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Interrelationships Among Stakeholder-Perceived Factors Influencing Solar PV Adoption in Passive Houses in New Zealand

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ABSTRACT

The adoption of solar photovoltaic systems (SPVS) in passive houses (PHs) is shaped by technical, economic and policy-related factors. Yet, the interactions among these factors have not been quantitatively modelled in the New Zealand context. Addressing this gap is critical to advancing Sustainable Development Goal 7 (Affordable and Clean Energy), particularly as SPVS integration in New Zealand PHs remains limited. Building on previous studies that identified adoption factors, this study applies Partial Least Squares Structural Equation Modelling (PLS-SEM) to survey data from 96 stakeholders in the building and energy sectors to examine the structural relationships influencing perceived SPVS–PH adoption. Results are reported using standardised path coefficients (β) and explained variance (R^2). Sustainability benefits (β = 0.372) and design synergy (β = 0.290) were the strongest drivers ($R^2 = 0.461$). Economic barriers (β = 0.460) and design/technological limitations (β = 0.333) were the dominant constraints ($R^2 = 0.332$). Integrated design and technical solutions (β = 0.501) and enabling policy and incentives (β = 0.199) were the strongest strategy factors ($R^2 = 0.487$). This study provides an empirically tested structural model of SPVS–PH adoption in New Zealand and offers evidence-based guidance for policy and design practice.

1 | Introduction

Decarbonising the residential sector is widely recognised as essential to meeting national and global climate commitments, with buildings accounting for a significant share of energy-related greenhouse gas emissions worldwide (Ahmed Ali et al. 2020; Prasad et al. 2021). Achieving meaningful emissions reductions in housing requires not only improvements in energy efficiency but also the wider integration of renewable generation, both of which are central to Sustainable Development Goals 7 (Affordable and Clean Energy) and 13 (Climate Action) (United Nations 2024).

Passive houses (PHs) represent one of the most rigorous pathways to low-energy residential design, achieving substantial reductions in operational demand through high-performance envelopes, airtight construction and mechanical heat-recovery ventilation (PHI 2024). This reduced demand profile creates a natural platform for solar photovoltaic systems (SPVS), which can further enhance energy autonomy, reduce grid dependence, and strengthen the environmental credentials of high-performance homes (Lou and Hsieh 2024; Wu and Skye 2021). Despite this technical complementarity, SPVS integration within PH projects remains limited in New Zealand, where uptake continues to be shaped by cost considerations, design choices and policy support (Nkado et al. 2026; PHINZ 2018).

Previous studies have identified a broad range of factors associated with SPVS and PH uptake, including sustainability benefits (Aigwi et al. 2024; Besen et al. 2017), energy resilience (Nkado et al. 2025), technical compatibility, economic uncertainty (McIntyre et al. 2025), and policy support (Cielo and Subiantoro 2021). Moreover, Nkado et al. (2026) extended this evidence in the New Zealand context by identifying and prioritising stakeholder-perceived drivers, barriers, and strategies for SPVS–PH adoption using interviews and survey data. However, while that study established the relative importance of individual factors, it did not examine how these factors interact structurally or which factor domains exert the strongest influence when considered simultaneously. As a result, an important empirical gap remains in understanding the structural relationships among stakeholder-perceived factors that shape SPVS–PH adoption in New Zealand.

Addressing this gap requires an analytical approach capable of modelling complex interrelationships among latent constructs. Partial Least Squares Structural Equation Modelling (PLS-SEM) is suitable for this purpose because it enables the simultaneous assessment of measurement quality and structural relationships among multiple constructs, while accommodating exploratory and prediction-oriented modelling in contexts characterised by relatively small samples and perception-based data (Asif et al. 2023; Hair et al. 2021c). Moreover, rather than treating adoption-related factors as isolated variables, PLS-SEM enables examination of how broader domains of stakeholder perception interact within an integrated explanatory framework.

Accordingly, this study investigates the interrelationships among stakeholder-perceived factors influencing SPVS adoption in PHs in New Zealand. Specifically, the study aims to: (1) validate the latent structure of the identified influencing factors, and (2) test the extent to which these constructs influence the perceived SPVS–PH adoption. The novelty of the study lies in its use of PLS-SEM to quantitatively test stakeholder-perceived relationships among SPVS–PH adoption factors in the New Zealand context, where previous research has mainly identified relevant factors descriptively rather than modelling their structural influence. To achieve these aims, three hypotheses are tested: (H1) stakeholder-perceived drivers, including sustainability benefits, design synergy, and energy autonomy and resilience, positively influence the perceived SPVS–PH adoption; (H2) stakeholder-perceived barriers, including economic barriers, design and technological limitations, and policy and market limitations, negatively influence the perceived SPVS–PH adoption; and (H3) enabling strategies, including integrated design and technical solutions, enabling policy and incentives, and education and capacity-building, positively influence the perceived SPVS–PH adoption. This study offers a more integrated explanation of perceived adoption dynamics in a high-performance housing context and provides evidence to inform policy, design practice and wider low-carbon housing transitions.

The remainder of the article is organised as follows. Section 2 reviews the relevant literature. Section 3 presents the research framework and hypotheses. Section 4 outlines the materials and methods, including instrument design and PLS-SEM procedures. Section 5 presents the results and discussion. Section 6 presents the propose conceptual framework. Finally, Section 7 concludes the article.

2 | Literature Review

2.1 | Influencing Factors Shaping the Perceived SPVS–PH Adoption

The adoption of SPVS in PHs is increasingly understood as a socio-technical decision process rather than a purely technical outcome. Although SPVS can complement PHs by reducing grid dependence, improving environmental performance, and supporting household energy resilience, adoption depends on stakeholders' perceptions of the value, feasibility and risks of integration (Nkado et al. 2026; Qin et al. 2022). Such perceptions matter because stakeholders, including homeowners, designers, builders, policymakers and energy professionals, collectively determine whether SPVS is considered early in the design process or treated as an optional add-on.

Among the factors supporting adoption, sustainability benefits remain central. Previous studies have linked SPVS and low-energy housing to reduced electricity expenditure, lower operational emissions and long-term financial returns (Hafez et al. 2023; Reddy et al. 2024). In the PH context, these benefits may be particularly influential because PHs already reduce heating and cooling demand, allowing SPVS to supply a greater proportion of remaining household energy needs (Jack and Konings 2024; Schwartz and Krarti 2023). Sustainability benefits, therefore, reflect a broader stakeholder judgement about whether SPVS–PH integration provides credible long-term value through lower emissions, reduced energy costs, and stronger alignment with low-carbon housing expectations (Nkado et al. 2026).

Design synergy is another important domain of adoption. PHs reduce operational energy demand through high-performance envelopes, airtightness and controlled ventilation, creating an opportunity to size SPVSs more efficiently when solar access and energy modelling are considered early in the design stage (Magrini et al. 2020; Schwartz and Krarti 2023). Design synergy, therefore, represents more than technical compatibility; it reflects stakeholders' perceptions that SPVS and PH principles can be optimised within a single performance strategy, making SPVS appear less like an additional technology and more like a logical extension of PH design (Nkado et al. 2026).

Energy autonomy and resilience also influence adoption. For example, households may value decentralised energy systems because they reduce dependence on centralised supply, improve control over energy use, and provide protection against price volatility or service disruption (Kotani and Nakano 2023; Wolske et al. 2017). However, the strength of this driver depends on whether stakeholders perceive backup capability, off-grid potential, and exported electricity as practically and financially meaningful in their local electricity market. Moreover, where buy-back rates are low or a seasonal mismatch is significant, resilience benefits may be recognised but still ranked below financial and design considerations (Cielo and Subiantoro 2021; McIntyre et al. 2025).

Despite these drivers, several barriers to adoption remain. Economic barriers are frequently reported, including high upfront costs, long payback periods, limited incentives, and low export tariffs (Cielo and Subiantoro 2021). These barriers are especially relevant in PH projects because high-performance construction already requires additional investment, which may defer SPVS when budgets are constrained (Brougham-Romney 2022; Nkado et al. 2026). Policy and market limitations further affect adoption, where incentives, export rules, and regulatory requirements are unclear or insufficient (Cielo and Subiantoro 2021). Design and technological limitations, including roof space, shading, seasonal mismatch, and system sizing, also shape perceived feasibility, particularly when SPVS is not considered during early design stages (Bošnjaković and Santa 2025; Jack and Konings 2024). These constraints can interact with economic and policy barriers rather than operate independently.

Conversely, enabling conditions can reduce uncertainty and strengthen confidence in adoption. For example, policy incentives, subsidies, grants, and dynamic pricing can improve the financial case for integration (Cielo and Subiantoro 2021; McIntyre et al. 2025). Furthermore, integrated design and technical solutions, including early energy modelling, battery readiness, and optimised installation, can address performance and usability concerns (Javeed et al. 2021; Magrini et al. 2020). Similarly, education, capacity-building, and collaboration are also important because they improve stakeholder understanding, reduce uncertainty, and support better decision-making across design, construction and operation (Palm and Lantz 2020; Scheller et al. 2021).

2.2 | Research Gap and Rationale for Modelling Interrelationships

Although existing research has identified several factors influencing SPVS–PH adoption, much of the evidence remains organised around separate lists of drivers, barriers and strategies rather than tested structural relationships. A study by Nkado et al. (2026) advanced this evidence in the New Zealand context by identifying and prioritising stakeholder-perceived factors through document analysis, 34 semi-structured interviews, and a survey of 96 stakeholders in the building and energy sectors. However, while that study established the relative importance of individual factors, it did not model the structural relationships among them. It therefore remains unclear whether sustainability benefits, design synergy, economic barriers, technological limitations, and enabling strategies operate independently, or whether some domains exert stronger predictive influence on perceived adoption than others when considered simultaneously.

This gap provides the rationale for applying Partial Least Squares Structural Equation Modelling (PLS-SEM). PLS-SEM is appropriate where the objective is to examine relationships among latent constructs and estimate the relative strength of multiple pathways within a single model (Abuzaid et al. 2024; Sarstedt et al. 2022). It is also well-suited to adoption studies, in which stakeholder perceptions are measured using multiple observed indicators that collectively represent broader constructs (Asif et al. 2023; Song et al. 2025). Accordingly, the present study extends prior factor-identification research by modelling the interrelationships among stakeholder-perceived domains that shape SPVS–PH adoption in New Zealand, moving beyond ranking factors to explain which domains exert the strongest structural influence on adoption.

3 | Research Framework and Hypotheses

Developing a structured research framework is crucial for advancing understanding in emerging areas, such as the integration of SPVS into high-performance buildings, such as PHs (Olawumi and Chan 2021). The proposed framework is theoretically grounded in the Diffusion of Innovations (DOI) framework, which analyses the uptake of innovations. Because SPVS integration within PHs represents a socio-technical innovation in the building sector, it aligns with built-environment studies that examine adoption through three core dimensions: drivers, barriers, and promotion strategies (Qin et al. 2022). Applying this driver–barrier–strategy logic to the SPVS–PH context, uptake can be understood as depending on stakeholders' perceptions of the innovation's benefits, compatibility, complexity, and enabling conditions. Within this logic, drivers represent perceived advantages and compatibility conditions that can motivate adoption; barriers represent perceived complexity, uncertainty, and constraints that can discourage adoption; and strategies represent enabling mechanisms that can reduce uncertainty and improve implementation feasibility. This theoretical framing aligns with adoption studies showing that renewable-energy and sustainable-building decisions are shaped by the interaction of perceived benefits, perceived constraints, technical compatibility and institutional support (Oliva and Atehortua Santamaria 2025). Therefore, the structural model is theory-informed and tests how stakeholder-perceived innovation attributes and enabling conditions are associated with Perceived SPVS–PH adoption.

The identified factors were organised into three higher-order explanatory domains: drivers, barriers, and strategies. These domains were then specified as latent constructs for PLS-SEM analysis. Moreover, because this study examines stakeholder perceptions, these constructs are treated as latent perception dimensions reflected by their measurement indicators, rather than as formative indices composed of independent causal components (Hair et al. 2020; Benitez et al. 2020; Sarstedt et al. 2022).

The drivers' category comprises sustainability benefits (SBT), design synergy (DSG) and energy autonomy and resilience (EAR). The barriers category consists of policy and market limitations (PML), design and technological limitations (DTL), and economic barriers (ECB). Then, the strategies domain includes enabling policy and incentives (EPI), integrated design and technical solutions (ITS), and education, capacity-building, and collaboration (ECS). The perceived SPVS–PH adoption (SPA) is specified as the dependent construct.

In this study, SPA refers to perceived SPVS–PH Adoption rather than actual adoption behaviour. It captures stakeholders' perceptions of adoption-supportive conditions, including policy alignment, future-readiness, technical feasibility, long-term value, environmental contributions and perceived implementation constraints. Therefore, SPA is interpreted as a perception-based adoption outcome construct rather than as direct evidence of household installation decisions. The resulting proposed model (see Figure 1) posits that uptake does not stem from single variables in isolation, but emerges from the interaction among multiple stakeholder-perceived factors (Scheller et al. 2021). To investigate this interaction, the study employs a logically structured

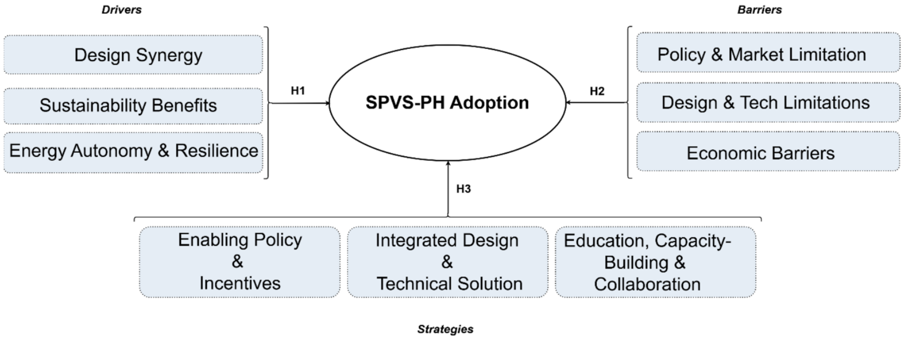

FIGURE 1 | Hypothetical model of factors influencing SPVS-PH adoption.

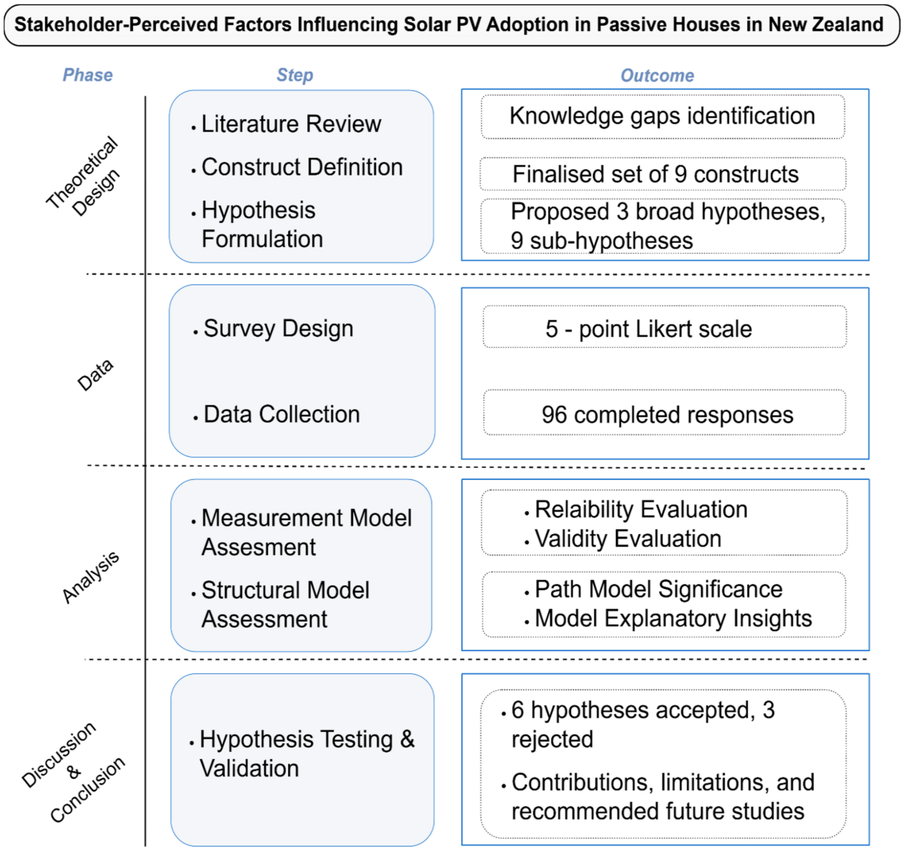

FIGURE 2 | Steps involved in conducting research.

approach, drawing exclusively on empirical constructs from a survey to capture and analyse the drivers, barriers and proposed strategies.

Based on this framework, the structural model tests three key hypotheses:

H1. *Drivers ('Design synergy', 'Sustainability benefits', 'Energy autonomy & resilience') have a significant positive influence on SPVS-PH adoption.*

H2. *Barriers ('Policy & market limitations', 'Design & technological limitations', 'Economic barriers') have a significant negative influence on SPVS-PH adoption.*

H3. *Strategies ('Enabling policy & incentives', 'Integrated design & technical solution', 'Education, capacity-building & collaboration') have a significant positive influence on SPVS-PH adoption.*

4 | Materials and Methods

This study adopts a quantitative modelling approach to examine the interrelationships among stakeholder-perceived factors influencing the perceived SPVS–PH adoption in New Zealand. The methodological design was structured to support the specification and testing of latent constructs that represent the principal explanatory domains of the proposed framework. Ethical approval was obtained from the Research Ethics Committee of [Auckland University of Technology, New Zealand] (Approval number: [25/210]). Figure 2 summarises the main stages of the research process.

4.1 | Survey Instrument and Data Collection

Data were collected using a structured survey administered to participants with relevant experience in New Zealand's building and energy sectors. The survey was designed to capture stakeholder perceptions of the factors influencing SPVS adoption in PHs and was organised into two sections. The first section gathered demographic and professional background information, including participants' industry role, organisation type and size, years of experience, and prior involvement in SPVS or PH projects. The second section measured perceptions relating to the study constructs, grouped into three higher-level domains: drivers, barriers, and strategies for improving SPVS–PH integration (see Table 1). Each item was assessed on a five-point Likert scale ranging from 1 ('Strongly disagree') to 5 ('Strongly agree'), a format commonly used for perception-based measurement and supported for data quality in agreement-scale research (Koo and Yang 2025).

To ensure informed responses, eligibility was restricted to participants with at least 3 years of experience in the New Zealand construction or energy sector and who had been involved in at least 1 SPVS or PH project. Because the target population was specialised, non-probability sampling was adopted, combining purposive sampling with snowball recruitment to reach experienced stakeholders across relevant professional groups (Memon et al. 2024; Ting et al. 2025). The survey was developed in Qualtrics and distributed online through email and LinkedIn. The data collection process followed a structured protocol. Invitations were sent individually to targeted professionals identified through industry directories, professional associations (including the New Zealand Green Building Council and Passive House Institute New Zealand networks), and LinkedIn searches using role-specific keywords (e.g., 'passive house designer', 'solar energy consultant', 'building energy engineer'). The recruited participants were subsequently asked to refer additional eligible colleagues through snowball referrals. Each invitation included a participant information sheet explaining the study's purpose, the voluntary nature of participation, and assurances regarding data confidentiality. Responses were collected anonymously, and participants were not identifiable in the dataset. No incentives were provided for participation.

Before the main data collection phase, the instrument was pilot-tested with 10 professionals to assess clarity, survey structure, and completion time. Feedback from the pilot informed refinement of wording and layout before full deployment (Kalkbrenner 2021; Ulpiani et al. 2025). The final survey was administered between 18 August and 10 October 2025. A total of 98 submissions were received, of which two were excluded because the respondents reported no experience with PHs, low-energy buildings, or SPVS. This resulted in a final sample of 96 valid responses for analysis. Given the specialist nature of the respondent pool, this sample size was considered adequate for the planned PLS-SEM analysis (Holtom et al. 2022).

The final sample reflected a broad cross-section of stakeholders from engineering, architecture, construction, energy consultancy, and sustainability-related practice in New Zealand. The respondents were generally highly experienced, with 46% reporting over 15 years of industry experience and 33% reporting between 6 and 15 years. The participants were drawn from organisations of varying sizes, with smaller firms constituting the largest share of the sample. Figure 3 presents a summary of the participant profile.

4.2 | Data Analysis

To investigate the drivers, barriers, and strategies to SPVS-PH adoption, a quantitative modelling approach is employed to test how these constructs influence one another within a broader adoption framework. Specifically, SEM is selected due to its ability to simultaneously test measurement models and hypothesised paths within a unified model structure (Hair et al. 2021b). It has become increasingly relevant to studies of energy transitions and sustainable building systems, offering a systematic approach for evaluating complex interdependencies among multiple constructs (Asif et al. 2023; Kineber et al. 2023).

For this study, SEM is preferred over regression analysis because it allows a more integrated and comprehensive assessment of direct and indirect effects among latent variables. Although regression techniques can be used to test individual hypotheses, SEM offers additional value by accounting for measurement error and enabling a comprehensive evaluation of model fit. Accordingly, PLS-SEM is used in SmartPLS 4.1.1.4 software to validate the measurement instruments and assess the hypothesised relationships.

SEM can be approached using either covariance-based methods (CB-SEM) or variance-based methods, such as PLS-SEM. In contrast to CB-SEM, PLS-SEM is better suited for exploratory research, smaller sample sizes, and non-normal data distributions (Sarstedt et al. 2022). These characteristics make it particularly appropriate for this study. SEM models include two types of variables: indicators (directly measured survey items) and latent variables (unobserved constructs inferred from indicators). The general rule for sample size in PLS-SEM is that it should be at least 10 times the maximum number of structural paths directed at any endogenous construct, or 10 times the largest number of indicators used to measure a construct, depending on the model specification (Hair et al. 2021a; Sarstedt et al. 2022). This rule is commonly used as a minimum heuristic in PLS-SEM studies, particularly where the research is prediction-oriented and based on specialised stakeholder samples (Hair et al. 2021c). In this study, the structural analysis was organised into three domain-specific PLS-SEM models covering drivers, barriers, and strategies. In each model, the maximum number of structural paths directed at the endogenous construct, Perceived SPVS–PH Adoption, was three. Applying the 10-times rule yields a minimum sample size of 30 responses ($3 \times 10 = 30$). The final sample of 96 valid responses, therefore, exceeded this minimum requirement.

The measurement model specifies how observed variables represent latent constructs. The constructs in this study were specified as reflective because the indicators were conceptualised as manifestations of broader stakeholder-perceived latent variables rather than as independent components forming an index. In reflective measurement, the direction of explanation

TABLE 1 | The measurement items with their constructs.

	Measurement indicators	Code
Drivers category/Construct		
Design synergy (DSG)	PH efficiency enables smaller, cost-effective SPVS installations.	DGS1
	SPVS and PH design compatibility simplifies integration decisions.	DSG2
Sustainability benefits (SBT)	The declining cost of SPVS makes adoption in PHs more financially feasible	SBT1
	Reducing electricity bills is a key motivation for integrating SPVS in PHs	SBT2
	SPVS integration delivers long-term financial returns for homeowners.	SBT3
	Combining SPVS with PH buildings is an effective way to demonstrate a commitment to sustainability.	SBT4
	SPVS increases the market value and desirability of PHs.	SBT5
Energy autonomy & resilience (EAR)	SPVS integration reduces dependence on the national electricity grid.	EAR1
	The potential for off-grid and backup power drives SPVS adoption.	EAR2
	SPVS improves PH resilience to extreme weather.	EAR3
	Exporting surplus solar electricity motivates the adoption of SPVS.	EAR4
Barriers category/Construct		
Design-technological limitations (DTL)	Embodied versus operational carbon trade-offs complicate SPVS–PH design.	DTL1
	Seasonal mismatch between solar generation and heating demand.	DTL2
	Limited roof space and shading constrain the installation of urban SPVS.	DTL3
	Lack of load-shifting enablers reduces SPVS value.	DTL4
	Equipment lifespan and reliability concerns deter SPVS adoption.	DTL5
	Fabric-first focus delays early SPVS consideration.	DTL6
Economic barriers (ECB)	Low buy-back rates reduce the appeal of SPVS installation.	ECB1
	Short occupancy periods discourage long-term SPVS investment.	ECB2
	Lack of financial incentives reduces SPVS's attractiveness.	ECB3
	High PH construction costs limit SPVS adoption.	ECB4
	Long payback periods discourage SPVS investment in PHs.	ECB5
	High SPVS equipment and installation costs remain barriers.	ECB6
Policy & market limitations (PML)	Limits on exporting solar electricity to the grid discourage investment in SPVS for PHs.	PML1
	The perception that New Zealand's electricity grid is already mostly renewable reduces interest in installing SPVS in PHs.	PML2
	Concerns about the visual impact of solar panels affect SPVS adoption in PHs.	PML3
	Reluctance among some clients (e.g., homeowners/developers) to adopt SPVS reduces uptake of SPVS in PHs.	PML4
Strategies category/Construct		
Enabling policy & incentive (EPI)	Government incentives increase SPVS adoption in PHs.	EPI1
	Targeted subsidies and grants encourage SPVS–PH integration.	EPI2
	Time-of-use pricing and batteries increase the value of SPVS.	EPI3
Integrated design & technical solutions (ITS)	Advanced battery management increases SPVS value	ITS1
	Building-integrated PV improves aesthetics and reduces installation costs.	ITS2
	Batteries enhance household resilience and grid support.	ITS3
	Early energy modelling supports optimal sizing of SPVS systems.	ITS4
	Purpose-specific SPVS technologies reduce system size and costs.	ITS5
	Non-battery SPVS primarily support the grid rather than resilience.	ITS6
Education, capacity-building & collaborative strategy (ECS)	Flexible SPVS mounting addresses site and roof constraints	ECS1
	Early communication of SPVS value shifts client budget priorities	ECS2
	Training complements fabric-first approaches for integrated SPVS design	ECS3
	Whole-life carbon tools optimise embodied–operational carbon trade-offs	ECS4
	Alternative storage reduces reliance on dedicated batteries and SPVS costs	ECS5
Percieved SPVS-PH adoption (SPA)		
	Mandating SPVS-ready building features supports future adoption.	SPA1
	Aligning PH standards with renewable energy policies.	SPA2
	Framing SPVS as resilience and long-term value encourages adoption.	SPA3
	Optimised SPVS design and installation maximise performance.	SPA4
	SPVS–PH integration supports New Zealand's low-emissions energy transition.	SPA5
	The technical complexity of integrating SPVS into PHs (e.g., roof angle, space, wiring/conduit) often hinders SPVS adoption in PHs.	SPA6
	Budget constraints prioritise other construction needs over SPVS.	SPA7
	SPVS improves the environmental performance of PHs.	SPA8

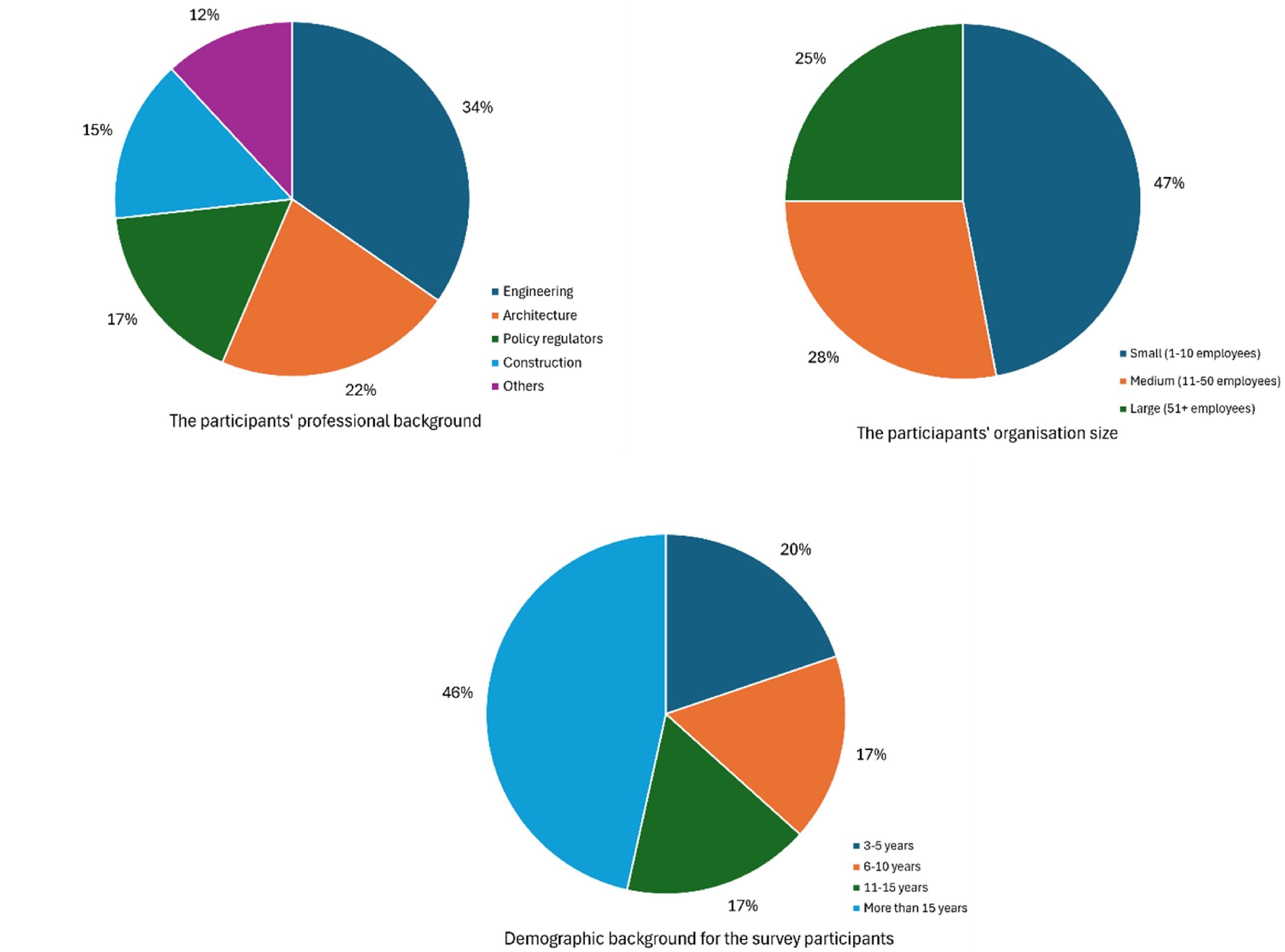

FIGURE 3 | Demography of the participants.

runs from the latent construct to its observed indicators; therefore, respondents with stronger perceptions of a construct are expected to show higher agreement across its related indicators (Hair et al. 2020). In contrast, formative measurement is more appropriate when indicators represent distinct components that combine to form the construct and are not necessarily interchangeable (Sarstedt et al. 2022). Because this study examines perception-based latent dimensions, the indicators were treated as reflective manifestations of their respective constructs. Based on this logic, reflective measurement assessment procedures, including indicator loadings, internal consistency reliability, convergent validity, and discriminant validity, were applied (Hair et al. 2021c; Sarstedt et al. 2022).

Table 1 shows the measurement items and associated constructs used to develop both the measurement and structural models in this study. All indicators were tested for reliability and validity before proceeding to the structural model evaluation. This step is critical to ensure the soundness of the latent constructs and to enable meaningful interpretation of hypothesised relationships within the full model.

4.2.1 | Evaluation of Measurement Model

4.2.1.1 | Internal Consistency Reliability Evaluation. Reliability refers to the extent to which a multi-item scale consistently measures its intended construct, accounting for measurement error (Hair et al. 2020). To evaluate this, Cronbach's alpha and Composite reliability were calculated for each construct in the model. While both indicators offer insight into internal consistency (Hair et al. 2020), Composite reliability values above 0.7 are considered acceptable (Sarstedt et al. 2019). Moreover, Cronbach's Alpha values ranging from 0.6 to 0.8 also indicate adequate reliability (Hair et al. 2020). After establishing reliability, the next step is to assess construct validity, including convergent and discriminant validity.

4.2.1.2 | Convergent Validity Evaluation. Convergent validity evaluates the extent to which the indicators of a construct share a high proportion of variance. This is assessed using factor loadings and Average Variance Extracted (AVE). Ideally, each indicator should load at 0.5 or higher on its construct (Asif et al. 2023). AVE values should also be at least 0.5 to reflect acceptable shared variance among indicators (Hair et al. 2020). When AVE is slightly below the threshold, but composite reliability exceeds 0.6, validity is considered adequate (Sarstedt et al. 2019). Any indicator with a loading below 0.5 was considered for removal, and the analysis was repeated after removal. This iterative process was used to improve measurement quality while ensuring that the retained indicators continued to preserve the conceptual meaning of their respective constructs. Following model re-estimation, the retained indicators yielded acceptable reliability and validity (Hair et al. 2020).

4.2.1.3 | Discriminant Validity Evaluation. Discriminant validity checks whether constructs are empirically distinct. Two approaches were used, including the Fornell–Larcker criterion and cross-loadings. For the Fornell–Larcker test, each construct's AVE should be greater than its squared correlation with any other construct (Rasoolimanesh 2022). Cross-loadings were also examined to ensure that each indicator loaded highest on its corresponding construct rather than on unrelated constructs (Rönkkö and Cho 2022).

4.2.1.4 | Common Method Bias Assessment. Common method bias (CMB) was assessed to determine whether the observed relationships were inflated by the measurement method (Kock et al. 2021). Procedurally, CMB was reduced through pilot testing, clear survey wording, respondent anonymity, and item grouping by construct, in line with recommended procedural remedies for survey-based research (Kock et al. 2021; Podsakoff et al. 2024). Statistically, CMB was assessed using the full collinearity variance inflation factor (VIF) approach. The inner model VIF values for the driver, barrier, and strategy models ranged from 1.260 to 1.696, which are below the commonly used 3.3 threshold for full collinearity (Kock et al. 2021). This indicates that collinearity among the predictor constructs was not a concern and suggests that common method bias was not a serious threat to the interpretation of the PLS-SEM results. The detailed VIF results are presented in Table D1.

4.2.2 | Evaluation of Structural Model

4.2.2.1 | Path Coefficient Significance Evaluation. The path coefficients in the structural model represent the hypothesised relationships between constructs and are analogous to standardised regression weights (Hair et al. 2020). A larger coefficient indicates a greater effect of the independent variable on the dependent variable (Sarstedt et al. 2021). For interpretation, coefficients ranging from 0.1 to 0.3 are considered weak, 0.3 to 0.5 moderate, and 0.5 to 1.0 strong (Pereira et al. 2024). Following validation of the measurement models, the next step is to test the significance of these paths to evaluate the study's hypotheses. This is assessed using bootstrapping, a robust resampling method for estimating statistical significance without relying on distributional assumptions (Hair et al. 2021a). To generate reliable results, the analysis employed 5000 bootstrap subsamples, consistent with best-practice recommendations (Hair et al. 2021c). The significance of paths is assessed using two-tailed critical *t*-values. The *t*-values for a two-tailed test are interpreted using conventional cut-offs: 1.65 (10%), 1.96 (5%), and 2.58 (1%) (Hair et al. 2021c).

4.2.2.2 | Effect Size and Predictive Relevance Evaluation. In addition to path coefficients, *t*-statistics, and *p* values, the structural model was assessed using f^2 effect sizes and Q^2 predict values. The f^2 effect size was used to assess the relative contribution of each predictor construct, while Q^2 predict was used to assess the predictive relevance of each model for Perceived SPVS–PH Adoption.

5 | Results and Discussion

This section presents and discusses the findings on the interrelationships among key constructs influencing the perceived SPVS–PH adoption in New Zealand.

5.1 | SPVS-PH Adoption Drivers

5.1.1 | Measurement Model Results

For the SPVS-PH drivers, Table 2 presents the results of the measurement models. The factor loadings of the observable variables SBT5, EAR3, SPA4, SPA6, SPA7 and SPA8 with values of 0.5 or less were excluded from the list (Table 2), and the analysis was rerun. This study utilises reflective observable variables, as the constructs dictate the items; thus, the arrow in Figure 4 points from the constructs to the observable variables. Reflective observable variables exhibit high correlation and interchangeability,

TABLE 2 | Measurement model analysis for SPVS-PH drivers.

Drivers category/ Construct	Survey item code	Factor loading	Cronbach's alpha coefficient	Composite reliability	AVE
DSG	DGS1	0.854	0.730	0.879	0.785
	DSG2	0.917			
SBT	SBT1	0.627	0.686	0.806	0.513
	SBT2	0.784			
	SBT3	0.640			
	SBT4	0.796			
EAR	EAR1	0.694	0.667	0.809	0.587
	EAR2	0.841			
	EAR4	0.757			
SPA	SPA1	0.726	0.638	0.782	0.475
	SPA2	0.830			
	SPA3	0.672			
	SPA5	0.735			

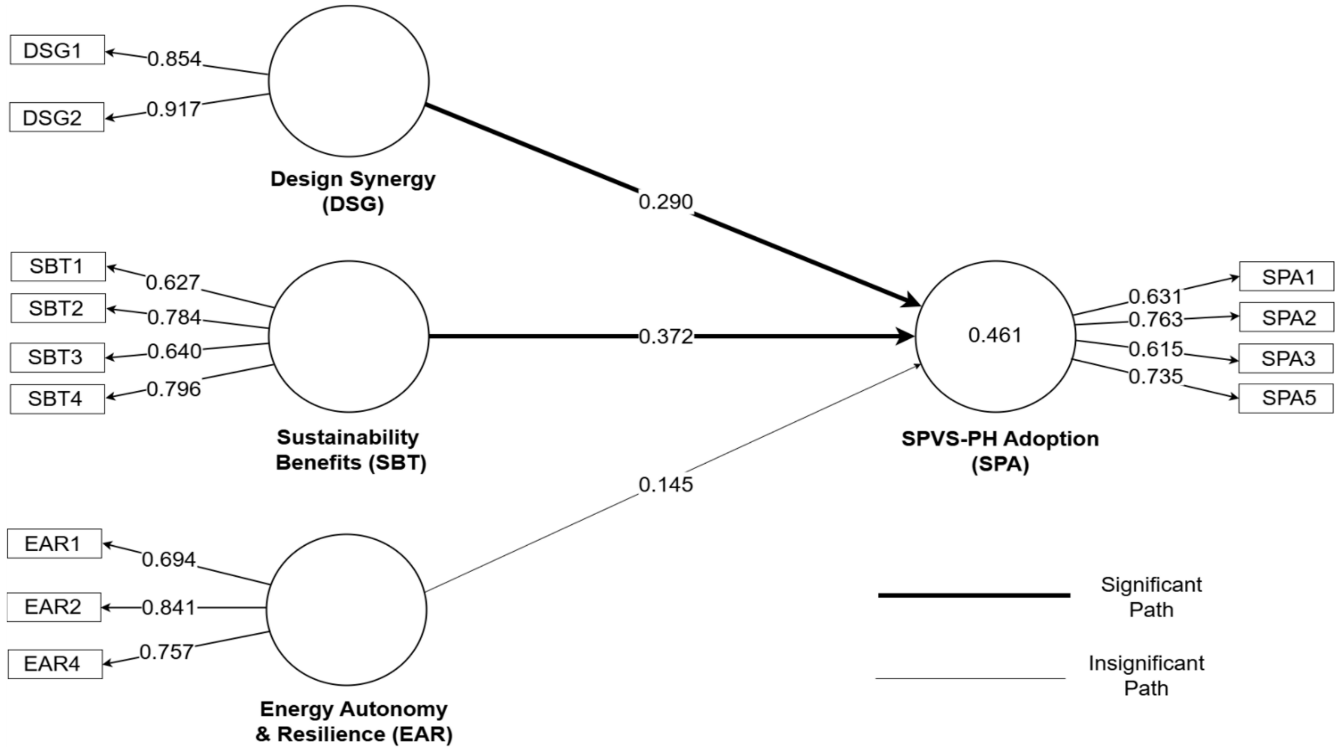

FIGURE 4 | SEM of drivers for SPVS-PH adoption.

and some can be disregarded without affecting the construct's meaning (Sarstedt et al. 2021).

The measurement model in Table 2 indicates that all construct alphas exceeded 0.60. The composite reliability scores for all constructs exceeded 0.70, indicating satisfactory internal consistency. Convergent validity of the constructs was established, as evidenced by AVEs exceeding 0.5, except for the SPA construct, which had an AVE of 0.475 in the final model. When the AVE exceeds 0.5, it indicates that the construct accounts for more than 50% of the variance in its observable variables.

Furthermore, discriminant validity among the constructs was demonstrated, as none of the correlations between any two constructs exceeded the square roots of their respective AVEs (see Table A1; the bold diagonal values represent the square roots of the AVEs for each construct). The analysis of cross-loadings among observable variables provided further evidence of discriminant validity (see Table A2). In line with discriminant validity requirements, the indicators loaded more strongly on their respective constructs than on other constructs. For instance, items DSG 1 and DSG 2 loaded highest on the DSG construct, with loadings of 0.854 and 0.917, respectively. Similarly, the three energy autonomy and resilience driver items, EAR1–EAR4, showed the highest loadings (0.694–0.841) under the EAR construct, and SBT1–SBT4 showed a strong association (0.627–0.796) with SBT. The three SPVS-PH adoption indicators (SPA1, SPA2, SPA3, SPA5) also loaded strongly (0.615–0.736) onto their respective constructs. These results show that each indicator exhibited the highest loading on its assigned construct, thus supporting discriminant validity within the measurement model.

TABLE 3 | Structural model evaluation for SPVS-PH drivers.

	Path coefficient	*T* statistics	*p*	Interpretation
DSG → SPA	0.290	2.762	0.006	Supported
EAR → SPA	0.145	1.437	0.156	Not supported
SBT → SPA	0.372	3.173	0.002	Supported

5.1.2 | Structural Model Results

Table 3 presents the results for the structural model assessing the drivers of SPVS adoption in PHs. The final structural equation model depicting the influence of each driver construct on the SPA construct is shown in Figure 4. The findings from the structural model analysis indicate partial support for the hypothesised relationships.

The path from DSG to SPA is positive and statistically significant, with a path coefficient ($\beta = 0.290$) and *t*-statistic ($t = 2.762$) exceeding the t-statistic's critical value of 1.96, supporting the corresponding hypothesis. Similarly, SBT demonstrates a strong, statistically significant influence on perceived SPVS–PH adoption ($\beta = 0.372$, $t = 3.173$).

In contrast, the relationship between EAR and SPA is not statistically supported ($\beta = 0.145$, $t = 1.437$). Although the coefficient is positive, the t-value falls below the 1.96 threshold, indicating insufficient evidence to confirm a direct effect. The determination coefficient (R^2) for the dependent variable 'SPV-PH Adoption' was 0.461, indicating moderate predictive accuracy for the model.

The findings from the structural model analysis indicate that DSG and SBT exert significant direct effects on SPVS adoption in PHs in New Zealand, whereas EAR does not. Among the supported drivers, SBT exhibits the strongest direct path, highlighting the importance of perceived environmental benefits, such as emissions reduction and alignment with low-carbon objectives, in motivating SPVS–PH adoption (Schulte et al. 2022).

Furthermore, the moderate and significant effect of DSG further underlines the role of technical compatibility and integrated design between SPVS and PHs, supporting prior research that emphasises early-stage coordination and system co-optimisation in high-performance and net-zero housing (Nkado et al. 2026).

The significance of DSG should be interpreted in light of the technical requirements and concerns for integrating SPVS with PH design. Although DSG was measured as a stakeholder-perceived construct in this study, the perception is grounded in practical engineering considerations. PH performance depends on minimising heating and cooling demand through high-performance envelopes, airtightness, thermal-bridge control, controlled ventilation, and careful design optimisation (Maghami et al. 2025; PHI 2024). In contrast, SPVS performance depends on solar access, roof orientation, available mounting area, shading control, structural suitability, wiring routes, and compatibility with inverter and battery-ready design (Jack and Konings 2024; Kumar et al. 2025). These requirements can be complementary when considered early in the design process because the reduced energy demand of PHs can support more efficient SPVS sizing and improve the balance between operational energy reduction and on-site renewable generation. However, the relationship is not automatically synergistic; they may also create design tensions where SPVS optimisation is considered separately from PH envelope performance. For instance, roof orientation that maximises PV yield may not always align with passive solar thermal optimisation, while panel mounting, service penetrations, wiring pathways, equipment placement, shading control, and structural loading should be carefully coordinated to avoid compromising airtightness, thermal continuity, envelope durability, or building-integrated design quality. Therefore, the significant positive effect of DSG suggests that stakeholders perceive SPVS–PH adoption as more feasible when PH envelope priorities and SPVS system requirements are co-optimised from the earliest design and feasibility stages.

In contrast, although the direct path from EAR to adoption is positive, it is not statistically supported, suggesting that resilience-related considerations may not independently drive SPVS-PH adoption decisions in this context. Instead, EAR may operate indirectly, reinforcing adoption through its interaction with other constructs, such as DSG or SBT (Wolske et al. 2017).

Furthermore, SBT shows a predominantly direct effect; it is likely to shape stakeholders' perceptions of the overall value proposition of SPVS–PH integration. Accordingly, SPVS–PH adoption drivers should be designed to couple SBT and DSG, as they should operate in parallel, with EAR providing the supporting factor.

5.2 | SPVS-PH Adoption Barriers

5.2.1 | Measurement Model Results

Table 4 and Figure 5 present the results of measurement models for the SPVS-PH barriers. The observed indicators DTL5, DTL6, PML3, PML4, ECB3, ECB5, SPA3, SPA4, SPA5 and SPA8 were excluded from the list because their factor loadings were below 0.5, and the analysis was rerun.

The measurement model in Table 4 shows that all constructs have Cronbach's alpha coefficients greater than 0.60. Moreover, the composite reliability scores for all constructs exceed 0.70, indicating satisfactory internal consistency.

Convergent validity of the constructs was established, as evidenced by AVEs exceeding 0.5, except for the SPA construct,

TABLE 4 | Measurement model analysis for SPVS-PH barriers.

Barriers category/ Construct	Survey item code	Factor loading	Cronbach's alpha coefficient	Composite reliability	AVE
PML	PML1	0.810	0.741	0.876	0.780
	PML2	0.951			
DTL	DTL1	0.694	0.694	0.811	0.517
	DTL2	0.767			
	DTL3	0.705			
	DTL4	0.709			
ECB	ECB1	0.678	0.664	0.815	0.597
	ECB2	0.806			
	ECB4	0.824			
SPA	SPA1	0.520	0.623	0.751	0.434
	SPA2	0.641			
	SPA6	0.720			
	SPA7	0.733			

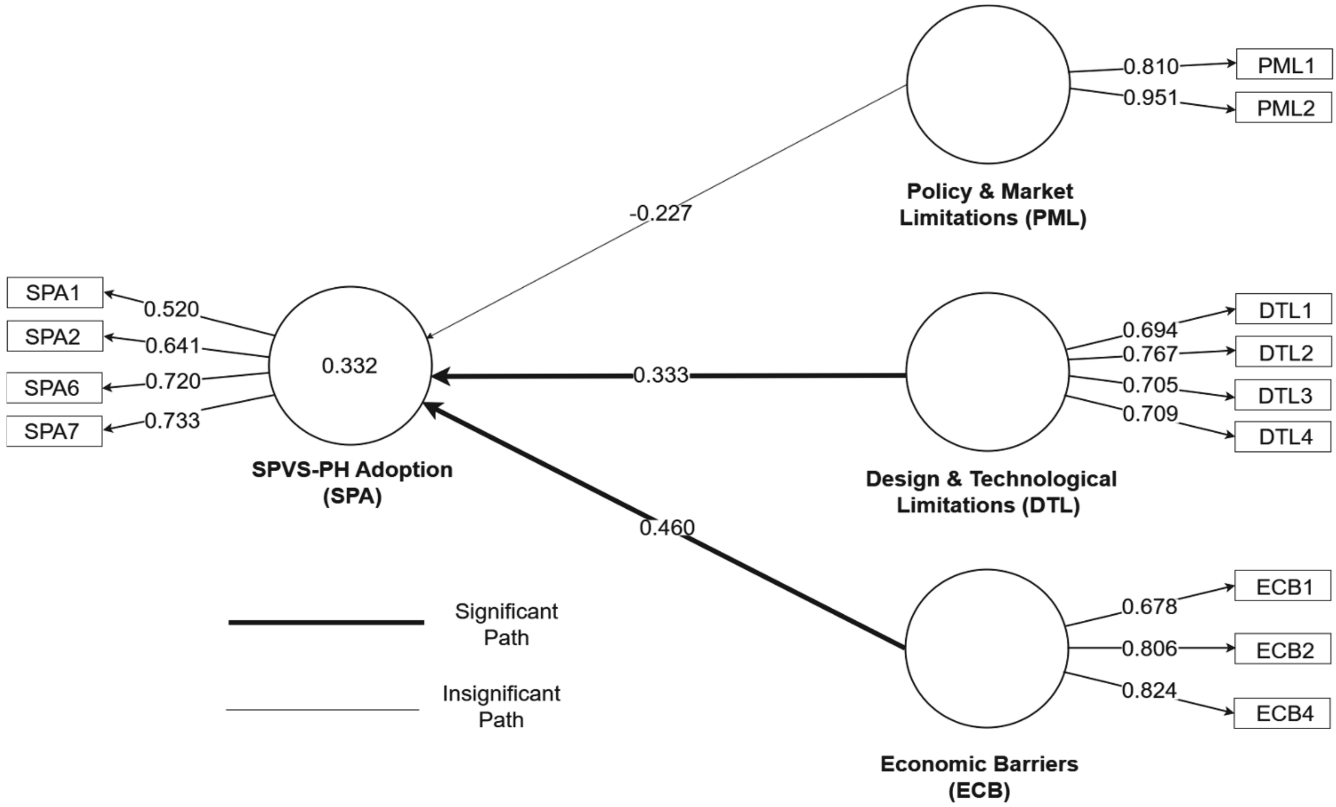

FIGURE 5 | SEM of barriers to SPVS-PH adoption.

which had an AVE of 0.475 in the final model. Additionally, discriminant validity among the constructs was demonstrated, as none of the correlations between any two constructs exceeded the square roots of their respective AVEs (see Table B1; the bold diagonal values represent the square roots of the AVEs for each construct). Moreover, an analysis of the cross-loadings of the observable variables provided further evidence of discriminant validity (see Table B2; the bolded loadings indicate that each indicator loads most strongly on its corresponding construct).

Table B2 presents the cross-loadings of observed items across constructs. In line with discriminant validity requirements, the indicators loaded more strongly on their respective constructs than on other constructs. For instance, items DTL1-DTL4 loaded highest on the DTL construct, with loadings ranging from 0.681 to 0.792. Similarly, the four economic barrier items, ECB1–ECB4, showed the highest loadings (0.584–0.826) under the ECB construct, and PML1 and PML2 showed a strong association (0.891) with PML. The three SPVS-PH adoption indicators (SPA1, SPA2 and SPA6) also loaded strongly (0.657–0.826) onto their respective constructs. These results confirm that each indicator exhibited the highest loading on its assigned construct, thus supporting discriminant validity within the measurement model.

5.2.2 | Structural Model Results

The structural model for SPVS–PH barriers was evaluated to assess the hypothesised relationships among the barrier constructs (see Table 5). As depicted in Figure 5, the completed SEM highlights the influence of each barrier construct on SPVS-PH adoption. The path from DTL to SPA is positive and statistically significant ($\beta = 0.333$, $t = 3.099$), with the t-statistic exceeding the 1.96 critical value. This result shows that DTL exerts a moderate and meaningful influence on SPA. Similarly, the path between ECB and SPA is substantial and statistically significant ($\beta = 0.460$, $t = 3.650$).

TABLE 5 | Structural model evaluation for SPVS-PH barriers.

	Path coefficient	T statistics	p	Interpretation
DTL → SPA	0.333	3.099	0.002	Supported
ECB → SPA	0.460	3.650	0.000	Supported
PML → SPA	−0.227	1.678	0.093	Not supported

In contrast, the path from PML to SPA is not statistically supported ($\beta = -0.227$, $t = 1.678$). Although the coefficient is negative, which suggests a potential inhibitory effect, the relationship does not meet the conventional 5% significance threshold.

The structural model results indicate that economic barriers represent the most influential direct constraint on the perceived SPVS–PH adoption in New Zealand. The strong, statistically significant path from ECB to SPA highlights the continued salience of upfront investment costs, perceived financial risk, and extended payback periods in shaping adoption decisions, even in high-performance housing contexts (Wu et al. 2025). This finding reflects prior studies that identify financial feasibility as a primary barrier to integrating renewable energy in low-energy residential buildings (Mathew and Nagaraja Pandian 2024).

The DTL also exerts a moderate, statistically significant influence on SPVS-PH adoption outcomes. The positive path coefficient suggests that challenges related to system integration complexity and coordination between building envelope design and SPVS installation remain important constraints (Bošnjaković and Santa 2025). Given that PHs prioritise airtightness and envelope optimisation, insufficient early-stage consideration of SPVS integration may amplify these technical challenges, reinforcing the need for coordinated design-stage solutions (Maghami et al. 2025).

In contrast, PML does not exhibit a statistically significant direct effect on SPA. Although the coefficient is negative, the relationship fails to meet conventional significance thresholds, indicating that policy-related factors do not independently deter adoption decisions. Instead, these findings suggest that policy and market conditions may operate indirectly, primarily by shaping the economic environment within which adoption decisions are made (Oliva and Atehortua Santamaria 2025). The determination coefficient (R^2) for the dependent variable was 0.332, indicating the model explains a moderate proportion of the variance in SPV-PH adoption.

5.3 | SPVS-PH Adoption Strategies

5.3.1 | Measurement Model Results

Figure 6 and Table 6 present the results of the measurement models for the SPVS-PH strategies. Indicators ECS4, ITS5, ITS6, SPA1, SPA2, SPA6 and SPA7 were excluded from further analysis due to insufficient factor loadings (≤ 0.5).

The measurement model in Table 6 shows that, aside from the 'ECS' construct, which has a Cronbach's alpha of 0.572, the other constructs' alphas were all above 0.60. The composite reliability scores for all constructs exceeded 0.70, indicating satisfactory internal consistency. Moreover, the constructs exhibited convergent validity, as evidenced by AVEs exceeding 0.5, except for EPI, which has an AVE of 0.487.

Additionally, discriminant validity among the constructs was demonstrated, as none of the correlations between any two constructs exceeded the square roots of their respective AVEs (see Table C1). An analysis of the cross-loadings of the observable variables provided further evidence of discriminant validity. There were no issues with cross-loading, as the observed variables exhibited the highest loadings on their corresponding constructs (see Table C2; the bolded loadings indicate that each indicator loads most strongly on its corresponding construct).

In line with discriminant validity requirements, the indicators loaded more strongly on their respective constructs than on other constructs (see Table C1). For instance, items ECS2, ECS3 and ECS5 loaded highest on the ECS construct, with loadings ranging from 0.550 to 0.759. Similarly, EPI1 – EPI3 showed the highest loadings (0.524 – 0.890) under the EPI construct, and ITS1, ITS3, and ITS4 showed strong loadings (0.512 – 0.827) with the ITS construct. The three SPVS – PH adoption indicators, SPA3, SPA4 and SPA8, also loaded strongly (0.685 – 0.844) onto the SPA construct. These results show that each indicator exhibited the highest loading on its assigned construct, thus supporting discriminant validity within the measurement model.

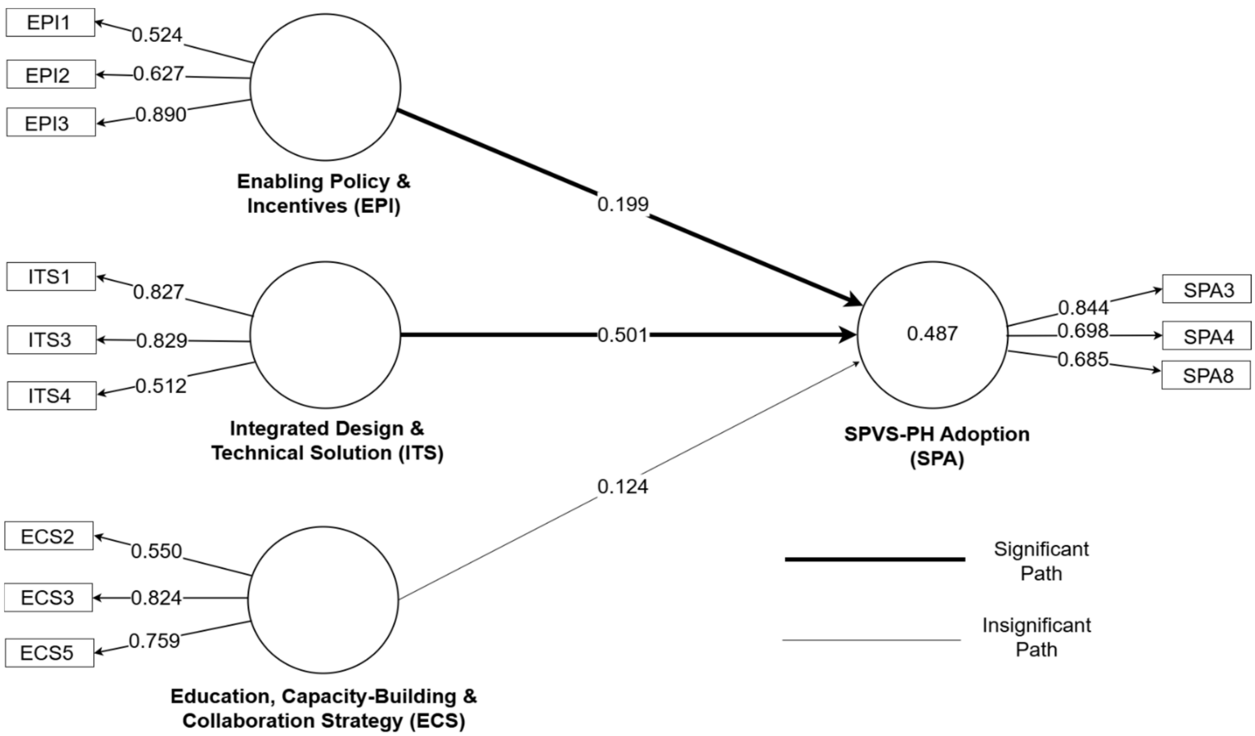

FIGURE 6 | SEM of strategies for SPVS-PH adoption.

TABLE 6 | Measurement model analysis for SPVS-PH strategies.

Strategies category/ Construct	Survey item code	Factor loading	Cronbach's alpha coefficient	Composite reliability	AVE
EPI	EPI1	0.524	0.632	0.730	0.487
	EPI2	0.627			
	EPI3	0.890			
ITS	ITS1	0.827	0.601	0.775	0.544
	ITS3	0.829			
	ITS4	0.512			
ECS	ECS2	0.550	0.572	0.759	0.519
	ECS3	0.824			
	ECS5	0.759			
SPA	SPA3	0.844	0.606	0.788	0.556
	SPA4	0.698			
	SPA8	0.685			

TABLE 7 | Structural model evaluation for SPVS-PH strategies.

	Path coefficient	*T* statistics	*p*	Interpretation
EPI → SPA	0.199	2.263	0.024	Supported
ITS → SPA	0.501	4.717	0.000	Supported
ECS → SPA	0.124	1.421	0.155	Not supported

5.3.2 | Structural Model Results

Table 7 presents the results for the structural model assessing the influence of the proposed strategies constructs on the perceived SPVS-PH Adoption. The final structural equation model illustrates the strength of each pathway to Perceived SPVS-PH Adoption, as shown in Figure 6. The findings from the structural model indicate partial support for the hypothesised relationships.

The path from ITS to SPA is positive and statistically significant, with a path coefficient ($\beta = 0.501$) and t-statistic ($t = 4.717$) exceeding the critical value of 1.96. Similarly, EPI demonstrates a statistically significant relationship with SPA ($\beta = 0.199$, $t = 2.263$), exceeding the 1.96 threshold and supporting the relevant hypothesis.

In contrast, the relationship between ECS and SPA is not statistically significant ($\beta = 0.124$, $t = 1.421$). Although the coefficient is positive, the t-value falls below the required threshold, indicating insufficient evidence to support a direct effect. The determination coefficient (R^2) for the dependent variable was 0.487, indicating the model accounts for a substantial proportion of the variance and demonstrates good explanatory power.

The findings from the structural model analysis indicate that ITS and EPI exert statistically significant direct effects on the adoption of SPVS-PHs in New Zealand, whereas ECS does not. Among the supported strategies, ITS exhibits the strongest direct path, underscoring the pivotal role of early-stage design coordination, system compatibility, and technical preparedness in facilitating SPVS-PH integration. This supports the existing literature, which highlights that well-integrated system design and cross-disciplinary collaboration significantly enhance the feasibility and attractiveness of SPVS deployment in high-performance housing (Javeed et al. 2021; Manikandan et al. 2025). Moreover, energy performance is strongly influenced by system configuration, geometry, and heating/cooling arrangements, particularly in applications such as solar collectors and thermal storage (Mandal et al. 2023; Manna et al. 2023).

Furthermore, the moderate yet significant effect of EPI suggests that policy support and incentive mechanisms, such as subsidies, streamlined consenting procedures, and SPVS-ready regulations, positively influence adoption (McIntyre et al. 2025). However, the smaller effect size compared to ITS implies that EPI's influence may be more impactful when enabling technical integration rather than acting independently, aligning with prior research suggesting that policy instruments are most effective when embedded in broader technical and market frameworks (McIntyre et al. 2025).

In contrast, although ECS shows a positive coefficient, the relationship is not statistically significant, indicating that stakeholder education, training, and collaboration efforts alone may not be sufficient to drive adoption decisions. This suggests that ECS may play a contextual or reinforcing role, indirectly influencing adoption through its interaction with technical and policy levers rather than serving as a standalone driver (Altassan 2023; Scheller et al. 2021).

The results indicate that SPVS-PH adoption strategies should prioritise integrated technical planning and policy alignment, with ECS operating as a supportive foundation that enhances stakeholder capability and confidence.

5.4 | Effect Size and Predictive Relevance

To further assess the robustness of the structural models, f^2 effect sizes and Q^2 predict values were examined. The detailed results are presented in Table E1. The f^2 effect size results indicate that the predictor constructs had small-to-medium effects on Perceived SPVS–PH Adoption. In the driver model, Sustainability Benefits had a medium effect ($f^2 = 0.168$), while Design Synergy ($f^2 = 0.092$) and Energy Autonomy and Resilience ($f^2 = 0.025$) had small effects. In the barrier model, Economic Barriers had a medium effect ($f^2 = 0.190$), while Design and Technological Limitations ($f^2 = 0.124$) and Policy and Market Limitations ($f^2 = 0.049$) had small effects. In the strategy model, Integrated Design and Technical Solutions had the strongest effect ($f^2 = 0.289$), indicating a medium effect, while Enabling Policy and Incentives ($f^2 = 0.053$) and Education, Capacity-Building and Collaborative Strategy ($f^2 = 0.024$) had small effects. Predictive relevance was assessed using the PLSpredict function in SmartPLS. The Q^2 predict values were 0.378 for the driver model, 0.241 for the barrier model, and 0.405 for the strategy model. Since all Q^2 predict values were greater than zero, the results indicate that all three models demonstrated predictive relevance for Perceived SPVS–PH Adoption.

5.5 | New Zealand Electricity Market Context of the Structural Findings

New Zealand presents a distinct context for residential SPVS-PH adoption, as its electricity system already has a high renewable share, largely supported by hydro and geothermal generation, although thermal generation remains relevant during dry years and during periods of peak demand (MBIE 2025). In this context, the roles of policy and market conditions may differ across countries, where fossil-fuel displacement, uniform feed-in tariffs, or large capital subsidy schemes primarily drive residential SPVS. This helps explain why 'Policy and Market Limitations' did not produce a significant direct effect on Perceived SPVS–PH Adoption, while 'Economic Barriers' and 'Enabling Policy and Incentives' remained important. Rather than indicating that policy is unimportant, the findings suggest that stakeholders may view policy as most relevant when it improves the household-level value proposition for distributed generation in high-performance homes.

The results suggest that policy and market conditions may influence SPVS–PH adoption mainly through their effects on economic feasibility and technical implementation. First, because New Zealand's residential SPVS market relies on retailer-specific buy-back arrangements rather than a single national feed-in tariff, the financial attractiveness of SPVS may depend more on how much generated electricity is used on-site rather than exported at variable buy-back rates (EECA 2025a, 2025b). This is particularly relevant for PHs because their reduced operational loads improve overall energy performance but may also affect the timing and scale of self-consumption. Second, connection and export arrangements are managed through electricity distribution businesses, meaning that export limits, approval processes, and local network conditions may vary across regions (Electricity Authority 2026). These conditions help explain why stakeholders may not perceive policy as a standalone barrier in the structural model, but may experience policy and market settings through economic risk, export-value uncertainty, connection processes, and the practical need for demand flexibility.

The significance of 'Economic Barriers' and 'Integrated Design and Technical Solutions' is also in harmony with this market reality. This may be because the value of residential SPVS in New Zealand depends on self-consumption, load shifting, storage readiness, and tariff structures. Adoption is likely to be strengthened when SPVS is integrated with demand-side flexibility rather than treated as an export-oriented technology. Moreover, recent studies on renewable-energy flexibility and zero-energy buildings similarly show that techno-economic performance improves when renewable generation is combined with storage, load management, and context-specific system optimisation rather than assessed solely by generation capacity (Hoseinzadeh and Garcia 2022; Hoseinzadeh et al. 2023). Therefore, the New Zealand-specific implication of the model is that SPVS–PH adoption should prioritise early energy modelling, battery-ready design, and flexible demand management. These measures may address the economic and technical conditions that stakeholders appear to interpret as policy and market barriers.

6 | Proposed Conceptual Framework

Following PLS-SEM analysis of the survey data, the empirically supported relationships were synthesised into the conceptual framework shown in Figure 7. The framework aims to guide relevant stakeholders, including policymakers, PH designers, builders, and energy-sector professionals, on how SPVS-PH integration can be effectively leveraged as a sustainable measure to achieve building decarbonisation and contribute to New Zealand's net-zero targets. The framework shows the interaction between drivers, barriers, and enabling strategies, and how these constructs collectively influence SPVS-PH adoption as a pathway toward a decarbonised built environment.

As shown in Figure 7, the framework organises the determinants of the perceived SPVS–PH adoption into three interconnected domains. First, SPVS–PH drivers capture the core motivations that promote adoption. These include Sustainability Benefits (SBT), such as declining SPVS costs, reduced electricity bills, enhanced financial returns, increased property value, and a commitment to sustainability. Moreover, design synergy (DSG), which reflects perceived technical alignment between SPVS integration and PH design (e.g., smaller-sized SPVS requirements and SPVS–PH compatibility). These drivers represent the combined influence of sustainability value propositions and early-stage design fit in motivating uptake.

Second, SPVS–PH barriers represent constraints that hinder adoption even when motivation exists. The framework distinguishes economic barriers (ECB), including low buy-back rates and short-term ownership. Furthermore, the design & technical limitations (DTL) include embodied versus operational carbon concerns, limited demand flexibility, seasonal mismatches in solar output in winter, and site infrastructure limitations. This separation clarifies that both financial risk perceptions and technical and delivery complexities across the building lifecycle can constrain adoption.

Third, the framework specifies enabling strategies that strengthen adoption pathways by mitigating key barriers and improving feasibility. Two strategic constructs are emphasised:

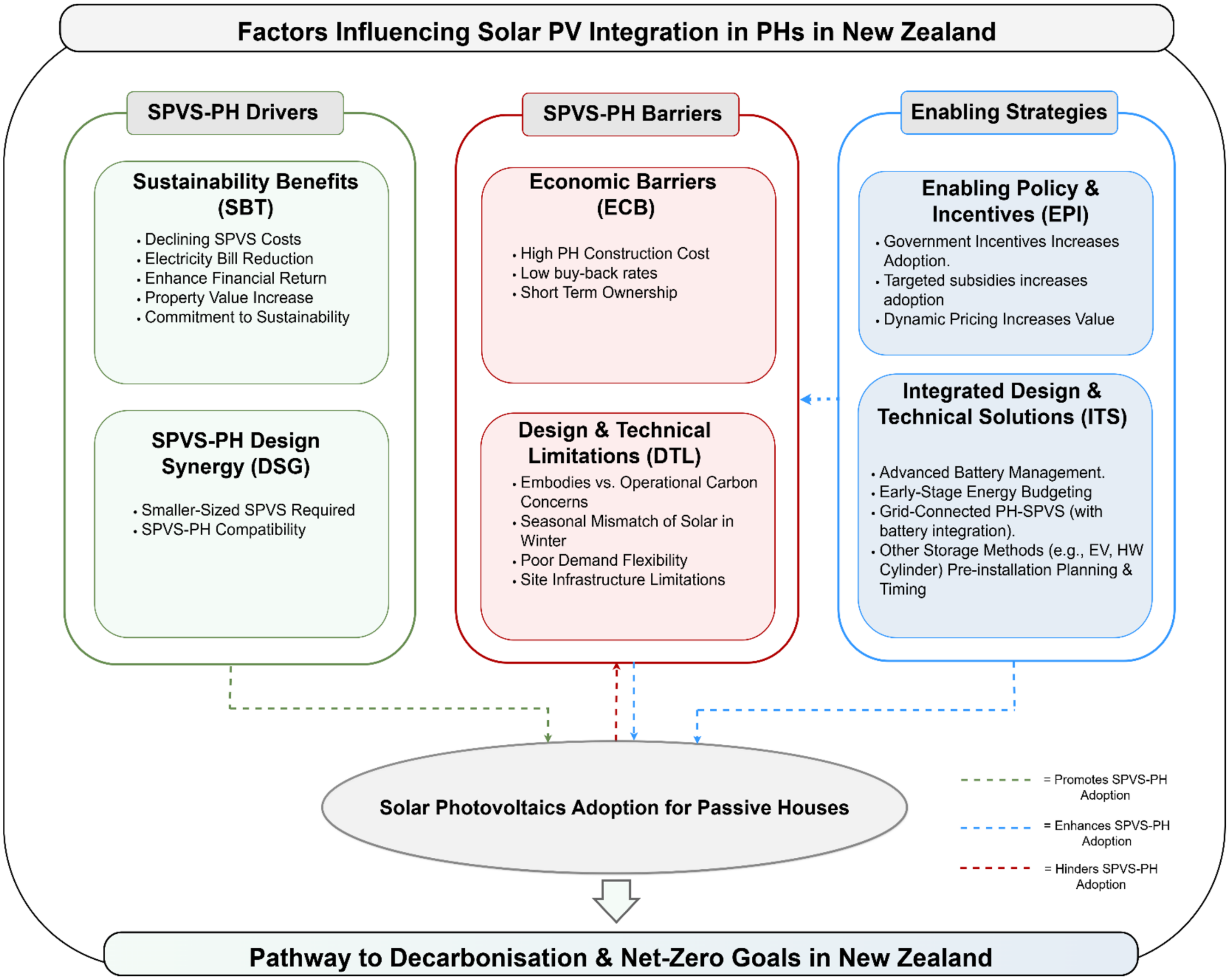

FIGURE 7 | The critical success factors influencing SPVS-PH adoption in New Zealand.

Enabling Policy & Incentives (EPI) (e.g., government incentives, targeted subsidies and dynamic pricing mechanisms that increase value) and Integrated Design & Technical Solutions (ITS) (e.g., advanced battery management, built-in PV material, DC-coupled SPVS for specific uses, early-stage energy budgeting, grid-connected PH–SPVS with battery integration and other storage methods). These strategies are positioned as practical levers that can enhance adoption, both directly and indirectly, by addressing economic and technical limitations.

7 | Conclusion

This study quantitatively examined stakeholder-perceived factors influencing SPVS–PH adoption in New Zealand using PLS-SEM. It tested the structural relationships among these factors and the perceived SPVS–PH adoption using survey data from 96 stakeholders in the building and energy sectors. The findings provide empirical evidence on which perceived factors exert the strongest influence within the New Zealand high-performance housing context.

For the driver model, sustainability benefits had the strongest positive effect on the perceived SPVS–PH adoption ($\beta = 0.372$), followed by design synergy ($\beta = 0.290$), with the model explaining 46.1% of the variance in adoption perceptions ($R^2 = 0.461$). These results show that stakeholders are more likely to support SPVS–PH integration when they perceive clear sustainability value, financial benefit, and technical compatibility between SPVS and PH. Energy autonomy and resilience showed a positive but non-significant effect, suggesting that resilience-related benefits may indirectly support adoption rather than act as a standalone driver.

In the barrier model, economic barriers had the strongest influence on perceived SPVS–PH adoption ($\beta = 0.460$), followed by design and technological limitations ($\beta = 0.333$), with the model explaining 33.2% of the variance ($R^2 = 0.332$). This confirms that cost-related concerns, financial risk, payback uncertainty, and technical integration challenges remain major constraints to the perceived SPVS–PH adoption. Policy and market limitations showed a negative but non-significant effect, suggesting that these conditions may influence adoption indirectly through economic or technical pathways rather than through a direct relationship.

For the strategy model, integrated design and technical solutions produced the strongest positive effect on the perceived SPVS–PH adoption ($\beta = 0.501$), followed by enabling policy and incentives ($\beta = 0.199$), with the model explaining 48.7% of the variance ($R^2 = 0.487$). This indicates that early-stage technical planning, energy modelling, system compatibility, battery readiness, and integrated design coordination are the most influential perceived strategies for improving the perceived SPVS–PH adoption. Education, capacity-building and collaboration showed a positive but non-significant effect, suggesting that these measures may be supportive but insufficient on their own without stronger technical and policy mechanisms.

The novel contribution of this study lies in providing an empirically tested PLS-SEM model of stakeholder-perceived SPVS–PH adoption factors in New Zealand. The results show that adoption perceptions are shaped most strongly by sustainability benefits, design synergy, economic barriers, design and technological limitations, integrated technical solutions, and enabling policy incentives. These findings provide quantitative evidence that the perceived SPVS–PH adoption is determined not by a single factor but by the combined influence of perceived benefits, financial constraints, technical feasibility, and implementation strategies.

The findings suggest that policy support for SPVS–PH adoption in New Zealand may benefit from targeted regulatory and market-design measures alongside financial incentives. For example, future updates to Building Code Clause H1 could provide clearer guidance on SPVS-ready and battery-ready design in high-performance housing, including roof orientation, conduit pathways, inverter location, and structural allowance. This could help align renewable-readiness with the existing energy-efficiency intent of H1 and reduce the risk of late-stage design conflicts. Moreover, the findings suggest that pricing structures that better reward flexible self-consumption, demand shifting, and battery-enabled export, rather than relying solely on flat buy-back rates, could improve the perceived economic case for SPVS–PH adoption. Similarly, targeted support mechanisms, such as low-interest finance, SPVS-ready design credits, or incentives linked to storage and demand flexibility, may be better suited to the New Zealand context than broad solar subsidies alone, given that the value of residential SPVS depends strongly on household load profiles, local pricing structures, storage readiness, and the extent to which generated electricity can be used on-site.

Furthermore, this study contributes to SDG 7 (affordable and clean energy) by identifying stakeholder-perceived conditions that enable more effective integration of renewable electricity generation into high-performance residential buildings. It contributes to SDG 13 (climate action) by demonstrating how stronger alignment among design, policy, and economic factors can support lower operational emissions and more effective transitions to low-carbon housing.

This study is based on stakeholder survey perceptions rather than actual measured post-occupancy performance. Therefore, the structural model should be interpreted as evidence of perceived relationships influencing SPVS–PH adoption, rather than as direct proof of actual adoption behaviour.

In addition, the use of purposive and snowball sampling may limit the external generalisability of the findings, as participants may not fully represent all stakeholders involved in SPVS–PH adoption across New Zealand. Therefore, the findings should be interpreted as stakeholder-perceived relationships within a specialised sample. Future research should validate and refine the model through a multi-criteria decision-making such as focus group workshops involving stakeholders including designers, builders, energy consultants, policymakers, PH professionals, homeowners, developers and SPVS installers.

Author Contributions

Franklin Chukwuebuka Nkado: conceptualization, methodology, software, data curation, writing – original draft. **Itohan Esther Aigwi:** supervision, writing – review and editing. **Dat Tien Doan:** supervision, writing – review and editing. **Ali GhaffarianHoseini:** supervision, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Appendix A

TABLE A1 | Discriminant validity of constructs for the drivers(Fornell-Larcker).

	DSG	EAR	SPA	SBT
DSG	**0.886**			
EAR	0.564	**0.766**		
SPA	0.539	0.499	**0.716**	
SBT	0.572	0.494	0.601	**0.689**

Note: The bold diagonal values represent the square roots of the average variance extracted (AVE) for each constuct.

TABLE A2 | Cross-loadings of observable variables in constructs (drivers for SPVS-PH).

	DSG	EAR	SBT	SPA
DSG1	**0.854**	0.422	0.371	0.434
DSG2	**0.917**	0.563	0.563	0.566
EAR1	0.416	**0.694**	0.237	0.272
EAR2	0.464	**0.841**	0.480	0.495
EAR4	0.420	**0.757**	0.376	0.309
SBT1	0.487	0.239	**0.627**	0.355
SBT2	0.387	0.416	**0.784**	0.440
SBT3	0.380	0.453	**0.640**	0.310
SBT4	0.343	0.349	**0.796**	0.558
SPA1	0.331	0.216	0.262	**0.631**
SPA2	0.418	0.307	0.317	**0.763**
SPA3	0.426	0.437	0.380	**0.615**
SPA5	0.389	0.357	0.603	**0.735**

Note: The bold values in the cross-loading tables represent the loading of each observable variable on its intended construct.

Appendix B

TABLE B1 | Discriminant validity of constructs for the barriers(Fornell-Larcker).

	DTL	ECB	PML	SPA
DTL	**0.719**			
ECB	0.467	**0.772**		
PML	0.416	0.581	**0.883**	
SPA	0.453	0.483	0.179	**0.659**

Note: The bold diagonal values represent the square roots of the average variance extracted (AVE) for each constuct.

TABLE B2 | Cross-loadings of observable variables in constructs (SPVS-PH barriers).

	DTL	ECB	PML	SPA
DTL1	**0.694**	0.368	0.370	0.290
DTL2	**0.767**	0.281	0.147	0.402
DTL3	**0.705**	0.223	0.316	0.325
DTL4	**0.709**	0.539	0.445	0.256
ECB1	0.418	**0.678**	0.535	0.305
ECB2	0.436	**0.806**	0.584	0.347
ECB4	0.270	**0.824**	0.293	0.448
PML1	0.281	0.552	**0.810**	0.102
PML2	0.426	0.509	**0.951**	0.192
SPA1	0.080	0.112	0.041	**0.520**
SPA2	0.190	0.225	0.008	**0.641**
SPA6	0.446	0.326	0.175	**0.720**
SPA7	0.319	0.459	0.164	**0.733**

Note: The bold values in the cross-loading tables represent the loading of each observable variable on its intended construct.

Appendix C

TABLE C1 | Discriminant validity of constructs for the strategies (Fornell-Larcker).

	ECS	EPI	ITS	SPA
ECS	**0.721**			
EPI	0.276	**0.698**		
ITS	0.454	0.560	**0.738**	
SPA	0.406	0.513	0.669	**0.746**

Note: The bold diagonal values represent the square roots of the average variance extracted (AVE) for each constuct.

TABLE C2 | Cross-loadings of observable variables in constructs (SPVS-PH strategies).

	ECS	EPI	ITS	SPA
ECS2	**0.550**	0.150	0.313	0.121
ECS3	**0.824**	0.181	0.315	0.366
ECS5	**0.759**	0.264	0.389	0.312
EPI1	0.041	**0.524**	0.131	0.161
EPI2	0.149	**0.627**	0.230	0.173
EPI3	0.284	**0.890**	0.586	0.537
ITS1	0.441	0.505	**0.827**	0.542
ITS3	0.258	0.370	**0.829**	0.609
ITS4	0.401	0.449	**0.512**	0.214
SPA3	0.370	0.413	0.653	**0.844**
SPA4	0.270	0.401	0.410	**0.698**
SPA8	0.250	0.336	0.379	**0.685**

Note: The bold values in the cross-loading tables represent the loading of each observable variable on its intended construct.

Appendix D

TABLE D1 | Common method bias assessment using inner model VIF values.

Model	Structural path	VIF
Driver model	DSG → SPA	1.684
Driver model	EAR → SPA	1.590
Driver model	SBT → SPA	1.530
Barrier model	DTL → SPA	1.333
Barrier model	ECB → SPA	1.663
Barrier model	PML → SPA	1.573
Strategy model	ECS → SPA	1.260
Strategy model	EPI → SPA	1.458
Strategy model	ITS → SPA	1.696

Appendix E

TABLE E1 | Effect sizes and predictive relevance of the structural models.

Model	Predictor construct	Endogenous construct	f^2 effect size	Effect interpretation	Q^2 predict	Predictive relevance
Driver model	DSG	Perceived SPVS–PH Adoption	0.092	Small effect	0.378	Yes
Driver model	EAR	Perceived SPVS–PH Adoption	0.025	Small effect	0.378	Yes
Driver model	SBT	Perceived SPVS–PH Adoption	0.168	Medium effect	0.378	Yes
Barrier model	DTL	Perceived SPVS–PH Adoption	0.124	Small effect	0.241	Yes
Barrier model	ECB	Perceived SPVS–PH Adoption	0.190	Medium effect	0.241	Yes
Barrier model	PML	Perceived SPVS–PH Adoption	0.049	Small effect	0.241	Yes
Strategy model	ECS	Perceived SPVS–PH Adoption	0.024	Small effect	0.405	Yes
Strategy model	EPI	Perceived SPVS–PH Adoption	0.053	Small effect	0.405	Yes
Strategy model	ITS	Perceived SPVS–PH Adoption	0.289	Medium effect	0.405	Yes

Note: f^2 values of 0.02, 0.15, and 0.35 indicate small, medium, and large effects, respectively. Q^2 predict values greater than zero indicate predictive relevance.