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Strategic configurations for solar PV adoption: Empirical insights from the commercial energy sector

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Abstract

This study aims to explore strategic pathways that lead to a high willingness to adopt solar photovoltaic (PV) technology in Indonesia's commercial energy sector, particularly within the retail fuel industry. A sequential mixed-method approach was employed, beginning with Partial Least Squares Structural Equation Modeling (PLS-SEM) to assess the measurement model, followed by fuzzy-set Qualitative Comparative Analysis (fsQCA) for configurational assessment on survey data from 160 decision-makers in the sector. The analysis reveals four distinct configurations that result in a high willingness to adopt PV, illustrating the principle of equifinality and the configurational complexity of organizational decision-making. Perceived environmental benefit consistently emerges as a core condition across all configurations, acting as a strategic catalyst when combined with institutional legitimacy and financial viability. Other conditions, such as perceived ease of use or social norms, vary across contexts. The study concludes that adoption outcomes emerge from multiple, rather than singular, causal pathways, highlighting the relevance of a configurational approach. Building on this insight, it offers actionable guidance for developing adaptable, context-aware strategies that integrate ecological, economic, technical, institutional, and behavioral dimensions to advance solar PV adoption in commercial settings.

Keywords: fsQCA, PLS SEM, Solar Photovoltaic Adoption, Strategic Configurations.

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1. Introduction

The global push for sustainable energy transition has accelerated interest in renewable technologies such as solar photovoltaic (PV) systems. Solar energy, derived from abundant and inexhaustible sunlight, has become central in tackling global energy and climate challenges. It offers a cleaner, low-emission alternative to fossil fuels, producing as little as 4-12 gCO_2eq/kWh compared to the 400–1000 gCO_2eq/kWh generated by coal and other fossil-based sources [1]. This stark contrast underscores solar PV's crucial role in decarbonization efforts. Technological advancements have not only boosted power conversion efficiencies but also significantly reduced production costs and improved the feasibility of mass deployment [2-4]. At the same time, solar PV systems are becoming more intelligent and flexible due to the integration of smart inverters, predictive control models, and hybrid energy storage systems, enabling efficient grid interaction and system stability [5, 6].

Beyond electricity generation, solar technologies are increasingly being applied in diverse sectors such as agriculture, residential heating, water desalination, and even atmospheric water harvesting [7, 8]. These multifaceted applications further reinforce solar's strategic role in ensuring energy security, environmental sustainability, and socio-economic development, particularly in regions with limited infrastructure or remote geographies. Urban centers too can benefit from the integration of solar PV into rooftops, which leverage solar potential in constrained environments [9]. Furthermore, global solar PV deployment is expanding at an unprecedented pace, with global capacity reaching 814 GW in 2022, driven by an annual growth rate of approximately 27% over the past decade Nugraha [10], with projections estimating solar to account for the largest share of power generation capacity under 1.5°C scenarios by 2030 and 2050 [11].

Despite these advancements and the global momentum, solar PV adoption remains uneven, especially in the commercial sector of emerging economies. Indonesia exemplifies this paradox. While endowed with vast solar potential exceeding 207 GW according to the Ministry of Energy Kementerian ESDM [12] and boasting solar radiation consistency across key regions like East Java, Bali, and Nusa Tenggara World Bank Group [13] the country's installed solar capacity remains low, reaching only 637 MW by the end of 2023 [14]. This figure represents less than 1% of its total technical potential, highlighting a significant underutilization of solar energy in a country with rapidly growing energy demands and ambitious climate goals. This gap between Indonesia's renewable energy potential and its low realization reflects ongoing challenges in aligning economic growth with carbon reduction targets due to continued reliance on non-renewable energy sources [15].

Multiple and interacting barriers contribute to this slow uptake. One of the significant limitations is economic feasibility, with the initial purchase price still being a major factor, including in countries with subsidies [16, 17]. Technological influences, including ease of use, compatibility and visibility, can also affect adoption decisions [18-20]. Furthermore, the non-continuous character of solar power production raises questions about its reliability, for which aggregation of resources and the use of integrated energy storage are strategies already under development [21-23]. Environmental awareness is found to facilitate adoption, Adnan [24] and Arroyo and Carrete [25]; however, its influence is often diminished due to limited understanding and skepticism regarding personal contribution [26, 27]. Environmental concerns regarding the management of PV waste or floating solar systems pose additional stumbling blocks to adoption [28-30]. This strong policy support is still critical, as good intentions and regulatory clarity can help turn positive dispositions into real investments [31-33]. The slow uptake is due to multiple and interacting barriers, underscoring that this calls for integrated and context-sensitive approaches.

Research on solar PV adoption has been growing rapidly in recent years, yet most studies have concentrated on the residential or household sector. Building on this foundation, recent findings highlight that adoption decision-making is shaped by a complex interplay of individual perceptions and contextual influences. Among these, the perception of economic benefits is consistently reported as the most influential factor. High upfront costs, expectations of long-term financial savings, and the availability of government incentives play a central role in shaping adoption intentions, even in high-income countries where subsidies are present [16, 17, 34, 35]. In addition to economic considerations, technological factors such as ease of use, system compatibility, and perceived performance also significantly affect adoption. Users tend to favor technologies that are simple, reliable, and easily integrated into existing energy infrastructures [18, 20, 36]. Furthermore, social influences, particularly peer effects, community engagement, and leadership support, can create a favorable social climate that promotes adoption, especially in rural or close-knit communities where collective behavior plays a vital role [37, 38]. In parallel, personal factors with renewable technologies serve to further strengthen adoption intentions when individuals feel capable and perceive clear benefits [24]. However, the influence of environmental concern remains mixed. While some consumers are motivated by ecological values, others are constrained by limited awareness, doubts about their personal impact, or apprehensions about the environmental implications of PV systems themselves [26, 29]. Finally, policy and regulatory support delivered through subsidies, tax incentives, and streamlined regulations continues to be a critical enabler. Such mechanisms are essential not only to alleviate financial and procedural barriers but also to transform positive attitudes into concrete adoption behavior [31-33].

Despite these valuable insights, existing research has largely centered on residential contexts, where adoption decisions are driven by individual motivations and household constraints. As a result, the commercial sector remains underexplored, even though its role is critical for accelerating broader solar deployment. Scholars highlight that commercial adoption involves distinct complexities and requires a different analytical lens due to organizational constraints and strategic objectives [39].

In addition to sector-specific challenges, methodological limitations further constrain our understanding of commercial solar PV adoption. Current methodologies in existing research primarily rely on quantitative, variable-oriented approaches such as regression analysis or structural equation modeling. These methods may assume linear and additive relationships and typically treat influencing factors in isolation [40, 41]. The nonlinear interactions between various influencing factors in commercial contexts create a scenario where traditional methods can fall short of capturing the complexity inherent in commercial adoption decisions [42, 43]. This is emphasized by researchers who argue that adopting PV technologies involves complex dynamics that frequently do not align with the linear assumptions of standard quantitative analyses [44, 45].

To overcome these limitations, the present study employs fuzzy-set Qualitative Comparative Analysis (fsQCA), a method designed to capture causal complexity and address the inadequacies of conventional approaches. This method has also been effectively utilized in other fields to explore how complex configurations of cognitive, behavioral, and organizational conditions jointly influence key outcomes [46]. FsQCA facilitates the identification of multiple configurations of conditions that lead to a specific outcome, embracing the principles of equifinality and causal asymmetry [47]. This is particularly important in commercial settings, where the decision-making process is influenced by various contextual factors that interact in nonlinear ways, not readily captured by simpler analytical models [41]. By focusing on how different combinations of factors lead to solar PV adoption, fsQCA allows for a richer analysis of the pathways through which commercial entities engage with solar technology, thereby providing deeper insights into their decision-making processes [39, 48]. In line with this approach, the central research question guiding this study is: "*What strategic configurations of conditions lead to a high willingness to adopt solar PV technology in the commercial energy sector?"*. Addressing this question is expected to generate empirically grounded insights that support the formulation of targeted, context-sensitive strategies for advancing solar PV adoption, particularly in the diverse settings of emerging markets.

This study applies to the case of retail fuel stations throughout Indonesia, a commercial subsector that offers a compelling yet underexplored context for solar PV integration. These stations operate across urban and rural areas, exhibit consistently high electricity demand, and are increasingly being positioned as potential sites for solar-powered electric vehicle charging infrastructure. They also represent a scalable model for decentralized energy transition due to their visibility, regulatory significance, and replication potential. By combining a novel methodological lens with a strategically important commercial context, this study provides fresh insights that address existing gaps in both theory and practice, informing more adaptive, sector-specific policies and accelerating the broader adoption of solar PV in emerging markets.

2. Literature Review

The adoption of solar photovoltaic technology is a complex decision-making process shaped by cognitive, affective, and social dimensions. While individual-level determinants provide valuable insights into the motivations and barriers influencing renewable energy behavior, limited attention has been paid to how these factors interact to form configuration-based pathways that drive adoption. This complexity is effectively explained by the Theory of Planned Behavior [49, 50]. This theory posits that an individual's intention to engage in a behavior is the most immediate predictor of action. This intention is shaped by their attitude toward the behavior (ATB), their perception of social expectations, subjective norms (SN), and their perceived control over the behavior, known as perceived behavioral control (PBC) [49-52]. In the context of solar photovoltaic adoption, these components reflect how individuals weigh potential costs and benefits, respond to social influence, and assess their own capability to adopt and manage the technology.

To enhance the explanatory power of this framework in pro-environmental contexts, researchers have proposed the inclusion of two additional variables: perceived environmental concern (PENC) and perceived authority support (PAS) [53-55]. PENC refers to an individual's awareness of and concern about environmental problems, such as climate change and pollution, and has been shown to positively influence attitudes, perceived norms, and behavioral control associated with sustainable practices. Similarly, PAS, a perceived support from government or environmental institutions, reinforces individuals' belief in the legitimacy and practicality of adoption, thereby strengthening their perceived social and institutional backing [53-55].

In addition to these two additional variables, recent studies highlight the relevance of perceived environmental benefit (PENB), perceived economic benefit (PECB), and perceived ease of use (PEOU) as critical factors influencing adoption. While PENC is grounded in internal values and moral responsibility, PENB reflects the belief that adopting solar energy will lead to measurable environmental improvements. Research indicates that this belief significantly enhances adoption intention, especially among individuals who prioritize tangible, results-oriented outcomes [56, 57]. Equally important is the role of PECB, which consistently emerges as one of the strongest predictors of adoption. These benefits include anticipated reductions in electricity costs, eligibility for financial incentives, and potential increases in property value. Particularly in contexts where economic rationality dominates, financial motivations often serve as the most compelling justification for adoption decisions [18, 20, 58]. In addition, PEOU also significantly shapes individuals' willingness to adopt solar technology. When the system is seen as easy to install, operate, and maintain, it reduces psychological resistance and builds confidence, especially among new or inexperienced users. Studies have shown that trialability, system compatibility, and a user-friendly design are critical in fostering trust and encouraging uptake [18, 20, 59].

Taken together, these psychological, institutional, economic, and technological factors do not act in isolation. Rather, they form interconnected and context-sensitive configurations that dynamically shape adoption behavior. Understanding how these elements interact is essential for identifying the conditions most conducive to widespread adoption. In response to this complexity, the present study adopts a configurational approach to explore how these multiple drivers work together to influence decision-making, with the aim of developing more targeted, effective, and contextually appropriate strategies for accelerating the deployment of solar photovoltaic technology.

This paper endeavours to present a conceptual framework that combines the prominent non-demographic variables at an individual level with a configurational analytical lens. There are several cognitive, affective, and social variables that have been found to be relevant to adoption decisions, such as perceived economic benefit, perceived environmental concern, perceived environmental benefit, perceived authority support, perceived ease of use, attitude toward behavior, subjective norms, and perceived behavioral control (see Figure 1). These factors each add a separate dimension to individual decision-making: rational assessments of costs and benefits, environmental perspectives, institutional trust, ease of technology, social influence, and behavioral considerations. While these factors have been widely studied, most existing research tends to examine them in isolation using linear, variable-based models. Such approaches overlook the reality that adoption decisions are rarely driven by single influences; instead, they result from the interaction of multiple conditions that work together in dynamic ways. To capture this complexity, the present study adopts fsQCA, a method well-suited for identifying causal configurations that lead to an outcome [60, 61]. This approach is grounded in the principles of equifinality and causal asymmetry, which acknowledge that different combinations of factors can produce the same result, and that the absence of adoption may follow entirely different pathways than its presence [62]. By uncovering these configurations, the study moves beyond explaining adoption behavior alone. It also aims to identify strategic, context-sensitive pathways that can inform more effective policy design, targeted interventions, and communication strategies to accelerate solar photovoltaic adoption, particularly in commercial sectors where decision-making is multifaceted and resource-dependent.

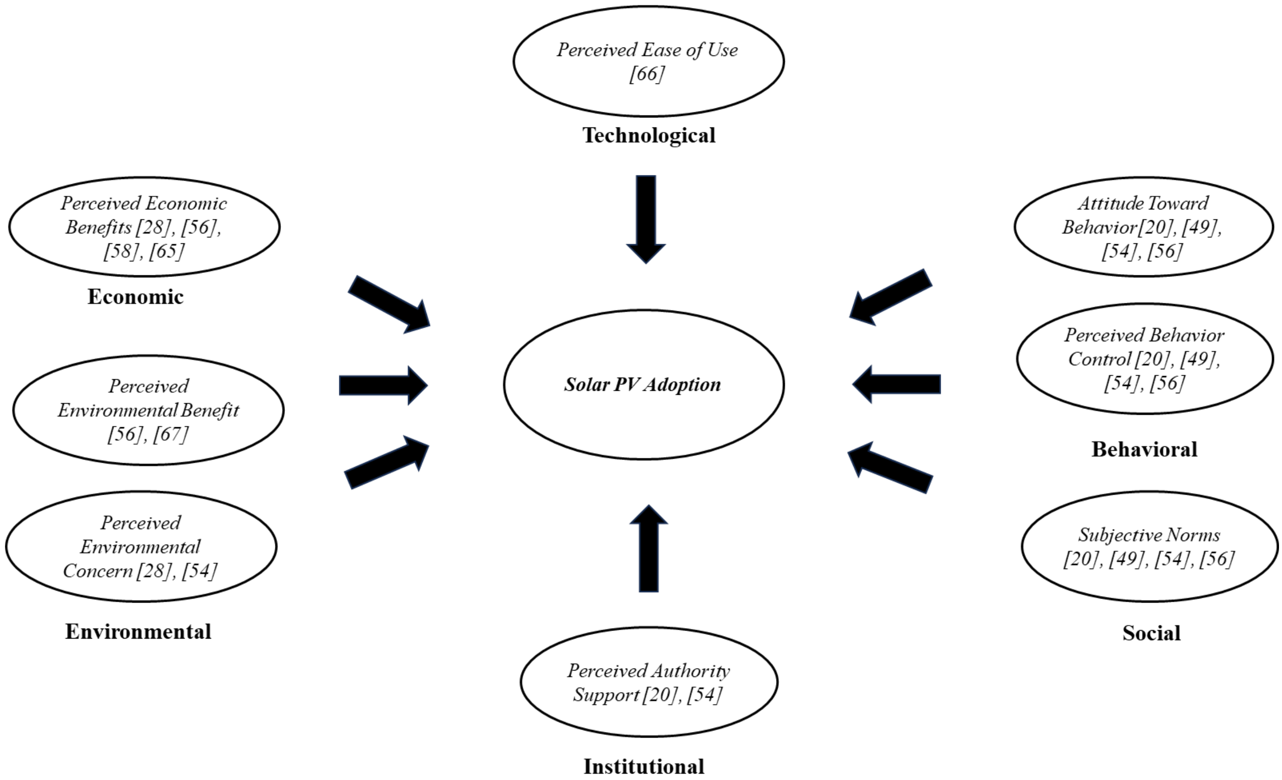

Figure 1.
Conceptual Framework.
Source: Wang, et al. [63]; Davis [64]; Huansuriya and Ariyabuddhiphongs [65]; Aghlimoghadam, et al. [57]; Li and Dai [58]; Ahmad, et al. [18]; Alam, et al. [20] and Angowski, et al. [28]

3. Methodology

This research employs a quantitative approach for data collection and measurement model analysis by using Partial Least Squares-Structural Equation Modelling (PLS SEM), which is then continued by a configurational set-theoretic method using fsQCA. This combined approach enables the exploration of causal complexity by identifying multiple interacting conditions that contribute to an outcome, going beyond the linear and additive assumptions typically associated with traditional statistical models [66, 67]. To operationalize this approach, the quantitative phase involved the development and administration of a structured questionnaire using a 5-point Likert scale.

Data were collected through purposive sampling to ensure respondents had relevant operational and investment authority. All measurement scales were adapted from validated instruments in prior literature and subjected to pre-testing and psychometric evaluation to confirm their reliability and validity.

The initial analysis involved Partial Least Squares Structural Equation Modeling (PLS-SEM) software to assess the measurement model, which confirmed convergent and discriminant validity through composite reliability, average variance extracted, and Heterotrait Monotrait (HTMT) criteria [68]. Building upon the insights derived from the measurement model assessment, the analysis then proceeded with fsQCA to capture the configurational nature of the adoption decision a methodology particularly suited for uncovering complex causality in real-world social phenomena [66]. FsQCA allows the identification of multiple combinations of conditions (configurations) that can lead to the same outcome, embodying the principles of equifinality and causal asymmetry [67]. This approach moves beyond variable-centric modeling by accounting for interactions among causal factors that are not easily revealed through regression-based methods [69].

The fsQCA procedure was implemented in several systematic stages. First, calibration transformed the raw Likert-scale responses into fuzzy-set membership scores using anchor points: 4 for full membership, 3 as the crossover point, and 2 for full non-membership [66]. Variables calibrated in this study included perceived economic benefits, perceived ease of use, perceived environmental benefits, perceived environmental concern, perceived authority support, attitude toward behavior, subjective norm, and perceived behavioral control. The outcome variable was willingness to use solar PV technology. Calibration was performed using the direct method in fsQCA 4.1 software. Following calibration, a truth table was constructed to enumerate all logically possible combinations of conditions and assess their consistency with the outcome. This allowed the identification of empirically valid configurations, which were then simplified through Boolean minimization. The software generated three types of solutions: complex, parsimonious, and intermediate, each offering different levels of abstraction [60, 61, 66].

To interpret these findings meaningfully, the final step involved analyzing the resulting configurations to identify core and peripheral causal conditions across pathways leading to a high willingness to adopt solar PV technology. This analysis provided a more nuanced understanding of how economic, environmental, institutional, and behavioral factors interact to influence decision-making. By contextualizing these findings within the broader theoretical and policy frameworks, the study contributes actionable insights for promoting solar PV adoption in commercial energy sectors.

4. Results

4.1. Pre Test

A pre-test was conducted to ensure methodological rigor and assess the precision of the measurement instrument. This preliminary evaluation aimed to examine the content validity of the questionnaire items and evaluate their reliability before launching the full-scale national survey. The pre-test also served to identify potential issues such as semantic ambiguity, redundancy among items, and inconsistencies in measuring the intended constructs. To assess item validity, a Pearson correlation analysis was performed by correlating each questionnaire item with its corresponding construct. The results revealed that all items had significant p-values (< 0.05), confirming that each item accurately represented its designated construct and was statistically valid.

To further establish the reliability of the measurement instrument, a reliability analysis was conducted using Cronbach's Alpha. The analysis produced a coefficient of 0.965 across all 34 items, indicating excellent internal consistency. This result suggests that the items are highly interrelated and capable of reliably measuring the underlying latent constructs. The high reliability coefficient strengthened the instrument's credibility and demonstrated its readiness for full-scale deployment in the main survey.

4.2. Data Collection and Respondent Profile

Following the pre-test, data were collected through an online survey completed by 160 decision-makers from Indonesian fuel station business units. Demographic and geographic profiling revealed that most respondents were male and aged between 30 and 50 years, representing a mature and experienced managerial cohort. Most had at least completed high school, with demonstrated business insight relevant to PV technology adoption. Geographical distribution spanned multiple regions in Indonesia, capturing perspectives from both urban and regional markets.

4.3. Measurement Model Analysis – PLS SEM

Prior to the measurement model analysis, descriptive statistics (mean and standard deviation) were calculated to examine data trends. PENB had the highest mean (3.59), indicating strong positive perceptions, while WTU had the lowest (3.24), reflecting barriers in adoption. PAS & PENC showed the highest standard deviation (1.07), suggesting differing views on institutional support & environmental concerns, possibly due to contextual factors. In contrast, SN had the lowest standard deviation (0.78), indicating shared norms among decision-makers. To ensure the robustness and psychometric quality of the measurement model, reliability and validity were then evaluated by using PLS SEM analysis based on the guidelines of Hair et al. [68]. All constructs surpassed the commonly accepted thresholds for Cronbach's Alpha and Composite Reliability (both > 0.70), confirming strong internal consistency. Factor loadings for all indicators were also examined, with every item exceeding the recommended threshold of 0.70, indicating strong relationships with their respective latent variables. This high indicator reliability confirmed that each item made a substantial contribution to measuring its intended construct. Furthermore, Average Variance Extracted values exceeded 0.50 across all constructs, demonstrating solid convergent validity and showing that the constructs explained the majority of variance in their indicators. Discriminant validity, which ensures that each construct is conceptually distinct from the others, was also assessed using the Heterotrait-Monotrait (HTMT) ratio. The HTMT scores for all construct pairs were below the threshold of 0.90, providing further evidence that the constructs in the model do not overlap and are empirically distinguishable. This confirms the soundness of the measurement model and supports its theoretical structure. A summary of both descriptive & measurement model analysis is presented in Table 1.

Table 1.
Respondent's Descriptive Statistics & Measurement Model Analysis.

Construct	Cronbach's Alpha (α)	Composite Reliability (CR)	Average Variance Extracted (AVE)	Mean	Standard Deviation	Loading Range	Discriminant Validity (HTMT ≤ 0.90)
ATB	0.926	0.927	0.819	3.39	0.87	0.835 – 0.931	Yes
PAS	0.936	0.937	0.839	3.35	1.07	0.871 – 0.938	Yes
PBC	0.907	0.908	0.783	3.28	0.88	0.837 – 0.918	Yes
PECB	0.925	0.927	0.87	3.48	1.01	0.901 – 0.949	Yes
PENB	0.915	0.917	0.797	3.59	0.89	0.846 – 0.930	Yes
PENC	0.907	0.911	0.785	3.53	1.07	0.776 – 0.927	Yes
PEOU	0.916	0.919	0.857	3.32	0.94	0.904 – 0.948	Yes
SN	0.900	0.905	0.772	3.29	0.78	0.774 – 0.919	Yes
WTU	0.936	0.937	0.84	3.24	0.91	0.888 – 0.936	Yes

Note:
PECB: Perceived Economic Benefit
PEOU: Perceived Ease of Use
PENC: Perceived Environmental Concern
PENB: Perceived Environmental Benefit
PAS: Perceived Authority Support
ATB: Attitude Toward Behavior
SN: Subjective Norms
PBC: Perceived Behavioral Control
WTU: Willingness to Use

The results demonstrated that the instruments used in this study were statistically valid, internally consistent, and theoretically coherent. With strong evidence of reliability and validity across all constructs, the dataset and measurement model are well-qualified for the subsequent stage of analysis using fsQCA.

4.4. Configurational Analysis - fsQCA

Following the validation of the measurement model, the study advanced to the configurational analysis stage using fsQCA, a method well-suited for capturing causal complexity in social phenomena [60, 61, 66]. This method explores non-linear causal relationships[66] underlying the willingness to adopt solar PV technology in commercial energy contexts. Unlike traditional linear methods, FsQCA recognizes that variables can exhibit degrees of membership in each set, ranging from 0 to 1, thus allowing for more nuanced insights into causality [60, 61]. This methodological flexibility makes it well-suited for analyzing combinations of conditions that may lead to the same outcome—a concept known as equifinality [66]. In this research, FsQCA is employed to reveal distinct causal paths, enabling a deeper understanding of how varying configurations of variables influence a given result.

The first stage in FsQCA involves data calibration, where raw data is converted into fuzzy-set scores based on predetermined thresholds. These thresholds are typically derived from the 5th, 50th, and 95th percentiles of the original data, representing full non-membership, crossover point (ambiguous membership), and full membership, respectively. For Likert-scale data, the commonly used thresholds are 2 (fully out), 3 (crossover), and 4 (fully in), as advised by Pappas and Woodside [66]. This transformation allows for each case's degree of membership in a fuzzy set to be measured more accurately, providing a foundation for configurational analysis. Using the calibrate function in the fsQCA 4.1 software, each variable's raw value is converted into a fuzzy score. For example, if a case has a value of 3.5 on a variable calibrated with thresholds 4, 3, and 2, the resulting fuzzy score will fall between 0.50 and 0.95 based on interpolation. This calibration ensures that the data reflects the fuzzy set membership more precisely, enabling a detailed configurational analysis. Once calibration is complete, all relevant variables are expressed within the fuzzy set range of 0 to 1, enhancing the analytical depth compared to conventional statistical techniques.

After calibration, a truth table is constructed to display all possible causal condition combinations that could lead to a specific outcome. This table then guides the identification of meaningful configurations, with researchers deciding whether conditions should be marked as "present" or "absent" in each configuration. Following Pappas and Woodside [66] recommendation, the "Present or Absent" setting is chosen to explore all potential combinations, forming the basis for intermediate, complex, and parsimonious solutions. This step ensures a systematic approach in mapping how different sets of causal conditions contribute to the outcome.

The final stage involves solution analysis, where fsQCA produces configurations that consistently lead to the desired outcome. In this study, four major configurations were found to collectively explain major cases with high consistency (see Figure 2). Each configuration presents a unique combination of factors that are either sufficient alone or in combination to generate the outcome. These findings highlight the strength of fsQCA in revealing multiple pathways to the same behavioral result, supporting a more nuanced understanding of complex social phenomena.

```
*TRUTH TABLE ANALYSIS*
**********************

File:  C:/Users/just4/Desktop/S3 Nanang/110125 Data Kuisioner Disertasi Final FSQCA data setelah kalibrasi.csv
Model: WTUx = f(PECBx, PEOUx, PENBx, PENCx, PASx, ATBx, SNx, PBCx)
Algorithm: Quine-McCluskey

--- COMPLEX SOLUTION ---
frequency cutoff: 1
consistency cutoff: 0.915078
                                                     raw       unique
                                                   coverage    coverage   consistency
                                                  ----------  ----------  ----------
PECBx*PEOUx*PENBx*PENCx*PASx*SNx*PBCx             0.752831    0.0119566   0.97226
PECBx*PEOUx*PENBx*PASx*ATBx*SNx*PBCx              0.765422    0.0245478   0.978758
PECBx*~PEOUx*PENBx*PENCx*~PASx*ATBx*SNx*~PBCx     0.223469    0.0187283   0.915078
~PECBx*~PEOUx*PENBx*PENCx*PASx*ATBx*~SNx*PBCx     0.191091    0.0149192   0.953538
solution coverage: 0.814412
solution consistency: 0.950013


**********************
*TRUTH TABLE ANALYSIS*
**********************

File:  C:/Users/just4/Desktop/S3 Nanang/110125 Data Kuisioner Disertasi Final FSQCA data setelah kalibrasi.csv
Model: WTUx = f(PECBx, PEOUx, PENBx, PENCx, PASx, ATBx, SNx, PBCx)
Algorithm: Quine-McCluskey

--- PARSIMONIOUS SOLUTION ---
frequency cutoff: 1
consistency cutoff: 0.915078
              raw       unique
            coverage    coverage   consistency
          ----------  ----------  ----------
PENBx     0.962121    0.962121    0.762516
solution coverage: 0.962121
solution consistency: 0.762516


**********************
*TRUTH TABLE ANALYSIS*
**********************

File:  C:/Users/just4/Desktop/S3 Nanang/110125 Data Kuisioner Disertasi Final FSQCA data setelah kalibrasi.csv
Model: WTUx = f(PECBx, PEOUx, PENBx, PENCx, PASx, ATBx, SNx, PBCx)
Algorithm: Quine-McCluskey

--- INTERMEDIATE SOLUTION ---
frequency cutoff: 1
consistency cutoff: 0.915078
Assumptions:
                                                     raw       unique
                                                   coverage    coverage   consistency
                                                  ----------  ----------  ----------
PECBx*PEOUx*PENBx*PENCx*PASx*SNx*PBCx             0.752831    0.0119566   0.97226
PECBx*PEOUx*PENBx*PASx*ATBx*SNx*PBCx              0.765422    0.0245478   0.978758
PECBx*~PEOUx*PENBx*PENCx*~PASx*ATBx*SNx*~PBCx     0.223469    0.0187283   0.915078
~PECBx*~PEOUx*PENBx*PENCx*PASx*ATBx*~SNx*PBCx     0.191091    0.0149192   0.953538
solution coverage: 0.814412
solution consistency: 0.950013
```

Figure 2.
fsQCA Results from fsQCA 4.1 Software (Screen Capture).

The summary of fsQCA results (see Table 2) uncovered four primary causal configurations associated with high willingness to use solar PV, as derived from the complex and intermediate solutions (solution consistency = 0.950013; solution coverage = 0.814412). Each configuration represents a unique pathway through which adoption willingness can be realized.

1. The first configuration consists of a full combination of PECBx (calibrated PECB), PEOUx (calibrated PEOU), PENBx (calibrated PENB), PENCx (calibrated PENC), PASx (calibrated PAS), SNx (calibrated SN), and PBCx (calibrated PBC), all present in their positive form, contributing significantly to willingness to use solar PV (raw coverage = 0.752831; consistency = 0.97226).
2. The second configuration similarly includes PEBCx, PEOUx, PENBx, PASx, SNx, and PBCx, but replaces PENCx with a strong ATBx, reflecting a pathway where behavioral disposition complements institutional and technological support (raw coverage = 0.756422; consistency = 0.978758).
3. The third configuration presents a contrasting structure, where the absence of PEOUx, lack of PASx, and low PBCx are offset by strong PENBx and PECBx, PENCx, ATBx, and SNx. Despite these barriers, the configuration still leads to high willingness (raw coverage = 0.223469; consistency = 0.915078), showcasing the principle of causal asymmetry.
4. The fourth configuration involves a different causal logic, where both PEBCx and PEOUx are absent, yet high willingness to adopt is achieved through strong PENCx, PASx, and ATBx, even in the absence of SNx. Here, the presence of PBCx appears to compensate for the lack of external social cues, SNx (raw coverage = 0.191091; consistency = 0.953538).

These diverse patterns reflect the multifaceted nature of adoption behavior, where different configurations of enabling and compensatory conditions can yield similar outcomes. A notable finding across all four pathways is the consistent presence of PENBx as a contributing condition. This recurring role suggests that PENBx serves as a foundational driver of adoption, regardless of the configuration, reinforcing the environmental rationale behind commercial investments in solar PV technology. Further supporting this insight, the parsimonious solution (see Figure 2) identified PENBx as the core condition sufficient to produce high willingness to adopt solar PV (solution consistency = 0.962121; raw coverage = 0.762516). While this simplified model does not capture the full configurational complexity, it highlights the indispensable influence of environmental benefit perception in shaping positive behavioral outcomes.

Table 2.
Resume of fsQCA Results.

	Solutions			
Configurations	**1**	**2**	**3**	**4**
PECBx	●	●	●	⊗
PEOUx	●	●	⊗	⊗
PENBx	⬤	⬤	⬤	⬤
PENCx	●		●	●
PASx	●	●	⊗	●
ATBx		●	●	●
SNx	●	●	●	⊗
PBCx	●	●	⊗	●
Consistency	*0.972260*	*0.978758*	*0.915078*	*0.953538*
Raw Coverage	*0.752831*	*0.765422*	*0.223469*	*0.191091*
Unique Coverage	*0.0119566*	*0.0245478*	*0.0187283*	*0.0149192*
Overall Solution Consistency	*0.950013*			
Overall Solution Coverage	*0.814412*			

Note:
Black circles (●) : "presence of a condition"; Circles with "×" (⊗) : "absence of a condition"; Blank : "don't care condition"
Large circles : "core condition" ; Small circles: "peripheral condition"
Source: fsQCA Output (2025).

5. Discussion

These findings highlight the configurational aspect of solar PV adoption choices in business environments. The propensity to adopt arises from several combinations of situations rather than a single dominating element. The existence of perceived environmental and economic benefits, bolstered by social influence and institutional support, significantly enhances the probability of adoption. This aligns with other studies which emphasize that perceived economic advantages, including cost savings, long-term energy efficiency, and return on investment, significantly facilitate adoption [28, 34, 70]. Notwithstanding substantial initial expenses, families and enterprises are progressively incentivized by the financial benefits provided by solar PV systems, as shown by Alipour et al. [35], Cherry and Sæle [16], and Arroyo and Carrete [25]. Likewise, the prominence of perceived environmental advantages, such as emission reductions and sustainability contributions, has been shown to affect adoption behavior in research conducted by Scheller et al. [56] and Aghlimoghadam et al. [57]. Notably, the perceived ease of use influences some configurations, although not critical in others, underscoring the intricate and asymmetric nature of the causal interactions at play. The fsQCA findings support the idea that ease of use may impact interactions with other variables. This discovery corresponds with other research conducted by Ahmad et al. [18] and Engelken et al. [71], which indicated that usability, compatibility, and trialability may indirectly influence adoption choices.

The intricate and intermediate solutions revealed four principal causal configurations that jointly accounted for over 81% of high adoption instances, all exhibiting great consistency. These results provide robust empirical evidence that a high propensity to adopt solar PV systems might arise from several diverse combinations of variables rather than a singular linear trajectory. This configurational approach corresponds with the Theory of Planned Behaviour [49, 50]. Which asserts that intention—a primary predictor of conduct is influenced by attitudes toward the activity, subjective standards, and perceived behavioral control. All components are represented in at least one identifiable configuration, hence affirming the model's ongoing relevance. Furthermore, the results illustrate the interaction between psychological and environmental elements rather than their independent functioning. Environmental concern and perceived authority support two factors suggested as expansions to the Theory of Planned Behavior in sustainability contexts, were pivotal in various configurations, either facilitating or offsetting the lack of other prerequisites. This aligns with the conclusions of German et al. [53], Lin et al. [54], and Mufidah et al. [55], who highlighted the significance of institutional and normative support in influencing environmental decision-making.

The first setup depicts a thorough array of reinforcing factors, including economic and environmental advantages, ease of use, environmental consciousness, institutional backing, societal expectations, and a perception of behavioral control. The second configuration indicates that in environments with less environmental concern, favorable sentiments regarding the technology might offset this, resulting in robust adoption effects. The third configuration illustrates that, while lacking user-friendliness, authoritative backing, and individual autonomy, the amalgamation of robust environmental values, positive attitudes, and encouraging social norms may facilitate adoption. The fourth configuration offers an alternative approach, whereby perceived constraints in economic and usability dimensions are mitigated by governmental endorsement, environmental incentives, and behavioral purpose. The results align with previous research indicating that perceptions of environmental and economic advantages, together with positive attitudes and external support, are essential for promoting adoption. This aligns with the research conducted by Ahmad et al. [18], Alam et al. [20], and Aghlimoghadam et al. [57], which highlight the interaction of economic, environmental, and normative factors in the adoption of renewable energy.

Perception of environmental advantages regularly constitutes a fundamental criterion for a strong readiness to adopt. The results reveal that perceived environmental benefit consistently emerged as a core condition across all high-adoption configurations. While not a sufficient condition on its own, this element plays a significant role in influencing adoption behavior. The considerable explanatory power indicates that environmental gains, when integrated with other facilitating factors, serve as a robust basis for promoting renewable energy adoption in the commercial sector. This corroborates the assertion of Scheller et al. [56] who emphasize that perceived environmental advantages, separate from general concern, are crucial in shaping favorable behavioral intentions. The persistent prevalence of this feature throughout configurations underscores the need to direct communications and interventions that highlight ecological benefits, especially when paired with financial and regulatory incentives that enhance feasibility and appeal for adoption.

In summary, this study identified four distinct configurations that explain high willingness to adopt solar PV in the commercial energy sector. Each configuration reflects a unique strategic combination of environmental, economic, social, ease of use of technology, behavioral, and institutional conditions, demonstrating that adoption decisions are shaped by interdependent and context-specific factors. Notably, perceived environmental benefit consistently emerged as a core condition across all high-adoption pathways, underscoring its central role in driving favorable behavioral intentions. These findings contribute to theory by reinforcing the value of a configurational perspective, which accommodates the complexity and variability inherent in organizational decision-making. They also provide a practical foundation for developing targeted strategies that align with the specific realities of commercial energy contexts.

Beyond its theoretical contributions, this research highlights the methodological strength of fsQCA in uncovering nuanced patterns of causality in adoption behavior. The analysis reveals that diverse psychological drivers, governance-related influences, operational feasibility, and market-based considerations interact asymmetrically and non-linearly, illustrating the principle of equifinality. Accordingly, policy and managerial interventions should move beyond one-size-fits-all approaches. Instead, effective strategies must be tailored to local conditions by leveraging the most relevant combinations of drivers to overcome context-specific barriers and foster the broader adoption of solar technologies.

Importantly, while most prior studies have concentrated on household-level adoption, this study offers novel empirical insights into the commercial context, where solar PV decisions are shaped by strategic, institutional, and operational dynamics unique to business environments.

6. Conclusion

This study enriches the discourse on sustainable energy transitions by offering a configurational lens to understand solar PV adoption in the commercial energy sector. Moving beyond linear and variable-centric approaches, the findings reveal that adoption readiness stems from diverse, context-dependent pathways, each shaped by mutually reinforcing environmental, economic, social, behavioral, and institutional elements. This highlights the need for more holistic and context-sensitive approaches to analyzing and supporting organizational decision-making in clean energy transitions.

Among the various drivers, perceived environmental benefits emerged consistently as a core condition across all high-adoption configurations. Rather than functioning solely as a reflection of pro-environmental values, it serves as a strategic catalyst, especially when integrated with institutional legitimacy and financial feasibility. These insights contribute to behavioral theory by extending models such as the Theory of Planned Behavior and offer valuable guidance for crafting targeted policies and business strategies that resonate with the complex realities of commercial adoption contexts.

Furthermore, by focusing on the commercial energy sector, this study also adds a contextual depth often overlooked in the predominantly household-centered adoption literature, broadening the theoretical and practical relevance of solar PV adoption research.

7. Limitations and Suggestions for Future Research

This study highlights the strength of fsQCA in revealing complex, context-specific pathways to solar PV adoption. While this method effectively captures configurational causality, it does not indicate the direction or statistical strength of individual relationships, which limits its ability to support broader generalizations. Additionally, the cross-sectional nature of the data offers only a snapshot in time, without accounting for how adoption drivers may evolve. These limitations point to important opportunities for future research, particularly the use of longitudinal as well as mixed-method approaches to capture temporal dynamics, compare adoption patterns across sectors, and integrate structural factors such as infrastructure, market maturity, and regulatory frameworks, especially within the context of emerging markets.

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