Energy & Buildings 347 (2025) 116386

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Dutch householders' intentions to adopt shallow geothermal systems for energy transition of existing buildings: A theory of planned behavior approach☆

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ARTICLE INFO

Keywords:
Shallow geothermal energy
Theory of planned behavior
Energy transition
Residential heating
Homeowner intentions
Adoption barriers
Renewable energy

ABSTRACT

This study explores Dutch homeowners' intentions to adopt shallow geothermal solutions for the energy transition in existing buildings, using the Theory of Planned Behavior (TPB) as a theoretical framework. Through a mixed-methods approach combining qualitative elicitation interviews with 20 homeowners and a quantitative survey of 800 representative Dutch households, the study identifies key psychological and socio-demographic factors influencing adoption intentions. The findings indicate that approximately 33% of surveyed homeowners express intention to adopt geothermal technology within the next five years. Structural Equation Modeling reveals that attitudes toward geothermal technology and subjective norms significantly influence adoption intentions, while perceived behavioral control has no significant impact on intention. Economic benefits and environmental protection emerge as the strongest attitudinal drivers, with uncertainty about investment payback periods acting as the primary barrier. Normative influences from environmental advocates, suppliers, and community members also strongly shape adoption intentions. Among socio-demographic factors, higher energy cost-to-income ratios, higher income levels, and homeowners' association membership positively influence adoption intentions, while age shows a negative correlation. These insights provide evidence-based guidance for policymakers to develop targeted interventions addressing specific psychological barriers experienced by different homeowner segments, potentially accelerating the transition to renewable heating systems in the Netherlands' existing housing stock.

1. Introduction

Buildings are the major contributors to greenhouse gas emissions, accounting for approximately 30 % of global final energy use and 25 % of CO_2 emissions [1]. In Europe, these figures rise to 40 % and 36 %, respectively [2]. The Netherlands faces a particularly significant environmental challenge, with approximately 79 % of residential heating still reliant on natural gas [3], thus exacerbating the sector's environmental impact. Despite this, the rate of deep building energy renovations remains low, underscoring the urgent need to transition to renewable energy sources [4].

Among various renewable energy sources, shallow geothermal energy has garnered significant attention due to its relative stability and sustainability [5]. It offers greater reliability through its near-constant subsurface temperature in contrast to the daily and seasonal variability of solar and wind systems. This technology has demonstrated substantial potential to replace traditional heating and cooling systems and has proven beneficial for advancing local sustainable development and meeting carbon reduction goals in many regions [6]. In the Netherlands, shallow geothermal energy—commonly referred to as soil energy—primarily involves geothermal systems with pipe depths less than 500 m [7]. Fig. 1 illustrates the common shallow geothermal energy systems and their applications, including vertical collectors, horizontal collectors, and looped collectors used for both individual and district heating or cooling purposes.

As of 2023, the annual heat extraction from soil-based heat pumps reached 6 643 TJ (≈ 6.6 PJ), while the total installed capacity rose by 11 % to 2 242 MW_{th}, supported by 26 563 new shallow geothermal

☆ This article is part of a special issue entitled: 'Decarbonising Built Env' published in Energy & Buildings.

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https://doi.org/10.1016/j.enbuild.2025.116386
Received 27 November 2024; Received in revised form 24 July 2025; Accepted 29 August 2025
Available online 30 August 2025
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installations in that year alone; open loop systems circulated 350 million m^3 of groundwater in 2022 for seasonal heat/cold storage in commercial, horticultural, and residential applications [9]. Fig. 2 shows the significant growth in both heat extraction and annual added capacity of geothermal energy in the Netherlands from 2008 to 2023. It is noteworthy that most of these installations have been deployed in new–build projects, with uptake in existing buildings still trailing. Despite this impressive growth trajectory, geothermal energy still represents only 2 % of the Netherlands' final renewable energy consumption [9]. The Dutch Climate Agreement and the 2018 Geothermal Master Plan set an ambition to scale up overall geothermal output from just 3 PJ today to 50 PJ by 2030 and more than 200 PJ by 2050 [10].

Currently, while public acceptance of geothermal energy varies significantly across countries [12,13]. A briefing by the European Parliamentary Research Service identifies acceptance as a major challenge, primarily due to limited awareness about geothermal technology and environmental concerns.[1] A systematic review [13] notes that in some countries like Iceland and New Zealand with established geothermal infrastructure, there appear to be minimal public concerns, while in countries like Germany, Switzerland, and Japan, social acceptance requires more active management through stakeholder engagement and transparent communication. In the Netherlands, while geothermal energy is generally considered a promising sustainable energy source that is stable and reliable, it has also led to controversies in various countries due to potential environmental risks [14].

This variation in public acceptance highlights the importance of understanding the psychological factors that influence adoption decisions at the household level. Several researchers have initiated studies on the application of shallow geothermal energy in existing buildings, with a particular focus on the most common ground-source heat pump (GSHP) systems [12,15,16]. However, the majority of existing research focuses on the technical and economic feasibility aspects [17,18], with limited attention to the psychological dimensions of adoption. This gap is particularly significant as psychological factors have been shown to play a crucial role in energy-related decision-making. Huijts et al. [19] developed a comprehensive framework demonstrating that public acceptance of sustainable energy technologies is influenced by a complex interplay of psychological factors including trust, procedural fairness, and perceived costs, risks, and benefits. Similarly, Perlaviciute and Steg [20] found that psychological values significantly shape how individuals evaluate different energy alternatives, with people prioritizing different aspects of energy options based on their underlying value orientations. In the specific context of heating systems, Gram-Hanssen [21] revealed that homeowners' decisions are influenced not only by rational cost-benefit calculations but also by social norms, symbolic meanings attached to technologies, and perceived compatibility with existing practices. Despite growing research on energy technologies adoption [15,22,23], there remains a significant gap in studies that systematically examine the specific psychological factors influencing homeowners' willingness to adopt geothermal technologies, with research being particularly limited and fragmented in the Dutch context where unique cultural, policy, and housing characteristics shape homeowners' decision-making processes.

Understanding homeowners' intentions to adopt shallow geothermal technology is crucial as intentions represent a primary antecedent to actual behavior [24,25]. While the relationship between intentions and behavior is complex—with various factors potentially creating an "intention-behavior gap" [26] —intention studies provide valuable insights into decision-making processes and potential adoption barriers. Research on sustainable heating systems has consistently demonstrated that understanding homeowners' intentions serves as a critical foundation for increasing adoption rates, even though factors like financial constraints and technical complexity may moderate the intention-behavior relationship [27,28].

To address this research gap, this paper employs the Theory of Planned Behavior (TPB) as the theoretical framework to investigate the specific key factors influencing Dutch homeowners' willingness to adapt shallow geothermal technology in existing buildings. TPB has been widely used across various fields, including energy-saving behaviors [29,30], renewable energy adoption [31], and energy transition [32].

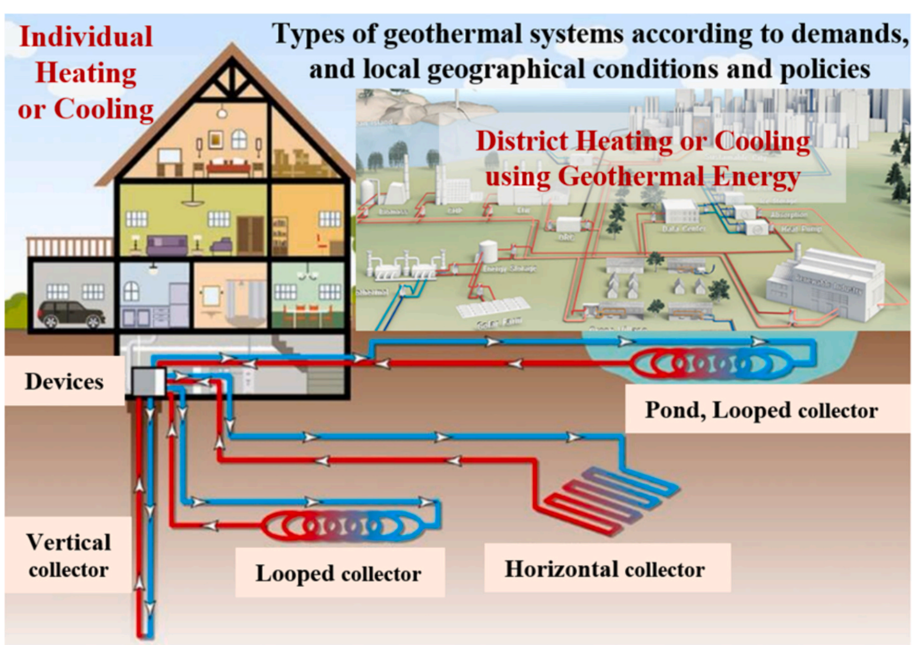

Fig. 1. Common types of Shallow Geothermal Energy Systems and Their Applications (adapted from Consolidated Electric Cooperative and Contractor, available at [8]).

[1] https://www.europarl.europa.eu/RegData/etudes/BRIE/2023/754566/EPRS_BRI(2023)754566_EN.pdf.

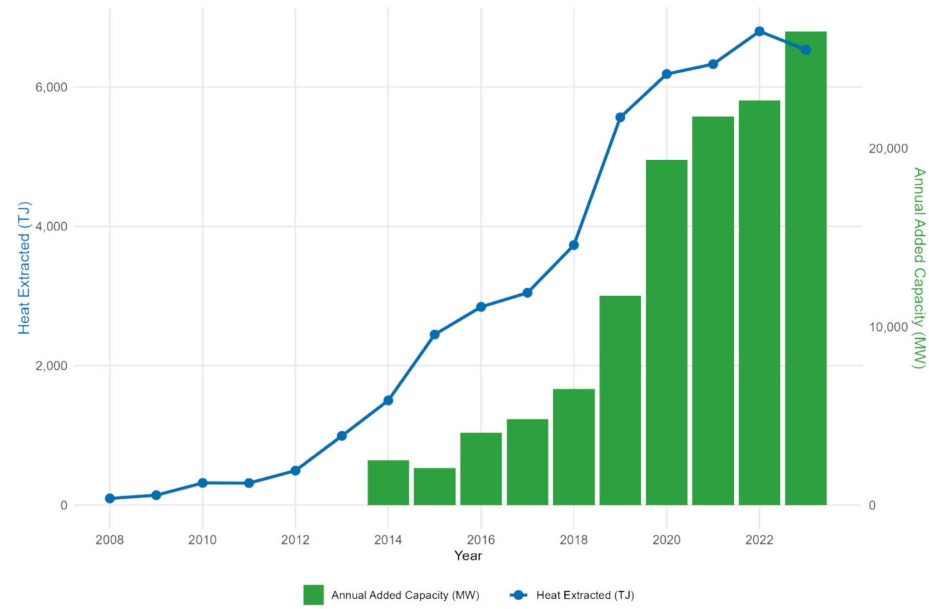

Fig. 2. Geothermal Energy Development in the Netherlands (2008–2023).
Source: Centraal Bureau voor de Statistiek 11

Specifically, this study aims to answer the following research questions:

RQ1: What is the current level of adoption intention for shallow geothermal technology among Dutch homeowners?
RQ2: What are the key psychological factors (attitudes, subjective norms, and perceived behavioral control) that influence Dutch homeowners' intentions to adopt shallow geothermal technology in existing buildings?
RQ3: Which specific beliefs underlying homeowners' attitudes, subjective norms, and perceived behavioral control most significantly affect their adoption intentions?
RQ4: How do socio-demographic characteristics influence Dutch homeowners' intentions to adopt shallow geothermal technology?

The scientific contribution of this study lies in its comprehensive and systematic examination of the psychological and contextual factors influencing Dutch homeowners' willingness to adopt shallow geothermal technology in existing buildings, addressing the fragmented nature of current research in this domain. By integrating the TPB with context-specific beliefs identified through a sequential mixed-methods approach, this research moves beyond isolated psychological variables to reveal the complex interactions between attitudes, social influences, perceived capabilities, and socio-demographic characteristics that shape adoption intentions in the unique Dutch context. Unlike previous studies that have primarily focused on technical and economic aspects, our model quantifies the relative importance of various psychological drivers – notably economic benefits, environmental concerns, and social influences – while also identifying how socio-demographic factors such as age, income, and energy cost-to-income ratio create differentiated adoption patterns among distinct homeowner segments. Additionally, our representative sample survey reveals how Dutch homeowners perceive shallow geothermal technology and their implementation intentions, providing the first comprehensive empirical baseline of attitudes and adoption readiness across the Netherlands. These insights address the critical knowledge gap regarding the psychological processes underlying Dutch homeowners' adoption decisions and provide an evidence-based framework for developing targeted policy interventions that address the specific psychological barriers experienced by different homeowner groups, thus contributing to more effective strategies for promoting renewable energy transitions in the Netherlands' existing housing stock.

2. Literature review and theoretical framework

2.1. Factors influencing heating system adoption decisions

Understanding homeowners' decisions to adopt renewable heating technologies, including shallow geothermal systems, requires examining the complex interplay of technical–economic, psychological-social, and contextual factors that shape adoption intentions. This section synthesizes key research findings to establish the foundation for our study.

2.1.1. Economic and technical factors

Economic considerations consistently emerge as primary drivers of heating system selection. High initial investment costs represent the most significant barrier to renewable heating adoption, particularly for geothermal systems [33,34]. Ruokamo [35] found that changes in operating costs had greater impact on Finnish homeowners' heating choices than equivalent changes in investment costs, highlighting the importance of long-term economic considerations.

However, homeowners' economic evaluations are often complicated by decision-making approaches that undervalue future benefits. Burlinson et al. [36] found that UK consumers applied internal discount rates of approximately 36 % when evaluating heating technologies, substantially undervaluing future energy savings. This "energy efficiency paradox" is further compounded by uncertainty regarding payback periods for renewable systems [37,38]. Technical performance, particularly reliability and comfort, also significantly influences adoption decisions, with technology quality often outweighing economic considerations [39].

2.1.2. Psychological and social factors

Environmental attitudes represent important drivers of heating system adoption, though often secondary to economic factors. While environmental concern can outweigh economic considerations for some homeowners [40], comfort and economic factors typically rank higher [41]. For geothermal technology specifically, Karytsas [15] found that environmental attitudes positively predicted interest in ground source heat pumps, but economic attitudes regarding operational cost savings were the strongest predictors.

Knowledge and awareness about heating technologies significantly influence adoption decisions. Vu et al. [42] demonstrated that environmental knowledge can reduce perceived monetary barriers. However, knowledge gaps appear particularly pronounced for geothermal systems, with Karytsas and Theodoropoulou [12] finding that while 76.5 % of Greek respondents understood environmental issues, only 23.7 % knew ground source heat pumps could be used for residential applications.

Social influences shape heating system decisions through multiple mechanisms. Professional advice represents a particularly important normative influence [41], while community influences and social networks significantly impact adoption patterns [23,43]. For geothermal systems, early adopters can serve as influential demonstration cases that reduce perceived risks for others in their social networks [13].

2.1.3. Socio-demographic characteristics

Recent TPB applications to renewable energy have revealed important theoretical developments that inform our study design. Jaber et al. [44] applied an extended TPB model to solar energy adoption in Jordan, incorporating perceived mandatory benefits alongside traditional TPB constructs, and found that socio-demographic factors like income and location significantly moderate the relationships between psychological factors and adoption intentions. This finding supports our approach of examining socio-demographic moderation effects.

Age significantly influences heating system preferences, with older homeowners generally less willing to choose renewable heating technologies [45]. Income level creates important capability differences, with higher-income households showing significantly greater willingness to adopt geothermal technology [35 36].

Homeowners' association (VvE) membership represents a significant contextual factor in the Netherlands, where collective decision-making processes can create barriers to individual heating system choices [46]. Building energy efficiency ratings and past energy expenditure also influence heating system decisions by providing information and creating financial pressure for change [47,48].

This literature review identifies three important gaps that our study addresses:

First, despite ambitious Dutch government targets for geothermal energy expansion, there remains a significant lack of empirical data on homeowners' attitudes toward shallow geothermal technology, particularly regarding awareness, perceptions, and willingness to adopt these systems in existing buildings.

Second, current research typically lacks comprehensive frameworks that integrate both psychological and socio-economic variables that jointly influence adoption intentions.

Third, few studies have systematically investigated the specific beliefs underlying homeowners' decisions about geothermal systems, leaving important questions about how these beliefs form and influence behavior in the Dutch residential context unexplored.

This study addresses these gaps by applying TPB to comprehensively analyze the psychological factors influencing Dutch homeowners' intentions to adopt shallow geothermal technology in existing buildings.

2.2. Theory of Planned behavior in heating system adoption

The TPB, developed by Icek Ajzen [24], provides a robust framework for analyzing the psychological processes underlying deliberate decisions such as heating system adoption. The application of TPB to renewable energy adoption has gained considerable momentum in recent years, with studies demonstrating varying patterns across technologies and contexts. Rahmani et al. [49] found that attitudes, subjective norms, and perceived behavioral control (PBC) significantly influenced Iranian households' renewable energy investment intentions, while Batool et al. [50] revealed that environmental concerns and cost considerations created differential adoption patterns among Indian consumers. Gamel et al. [51] applied TPB to German households' wind energy investment decisions, demonstrating that regional infrastructure differences created varying levels of perceived behavioral control.

According to this theory, behavior is determined by intentions, which are in turn shaped by three key factors: attitudes toward the behavior, subjective norms, and PBC. The interrelationship between these components as applied to heating system adoption is illustrated in Fig. 3. TPB has been widely applied to renewable energy adoption [23,32,42,52–56], though research on shallow geothermal systems remains limited to one study on accommodation operators in China [56].

Recent TPB applications in renewable energy contexts have confirmed the centrality of attitudes while revealing technology-specific patterns. Harorli and Erciş [57] found that attitudes toward green power varied significantly across Turkish demographic segments, while Waris et al. [58] demonstrated that knowledge about solar technology enhanced both attitudes and adoption intentions. Furthermore, recent research has revealed considerable variation in PBC's predictive power across renewable energy technologies and contexts. Almrafee and Akaileh [59] found that PBC significantly predicted Jordanian consumers' solar panel purchase intentions, while Fazal et al. [60] demonstrated minimal PBC impact among low-income households, suggesting that PBC's relevance depends on technology complexity and target population characteristics.

TPB is particularly suitable for understanding heating system choices because these decisions involve significant investments, technical considerations, and social influences that align with the theory's components. However, the standard TPB model only captures surface-level psychological constructs. To understand the psychological processes that drive adoption decisions, it is essential to examine the underlying beliefs that form these constructs—what Ajzen [61] terms "formative indicators".

2.2.1. The importance of Belief-Level analysis

TPB's strength lies not only in its three main constructs but in its ability to identify the underlying beliefs that form attitudes, subjective norms, and PBC. According to Ajzen [61], these "formative indicators" represent the specific considerations that individuals use when evaluating a behavior, and understanding them is crucial for developing effective interventions.

While TPB has been applied to various energy behaviors, research examining the specific beliefs underlying heating system adoption remains limited. Most studies focus on direct measures of attitudes, subjective norms, and PBC without exploring the underlying belief structures. This limitation is particularly pronounced for geothermal technology adoption, where belief-level research is virtually nonexistent. The few studies that have examined beliefs in heating contexts have focused on conventional systems or other renewable technologies. For example, research on general renewable energy adoption has identified economic and environmental outcome beliefs as important [52,53], while studies of heating system choices have noted the importance of comfort and reliability beliefs [33,62]. However, no studies have systematically investigated the specific beliefs that Dutch homeowners hold about shallow geothermal technology.

Ajzen [63] emphasizes that beliefs are highly context-specific and cannot be reliably transferred across different behaviors, populations, or technologies. This means that beliefs about solar panels or wind energy cannot be assumed to apply to geothermal systems, and beliefs identified in other countries may not reflect Dutch homeowners' considerations. This context-specificity necessitates conducting elicitation studies with target populations to identify salient beliefs before developing questionnaires. While methodologically demanding, this approach ensures that belief measures reflect the actual considerations that influence decision-making rather than researchers' assumptions about what might be important.

The absence of belief-level research on geothermal adoption represents a significant methodological gap. Without understanding the specific behavioral beliefs (outcome expectations), normative beliefs

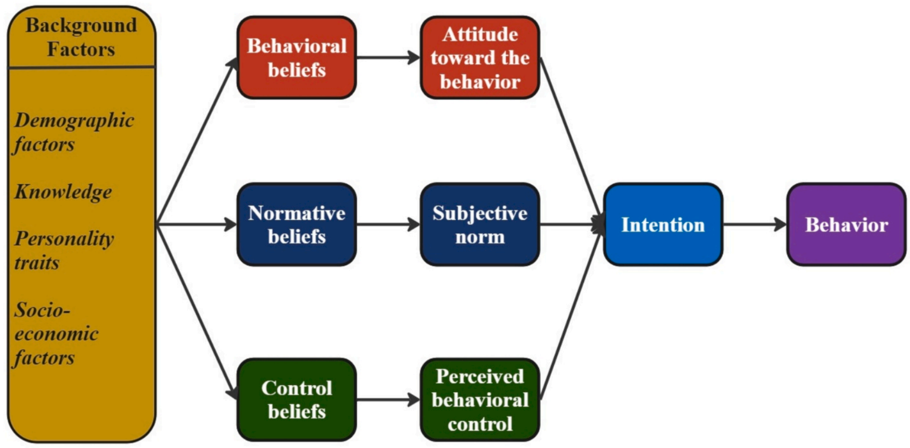

Fig. 3. The framework of the theory of planned behavior.
Source: Adapted from Ajzen 24

(social influences), and control beliefs (facilitating/inhibiting factors) that shape homeowners' decisions, interventions may address generic concerns rather than the actual psychological drivers of adoption or non-adoption. Our study addresses this gap by conducting comprehensive elicitation interviews with Dutch homeowners to identify the specific beliefs that influence their geothermal adoption intentions, providing the first systematic analysis of belief-level factors in this domain.

2.2.2. The role of background factors in TPB

TPB recognizes that background factors—including socio-demographic characteristics, personal experiences, and contextual variables—influence behavior indirectly by shaping the formation of behavioral, normative, and control beliefs [24,61]. Unlike direct predictors (attitudes, subjective norms, and PBC), background factors operate through belief systems rather than directly influencing intentions.

In heating system adoption contexts, background factors create systematic differences in how homeowners evaluate technology outcomes (behavioral beliefs), perceive social expectations (normative beliefs), and assess their capabilities (control beliefs). For instance, previous energy experiences may influence economic outcome beliefs, social network characteristics may shape normative belief formation, and financial resources may affect control belief development.

Understanding these indirect pathways is crucial for intervention design. While changing background factors is often impossible (e.g., age, housing type), identifying how they influence belief formation allows for targeted interventions that address specific belief patterns among different homeowner segments. This approach enables more effective policy design that accounts for the heterogeneous belief structures across different demographic groups.

The specific background factors relevant to geothermal adoption and their empirical relationships with beliefs and intentions are detailed in our analysis, building on the socio-demographic influences identified in Section 2.1.3.

Despite extensive TPB application across energy domains, significant gaps remain for geothermal technology adoption. Most studies employ simplified models focusing only on direct measures without examining underlying belief structures that form attitudes, subjective norms, and perceived behavioral control. This methodological limitation stems from the complexity of conducting proper elicitation studies, but as Ajzen argues, understanding formative beliefs provides critical insights for designing effective interventions [61]. Our study addresses these gaps by employing a comprehensive TPB model that examines both direct measures and underlying beliefs of Dutch homeowners, revealing the interplay between attitudes, subjective norms, behavioral control, and socio-demographic factors in this complex decision-making process.

3. Methodologies

3.1. Questionnaire development

The questionnaire development employed a two-step sequential approach following established TPB protocols [61]. This methodology was specifically chosen because TPB requires context-specific belief identification through proper elicitation procedures, as belief structures vary significantly across behaviors and technologies [64]. Given that geothermal heating represents a relatively novel technology option for Dutch homeowners, qualitative exploration was essential before quantitative measurement to identify relevant psychological drivers specific to this technology and context.

The questionnaire for this study was developed through a two-step process to gather insights from Dutch homeowners regarding their intentions to adopt shallow geothermal technology for residential heating. This study specifically targeted homeowners rather than renters because the adoption of shallow geothermal systems requires substantial property modifications, significant upfront investment, and involves long-term payback considerations. As such, homeowners represent the primary decision-makers with both the legal authority and financial incentive to implement such systems in existing buildings. The first step involved conducting an elicitation study to identify the significant beliefs that influence these intentions. In the second step, the results of the elicitation study were used to construct a TPB-based survey questionnaire.

3.1.1. Step One: Elicitation study

To ensure the scientific rigor of the questionnaire, the study began with an elicitation phase, involving semi-structured interviews with 20 homeowners across the four Nielsen regions of the Netherlands: the North (Groningen, Friesland, and Drenthe), the West (Noord-Holland, Zuid-Holland, and Utrecht), the East (Overijssel, Gelderland, and Flevoland), and the South (Zeeland, Noord-Brabant, and Limburg). This regional distribution was designed to capture potential variations in homeowners' perceptions and beliefs across different geographic contexts within the Netherlands.

The semi-structured interview method was selected for several reasons: First, it allows for comprehensive exploration of homeowners' spontaneous beliefs and attitudes toward geothermal technology without imposing predetermined response categories. Second, the flexible nature of semi-structured interviews enables researchers to probe deeper into participants' reasoning and uncover context-specific factors that may not be captured by standardized questionnaires. Third, this method aligns with Ajzen's recommendations for TPB elicitation studies, which emphasize the importance of identifying salient beliefs that are specific to the target population and behavior context [63].

The interviews were conducted using both online platforms and face-to-face meetings based on participant preferences and geographic accessibility. All interviews followed the same structured protocol, were audio-recorded with participants' consent, and lasted approximately 40–60 min. Participants were recruited through a combination of convenience sampling and snowball sampling to ensure representation across different demographic groups and regions. The sample included homeowners aged 18–92 (mean age: 50.74), with varied educational backgrounds, income levels, and housing types. To be eligible, participants had to be homeowners with decision-making authority over their heating systems and have some familiarity with renewable energy concepts. The interview protocol included 10 open-ended questions (see Table 1), allowing for a comprehensive exploration of homeowners' perspectives.

The responses were analyzed using a systematic thematic analysis approach to identify recurring themes and significant beliefs. All interviews were transcribed verbatim and imported into ATLAS.ti software for qualitative data analysis. The analytical procedure followed these steps: (1) Initial familiarization with the data through repeated reading of transcripts; (2) Open coding to identify initial concepts and ideas related to geothermal technology adoption; (3) Axial coding to group related codes into broader themes aligned with TPB constructs (behavioral beliefs, normative beliefs, and control beliefs); (4) Selective coding to identify the most salient beliefs within each category. The final coding framework categorized beliefs into six main themes: advantages, disadvantages, supportive groups, opposing groups, motivating factors, and hindering factors. Only beliefs mentioned by at least 25 % of participants (5 or more respondents) were considered significant and included in the subsequent questionnaire development.

3.1.2. Step Two: Questionnaire design

The questionnaire was divided into two main sections: The first section covers basic information about the individual and their household, while the second section includes questions based on the TPB.

Section 1: Basic information about respondents and residences.

This section aimed to gather essential demographic and housing-related data, including:

Table 1
TPB semi-structured interview questions.

NO.	Questions
Q1	Would you consider installing a geothermal energy system for your residence's heating, cooling, and/or hot water needs within the next 5–10 years?
Q2	In your view, what are the advantages of installing a geothermal energy system in your residence?
Q3	In your view, what are the disadvantages of installing a geothermal energy system in your residence?
Q4	Can you think of any other aspects related to the advantages and disadvantages of installing a geothermal energy system in your residence?
Q5	What individuals or groups of people would support or believe that you should install geothermal energy systems in your residence?
Q6	What individuals or groups of people would not support or believe that you should not install geothermal energy systems in your residence?
Q7	Besides some of the people mentioned above, who else do you think could influence you on this decision?
Q8	What factors or circumstances would motivate you to install a geothermal energy system in your residence?
Q9	What factors or circumstances would make it difficult or even impossible for you to install a geothermal energy system in your residence?
Q10	Besides the above-mentioned factors and circumstances affecting the installation of a geothermal energy system, can you think of any other factors that might be relevant?

- Demographics: Age, education, occupation, income, and geographic region.
- Housing Characteristics: Type of residence, year of construction.
- Energy Standards: Current energy ratings or certifications of the house.
- Heating Systems: Types of heating currently used.
- Heating Costs: Annual energy expenditures for heating.
- Renovation Status: Information on any ongoing or planned housing renovations.

Section 2: TPB constructs

Following Ajzen's (2002) [63] methodological guidelines for TPB research, we developed belief variables based on our elicitation study since no validated scales exist for beliefs about geothermal technology adoption. This approach is standard in TPB studies as beliefs are context-specific and must reflect the particular behavior and population under investigation. As Ajzen notes, belief measures, unlike direct measures of attitudes, subjective norms, and PBC, represent diverse considerations in decision-making and are not expected to demonstrate internal consistency. Our formative indicators were derived directly from the most frequently mentioned beliefs in our elicitation interviews, ensuring their relevance to Dutch homeowners considering geothermal technology adoption.

Based on Ajzen (2002) [65], three questions were asked to measure individuals' intentions, attitudes, subjective norms, and PBC (detailed in Appendix A). These variables are referred to by Ajzen (2020) [61] as reflective indicators. In contrast, behavioral, normative, and control beliefs, along with their evaluations, are termed formative indicators because they are assumed to shape attitudes, subjective norms, and PBC, respectively [61]. In Step 1, we identified the most frequently mentioned beliefs through a survey of 20 homeowners in the Netherlands. To quantitatively measure the formative indicators, these beliefs were converted into a set of statements, and respondents were asked to rate the strength or value of each belief. Respondents rated the strength of each belief on a scale of 1 to 7, with higher scores indicating stronger agreement with positive attitudes, subjective norms, or PBC toward geothermal technology adoption. The specific wording of the formative indicators and their corresponding statements are detailed in Appendix B, while mean values of these responses are illustrated in Fig. 4.

After developing the questionnaire based on the elicitation study, we conducted pre-testing with 15 different Dutch homeowners to assess clarity, comprehensibility, and completion time. Based on their feedback, technical terminology was simplified, instructions were improved, and the question flow was optimized before final deployment.

3.2. Data collection

The data was collected by Panel Inzicht N.V. (https://panelinzicht.nl/), a leading research panel provider in the Netherlands. The survey was primarily conducted online, with the questionnaires translated into Dutch to ensure clarity and ease of response. To ensure the sample was representative, the distribution method accounted for key demographics such as age (18 +), gender, and Nielsen regions. This sampling approach adhered to the standards of the Gouden Standaard, a nationally recognized calibration tool developed by the MOA (Market Research Association) in collaboration with ABF, based on data from the Dutch Central Bureau of Statistics (CBS). The Gouden Standaard ensures consistent and reliable data collection across the industry by using the latest available data, including the 2022 field survey. More information about the Gouden Standaard is available at https://www.moa.nl/gouden-standaard-expertise-center.html.

Initially, Panel Inzicht sent a "soft launch" email to a random subset of panel members to estimate response rates before the full-scale survey. After verifying the initial data, the survey was launched in batches to meet response quotas without exceeding them. Panel Inzicht reported a

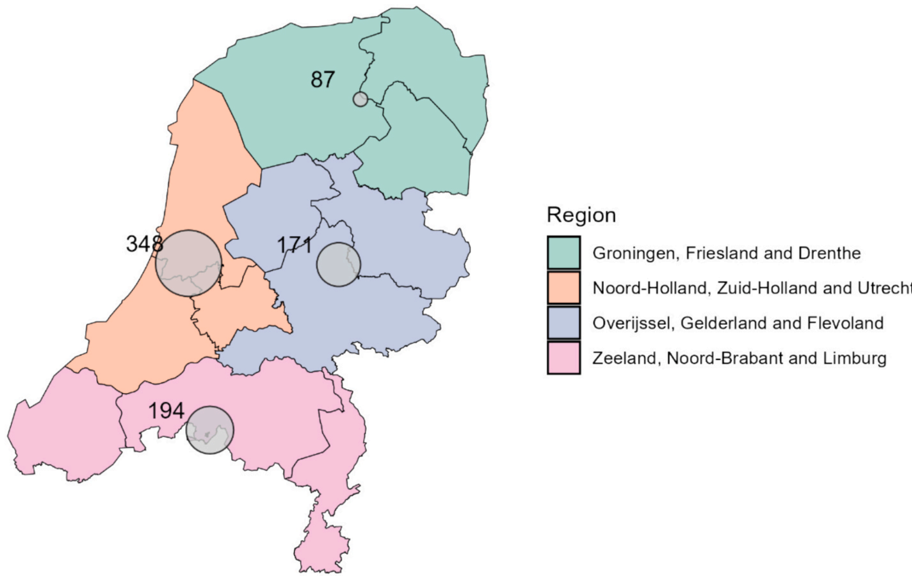

Fig. 4. Distribution of sample and sample size.

click-through rate of 17 %, with a completion rate of 60.5 %. Following the panel provider's standard protocol of oversampling by 10 % for quality assurance purposes, 880 questionnaires were initially collected. After the data cleaning process conducted by Panel Inzicht, which included removing incomplete responses, screening out speeders (participants who completed the survey unrealistically quickly), eliminating inconsistent response patterns, and adjusting the sample to ensure representative socio-demographic characteristics based on the Gouden Standaard benchmarks, the final sample size was 800. Table 2 outlines the basic demographic statistics of the respondents.

To assess the representativeness of our sample, we compared its key characteristics against national benchmarks. Overall, the sample aligns well with the broader homeowner population, though some deviations are apparent. Participants are slightly younger on average and include a modestly lower share of men. Education levels in our sample trend higher than national figures, while family income and detailed energy-rating comparisons are challenging due to differing category definitions. Housing-type distributions closely mirror national shares. Average heating costs are practically equivalent, and VvE membership appears higher in our data, though those figures should be treated cautiously given known limitations in association-membership reporting. Collectively, these insights suggest our respondents form a reasonably representative cross-section of Dutch homeowners, albeit with some minor biases.

Fig. 4 illustrates the geographic distribution of surveyed location: 87 participants were from Groningen, Friesland, and Drenthe participated; 348 respondents came from Noord-Holland, Zuid-Holland, and Utrecht; 172 respondents were from Overijssel, Gelderland, and Flevoland, and Zeeland, Noord-Brabant, and Limburg had 194 respondents.

Although the survey covered a broad range of respondent demographics, this study highlights six key respondent characteristics: gender, education level, family income, energy level, current heating system, and heating costs. The average respondent age was 50.74 years, which reflects the target demographic of homeowners who typically have decision-making authority. Gender distribution was nearly equal, with 49.4 % male and 50.6 % female. Educational attainment was classified according to the Dutch system, with 54.9 % holding a bachelor's degree or higher, closely aligning with Statistics Netherlands (CBS) data. In terms of income, 45.9 % of homeowners reported a monthly after-tax family income between €3,000 and €5,000, reflecting national income distribution patterns.

3.3. *Statistical methods*

This study applied Structural Equation Modeling (SEM) to test the proposed TPB model. SEM was selected for its ability to handle multiple independent and dependent variables simultaneously, making it well-suited to analyzing complex causal relationships. Additionally, SEM allows for the examination of both observed and latent variables, while accounting for measurement error, offering a robust analysis framework.

To assess the reliability and validity of the measurement model, we used Confirmatory Factor Analysis (CFA). Internal consistency was evaluated through both Composite Reliability (CR) and Cronbach's Alpha (CA). Convergent validity was assessed using Average Variance Extracted (AVE), while discriminant validity was examined using the Heterotrait-Monotrait (HTMT) ratio, which provides more accurate discriminant validity assessment than traditional approaches [69].

Since the ML method cannot directly test the significance of indirect or total effects, we used bootstrapping techniques to assess these effects. Bootstrapping allowed for resampling and offered a more comprehensive view of the model's significance, particularly for non-normally distributed indirect effects. Descriptive analyses and plotting were performed using R, while the SEM analyses were conducted with AMOS 21 software within SPSS.

4. Results

4.1. *Descriptive analysis*

The descriptive analysis of this study offers valuable insights into Dutch homeowners' intentions, attitudes, subjective norms, and PBC toward adopting geothermal technology for building indoor heating. Prior to analysis, comprehensive reliability and validity tests were conducted for all constructs. During the initial assessment, the PBC construct required refinement. Specifically, pbc1 was removed from the PBC construct to improve internal consistency, as reliability analysis indicated that its exclusion increased Cronbach's alpha from 0.56 to 0.75. Following this methodological adjustment, all constructs demonstrated satisfactory reliability (Cronbach's Alpha > 0.7, CR > 0.7) and validity (AVE > 0.5, HTMT < 0.85) as shown in Appendix C (Confirmatory factor analysis), ensuring that only reliable and valid measures were used in subsequent analyses.

A comprehensive summary of these factors is presented in Appendix

Table 2
Demographic statistics of respondents and target population.

Demographic Variable	N	Percentage/Mean (Our sample)	Target population
Age	800	50.74	54 (median)
Gender			
Male	395	49.4 %	53.3 %
Female	405	50.6 %	46.7 %
Education Level			
Master's degree or above (above 23 years)	115	14.4 %	44.9 %
Bachelor's degree (17–22/23 years)	324	40.5 %	
Vocational or secondary vocational education (16–19 years)	197	24.6 %	54.6 %
High school education (12–17 years)	130	16.2 %	
Lower level of secondary education (12–16 years)	34	4.3 %	
Family Income (monthly, after-tax)			
a) less than €1.000	20	2.5 %	€3457 (mean, before tax)
b) €1.000 – €2.000	62	7.8 %	
c) €2.000 – €3.000	150	18.8 %	
d) €3.000 – €4.000	208	26.0 %	
e) €4.000 – €5.000	159	19.9 %	
f) €5.000 – €7.500	138	17.3 %	
g) €7.500—–10.000	43	5.4 %	
h) more than €10.000	20	2.5 %	
Housing Type			
Terraced house	314	39.3 %	40.5 %
Detached House	162	20.3 %	20.2 %
Semi-Detached House	202	25.3 %	19.8 %
Apartment	104	13.0 %	16.6 %
other	18	2.3 %	2.2 %
Energy Level of Dwelling			
A	169	21.1 %	16 %
B	148	18.5 %	7 %
C	150	18.8 %	12 %
D	58	7.2 %	5 %
E	45	5.6 %	3 %
F	15	1.9 %	2 %
G	17	2.1 %	2 %
I don't know	198	24.8 %	52 %
Heating Cost (Euros, last year)	800	1422	1387
VvE (Vereniging van Eigenaren, homeowners' association) member	221	27.6 %	15 %

Note: There are no official statistics on the demographics of Dutch homeowners. Data on age, gender, education level, income, and housing type are drawn from [66], with different variable categories. Energy performance ratings come from WoON 2024 (https://woononderzoek.nl/documenten/WoON-2024). Information on heating costs and VvE membership is sourced from [67] and [68].

A, with corresponding visual representation in Fig. 5. The purpose of Fig. 5 is to establish baseline descriptive statistics for our TPB constructs and reveal key distributional patterns that inform our subsequent SEM analyses. Fig. 5 reveals that 33 % of surveyed homeowners indicate an intention to upgrade their indoor heating systems to geothermal technology within the next five years, while a substantial 47 % show low adoption willingness. This relatively high intention rate (33 %) is noteworthy when compared to the actual implementation of geothermal energy in the Netherlands, which represents only 2 % of the country's final renewable energy consumption as of 2023. This discrepancy illustrates the well-documented "intention-behavior gap" in environmental behavior research, where stated intentions often exceed actual adoption rates due to various practical, economic, and social barriers. Notably, the figure demonstrates a significant attitude-intention gap: while 56 % of homeowners maintain positive attitudes toward geothermal technology, only 33 % express concrete adoption intentions. This pattern motivates our detailed examination of underlying belief structures through SEM modeling to understand what drives this discrepancy.

This pattern indicates that significant barriers exist between positive perceptions and concrete implementation decisions. Regarding subjective norms, merely 29 % of homeowners reported positive support, indicating that influential social and professional circles may not fully endorse geothermal system adoption. Dutch homeowners showed moderate PBC, with 42 % expressing confidence in their ability to adopt and implement geothermal technology successfully within five years.

Fig. 6 illustrates the strength of behavioral, normative, and control beliefs on a scale from 1 to 7, with 1 as the weakest and 7 as the strongest. The specific wording for each belief can be found in Appendix B. The purpose of Fig. 6 is to examine the prevalence and strength of different beliefs among Dutch homeowners, providing insight into which concerns and considerations are most commonly held in the population regarding geothermal technology adoption. It is evident that the three strongest behavioral beliefs are the high initial investment for installing geothermal systems, the uncertainty of the payback period, and the contribution to environmental protection. The most influential groups affecting individuals' decisions are the homeowners' association (VvE), family, and government. As for control beliefs, the three strongest are the rising energy costs, a better understanding of geothermal systems, and the availability of reliable contractors. This analysis reveals which beliefs are most salient in the Dutch context, showing that economic concerns (high costs, unclear payback) are widely held, environmental benefits are commonly recognized, and institutional influences (VvE, government) are perceived as most important among social groups. Understanding the popularity of these beliefs helps identify the most common considerations in homeowners' decision-making processes.

4.2. SEM results

Based on the validated measurement model (Section 4.1, Appendix C), bivariate correlation analyses were performed between behavioral, normative, and control beliefs, along with relevant socio-demographic variables, to identify potential significant predictors of intention for inclusion in the SEM model. In this analysis, intention was calculated as the average of three reflective indicators, achieving a Cronbach's Alpha of 0.939, confirming high internal consistency. Pearson correlation tests were utilized for continuous socio-demographic variables (e.g., age), independent samples t-tests for dichotomous variables (e.g., gender), and ANOVA for categorical variables (e.g., income). The results indicated significant correlations between intention and socio-demographic variables such as age, income, VvE membership, energy level, and the percentage of heating costs relative to income ($p < 0.05$). These significant socio-economic variables were retained for the SEM model. To determine specific paths between these variables and beliefs, we then tested bivariate relationships, including only statistically significant connections in our model specification. All path coefficients in Fig. 7 were estimated simultaneously within the integrated SEM framework. Among behavioral beliefs, only "Reduce cost," "Help environment", "Safer", "Stable", and "Unclear payback" were significantly linked to intention, while all normative and control beliefs showed significant correlations with intention.

The final SEM model, illustrated in Fig. 7, displays model fit indices within acceptable ranges, confirming that our study model aligns well with empirical data. The squared multiple correlation (R^2) for the dependent variable is 0.595, indicating that 59.5 % of the variance in intention is explained by the predictors. This level of explanatory power significantly surpasses the average of 39 % reported by Armitage and Conner [70] in their *meta*-analysis of the TPB.

Table 3 presents the standardized direct, indirect, and total effects of various variables on respondents' intention to install a geothermal energy system. The analysis reveals that the strongest influence on intention comes from the respondents' attitude toward geothermal technology, followed by subjective norms. In essence, a more positive attitude and supportive social norms are associated with a greater

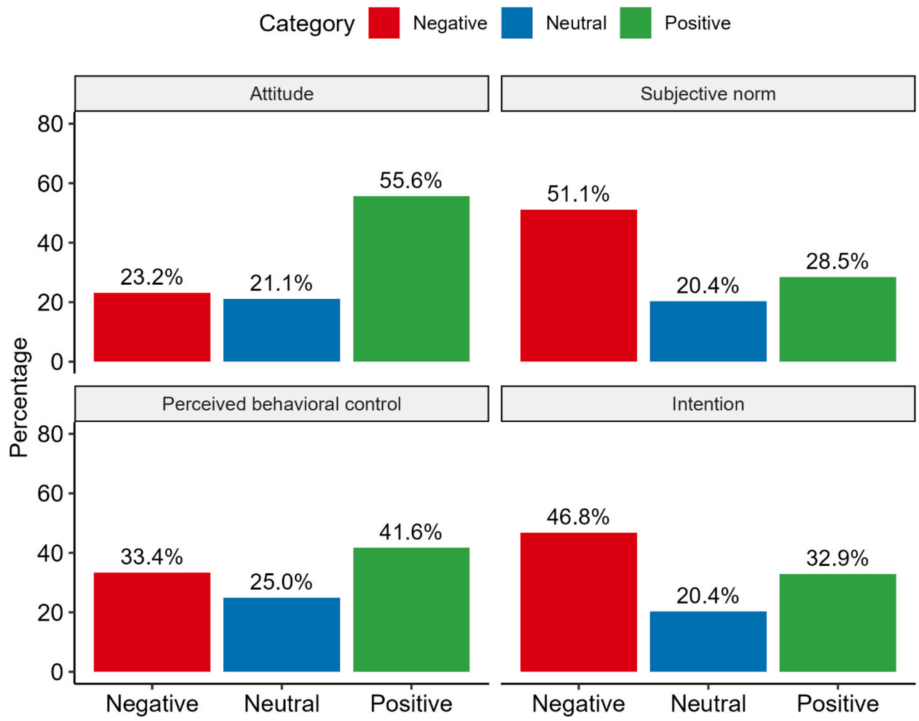

Fig. 5. General Intentions, Attitudes, Subjective Norms, and PBC of Respondents.

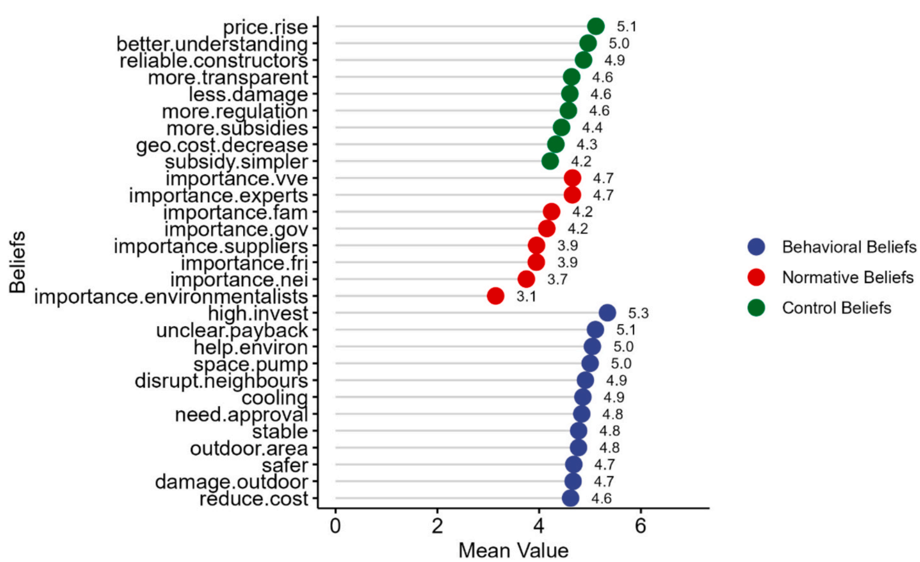

Fig. 6. Mean value of behavioral, normative, and control beliefs.

intention to adopt geothermal energy systems. Notably, PBC does not show a significant impact on intention.

As depicted in Fig. 7, all beliefs (formative indicators) exert a significant direct influence on attitude, subjective norm, or PBC. Among the formative indicators of attitude, beliefs regarding cost reduction and environmental benefits have the most substantial positive influence. Additional factors include perceptions of safety (i.e., lower risk of accidents like gas leaks) and stability, providing reliable energy regardless of external conditions. Conversely, the belief that the payback period for investing in geothermal technology is unclear negatively impacts attitude, suggesting that uncertainty regarding financial returns leads to more negative perceptions of geothermal adoption.

For subjective norms, the perceived importance of various groups significantly affects these norms. Specifically, the opinions of environmentalists have the greatest impact, followed by suppliers, friends, and government influences. Although formative indicators of PBC significantly affect PBC, their overall impact on intention remains insignificant.

According to our theoretical framework, socio-demographic factors can indirectly influence homeowners' intention to adopt geothermal systems by affecting the formative indicators. The final SEM model includes five socio-demographic variables: age, VvE membership status, household monthly after-tax income, energy efficiency rating of the current home, and the proportion of last year's heating costs relative to household income. Other socio-demographic variables, such as gender, region, housing type, educational background, and last year's energy costs, were excluded from the SEM model due to lack of significant relationships identified in bivariate analysis.

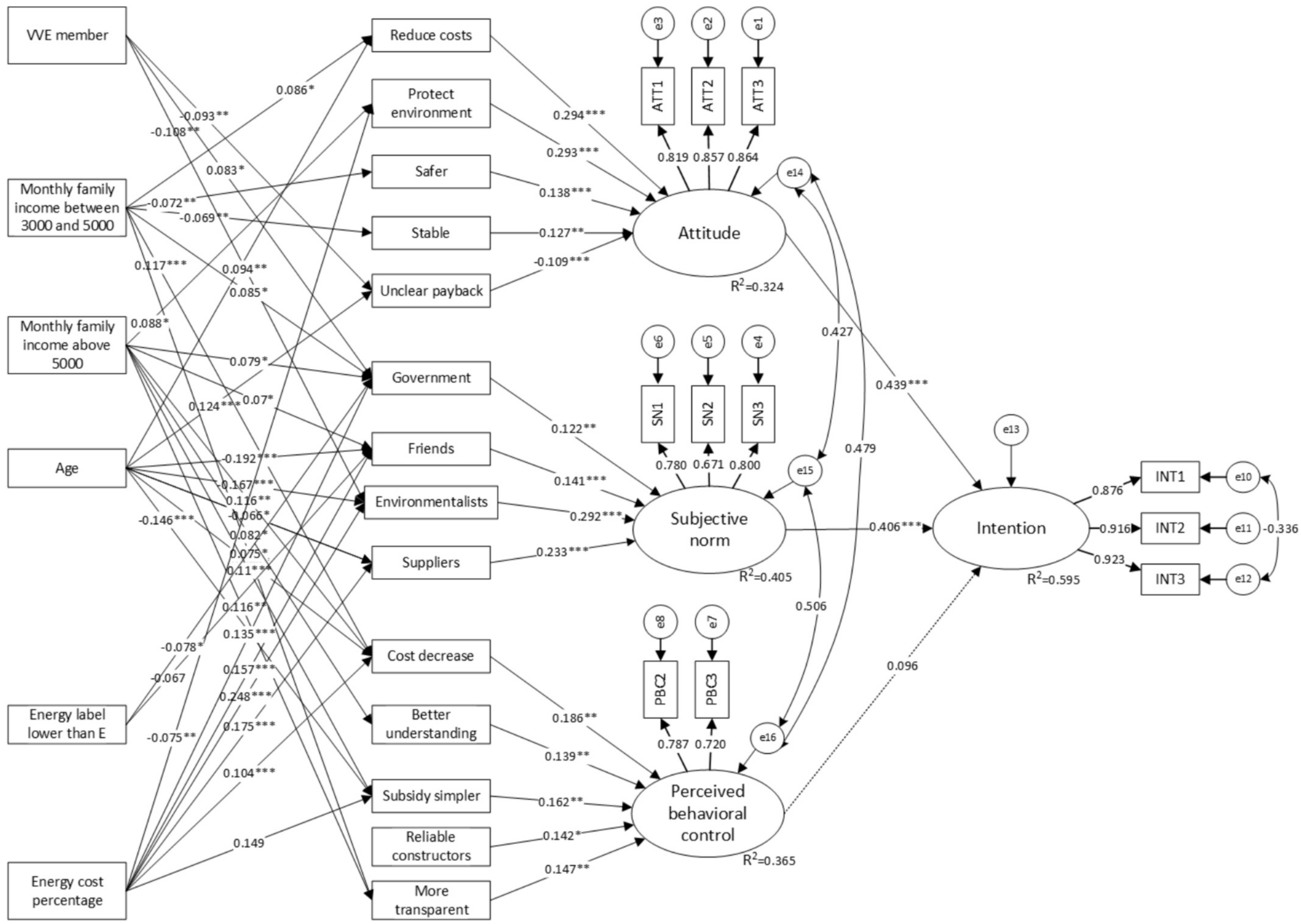

Fig. 7. The results of SEM. Notes: 1. *p < 0.05; **p < 0.01; ***p < 0.001; 2. Model fit indices: CMIN/DF = 5.507, CFI = 0.887, RMSEA = 0.075, SRMR = 0.138; 3. All coefficients are standardized; 4. All lines denote direct effects. Dotted lines denote insignificant relationships. Non-significant paths between background factors and belief variables are omitted for visual clarity.

To ensure adequate sample sizes in each category, we regrouped household after-tax monthly income and current home energy efficiency ratings. Household income was categorized into low (below €3,000), middle (€3,000–€5,000), and high (above €5,000), while energy efficiency ratings were grouped into A-B, C-D, E and below, and "unknown".

According to Table 3, the proportion of last year's heating costs relative to household income significantly impacts the intention to install geothermal systems. Households allocating a larger share of their income to heating are more likely to express an intention to adopt geothermal technology. Age also plays a role, with older individuals less inclined to adopt geothermal systems. Moreover, households with middle and high incomes show a significantly greater intention to adopt geothermal technology compared to low-income households. VvE members display a higher likelihood of intending to install geothermal systems than non-members. However, the current home's energy efficiency rating does not significantly affect the intention to adopt geothermal technology.

5. Discussions

5.1. The impact of attitude, subjective norms, and PBC

Our analysis reveals that attitude has the most significant influence on homeowners' intention to adopt geothermal technology, followed closely by subjective norms. This finding aligns with several studies in the broader field of renewable energy adoption, for example, Halder et al. [52] conducted a cross-cultural study of Finnish and Indian students' intentions to use bioenergy and found that attitude had the strongest influence on students' intentions across different cultural contexts, followed by subjective norms, while PBC had a negligible effect on intention Similarly, Kaffashi and Shamsudin [53] studied Malaysian citizens' intentions toward adopting behaviors that support a low carbon society and found that subjective norm had the largest impact on intentions to transform to a low carbon society.

Attitudes towards geothermal technology play a crucial role in shaping adoption intentions. Positive perceptions of the technology's benefits, such as environmental friendliness and long-term cost savings, strongly correlate with higher adoption intentions. This underscores the importance of educational campaigns and information dissemination in fostering favorable attitudes towards geothermal technology.

Subjective norms also emerge as a significant predictor of adoption intentions, highlighting the role of social influence in decision-making processes. The opinions of family, friends, and respected community members can substantially impact an individual's willingness to adopt geothermal technology. This suggests that community-based initiatives and peer-to-peer knowledge sharing could be effective strategies for promoting adoption.

Interestingly, despite PBC being a key component of TPB, this factor did not significantly predict adoption intentions in our study. This finding is not unprecedented in the literature on renewable energy adoption [52,53]. Two explanations seem particularly relevant: First,

Table 3
Standardized direct, indirect, and total effects on the intention to use geothermal technology.

Variable	Standardized direct effect on intention	Standardized indirect effect on intention	Standardized total effect on intention
Attitude	0.439***		0.439***
Reduce cost		0.129***	0.129***
Help environment		0.129***	0.129***
Safer		0.061***	0.061***
Stable		0.056**	0.056**
Unclear payback		−0.048***	−0.048***
Subjective norm	0.406***		0.406***
Government		0.05**	0.05**
Friends		0.057***	0.057***
Environmentalists		0.119***	0.119***
Suppliers		0.095***	0.095***
PBC	0.096		0.096
Cost decrease		0.018	0.018
Better understanding		0.013	0.013
Subsidy simpler		0.016	0.016
Reliable constructors		0.014	0.014
More transparent		0.014	0.014
Socio-demographic factors			
Age		−0.054***	−0.054***
VVE		0.029**	0.029**
Middle income		0.033**	0.033**
High income		0.04***	0.04***
Energy level C-D		0.008	0.008
Energy level below E		−0.008	−0.008
Energy level unknown		−0.008	−0.008
Cost percentage		0.059***	0.059***

Note: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

the relative novelty of geothermal technology for residential applications may result in less developed perceptions of behavioral control, making this factor less predictive than attitudes and social norms. Second, in the Dutch context, homeowners' decisions about geothermal adoption appear to be more strongly influenced by personal attitudes (particularly economic considerations) and less by perceived control. These findings suggest policy interventions should focus more on shaping attitudes and leveraging social influence rather than addressing perceived barriers to implementation. The significance of PBC varies across renewable energy studies. While our findings align with Halder et al. [52] and Kaffashi and Shamsudin [53] who found PBC to have minimal impact, other research has yielded different results. Harorli and Erciş [57] found that PBC played an important role in individuals' intention to adopt green energy. These contrasting outcomes suggest that the significance of PBC depends on the local context and the perceived difficulty associated with adopting the energy system in question. In regions where structural barriers are minimal and adoption is relatively easy, PBC may not emerge as a decisive factor. The relative influence of attitude and subjective norms also varies across different countries. In individualistic cultures, attitudes tend to dominate decision-making processes, whereas in collectivist cultures, subjective norms typically exert greater influence. This cultural variation helps explain why different studies have identified different primary drivers of adoption intentions.

Furthermore, the relative influence of attitude and subjective norms varies across different countries. Some studies have shown that attitude has the greatest influence [57], while others have found that subjective norms play a more significant role [53]. This variability suggests that the relative importance of these two factors may be context-dependent. In individualistic cultures, attitudes tend to dominate, whereas in collectivist cultures, subjective norms are more influential [71].

5.2. The influence of formative indicators

In the present study, four out of five beliefs significantly and positively influenced homeowners' attitudes towards adopting geothermal technology. Among these, the belief that "using geothermal technology can reduce energy costs" had the most substantial effect on attitude (0.294***). This finding highlights that the perceived cost-saving benefits of geothermal technology are a key factor influencing homeowners' attitudes. Reducing energy costs not only directly enhances homeowners' economic benefits but also increases their willingness to invest in geothermal technology in the long term. Therefore, this result underscores the importance of emphasizing economic benefits when promoting geothermal technology. The dominance of economic benefits in shaping attitudes finds support in recent research by Batool et al. [50], who identified cost concerns as the primary barrier to renewable energy adoption among households. Similarly, Rahmani et al. [49] found that financial considerations significantly influenced Iranian households' investment intentions in renewable energy projects, suggesting that economic factors remain paramount across different cultural contexts.

The belief that "using geothermal technology can reduce carbon emissions and environmental pollution" was the second most influential (0.293***), reflecting that Dutch homeowners' environmental concerns increase their willingness to adopt such technology. This finding, corroborated by Reyes-Mercado [72] mirrors the broader rise in environmental awareness in contemporary society, especially in European countries where public interest in sustainable development has notably increased. The motivation to protect the environment not only strengthens public support for geothermal technology but also serves as a crucial entry point for policymakers and promoters. Emphasizing the environmental benefits of geothermal technology can thus serve as an effective strategy for increasing public acceptance.

Furthermore, the beliefs that "geothermal technology is safer" (e.g., fewer incidents of gas leaks, fires, etc.) (0.138***) and "geothermal technology is more stable" (not affected by climate or weather conditions) (0.127**) also had significant positive impacts on attitude. These findings align with Claudy et al. [73], who found that perceived product characteristics, including safety features, significantly affect homeowners' willingness to adopt renewable energy technologies. Similarly, Mondani et al. [74] demonstrated that safety perception is a critical determinant in public acceptance of sustainable energy systems, particularly in contexts where households transition from conventional heating sources. Our finding regarding stability as a positive driver echoes research by Chen et al. [75], who demonstrated that reliability and consistency in performance are key social-psychological predictors of adoption intention for alternative energy systems.

Conversely, the belief that there is "uncertainty regarding the system's payback period" had a negative impact on homeowners' attitudes towards geothermal adoption (−0.109***). This indicates that the more unclear homeowners are about the payback period of geothermal systems, the more negative their attitude becomes. This finding is consistent with Ru et al. [76], who found that financial uncertainties reducing adoption willingness. This finding emphasizes the importance of transparent information. To increase acceptance of geothermal technology, businesses and suppliers could provide clear cost-benefit analyses and detailed payback period information to alleviate potential users' concerns, while policymakers should establish frameworks for standardized assessment methodologies that ensure these analyses are reliable and comprehensive.

In terms of subjective norm beliefs, this study shows that "environmentalists" have the greatest influence on homeowners' intention to adopt geothermal technology (0.292***). Interestingly, our frequency analysis revealed that many respondents (40.1 %) rated environmentalists' opinions as "unimportant" or "extremely unimportant" to their decision-making—significantly higher than for friends (18.9 %) or neighbors (23.3 %). This apparent contradiction suggests that environmentalists' influence may be particularly powerful among certain segments while facing resistance in others, aligning with Gromet et al. [77], who found that explicit environmental labeling can produce negative reactions in some consumer groups. The strong but unevenly distributed normative influence suggests that environmental advocacy creates social expectations that legitimize geothermal adoption, though messaging strategies should be tailored to different homeowner segments.

Geothermal system suppliers rank second in influence (0.233***). Suppliers determine the quality and operational stability of geothermal systems and influence homeowners' decisions through community outreach activities. This finding aligns with Soltani et al. [78], who identified suppliers as key stakeholders in the social acceptance of geothermal technology. Their research similarly found that suppliers serve not only as technology providers but also as important facilitators of community engagement, though our study quantifies this influence more precisely.

Support and advocacy from friends and colleagues also have a certain impact on homeowners' intention (0.141***). He et al. [79] found that information about renewable energy technologies spreads most effectively through trusted network members such as friends and family. Our research confirms this finding for geothermal technology specifically, establishing friends and colleagues as the third most important influence group after environmentalists and suppliers.

Government agencies also have some influence on homeowners' subjective norms regarding geothermal adoption (0.122**), which, in turn, affects their willingness to participate in geothermal use. This finding aligns with Nkinyam et al. [80], who found that despite geothermal energy's potential as a sustainable energy source, its competitiveness requires stronger government backing through favorable feed-in tariffs and preferential tax treatment to overcome adoption barriers. However, government policies are not always widely accepted by homeowners. For instance, in Malaysia, most citizens believe that the government's plans and policies regarding renewable energy have not been successful [81]. This may be due to an unfavorable policy environment and context that hinder the effective implementation of these measures.

5.3. The influence of socio-demographic factors

This study examined five socio-demographic factors, and the results show a significant association between homeowners' willingness to adopt geothermal technology and the following factors, listed in order of impact: the proportion of energy expenses to income in the previous year, the homeowner's age (with a significant negative correlation, meaning older individuals are less willing to adopt), income level (lower-income groups show weaker willingness), VvE membership (VvE members exhibit stronger willingness), and the energy efficiency grade of the home (households with energy grades C and D display the strongest willingness).

Among these variables, the proportion of energy expenses to total household income in the previous year had the most significant influence on the willingness to install geothermal systems. The study indicates that as energy expenses take up a larger share of the household budget, homeowners have a more pressing need to reduce these costs and are thus more inclined to seek cost-effective solutions, such as geothermal systems. This finding aligns with economic theory, which suggests that when a particular expenditure exerts pressure on a household budget, families are more likely to take action to mitigate that burden. It also highlights that economic strain is one of the key drivers for adopting energy-saving technologies, especially in households with fluctuating energy prices or low energy efficiency. This result is consistent with Kardooni et al. [81], who found that income significantly impacts the willingness to pay for renewable energy, suggesting that higher income may facilitate greater willingness to adopt such technologies.

Age was the second most significant determinant of homeowners' willingness to adopt geothermal systems. This finding is supported by Michelsen & Madlener[22], who report that older German homeowners favor conventional oil-fired solutions over innovative systems—such as heat pumps or wood-pellet boilers. Similarly, Sopha et al. [82] show that in Norway, younger people are more open to considering new heating technologies like heat pumps and wood pellet stoves, while older people tend to prefer more traditional electric heating systems that they are familiar with. Willis et al. [83] found older households (over 65) are more resistant to investing in new energy technologies like solar, wind, and heat pumps. These patterns likely stem from seniors' more conservative attitudes toward new technologies and their emphasis on financial and lifestyle stability, which make the high initial cost and slow payback of geothermal systems less attractive. Therefore, rather than direct promotional campaigns aimed at seniors, policy could prioritize cohorts with higher receptivity, while structural measures (e.g., mandatory efficiency upgrades during renovations, neighborhood-scale geothermal schemes, or integration into building codes) can help overcome older homeowners' resistance.

The study shows that middle- and high-income families are significantly more willing to adopt geothermal systems compared to low-income households. Rezaei & Ghofranfarid [84] found that people with sufficient financial resources are more likely to use renewable energy. This finding also coincides with Kardooni et al. [81], who highlighted that as Lithuania's economy grows, higher personal income could increase the willingness to purchase renewable energy in the future, as income level significantly influences the willingness to pay for renewable energy. This phenomenon may reflect the financial burden of geothermal systems' high initial installation costs on low-income families. Although geothermal systems can reduce energy costs in the long run, the high initial investment may deter low-income households from taking the risk, thereby suppressing their adoption willingness. On the other hand, middle- and high-income families have more financial capacity to absorb the upfront costs and are more likely to see the long-term cost savings as a worthy investment. Therefore, promotional strategies targeting low-income households may need to include financial support measures, such as subsidies or loans, to reduce their economic barriers.

VvE members demonstrated a higher willingness to install geothermal systems. In the Netherlands, VvEs are primarily responsible for building management and maintenance, including external payments and regular homeowner meetings [85]. Unlike in some countries like Germany where unanimous votes are often required, Dutch VvEs operate with a more flexible decision-making structure. According to the Dutch Civil Code (Article 5:127), regular maintenance decisions typically require only a simple majority (50 % plus one), while significant non-maintenance expenditures require both a minimum attendance quorum (usually two-thirds) and a qualified majority vote. VvE members often engage in collective decision-making and are influenced by social dynamics and information sharing within the group. They typically discuss and decide on technical upgrades or retrofitting projects in their residential areas, making geothermal systems, as a collectively beneficial technology, more likely to gain traction within VvE contexts. The ability to share substantial initial costs across multiple owners makes expensive renewable investments more financially feasible. The positive influence of VvE membership on adoption intentions provides empirical support for collective efficacy theory [86], which suggests that group-level perceptions of capability can enhance individual behavioral intentions. This finding extends beyond individual-level TPB applications to demonstrate how collective decision-making structures can fundamentally alter the psychological processes underlying technology adoption, contributing to our understanding of how institutional contexts shape individual behavior.

In this study, the energy efficiency grade of homes did not have a significant impact on homeowners' willingness to adopt geothermal systems. Although homes with lower energy grades are theoretically more motivated to improve energy efficiency, the results indicate that energy efficiency grades were not a primary factor in homeowners' decisions to install geothermal systems. This may be because other factors, such as economic pressures or social influence, play a more prominent role in decision-making, or because households may prioritize more familiar or easier-to-implement technologies when considering energy efficiency improvements. Additionally, homeowners might lack sufficient awareness of the benefits of energy efficiency improvements or may have doubts about the effectiveness of geothermal systems, affecting the significance of this variable.

It is worth noting that while education level is often assumed to be related to willingness, with higher education levels leading to a deeper understanding of renewable energy systems and stronger adoption intentions [87,88], the bivariate analysis in this study found no significant correlation between education level and homeowners' willingness to adopt geothermal technology. Possible explanations for this are: although higher education levels may indeed increase individuals' awareness and understanding of geothermal technology, this enhanced knowledge may not necessarily translate into higher adoption willingness. For instance, even though highly educated homeowners may better understand the principles and advantages of geothermal systems, they might still be deterred by high initial costs, uncertain payback periods, or other financial concerns, reducing their actual willingness to adopt.

Collectively, our findings make several important theoretical contributions to TPB literature and renewable energy adoption research. The non-significant role of PBC challenges Ajzen's (2020) [24] assertion of universal construct applicability, suggesting that for technologies requiring extensive external infrastructure and professional expertise, individual perceptions of control become less relevant than evaluative and normative considerations. This finding extends recent critiques of TPB's assumption that all three constructs universally predict intentions across contexts [89]. More importantly, our discovery that socio-demographic factors create differentiated psychological pathways extends TPB beyond its traditional individual-level focus, demonstrating how structural factors can fundamentally alter psychological processes. The significant role of energy cost-to-income ratio as a motivational catalyst supports social cognitive theory's emphasis on the reciprocal interaction between personal, behavioral, and environmental factors [90], while the positive influence of VvE membership provides empirical support for collective efficacy theory [86]. These findings contribute to a more nuanced understanding of how economic constraints and institutional contexts shape individual technology adoption decisions, with implications for TPB applications across various domains of sustainable behavior.

5.4. Limitations and future research

While this study provides valuable insights into the factors influencing homeowners' intention to adopt geothermal technology, this study has several limitations that should be considered when interpreting the results.

Firstly, this research focused exclusively on measuring homeowners' intentions to adopt geothermal systems rather than tracking actual adoption behavior. While intentions are strong predictors of subsequent behavior [25,70], an intention-behavior gap clearly exists. We found a relatively high adoption intention rate (33 %) among respondents, yet actual geothermal energy implementation represents only about 2 % of renewable energy consumption in the Netherlands. This discrepancy may reflect differences between perceived and actual behavioral control. Future research would benefit from longitudinal designs that track both intentions and subsequent behaviors while measuring actual control factors that may prevent implementation.

Secondly, this study faces methodological limitations. Our sample size of 800 Dutch homeowners may be insufficient to capture nuanced demographic differences. Additionally, potential social desirability bias may have influenced responses, particularly regarding environmental attitudes. Furthermore, the operationalization of belief variables presents another methodological limitation. While our elicitation study followed standard TPB procedures [71,92], the process of translating qualitative interview responses into quantitative belief measures may have resulted in some information loss or oversimplification. The belief variables identified through our 20-participant elicitation study, though reaching theoretical saturation, may not capture the full spectrum of beliefs held by the broader Dutch homeowner population. Additionally, the representativeness of the 20 elicitation study participants may be limited, as their demographic characteristics and regional distribution could have influenced which beliefs were identified as most salient, potentially affecting the comprehensiveness and generalizability of the belief-based constructs.

Thirdly, this research does not compare homeowners' willingness to adopt geothermal systems with their willingness to adopt alternative heating technologies, both renewable (e.g., solar thermal, air-source heat pumps) and non-renewable. Such comparisons would provide a more comprehensive understanding of how geothermal systems compete with other options in homeowners' decision-making processes.

Thirdly, this research lacks comparison with alternative heating technologies, limiting understanding of how geothermal systems compete with other options. Additionally, excluding other stakeholders (government agencies, energy service companies, and technology providers) provides an incomplete view of the adoption ecosystem. Finally, transferability to other countries with different cultural contexts and policy environments represents another limitation.

Future research should address these limitations through longitudinal designs, expanded samples, comparative analyses with alternative technologies, multiple stakeholder perspectives, and cross-cultural studies to facilitate more effective geothermal technology promotion strategies.

6. Conclusion and policy implications

The ongoing challenges of climate change and energy crisis within the European Union highlight the urgent need to understand households' renewable energy adoption decisions. This paper investigated Dutch homeowners' intentions to adopt geothermal systems using the TPB, analyzing data from 800 representative households. This study provides a multidimensional analytical framework for understanding the willingness of Dutch households to adopt geothermal technology, revealing the interplay between attitudes, subjective norms, behavioral control, and socio-demographic factors in this complex decision-making process.

Our findings reveal that attitudes and subjective norms significantly influence geothermal adoption intentions, with PBC playing a smaller role—likely due to generally high confidence levels among Dutch households. This finding contributes to TPB literature by demonstrating that PBC's predictive power may be context-dependent, particularly in situations where technological adoption requires significant external infrastructure and professional expertise rather than individual behavioral control. The dominance of attitudes and subjective norms over PBC suggests that for complex technological decisions, homeowners' evaluations of technology benefits and social influences outweigh their perceptions of personal control capabilities.

Economic benefits emerged as the strongest factor motivating adoption, followed by environmental protection, safety, and energy stability benefits. Uncertainty about investment payback periods represented the primary barrier. Regarding normative influences, environmental advocates had the strongest impact on adoption intentions, followed by geothermal suppliers, social networks, and government agencies. Among socio-economic factors, the proportion of energy costs to income most significantly affected adoption intentions, with households facing higher energy cost burdens more likely to consider geothermal systems. Age showed a negative correlation with adoption willingness, while higher income and homeowners' association membership positively influenced adoption intentions.

Based on these findings, this study offers several concrete policy recommendations. Policymakers should develop standardized cost-benefit assessment tools that provide transparent payback period calculations, directly addressing the primary barrier identified in our study. Rather than generic promotional campaigns, governments should implement differentiated policy instruments: graduated subsidy structures that increase support for households with higher energy cost-to-income ratios, streamlined VvE decision-making processes through regulatory reforms that lower voting thresholds for renewable energy investments, and mandatory energy transition planning requirements for homeowners' associations. To leverage the identified normative influences, policies should establish geothermal technology demonstration sites in diverse communities to activate descriptive norm influences and create professional certification programs that enhance supplier credibility.

For households facing high energy costs, governments should offer targeted economic assistance including income-adjusted subsidies and low-interest financing products that align with household energy cost burdens. For older adults and low-income groups, who showed lower adoption intentions in our study, policymakers should develop alternative participation pathways such as community-based shared ownership models, long-term financing schemes with minimal upfront costs, and phased approaches to energy transition that align with their economic capabilities. Simultaneously, governments should fully leverage community organizations like VvEs to promote geothermal technology through collective action and resource sharing, creating opportunities for participation by those unable to invest individually.

For industry practitioners, our findings suggest prioritizing economic benefits in marketing messages while emphasizing environmental co-benefits, reflecting the co-dominant belief structure identified. Companies should develop targeted communication campaigns that leverage environmental advocate endorsements and establish transparent pricing models with standardized payback period calculations to address uncertainty barriers. The significant role of suppliers as normative influencers suggests that professional credibility and community engagement are crucial for market development.

This study's theoretical contributions extend TPB's applicability to geothermal energy adoption while revealing context-specific mechanisms that inform both theory development and practical intervention design. The finding that economic and environmental benefits can be mutually reinforcing rather than competing provides optimism for sustainable energy transitions. The 33 % stated intention rate versus the current 2 % actual geothermal energy consumption in the Netherlands highlights the persistent intention-behavior gap in environmental decision-making, suggesting that while psychological factors are necessary for adoption, they may not be sufficient without addressing structural and institutional barriers.

As the Netherlands pursues its ambitious geothermal energy targets, understanding and addressing the psychological processes underlying homeowner decisions will be crucial for achieving widespread adoption of this promising renewable technology. This approach will facilitate the widespread adoption of geothermal technology, contributing to sustainable energy transitions globally.

CRediT authorship contribution statement

Zhengxuan Liu: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Data curation. **Queena K. Qian:** Writing – review & editing, Supervision, Resources, Project administration. **Bo Li:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Chi Jin:** Writing – review & editing, Validation, Methodology, Investigation. **Henk Visscher:** Writing – review & editing, Supervision, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors are grateful to acknowledge financial support from the Horizon Europe (101066635-PSGHCERB).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2025.116386.

Data availability

Data will be made available on request.

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