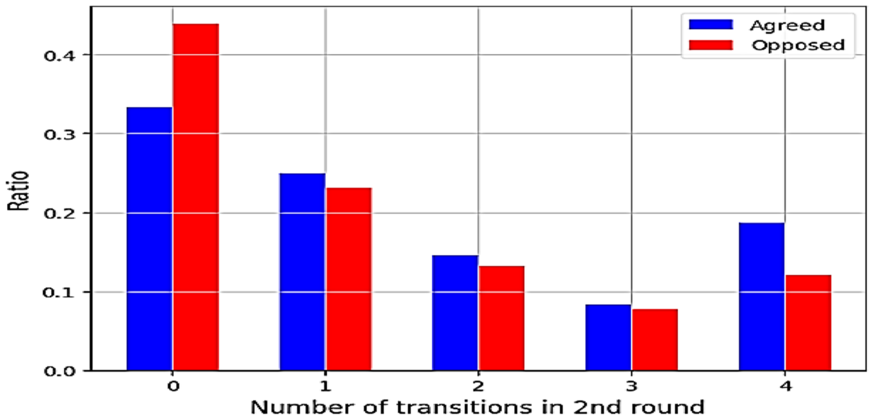

Fig. 2 Number of transitions in the second round.

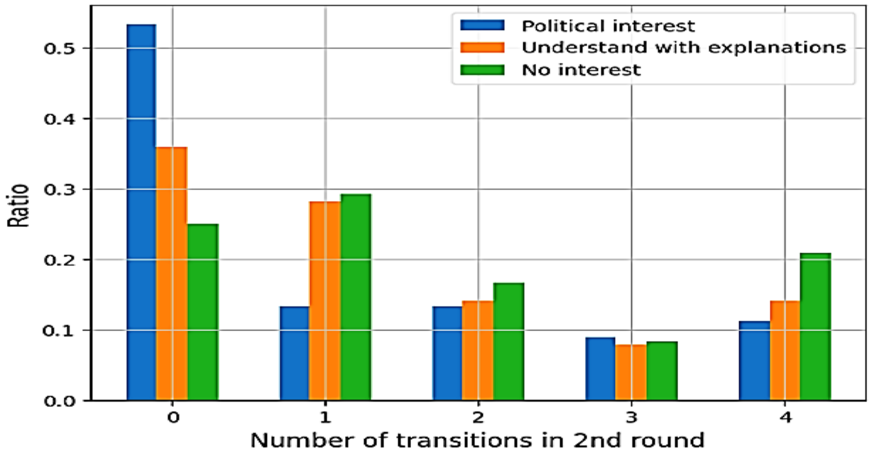

Fig. 3 Number of transitions for question 1 in the second round.

opinion updating. Older individuals have broader life experiences, making them more open to reconsidering policy positions (Haslam et al. 2003).

Distributions according to the knowledge level and policy values for nuclear power plants. Tables 9 and 10 list the sums, percentages, and response rankings by question for and against increasing the share of nuclear power plants, respectively. Respondents have two opportunities to respond to the same item per round. Hence, the maximum number of responses per item was twice that of the respondents, and the minimum number of responses was zero.

The group favoring expanding nuclear power generation showed little difference between the first and second rounds. Moreover, the reasons for support, safety, economy, and sufficient information showed little change, as shown in Table 9.

On the other hand, Table 10 indicates that confirmation bias and ideological and generational sympathies were much stronger than rationality. Hence, the 1980s anti-dictatorship activist generation tended to support the progressive Moon Jae-in government's nuclear phase-out policy, mainly because of the

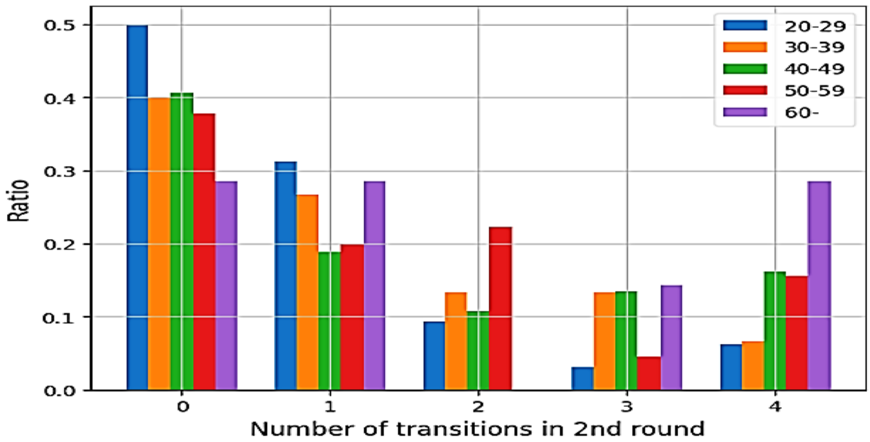

Fig. 4 Number of transitions according to age in the second round.

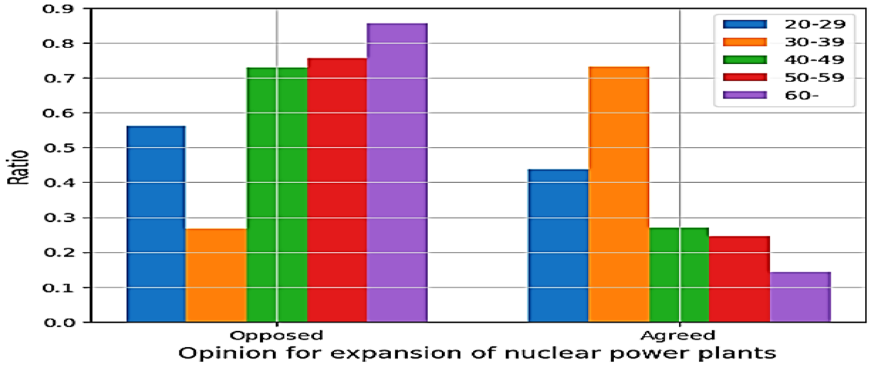

Fig. 5 Opinion for nuclear power plant expansion.

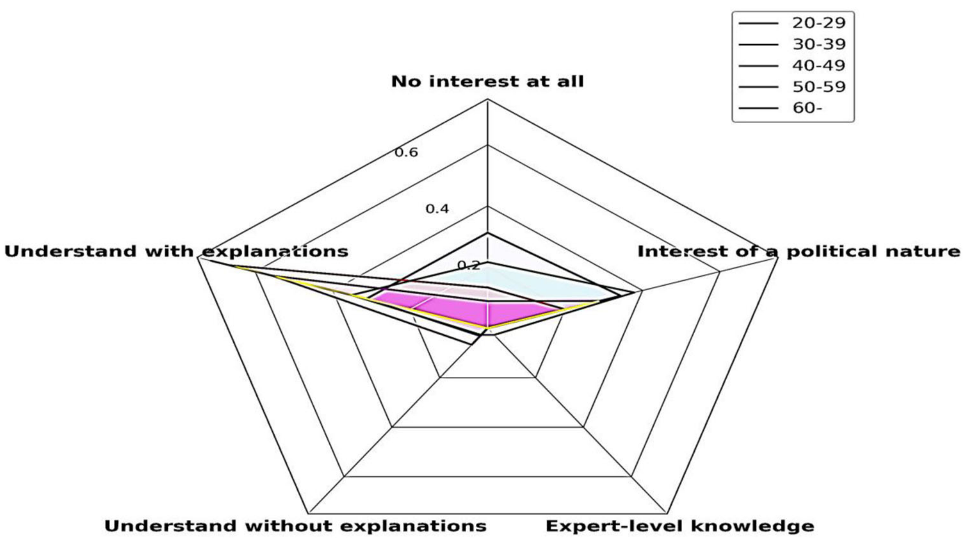

Fig. 6 Level of Understanding by Knowledge for Nuclear Power Plant Expansion.

safety issue of nuclear power generation. Regarding political interest in the nuclear phase-out issue, the 1980s activist generation did not change their opposition to expanding nuclear power plants. They even believed the atomic power plant was less feasible (20.0% –>15.6%) in the second round in Table 10. In particular, the 30 s were similar, and they also believed the nuclear energy policy was inferior in terms of economic efficiency.

The anti-nuclear group is interpreted as the working generation, which has a strong antipathy towards the conservative governments of Lee Myung-bak (2008–2013) and Park Geun-hye (2013–2017), who was impeached. Since then, the Moon Jae-in administration (2017–2022) has been a progressive government that has reduced the number of nuclear power plants and strengthened solar, wind, and hydrogen energy policies. An article published in Heinrich-Böll-Stiftung Asia Global Dialog

Table 9 Distributions of respondents in favor of the expansion of nuclear power plants.

		I	S	F	E	Subtotal
Expert-level knowledge (1 person)	R1	0	2 (50%, 1st)	2 (50%, 1st)	0	4
	R2	0	2 (50%, 1st)	2 (50%, 1st)	0	4
Able to understand unexplained nuclear materials (4 people)	R1	5 (29.4%, 2nd)	6 (35.3%, 1st)	1 (5.9%, 4th)	5(29.4%, 2nd)	17
	R2	4 (33.3%, 1st)	4 (33.3%, 1st)	1 (8.3%, 4th)	3 (25%, 3rd)	12
I can understand the material with commentary (26 people)	R1	33 (27.5%, 2nd)	31 (25.8%, 3rd	16 (13.3%, 4th)	40 (33.3%, 1st)	120
	R2	33 (28.9%, 2nd)	30 (26.3%, 3rd)	15 (13.1%, 4th)	36 (31.6%, 1st)	114
Interest at the political level (11 people)	R1	12 (23.1%, 3rd)	18 (34.6%, 1st)	7 (13.5%, 4th)	15 (28.2%, 2nd)	52
	R2	11 (25.6%, 3rd)	14 (35.6%, 1st)	5 (11.6%, 4th)	13 (30.2%, 2nd)	43
Not interested at all (6 people)	R1	1 (4.5%, 4th)	9 (41.0%, 1st)	6 (27.3%, 2nd)	6 (27.3%, 2nd)	22
	R2	3 (12.5%, 4th)	10 (41.7%, 1st)	5 (21.0%, 3rd)	6 (25%, 2nd)	24
Total (48 people)	R1	51 (23.7%, 3rd)	66 (30.7%, 1st)	32 (14.9%, 4th)	66 (30.7%, 1st)	215
	R2	51 (25.9%, 3rd)	60 (30.5%, 1st)	28 (14.2%, 4th)	58 (29.4%, 2nd)	197

Table 10 Distributions of respondents opposing the expansion of nuclear power plants.

		I	S	F	E	Subtotal
Expert-level knowledge (0 people)	R1	-.	-.	-.	-.	0
	R2	-.	-.	-.	-.	0
Able to understand unexplained nuclear materials (1 person)	R1	2 (50%, 1st)	1 (25%, 2nd)	-.	1 (25%, 2nd)	4
	R2	2 (50%, 1st)	1 (25%, 2nd)	-.	1 (25%, 2nd)	4
I can understand the material with explanations (38 people)	R1	36 (24.3%, 2nd)	59 (39.9%, 1st)	31 (21.0%, 3rd)	22 (14.9%, 4th)	148
	R2	40 (28.4%, 2nd)	59 (41.8%, 1st)	22 (15.6%, 3rd)	20 (14.2%, 4th)	141
Interest at the political level (34 people)	R1	31 (25.2%, 2nd)	52 (42.3%, 1st)	23 (18.7%, 3rd)	17 (13.8%, 4th)	123
	R2	26 (21.8%, 2nd)	56 (47.1%, 1st)	16 (13.4%, 4th)	21 (17.6%, 3rd)	119
Not interested at all (18 people)	R1	16 (20%, 3rd)	28 (35%, 1st)	24 (30%, 2nd)	12 (15%, 4th)	80
	R2	19 (23.8%, 3rd)	29 (36.3%, 1st)	22 (27.5%, 2nd)	10 (12.5%, 4th)	80
Total (91 people)	R1	85 (24.0%, 2nd)	140 (39.4%, 1st)	78 (22.0%, 3rd)	52 (14.6%, 4th)	355
	R2	87 (25.3%, 2nd)	145 (42.2%, 1st)	60 (17.4%, 3rd)	52 (15.1%, 4th)	344

(Kim, 2023) revealed the biased confirmation and ideological and generational sympathies:

> In a survey on the future path of nuclear energy conducted during the public deliberation of Shin-Kori Units 5 and 6 in 2017, 53.2% said that nuclear power should be reduced, and 35.5% opted to maintain the status quo. Only 9.7% were in favor of the expansion of atomic energy. In a poll conducted in 2018, 84.6% and 72%, respectively, favored reducing nuclear and coal power plants and increasing renewable energy and natural gas power plants. In a survey conducted by the Korean Nuclear Society in August of the same year, however, 71.6% answered in favor of using nuclear power to generate electricity during the height of the heat wave. In contrast, a survey commissioned by the Korean Nuclear Society in 2021 showed that public opinion had changed. 72.1% supported nuclear energy, far higher than the 24.2% against it, and 35.9% answered that nuclear power generation should be increased from 25–30%.
>
> In comparison, 34.0% wanted to maintain the status quo, and 28.1% favored reducing the nuclear share. When asked to choose two main future sources, solar energy was the highest at 33.8%, followed by nuclear power at 30.6%. For NPPs whose lifespan is about to expire, 78.9% of the respondents said that a decision on whether to extend the operation should be made after evaluating the safety and economic feasibility, which was overwhelmingly higher than the 18.5% who said that they should be permanently shut down without lifespan extension. In a 2022 opinion poll about the direction of energy policy, when asked about their evaluation of the Moon Jae-In government's nuclear phase-out policy, such as banning the construction of new NPPs and the lifespan extension of existing ones, 37.8% responded that they like the policy (25.0% very good and 12.8% good), while 54.0% said it was undesirable (42.2% very wrong and 11.8% wrong). In the same year, in KHNP's survey, 69.2% said nuclear energy for power generation was necessary. In summary, recent public opinion polls show that support for nuclear power outweighs opposition.

A previous study on the public deliberation on the national nuclear energy policy in Korea (Chung, 2020) reported that most people participating in the nuclear power plant expansion called the 'Shin-Kori' deliberation process kept their initial opinions the same. The study found that the information gained during the public hearing did not affect the participant's original decisions. Moreover, more educated and knowledgeable participants tended to be more negative toward nuclear energy; their political bias greatly influenced them. Usually, people use their value predispositions to decide on complicated issues rather than being fully informed (Nisbet, 2005). Over the last 15 years, nuclear energy has been a political issue in Korea. In the case of the Shin-Kori nuclear power plant, the conflicts between the ruling party that insisted on a denuclearization policy and the opposition party that opposed it developed the argument into a fierce political struggle. Therefore, the greater the influence of these political interests or friendships, the more likely they are to insist on their original opinions.

Theoretical and policy implications

The survey results showed that the processes of obtaining knowledge through measurement and verification through past quasi-experiments and observation of social phenomena are limited to receiving information from the subjects and that decisions can only be made at a satisfactory level due to the limited rationality of the subjects because logical sequences and interactions among variables are not allowed because they undermine the validity of the study. Nevertheless, although it still requires repeated efforts to validate and generalize assumptions through numerous exploratory studies and repeated experiments, quantum mechanics is attracting attention as a new decision-making model because it breaks this principle and inevitably affects the participants, who are the subjects of the experiment, in the process of exchanging information. Hence, information or knowledge is not a static property of the provider or one side but flows out in a new form in the interaction between the subject and oneself. Suppose the interview process yields richer and more interesting results than originally planned. Thus, interaction and consensus-building have changed the current state of affairs. Therefore, if one desires various government policies to be more transparent and reflect various policy values, they will inevitably require an iterative process of correction such as interaction, correction, feedback, and recalibration between policy providers and stakeholders in the process of policy agenda selection, alternative analysis, alternative evaluation, implementation, and evaluation. While it is important to avoid relying solely on quantitative indicators, such as cost-benefit analysis, cost-effectiveness analysis, interest discount rates, and depreciation costs, it is also important to prevent heuristic decision-making that relies too heavily on intuition, emotion, and inconclusive discussions and public hearings (Arias-Yurisch et al. 2024; Mewhirter et al. 2024).

Therefore, for a more rigorous analysis of the cost-benefit, appropriate policy agenda, or policy transparency per se, it is necessary to systematize the scope of policy values on each policy agenda. As discussed in the case of policy transparency and values above, the scope of the policy debate can be broadened by linking the policy agenda to different policy values. For example, nuclear energy policy from the perspective of economic efficiency based on rational consumer choice, the nuclear policy in a situation where the bureaucracy is a reactor and needs to engage in considerable dialog to reduce the gap in mutual expectations, and a policy issue when the bureaucracy's ability to engage and mediate with various stakeholders is required. For this reason, theories and analytical methods for evaluating and reflecting on existing policies must also differ. The level and scope of necessary transparency in relatively standardized and simple tasks, such as procurement and taxation, are very different from those required in social issues (nuclear power plants, North Korea relations, low birthrate, aging, pensions, and climate changes), where the requirements of various stakeholders should be collected and mediated. Luhmann's social system emphasizes the contexts and meanings that need to be more important than fragmented individuals in modern social systems. Hence, it is time for a detailed analysis of communication and transmission methods, such as language, symbols, and information, structurally embedded in individuals (Luhmann, 2011).

In sum, our findings provide essential insights for policy-making:

- Effective policy-making requires recalibrating in real time and engaging with stakeholders on an ongoing basis (Busemeyer and Wang, 2018).
- Transparency in the policy-making process, including the availability of both data and active engagement mechanisms, is a cornerstone of building stakeholder trust. When this transparency is dynamically adapted to stakeholder preferences, it reassures them of the integrity and fairness of the process.
- Quantum probabilistic models have the potential to transform policy-making. They can anticipate non-linear policy dynamics. By reducing the risks of deterministic decision-making, these models open up new avenues for policy analysis and decision-making. They challenge traditional approaches and invite a fresh perspective.
- Effective policy-making requires recalibration in real time and continuous interaction with stakeholders (Busemeyer and Wang, 2018).
- Transparency in policy-making, in terms of data availability and active engagement mechanisms, is a cornerstone of stakeholder trust building. Such transparency reassures stakeholders of the integrity and fairness of the process when it is dynamically adapted to their preferences.
- Quantum probabilistic models, with their ability to anticipate non-linear policy dynamics, represent a transformative potential in policy-making. They open new avenues for policy analysis and decision-making, challenging traditional approaches and inviting a fresh perspective by reducing the risks of deterministic decision-making.

From a governance perspective, policy-making should shift toward iterative, feedback-driven approaches prioritizing flexibility, adaptive strategies, and transparency through continuous stakeholder interaction and recalibration (Capano and Howlett, 2024; Moynihan and Soss, 2014).

Conclusion

This study presented the limitations and alternative perspectives of the deterministic view. It examined various quantum probability theories, mathematical models that describe the behavior of systems at the quantum level, and multi-dimensional decision-making models from a quantum perspective. The multi-faceted concept of policy transparency, including policy values and other conditions, was analyzed. Finally, means and directions were suggested to overcome deterministic thinking in the policy agenda by investigating Korea's nuclear power plant issue.

This study attempted to raise the following issues. First, to improve the effectiveness of policies, it is necessary to identify the actual policy needs accurately through a series of interactions, corrections, and recalibration processes in the policy process. Therefore, it is necessary to introduce the concept of quantum theory and a multi-dimensional decision-making model that approaches variables, such as norms, institutions, and technology, in a situational context by breaking away from the existing deterministic view. Second, it is necessary to conduct multi-dimensional research on various forms of bloggers, influencers, and collective intelligence (e.g., Instagram, Facebook, Threads, and Kakao Talk) that exert influence through policy promotion, public opinion polls, and social media in the process of deriving a multi-dimensional policy agenda and exploring and analyzing alternatives. Finally, accurate information and data cannot be accumulated if transparency in the policy process is not guaranteed, and the level of integrity and reliability of data decreases. Accordingly, reviewing the policy input process and designing an intelligent government that considers these multi-dimensional analysis levels, social variables, and interchange processes is necessary. A virtuous policy process must be established through data connection and artificial intelligence to increase government credibility and policy efficacy.

Stakeholders frequently exhibit strong emotional commitments to their respective positions in policy domains characterized by significant contention, such as nuclear energy. Consequently, traditional deterministic decision models often fail to account for such complex stakeholder dynamics adequately. In contrast, quantum decision models present an alternative framework that captures inherent uncertainties, dynamic shifts in stakeholder preferences, and the interactive processes among stakeholders. Applying quantum probabilistic approaches in policy-making contexts thus holds considerable potential for advancing more nuanced and adaptive decision-making paradigms.

The current study's findings highlight notable limitations inherent in conventional policy models, particularly their tendency toward oversimplification when addressing decision-making complexities within governance frameworks. This recognition underscores the necessity for adopting more sophisticated and flexible analytical methodologies within policy analysis.

Future research should explore hybrid modeling approaches integrating quantum probability frameworks with heuristic-based decision-making techniques. Such integrative methodologies are anticipated to significantly contribute to the ongoing evolution and refinement of policy analysis and decision-making models. Additionally, extending quantum probabilistic approaches to broader policy domains, including climate change mitigation, artificial intelligence governance, and economic planning, represents an essential avenue for future investigation.

Data availability

Data sharing is not applicable to this study.

Received: 29 August 2024; Accepted: 8 May 2025;
Published online: 26 June 2025

Notes

1 In physical quantum mechanics, a vector in Hilbert space represents the state of a dynamical system. Operators acting on this vector represent physical quantities such as position and momentum. The state vector changes with time under the action of an energy operator called the Hamiltonian, and the wave function represents the state vector.

2 Entanglement theory offers another view of the observer theory. In contrast to the previous 1-2-1 argument, which states that the universe exists because the observer exists, the disconnection theory states that the observer's consciousness does not affect reality because the interaction occurs through the external environment. Hence, the object does not exist because it is observed, but because the individual and the object have interacted countless times without the individual's knowledge, and both can exist. It can be seen as a theory defeating the superiority of human intellect.

3 Myeong, Seunghwan 2006. "Limitations of deterministic thinking in e-government research and ways to overcome them: Focusing on administrative transparency," Information Policy, 13(1). pp: 100–115. it is reprinted with permission.

4 Peters (1996) classified governance into four models: the market model, which emphasizes competitiveness and decentralization of governmental organizations; the participation model, which emphasizes democratic participation, including citizen participation and participation at lower levels of the organization; the flexibility model, which emphasizes organizational structure for flexible response to environmental changes; and the deregulation model, which relaxes internal regulations and grants discretion to agencies in charge of actual operations.

5 It includes external administrative bodies (legislative, judicial, higher authorities), local and regional government agencies, and private organizations (suppliers, advisory bodies, professional associations, broadcast media).

6 Busemeyer, J. R., & Wang, Z. (2018). Hilbert space multi-dimensional theory. *Psychological Review*, *125*(4), 572–591.

References

Arias-Yurisch K, Retamal-Soto K, Ramos-Fuenzalida C et al. (2024) Participation in multiple policy venues in governance of Chile's Santiago Metropolitan Region: when institutional attributes can make the difference. Policy Stud J 52(3):583–602. https://doi.org/10.1111/psj.12527
Bruza PD, Kitto K, Nelson D et al. (2009) Is there something quantum-like about the human mental lexicon? J Math Psychol 53(5):362–377
Busemeyer JR, Bruza PD (2012) Quantum models of cognition and decision. Cambridge University Press, Cambridge
Busemeyer JR, Wang Z (2018) Hilbert space multi-dimensional theory. Psychol Rev 125(4):572–591. https://doi.org/10.1037/rev0000106
Busemeyer JR, Pothos E, Franco R et al. (2011) A quantum theoretical explanation for probability judgment "errors". Psychol Rev 118(2):193–218. https://doi.org/10.1037/a0022542
Capano G, Howlett M (2024) Calibration and specification in policy practice: micro-dimensions of policy design. Policy Des Pract 7(2):115–128. https://doi.org/10.1080/25741292.2024.2353929
Castells M (2000) Toward a sociology of the network society. Contemp Sociol 29(5):693–699. https://doi.org/10.2307/2655234
Chung J-B (2020) Public deliberation on the national nuclear energy policy in Korea—small successes but bigger challenges. Energy Policy 145:111724
Gigerenzer G, Todd PM (1999) Simple heuristics that make us smart. Oxford University Press
Griffiths DJ, Schroeter DF (2020) Introduction to quantum mechanics. Cambridge University Press, Cambridge
Griffiths RB (2003) Consistent quantum theory. Cambridge University Press, Cambridge
Haslam SA, Eggins RA, Reynolds KJ (2003) The ASPIRe model: actualizing social and personal identity resources to enhance organizational outcomes. J Occup Organ Psychol 76:83–113
Howlett M, Ramesh M (2023) Designing for adaptation: static and dynamic robustness in policy-making. Public Adm 101:23–35. https://doi.org/10.1111/padm.12849
Ingold K (2011) Being Alive: Essays on Movement, Knowledge and Description. Routledge
Kim SJ (2023) South Korea's "unstable" nuclear energy policy: from Lee through Moon to Yoon governments. Heinrich-Böll-Stiftung Asia Global Dialogue. (Online article)
Leung L (2005) Virtual ethnicity: race, resistance and the world wide web. Routledge, London. https://doi.org/10.4324/9781315234991
Luhmann N (2011) Theory of Society, Volume 1 (R. Barrett, Trans.). Stanford University Press. (Original work published 1997)
Maor M (2014) Policy overreaction. Public Adm Rev 74(3):389–401
March JG (1997) Understanding how decisions happen in organizations. In: Shapira Z (ed) Organizational decision making, pp 9–32. Cambridge University Press, Cambridge
March JG, Simon HA (1958) Organizations. Wiley, New York
Markus ML, Robey D (1988) Information technology and organizational change: causal structure in theory and research Manag Sci 34(5):583–598. https://doi.org/10.1287/mnsc.34.5.583
Mewhirter J, McLaughlin D, Calfano B (2024) Manifesting symbolic representation through collaborative policy-making. Policy Stud J 52(2):283–318. https://doi.org/10.1111/psj.12525
Montin S, Elander I (1995) Citizenship, consumerism and local government in Sweden. Scand. Political Stud 18(1):25–51. https://doi.org/10.1111/j.1467-9477.1995.tb00154.x
Moynihan DP, Soss J (2014) Policy feedback and the politics of administration. Public Adm Rev 74(2):20–30
Myeong S (2006) Limitations of deterministic thinking in e-government research and ways to overcome them: focusing on administrative transparency. Inf Policy 13(1):100–115
Myeong S (2023) Theory and practice of smart e-government: theory and practice of information systems and e-government (5th ed.). Yunsungsa, Seoul
Nam T, Pardo TA (2011) Smart city as urban innovation: Focusing on management, policy, and context. In Proceedings of the 5th International Conference on Theory and Practice of Electronic Governance (pp. 185–194). ACM. https://doi.org/10.1145/2072069.2072100
Nevill AM, Atkinson G, Hughes MD et al. (2002) Statistical methods for analyzing discrete and categorical data recorded in performance analysis. J Sports Sci 20(10):829–844. https://doi.org/10.1080/026404102320675666
Nisbet MC (2005) The competition for worldviews: values, information, and public support for stem cell research. Int J Public Opin Res 17(1):90–112
Oaksford M, Chater N (1994) A rational analysis of the selection task as optimal data selection. Psychol Rev 101(4):608–631
Orlikowski WJ (1995) Organizational change and groupware technology. (Working Paper No. 186). MIT Sloan School, Cambridge, MA
Pelopidas B (2017) Nuclear weapons scholarship as a case of self-censorship in security studies. J Glob Secur Stud 2(4):326–336
Peters BG (1996) The future of governing: four emerging models. University of Kansas Press, Lawrence, KS
Pothos EM (2010) The quantum probabilities approach to cognitive modeling. Cogn Sci 34(6):967–1032
Pothos EM, Busemeyer JR (2013) Can quantum probability provide a new direction for cognitive modeling? Behav Brain Sci 36:255–327
Pothos EM, Busemeyer JR, Trueblood JS (2013) A quantum geometric model of similarity. Psychol Rev 120(3):679–696

Schelling, TC (1960). The strategy of conflict. Harvard University Press
Sharot T, Velasquez CM, Dolan RJ (2010) Do decisions shape preference? Evidence from blind choice. Psychol Sci 21(9):1231–1235
Simon HA (1955) A behavioral model of rational choice. Q J Econ 69:99–118. https://doi.org/10.2307/1884852
Tversky A, Kahneman D (1983) Extensional versus intuitive reasoning: the conjunction fallacy in probability judgment. Psychol Rev 90(4):293–315
Vantaggiato FP, Lubell M (2022) The benefits of specialized knowledge in polycentric governance. Policy Stud J 50(4):849–876
Walther P, Resch KJ, Brukner Č et al. (2006) Experimental entangled entanglement. Phys Rev Lett 97(2):020501. https://doi.org/10.1103/PhysRevLett.97.020501
Weaver RK (2018) Policy tools and performance accountability: A comparative perspective. Journal of Comparative Policy Analysis 20(6):560–575
Zahariadis N (2007) The multiple streams framework. In: Moran M, Rein M, Goodin RE (eds) The Oxford Handbook of Public Policy, pp 65–90. Oxford University Press, Oxford

Acknowledgements
This work was supported by the Ministry of Education of the Republic of Korea and the National Research Foundation of Korea (NRF-2022S1A5C2A03093690).

Author contributions
The corresponding author is SHM. SHM designed the research, collected and analyzed data, wrote and revised the manuscript, and provided funding. JWL analyzed data and wrote the manuscript. JHB collected and analyzed data. CHC analyzed the data and the manuscript.

Competing interests
The authors declare no competing interests.

Ethical approval
This article does not involve any studies with human participants conducted by any of the authors.

Informed consent
This article does not contain any studies with human participants performed by any of the authors.

Additional information
Correspondence and requests for materials should be addressed to Seunghwan Myeong.

Reprints and permission information is available at http://www.nature.com/reprints

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.