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ORIGINAL ARTICLE

Estimating implicit discount rate for energy efficiency investment using the contingent valuation method: a case study in South Korea

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Abstract This study measures the implicit discount rate (IDR) for energy efficiency investment at the household level. Our pioneering attempt to use the contingent valuation method suggests fresh insights into relieving the possible problems induced when the IDR is estimated using multiple price list and open-ended questions. Using the survey data from 2392 respondents in South Korea, we measured the IDR for appliances with high energy efficiency. The measurement ranges from 21.80 to 25.94%, implying the overestimation in existing literature. This study contributes to the literature by determining the role of cognition and experience in energy efficiency investment. Cognition has a statistically significant negative impact on IDR and depends on the appliance type, whereas risk preference has no meaningful impact. Energy efficiency improvement experiences are the critical factor in reducing IDR, that is, promoting energy efficiency investment, especially for recently introduced appliances. Overall, our finding suggests that information that induces high cognition on the cost–benefit analysis and energy efficiency labeling can lower IDR and thus promote energy efficiency. Our study also suggests that targeting energy consumers who have experience in energy-saving campaigns or programs could be a priority because such experiences are crucial to IDR reduction.

Keywords Contingent valuation method · Implicit discount rate · Energy efficiency investment · Cognitive reflection test

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Introduction

Climate change is a critical threat to the future and should be addressed for the next generation (Chan, 2018). Energy production and usage have been mentioned as a main contributor to greenhouse gas (GHG) emission, accounting for 87% of world emissions (IEA, 2020). The energy sector devotes global efforts to mitigate GHG emissions with various measures, such as renewable energy source adoption and consumption curb through demand management. Especially in advanced countries, energy-related carbon emissions have been successfully mitigated through clean energy development (IEA, 2020). However, energy-related GHG emissions are projected to increase in developing economies (EIA, 2019), keeping the current status of the energy-climate issue to be an international issue.

Although energy consumption involves GHG emissions, policymakers cannot call for drastic energy reduction because energy also plays a vital role in economic growth (Apergis & Payne, 2012). According to the energy-growth nexus theory, a significant relationship exists between energy consumption and economic growth (Apergis & Payne, 2009). Under the circumstances that energy consumption is essential for economic growth, scholars have attempted to determine how the environment is conserved without reducing the production factor.

IEA (2019) emphasized that energy efficiency is the first fuel, which should be prioritized to address climate change. Energy efficiency improvement can save energy consumption that is deeply related to carbon emissions, as mentioned above. Naturally, 10% improvement in energy efficiency is directly connected to 10% reduction of energy consumption, assuming the absence of the energy rebound effect (T. Jin & Kim, 2019). Accordingly, energy efficiency improvement can mitigate carbon emissions by reducing energy usage involving GHG. If energy-related emissions become zero by making energy transition to clean energy mix, energy efficiency improvement might be an ineffective tool for coping with climate change. However, renewable expansion with the energy transition policy will overburden the electricity system. Energy efficiency improvement can also be an effective tool to mitigate it (X. Jin et al., 2017). According to Karatasou et al. (2014), energy policy for efficiency must be established because energy efficiency with consumer behavior change takes a long time. At this point, how to improve energy efficiency with consumer behavior correction must be determined.

To address the climate problem, the Paris Agreement in 2015 demands the parties to submit the modified action plan every 5 years. In 2020, Korea also constructed a long-term low GHG emission development strategy. As a result, the Korean government declared the "2050 Carbon–Neutral Strategy" that emphasizes the innovation of energy efficiency as a tool for carbon–neutral. Specifically, the supply of appliances with high energy efficiency has been listed in the policy goals. Moreover, the role of households in energy efficiency improvement becomes important (Lakić et al., 2021).

The supply program supported by determinants of adopting appliances with high energy efficiency in the household sector should be planned to magnify the policy impact on energy efficiency. This study measures the implicit discount rate (IDR) of consumers on energy efficiency investment, in the context of South Korea. The estimated IDR can show consumers' evaluation of the future value of energy reduction benefit induced by energy efficiency investment. The energy efficiency policy, which does not reflect the IDR of household consumers, may be ineffective (Solà et al., 2021). Additionally, policymakers can diversify policy design and evaluation according to the IDR results. This also promotes the outcome of energy efficiency policy.

This study contributes to the literature on several points. First, we introduce the contingent valuation method (CVM), which is frequently adopted to measure the willingness-to-pay (WTP) or willingness-to-accept (WTA), to estimate the IDR of household energy efficiency investors (Woo et al., 2019). This can supplement the shortcoming of multiple price list (MPL) that can be a representative method to estimate IDR in that MPL elicits interval responses rather than "point" valuations (Andersen et al., 2006).[1] Additionally, the IDR depends on the appliance type and trend. Second, we confirm that the energy efficiency improvement experiences are the additional determinants of IDR. The experiences lower IDR, and thus, it leads to the energy efficiency investment, which demonstrates the useful information to make energy efficiency policy. Finally, the cognitive reflection test (CRT) is adopted as a proxy of cognition to determine the impact of cognition on IDR. Our novelty can be focused in that we estimate IDR with CVM combining behavior economics and cognition psychology, suggesting fresh insight in energy efficiency investment field.

The rest of the paper is organized as follows. The "Literature survey" section introduces the existing literature about IDR, especially focusing on the energy field. The "Methodology" and "Empirical results" sections present the estimation methods and empirical results, respectively. Finally, the "Conclusion and

[1] The disadvantages of MPL are elaborated in "Advantages of CVM for IDR estimation".

policy implications" section presents the conclusions and policy implications.

Literature survey

For the household sector, electricity consumption is expected to increase, whereas energy consumption will decrease, owing to the enlargement and enhancement of house appliances, with electrification policy (Jihyo Kim et al., 2016). Appliances with high energy efficiency are more expensive than general ones, but they can reduce the future cost of energy consumption in the lifetime of appliances. The results of cost–benefit analysis on highly energy-efficient appliances revealed that most appliances with high energy efficiency are more cost-effective than the general ones (Ellis et al., 2007).

However, an energy efficiency gap exists between energy efficiency investment and consumer purchase behavior. Gerarden et al., (2015) explained why the energy efficiency gap has induced much higher IDR for energy efficiency investment than general purchase of goods among consumers. Because of the gap in time between cost and benefit, a consumer with high IDR must underestimate the future benefit from energy reduction. According to Stadelmann, (2017), existing literature covering IDR has overestimated IDR because estimated IDR includes irrational behavior and market failure.

Studies on IDR estimation have been based on purchasing data of consumers. For instance, Hausman, (1979) and Train, (1985) have attempted to estimate IDR for appliance purchase, but they derived seriously overestimated IDR. To measure precise IDR on energy efficiency investment, several scholars have developed the survey techniques and estimation methods. Recently, Haq & Weiss, (2018) conducted a meta-analysis based on 21 research papers covering IDR for energy efficiency investment in households. Studies investigating IDR for energy efficiency investment have commonly derived much higher IDRs than market interest rate. Additionally, they concluded that the IDR depends on socio-demographic factors such as income and the type and price of highly energy-efficient appliances.

According to Sanstad & McMahon, (2008), who reviewed IDR of energy decision-making, personal IDRs have huge gap and are widely distributed with a range from 17 to 300%. The IDR has been found to exhibit time-variant characteristics and depend on equipment type; thus, the IDR is hard to be generalized (Frederick et al., 2003). The other study on the IDR for energy efficiency investment found large deviations of IDRs, according to the estimated standard deviation of 23% (Newell & Siikamki, 2015).

From the experimental studies on IDR with survey data, Schleich et al., (2016) defined three categories on IDR determinants. The first category is personal preferences, including time, risk, and environmental-friendly preferences. The second category is the building block of IDR, that is, predictable irrational behavior explained by limited rationality, carelessness, and biases. The third determinant category denotes external barriers such as lack of information.

Existing literature on the IDR has commonly concluded that the estimated IDR depends on household income and equipment (Busic-Sontic et al., 2017). Kubiack, (2016) investigated the literature on IDR for energy efficiency investment and found a negative relationship between estimated IDR and annual income from the empirical results of 13 studies. The negative relationship between IDR and income has been explained: high-income level represents a low credit limitation, risk-loving, time-preference endurance, and high awareness of energy-environmental issues (DEFRA, 2010).

The IDR for thermal shell investments depended on household income, ranging from 0.4 to 88% (Little, 1984). Moreover, energy investors have relatively low IDR for fuel switching on the heating system, ranging from 14 to 56%, that also depended on income level (Berkovec et al., 1983). Also, existing literature revealed that the IDRs for energy efficiency investment are also heterogeneous by socio-demographic factors, such as education level and cultural background (Kubiack, 2016).

Wang et al., (2021) did not investigate the IDR using survey data, but they adopted econometric analysis. Nonetheless, they determined that labeling of high energy efficiency on appliances, especially in the case of refrigerator, increases the purchase of appliances. This result implies that the labeling of energy efficiency on appliances decreases the IDR of energy investors (Z. Wang et al., 2019). To control the effects from labelling, we collected the survey data of labelling confirmation when purchasing that is included as individual self-awareness variable.

Meanwhile, Lakić et al., (2021) surveyed Slovenian households to investigate the willingness to invest in more efficient heating controls which can be elicited into the IDRs. The estimated IDRs ranged from 29.8 to 47.3%, which is close to our results. Likewise, the IDRs are found to depend on socioeconomic factors, such as gender and marriage. Kim & Nam, (2021) conducted a Korean case study to determine whether time, risk, and social preferences affect energy efficiency investment using the probit model. They concluded that risk and social preferences are determinants of energy efficiency investment, whereas time-preference partially affects it.

The literature introduced above have mostly adopted CVM method to elicit the IDR for energy efficiency investment. Damigos et al., (2021) conducted a stated preference survey in Greece to estimate IDRs used in energy efficiency decisions. They concluded that the IDRs for energy efficiency investment ranged from 92 to 136%, which seems to be highly overestimated by the problem of open-ended questions of CVM. In the same study, choice experiment (CE) was conducted to show the distribution of IDR ranging from − 10 to 60%, and mean IDR is equal to 5.5%. It implies that IDR for energy efficiency investment is not robust to the method. In addition, it was suggested that open-ended question CVM may have more consistency than CE to elicit WTP (Brouwer et al., 2017). Compared to open-ended question, the dichotomous choice (DC) method can take the advantage that the probability of strategic response bias is low in the dichotomous choice option. Therefore, we decided to adopt the DC CVM model.

Nevertheless, CE was frequently adopted as the empirical method to derive IDR for energy efficiency investment. Revelt & Train, (1998) attempted to find out households' choice of appliance efficiency level with repeated choice questions indicating CE method. While this study was not to derive IDR, they concluded that household prefer to invest high-efficiency appliances with the loan. Heinzle, (2012) found implicit WTP in energy efficiency investment can be increased by the energy efficiency label, tackling the importance of information in the energy efficiency investment of household sector. The implicit discount rate for TV was estimated with the range from − 4.95 to + 5.96%, implying that CE method may underestimate IDR of investing high-efficiency appliances (Damigos et al., 2021).

Min et al., (2014) conducted case study on light bulbs of experimental studies with CE method to emphasize the importance of labeling in similar to the study of Heinzle, (2012). This study results in the changes from 560 to 100% of IDR that induced by shown operating cost when purchasing high-efficiency appliances. Davis & Metcalf, (2016) derived same results that energy efficiency labels can promote energy efficiency investment from experimental research with CE method. While the multi-country CE study of Schleich et al., (2022) was not for energy efficiency, the preferences for new heating systems across countries have been investigated and heterogeneity of countries can be controlled in the CE study, implying the adaptability of CE method to apply consumer choice study on energy efficiency preference.

Lastly, Solà et al., (2021) reviewed the literature covering energy efficiency investment at the household level. Their research drew the consensus between existing studies. The underinvestment in energy efficiency can be induced by market failure, including informational failure, behavioral failure, and other factors. Therefore, the energy efficiency policy needs to be diversified with the consideration of characteristics and promotion purpose to promote energy efficiency investment.

As summarized above, the IDR for energy efficiency investment has been addressed by many scholars and its estimation methods. Although the MPL and open-ended question survey have been used to measure IDR and its determinants, the existing literature tended to overestimate the IDR for energy efficiency investment at the household sector because of the nature of questionnaires. To overcome this problem, we adopt the CVM method to elaborate the IDR question to respondents.

Methodology

Theoretical framework

Highly energy-efficient appliances take advantage of energy cost savings through its long-run usage, despite the high price. In this paper, energy efficiency investment indicates the decision-making of energy consumers who purchase appliances with high energy efficiency and recover the purchasing cost through energy cost savings in the long-term years of usage (Miller, 2015).

Assuming that an investment decision-making of enterprises is affected by several factors, energy efficiency investment of households is also derived by a combination of economic factors and personal characteristics. Existing literature has defined the economic factors affecting decision-making of energy efficiency investment with the following objective function of cost minimization (T. Gerarden et al., 2015; T. D. Gerarden et al., 2017; Stadelmann, 2017).

$$\min T(C) = K(E) + \sum_{t}^{T} \left(O\left(E, P_E\right)_t \times D(r,t) \right) \quad (1)$$

where $T(C)$ and $K(E)$ denote the total cost of energy efficiency investment and appliance purchase cost that is the initial investment cost. $O\left(E, P_E\right)$ indicates annual energy cost discounted by discount function ($D(r,t)$). E and P_E are energy consumption and energy price, respectively. Finally, r and T represent the discount rate and lifetime of appliances, respectively.

Energy consumer decides on energy efficiency investment by comparing the initial investment cost for highly energy-efficient appliances and future energy cost reduction for the appliance's lifetime. The investment potential rises in the initial investment cost-cutting or the increase in benefits from future energy cost reduction. Future energy cost reduction can be affected by future energy price increase and low IDR, which in turn increase the benefit of energy efficiency investment.

The appliance purchase cost, $K(E)$, is an incremental cost presented by the price gap between highly energy-efficient and general appliances. This is determined by energy consumption (E), with an inverse proportion relationship. The high energy efficiency indicates the reduction in energy consumption and the increase in the appliance purchase cost, which reduces the possibility of energy efficiency investment. Alternatively, the adoption of appliances with high energy efficiency reduces future energy cost ($O\left(E, P_E\right)$). Energy cost reduction depends on personal discount rate that is demonstrated by IDR, reflecting personal characteristics of how much weight the future value. High IDR causes people to underestimate future benefits from the energy cost reduction, which is connected to the low chance of energy efficiency investment.

CVM method

This study adopts a CVM to estimate the IDR of household energy consumers. The CVM is well-known as a valuation method to measure the value of non-market goods based on the survey data. In general CVM analysis, a structured questionnaire suggests a hypothetical situation change to ask direct question of WTP or WTA to respondents. Especially for the energy field, the CVM is often used to determine the WTP and WTA about renewable preference, energy supply security evaluation, and social value (Jinsoo Kim & Kim, 2015; Junghun Kim et al., 2018; K. Kim et al., 2015; Lee & Cho, 2020).

There are several forms to organize questions for deriving the WTP information from respondents such as open-ended, payment card, and dichotomous choice formats (Welsh & Poe, 1998). For most respondents, answering the open-ended WTP questions is difficult because they are not an expert on this field (Loomis, 1990). By this reason, many CVM studies have constructed the questionnaire consisting of dichotomous choice question. The CVM with dichotomous questions has few biases and reliability (Yoo & Kwak, 2002). The dichotomous choice question suggests two options of yes or no to respondents based on a certain level of WTP. Based on the survey results of dichotomous choice, the interviewer can calculate the WTP through the econometric analysis assuming the consumer utility function with logit and probit model (Lee & Cho, 2020).

Bishop & Heberlein, (1979) and Hanemann, (1985) proposed the two dichotomous choice question methods: a single-bounded dichotomous choice (SBDC) and a double-bounded dichotomous choice (DBDC). The two methods differ in terms of question times: SBDC questions just once, whereas DBDC does twice. Among the two methods, DBDC model is used in this study.

In the DBDC model, if the respondents choose the answer "yes" in the initial question of WTP, the twice WTP question is followed. Alternatively, when the respondents say "no" in the initial question, the follow-up question goes to the half WTP. Most literature covering CVM has adopted the DBDC model rather than SBDC because the SBDC tends to be statistically more inefficient than the DBDC (Cameron & Quiggin, 1994).

Hanemann, (1984) suggested using the indirect utility function measured by the Hicksian compensation surplus that can be observed from the discrete choice survey data. In the survey system, energy consumers, that is, respondents, are assumed to behave to maximize their own utilities. By using the utility difference approach, we can present the indirect utility function of respondents as follows.

$$u(1, m - A; S) + \varepsilon_1 \geq u(0, m; S) + \varepsilon_0 \tag{2}$$

where u denotes indirect utility function. The first term in utility function expressed in one or zero means whether purchase a product or not. In this study, state 1 means purchasing the highly energy-efficient appliances. m and A are each respondent's income and WTP, respectively. The energy consumers respond to question based on their income (m) and socio-economic characteristics of themselves (S). ε indicates the disturbance assuming identical and independent distribution that influences consumer's decision-making. Equation (2) expresses that the respondents check "yes" when the utility gap between the adoption and non-adoption of appliances with high energy efficiency is bigger than the random error gap ($\varepsilon_0 - \varepsilon_1$).

In the CVM literature, zero value of WTP has been questionable problem. Even though the CVM survey uses the DBDC structure that questions twice, the WTP becomes zero value of the respondent selecting "no" several times in a row. In real, sometimes most CVM respondents express their WTP of zero (Lim et al., 2014). Some studies decided to exclude the respondents of zero WTP. If the WTP estimation omits a part of respondents, the WTP will be biased and overestimated. To overcome this problem, the spike model that can handle the zero WTP value was introduced (Kriström, 1997).

Since we use DBDC spike model, the possible outcomes of DBDC question can be categorized into five combinations: "no–no (I_i^{NN})," "no-yes (I_i^{NY})," "yes–no (I_i^{YN})," "yes-yes–no (I_i^{YYN})," and "yes-yes-yes (I_i^{YYY})." The I denotes the indicator function that shows 1 value in case that the respondents answer the combination to the survey as presented in Eq. (3). For instance, if a respondent answered "no" to the initial question of WTP and "yes" to follow-up question, the indicator function (I_i^{NY}) presents 1, the others are zero. Our empirical analysis is based on the DBDC spike model to estimate the IDR of household energy efficiency investors considering zero IDR value. The third follow-up question in case that the respondent answers "yes-yes" is intended to confirm either the devoid IDR or at least a positive IDR of potential energy efficiency investors.

$$I_i^{NN} = 1 \ \textit{if} \ IDR > A_i^N (0 \ \textit{otherwise})$$

$$I_i^{NY} = 1 \ \textit{if} \ A_i < IDR \leq A_i^N (0 \ \textit{otherwise})$$

$$I_i^{YN} = 1 \ \textit{if} \ A_i^Y < IDR \leq A_i (0 \ \textit{otherwise})$$

$$I_i^{YYN} = 1 \ \textit{if} \ 0 < IDR \leq A_i^Y (0 \ \textit{otherwise})$$

$$I_i^{YYY} = 1 \ \textit{if} \ IDR = 0 \ (0 \ \textit{otherwise}) \tag{3}$$

In this study, we adopt the DBDC spike model to estimate the IDR of household energy consumers for energy efficiency investment with handling the zero WTP problem that respondents may express the none of investment. The log-likelihood function for the DBDC spike model can be expressed as follows:

$$\ln L = \sum_{i=1}^{N} \{ I_i^{NN} \ln[1 - G(A_i^N)] + I_i^{NY} \ln[G(A_i^N) - G(A_i)] + I_i^{YN} \ln[G(A_i) - G(A_i^Y)] + I_i^{YYN} \ln[G(A_i^Y) - G(0)] + I_i^{YYY} \ln G(0) \} \tag{4}$$

where A_i indicates the IDR of energy efficiency investor in the initial question. A_i^Y and A_i^N are the follow-up questions when the response to the initial bid was "yes" or "no," respectively. For the spike model, logistic distribution function ($G(\bullet)$) is assumed to follow a half logistic distribution as follows.

$$G(A) = \begin{cases} [1 + \exp(a - bA)]^{-1} & \textit{if} \ A > 0 \\ [1 + \exp(a)]^{-1} & \textit{if} \ A = 0 \\ 0 & \textit{if} \ A < 0 \end{cases} \tag{5}$$

where a and b are the parameters to be estimated by a logit. The maximum likelihood estimator (MLE) is used to estimate the parameters. The mean IDR can be calculated using Eq. (6).

$$mean\ IDR = \frac{1}{b}\ln[1 + \exp(a)] \quad (6)$$

Advantages of CVM for IDR estimation

The MPL has three possible disadvantages. (1) It only elicits interval responses, rather than "point" valuations. (2) The subjects can switch back and forth from row to row, implying potentially inconsistent preferences. (3) It could be susceptible to framing effects, as subjects are drawn to the middle of the ordered table irrespective of their true values (Andersen et al., 2006).

One of the main disadvantages of complex methods for eliciting risk preferences is that, depending on the population, a significant number of subjects will fail to understand the procedure. This reduces the reliability of the risk preference measure and can bias the results. With the standard MPL method, individuals are typically allowed to switch freely between options A and B as they progress down the decision rows. As such, participants may make inconsistent decisions either by switching more than once or making "backward" choices—starting with option A and switching to B (Dave et al., 2010; Holt & Laury, 2002).

Depending on the participant pool, this problem could be significant. For example, Jacobson & Petrie, (2009) found that in a sample of Rwandan adults, 55% made inconsistent choices; Charness & Viceisza, (2012) found that 75% of farmers from rural Senegal made inconsistent choices (51% switched more than once and 24% always chose option A). This poses an obvious problem because the inference of risk preferences, and in turn, parameter estimation, requires a unique switch point, and such inconsistent behavior is difficult to rationalize under standard assumptions on preferences (Gary Charness et al., 2013).

The problems addressed above can be solved and alleviated by applying CVM. The CVM can take advantage of eliciting WTP with successive "point" questions. The second problem, that is, switching-back problem, also does not occur in CVM because the second and third questions are followed according to the response of the former question. To mitigate the problem of MPL and elaborate the estimation of the IDR, we adopt the CVM method with well-designed survey to measure IDR for energy efficiency investment.

Survey form and data descriptions

The survey for CVM is designed to investigate the determinants of IDR of household energy efficiency investors. According to Schleich et al., (2016), the IDR is determined by preferences, predictable rational behavior, and external barriers to energy efficiency factors. To consider these determinants in a microsurvey system, we add the questionnaire to ask risk preference, experience, and cognition. The survey is constructed into four parts. First, the IDR questions are conducted for four home appliances: TV, air conditioner, dehumidifier, and air cleaner. In the second part, to measure the priority of consumers under the consideration of risk, the survey consists of the questions about risk on high energy efficiency investment and general efficiency investment.

Third, we attempt to control the impact of cognition on energy efficiency investment with the CRT results. The third part is elaborated with the questions to measure the cognitive power of each energy efficiency investor. Finally, general socioeconomic information, the current status of home appliance usage, and energy efficiency improvement experiences of energy efficiency investors are investigated. Survey questions are summarized in Appendix 2.

We set based an initial value of IDR as 50% of IDR only except high energy efficiency TV. Other than the CVM study estimating WTP, our analysis targets the IDR estimation, which is bounded 0 to 100. To determine the impact of initial suggestion on IDR, we diversify the initial value of 30% and 40% in addition to the initial base value. The lowest initial IDR is 30%, derived by considering the prices of actual high energy efficiency appliances and household electricity charge level. The follow-up question is designed to depend on the initial suggestion. According to Arrow et al., (1993), the best way to conduct the CVM survey is through face-to-face interaction. However, conducting offline survey was unsuccessful due to the COVID-19 pandemic. We collect the survey data with interned responded by 2392 effective respondents.

When we build up the questionnaire, it was not certain that the respondents are aware of the concept of interest rate. The discount rate or interest rate to estimate the investment returns such as payback period would be not familiar to the respondents. Therefore, in the questionnaire, the IDR bid are presented together with the underlying payback period

Table 1 Demographic factors of respondents

Characteristics	Group	Number of respondents ($N = 2392$)	Percentage (%)
Age		38.09 (average)	
Gender	Male	1191	49.79
	Female	1201	50.21
Dwelling type	Own	1452	60.70
	Rent	773	32.32
	Etc	167	6.98
Number of family members	1	465	19.44
	2	388	16.22
	3	627	26.21
	4	746	31.19
	Over 5	160	6.66
	Etc	6	0.25
Education level	Lower than high school	43	1.80
	High school	351	14.67
	University	1,688	70.57
	Graduate school	310	12.96
Monthly income (KRW 10,000)	Lower than 200	517	21.61
	200–300	673	28.14
	300–400	494	20.65
	400–500	264	11.04
	500–600	195	8.15
	600–1000	204	8.53
	Over 1000	45	1.88
Monthly electricity consumption (kwh)	0–100	129	5.39
	100–200	374	15.64
	200–300	548	22.91
	300–400	426	17.81
	400–500	169	7.07
	500–600	44	1.84
	Over 600	21	0.88
	Unknown	681	28.47

and financial returns with energy efficiency investments based on the current electricity charge level so that the respondents can recognize that the suggested IDR can be translated into the energy efficiency investment and financial returns.

The demographic characteristics of survey respondents are presented in Table 1. Our socio-economic factor investigation of each potential energy efficiency investor include age, gender, dwelling type, number of family members, education level, monthly income, and monthly electricity consumption. Overall, the demographic factors of respondents are regularly distributed. The age we use is not discrete but continuous variable. Although the tenant, the actual resident, pays the bill for energy in South Korea, the energy efficiency investment decision may depend on home ownership; hence, the variable can be a critical factor. Other factors such as monthly income and electricity consumption are directly connected to the willingness to invest of household energy consumers.

Other than the demographic factors, we conduct an additional survey to measure the abovementioned other factors: risk preference, experience,

Table 2 Risk preferences of respondents

Risk preference	Level	Number of respondents (N=2392)	Percentage (%)
Risk-loving	1	176	7.36
	2	440	18.39
	3	115	4.81
	4	186	7.78
Risk-neutral	5	345	14.42
Risk-averse	6	239	9.99
	7	22	9.49
	8	187	7.82
	9	127	5.31
	10	350	14.63

Group 1 indicates extreme risk-loving whereas group 10 denotes extreme risk-aversion.

Table 3 CRT results of respondents

Cognition level	Number of respondents (N=2392)	Percentage (%)
0	993	41.51
1	487	20.36
2	453	18.94
3	459	19.19

Group 1 indicates extreme risk-loving whereas group 10 denotes extreme risk-aversion.

and cognition. The risk preference for energy efficiency investment is measured by MPL, the results of which are presented in Table 2. One of the most important contributions of this research is to attempt to control the individual cognition reflecting individual decision-making process and heterogeneity, which measured by CRT, in the empirical analysis (Dohmen et al., 2010; Sajid & Li, 2019). Based on the behavior economic theory, the individual cognition can be classified into systems 1 and 2. The system 1 indicates quick but imprecise decision-making person, whereas a person with time-taking and precise decision-making falls to system 2 (Frederick, 2005). The existing literature has shown that a person with system 2 tends to have low IDR for time and risk preferences. Table 3 summarizes the results of CRT. In the questionnaire, CRT part consists of three questions. The CRT variable denotes the number of correct answers by the respondents, indicating that the higher CRT variable is, the higher cognition of respondents is.

Moreover, the self-awareness of energy consumption pattern and energy efficiency investment experience can be determinants of IDR (Stadelmann, 2017). The last part of survey was constructed to investigate them. The summarization of the survey results for self-awareness of energy consumption pattern and energy efficiency investment experience are suggested in Appendix 1.

Lastly, Table 4 shows the results of the survey for IDR eliciting questions. We conduct the survey for four home appliances with high energy efficiency. As described in Eq. (3), the IDR estimation has reverse form with traditional WTP estimation. The answer to the initial bid was "yes" which can be translated into high willingness to invest, which indicates lower IDR. That is, successive "yes" presents the low IDR, and energy investors are willing to invest the highly energy-efficient appliances. Although the final question of a traditional DBDC CVM is to ask the zero WTP with successive "no" responses, a three-time successive "yes" translates into zero IDR in our analysis. Unlike the literature concerned about zero WTP, our survey results show a few respondents expressing zero IDR (about 0.2% of sample), so that the estimated mean IDR has few chances of underestimation.

Empirical results

The survey to investigate IDR of household energy efficiency investors is conducted with a questionnaire consisting of IDR questions on four home appliances, risk preferences, CRT, awareness, experiences, and demographic factors. MLE examines the potential IDR of energy efficiency investment. Table 5 presents the mean IDR results and its determinants. The empirical results were estimated by the extension of Eq. (4) with addition of determinants of IDR. The dependent variable denotes the rejection rate of bidding. Therefore, the estimated coefficients of covariate represent the impact of covariate on estimated IDR. In the conventional CVM, the dependent variable should be the acceptance rate of bidding converse to our study.

For estimating the mean IDR, we use the model without additional explanatory variables. The empirical results to measure mean IDR are statistically significant at the 1% significance level for all home appliances.

Table 4 IDR eliciting question results

Response	IDR level	Television	Air conditioner	Dehumidifier	Air cleaner
No/no	$IDR > A_i^N$	288	238	327	306
No/yes	$A_i < IDR \leq A_i^N$	165	187	206	201
Yes/no	$A_i^Y < IDR \leq A_i$	319	311	326	317
Yes/yes/no	$0 < IDR \leq A_i^Y$	1615	1656	1529	1565
Yes/yes/yes	$IDR = 0$	5	5	4	3

The acceptable IDRs for TV, air conditioner, dehumidifier, and air cleaner are derived as 23.30, 21.80, 25.94, and 24.91%, respectively. The potential household energy investor's IDR for energy efficiency investment is in the 20%, which is slightly lower than the IDR estimated from the existing literature.

In addition, the IDR depends on the appliances; relatively higher IDRs are observed for recently introduced appliances, dehumidifier, and air cleaner than the ones of TV and air conditioner. For recently introduced appliances, risk and uncertainty affected by the absence of information increase the IDR of energy efficiency investors. Moreover, the purchasing power for recently introduced appliances is much higher than older ones; the consumers decide to purchase the appliances according to the attraction and performance, rather than energy efficiency. The other consistent evidence also supports it. The current home appliance usage decreases the IDR for dehumidifier and air cleaner. It means that the information and experiences on new appliances can lower the IDR and are the critical factors for energy efficiency investment. The estimated coefficients for the IDR in initial bid variable are statistically significant at 1% significance level for all appliances. The variable indicates the first offer IDR in the questionnaire. As mentioned above, we diversify the initial IDR into 30%, 40%, and 50%. The questionnaire was randomly allocated to the respondents to avoid anchoring effect of initial bid. The positive and statistically significant parameters denote that the first offer IDR positively affects the mean IDR.

Although the determinants of IDR are slightly different from each other for four house appliances, the IDR in general is affected by gender, age, dwelling type, cognition, energy-saving, and experiences. The IDR increases when the household energy efficiency investor is male and dwells in rent. Age affects the IDR positively, indicating that old age is conservative for the energy efficiency investment, whereas the cognitive power is negatively related to the IDR. Note that energy-saving program and energy efficiency experiences can reduce the IDR for energy efficiency investment; therefore, they are essential factors to consider for the residential energy efficiency improvement policy. Alternatively, demographic factors, such as income and electricity consumption, have no meaningful information to explain the IDR of potential energy efficiency investors.

It was surprising that the socio-demographic factors intended to control the heterogeneity across households have not affected the estimated IDR. We assume that the regulated electricity price in Korea may result in this cautiously. Electricity is recognized as the essential goods, since the price and income elasticity are considerably small compared to the other general goods (Fabra et al., 2022). Furthermore, regulated electricity price in Korea makes the share of energy costs of household budget to be smaller (Jihyo Kim et al., 2022), implying that income and monthly consumption are not the determinants of IDR. The low electricity cost cognition of households in Korea can be observed in the literature covering willingness-to-pay (Huh et al., 2015).

For the impact of cognition by appliance, CRT is found to reduce the IDR for energy efficiency investment. Furthermore, the CRT has a much negative impact on IDR for recently introduced appliances rather than familiar ones, such as TV. This implies that individual cognition level highly affects the adoption of new and highly energy-efficient appliances. For the familiar appliance, energy consumers are used to it and have learned information. Otherwise, for recently introduced appliances, energy consumers decide of purchasing through information delivery and promotion. In the process, the cognition measured by CRT seems to affect energy efficiency investment.

Also, the electricity consumption and operating hours may implicitly explain different IDR across the appliances, whereas we attempted to explain the reason to derive different IDR with the experience and recognition of the appliances, which may appear in

Table 5 Mean IDR with covariates

Variables	Estimated coefficient			
	TV	Air conditioner	Dehumidifier	Air cleaner
Mean IDR	23.30%	21.80%	25.94%	24.91%
95% Confidence interval[2]	[22.44, 24.19]	[21.00, 22.63]	[24.96, 26.96]	[24.00, 25.88]
Risk preference	−0.0413	−0.0157	−0.0092	0.0348
Gender	0.1165	0.4010[a]	0.3250[a]	0.3448[a]
Age	0.0041	0.0346[c]	0.0195[a]	0.0248[b]
Number of family members	0.1360[a]	0.0201	−0.0069	−0.0327
Education level	0.0875	0.1191	−0.0284	0.1607
Dwelling type	−0.6191[c]	−0.3739	−0.4165[b]	−0.1820
Monthly income	0.0563	−0.0600	0.0391	−0.0588
Monthly electricity consumption	−0.0544	−0.0447	0.0175	0.0502
Cognition (CRT)	−0.1833[b]	−0.3825[c]	−0.3129[c]	−0.3919[c]
Current home appliance usage	−0.0848	0.0221	−0.3676[a]	−0.8390[c]
Purchasing plan	0.2767	0.0251	−0.3783[a]	−0.3294
Self-awareness of energy consumption pattern				
Confirming energy efficiency level when purchasing	0.0211	−0.0672	0.0164	0.0264
Confirming electricity charge when paying	0.0192	0.0046	−0.0261	−0.00002
Participating in energy-saving program	−0.0190	0.0536	0.0497	0.0770[a]
Considering fuel cost in heating and cooling	0.0588	0.0990	0.0558	0.1397[b]
Multi-tap usage	0.1497[b]	0.0075	−0.0078	−0.1112[a]
Turn-off the unnecessary light	−0.1892[c]	−0.1966[b]	−0.1005	−0.1396[a]
Energy efficiency improvement experiences				
Adopting appliances with high energy efficiency	0.1425	−0.4990[b]	−0.4011[b]	−0.4156[b]
Replacing windows and doors	−0.1373	−0.0766	−0.1273	−0.0566
Setup insulator	0.0305	0.5053[b]	−0.1538	−0.0293
Constant	−6.3631[c]	−6.3327[c]	−5.3351[c]	−5.9910[c]
IDR in initial bid	0.0760[c]	0.0738[c]	0.0770[c]	0.0769[c]
Log likelihood	−430.7413	−378.5375	−447.7442	−432.7499

a, b, and c denote rejection of the null hypothesis at 10%, 5%, and 1% significance level, respectively.

the form of consumer utilities. In addition, it is highly affected by the marketing and circumstances of appliances in Korea. In Korea, the air conditioner and TV are regarded as the essential home appliances, implying estimated lower IDR. Furthermore, dehumidifier and air cleaner that have been introduced in relatively recent were derived to have bigger barrier in energy efficiency investment than TV and air conditioner, emphasizing the importance of experiences and cognition in energy efficiency investment in household.

Overall, we presume that energy efficiency investment behaviors can be affected by the awareness of environmental issues such as carbon neutrality around the world recently. In addition, the recent policy trend that increases electricity charge in Korea to reflect the fuel cost of generation sector may affect the willingness to invest in energy efficiency to avoid increased energy cost through energy savings from energy efficiency improvement. It would be better to include questions why the zero WTP and the determinants of IDR in household appliances. In case of estimating IDR, we suggest that the research consider including the questions into the questionnaire so that the empirical research can detect the barriers of energy efficiency investments in household.

[2] The 95% confidence interval is calculated using the Monte Carlo simulation suggested by Krinsky and Robb (1986).

Conclusion and policy implications

Our study suggests a new approach for assessing the IDR for energy efficiency investment by adopting the CVM method, which is frequently used to estimate the WTP of non-market goods. Our CVM analysis is based on data derived from 2392 online survey respondents. The DBDC method is adopted to elicit the IDR of potential energy efficiency investors in household sector. We aim to derive IDR, not WTP; hence, our survey form is a reverse of the survey for eliciting WTP. Traditional CVM for WTP regards "no–no-no" as zero WTP, whereas our CVM takes zero IDR from three-time successive "yes" question.

Our empirical results are robust to zero WTP problem (in our analysis, zero IDR problem) due to few zero IDR respondents. We found that the IDR for household energy efficiency investment is around 20%, depending on the appliances. The estimated IDR is relatively smaller than the ones of existing literature. We adopt the CVM method to provide specific information to respondents; therefore, the IDR of potential energy efficiency investors seems to be diminished by the risk reduction from information security. The statistical insignificance of risk preference variable indirectly proves it. Moreover, the socio-demographic factors of the survey respondents are regularly distributed. To determine the additional determinants of IDR for energy efficiency investment other than demographic factors, few surveys are conducted for risk preference, CRT, self-awareness, and experiences. Risk preference is found to have no significant impact on the IDR, whereas CRT, energy-saving program participation, and experiences reduce the IDR. It implies that cognition, experience, and information are critical factors for adopting highly energy-efficient appliances in the household sector.

The other major finding is that the estimated IDRs vary according to appliances. Moreover, energy efficiency investors have relatively higher IDRs for the recently introduced appliances, such as dehumidifier and air cleaner, than traditional ones, such as air conditioner and TV. This can be explained by the impact of the current home appliance usage variable. The estimated parameters for dehumidifier and air cleaner have statistically significant and negative effect on IDR, emphasizing the importance of information and experiences in energy efficiency investment.

The existing literature drew the results that cognition can reduce investment IDR, which is in line with our results that cognition can break down the barrier of high energy efficiency investment. It implies that the cost–benefit and energy efficiency labeling that provides information to consumer can lead to energy efficiency investment by increasing the cognition of potential energy efficiency investors. Consistent with these results, for self-awareness of energy consumption patterns, the consumer with a tendency to confirm the energy efficiency level is a potential energy efficiency investor having low IDR.

Energy efficiency improvement experiences can also reduce the IDR of investors, especially for participating in energy-saving program. Experiences of energy efficiency improvement induce perception, advancing the adoption of appliances with high energy efficiency. Using CVM to measure IDR can be shorthanded in that the estimated IDR depends on the initial suggestion, which may be occurred by the "anchoring effect" in behavioral economics. Nevertheless, policymakers did not take advantage of CVM in modifying the discount rate resented in the current energy efficiency support program.

The estimated IDRs are the criteria that is the basis of energy efficiency investment decisions. Energy efficiency policy can also be established using IDR, by providing the initial investment cost and energy efficiency improvement acceptable for energy consumers. The IDR should be reflected in efficiency policy to draw natural energy efficiency investment and thus supply the highly energy-efficient appliances in household sector. Otherwise, efficiency policy through support fund has limits of budget and effectiveness, eventually leading to regulation-based policy.

The estimated IDR depends on appliances. Especially for recently introduced appliances, energy consumers tend to have high IDR. Energy efficiency policy should extend the range to diffuse information for energy-efficient appliances and to increase chances to experience appliances with high energy efficiency because the barriers of newly introduced appliances come from them. Furthermore, the energy efficiency policy taking the IDR into account can synergize the existing policy because the experiences in energy efficiency improvement and energy-saving program reduce IDR.

Our study has several limits. We applied DBDC CVM model to estimate the IDR on household appliances. Although we attempted to avoid the anchoring effect by allocating initial bid randomly, still the initial bid was limited to range from 30 to 50% of IDR. To overcome this, we need to extend the experiments that have widen initial bid range with a lot of respondents. In addition, there is no comparison since IDRs on household appliances with high energy efficiency in Korea have not been investigated. The open-ended question would be a good control group for comparison. In addition, the follow-up questions are required in the IDR research to find out the determinants of willingness-to-investment other than socio-demographic factors. Lastly, high energy efficiency appliances have own characteristics. For example, the monthly electricity saving by adopting high energy efficiency appliances depends on the appliance, despite same energy efficiency level. This is because of the difference in the using intensity between appliances. The IDR estimation study would benefit from reflecting it in the questionnaire.

Consequently, the IDR should be diversified in energy efficiency policy according to the socio-demographic factors and appliance types. Second, to secure the effectiveness of supportive policy for energy efficiency investment, the level of subsidies is determined through a bottom-up approach based on consumer's decision-making on energy efficiency investment. After then, the level of subsidies is adjusted in consideration of consumer income and education level. In this basis, the IDR should be reduced by campaigns such as specialized education.

DeclarationsDeclarations

Conflict of interest The authors declare no competing interests.

Appendix 1

Table A1 Additional explanatory variables: self-awareness and energy efficiency investment experiences

Variables	Contents	Level	Number of respondents (%)
Current status of home appliances usage	Air cleaner	Yes	1481 (61.91%)
		No	911 (38.09%)
	Washing machine	Yes	2338 (97.74%)
		No	54 (2.26%)
	Clothes dryer	Yes	767 (32.07%)
		No	1625 (67.93%)
	Air conditioner	Yes	2209 (92.35%)
		No	183 (7.65%)
	Refrigerator	Yes	2345 (98.04%)
		No	47 (1.96%)
	Television	Yes	2179 (91.10%)
		No	213 (8.9%)
	Dehumidifier	Yes	1063 (44.44%)
		No	1329 (55.56%)
	Clothes manager	Yes	363 (15.18%)
		No	2029 (84.82%)
Purchasing plan (within 3 years)	Air cleaner	Yes	888 (33.78%)
		No	1584 (66.22%)
	Washing machine	Yes	635 (26.55%)
		No	1757 (73.45%)
	Clothes dryer	Yes	795 (33.24%)
		No	1597 (66.76%)
	Air conditioner	Yes	585 (24.46%)
		No	1807 (75.54%)
	Refrigerator	Yes	649 (27.13%)

Table A1 (continued)

Variables	Contents	Level	Number of respondents (%)
		No	1743 (72.87%)
	Television	Yes	675 (28.22%)
		No	1717 (71.18%)
	Dehumidifier	Yes	578 (24.16%)
		No	1814 (75.84%)
	Clothes manager	Yes	862 (36.04%)
		No	1530 (63.96%)
Self-awareness of energy consumption pattern	Confirming energy efficiency level when purchasing	1	30 (1.25%)
		2	16 (0.67%)
		3	27 (1.13%)
		4	51 (2.13%)
		5	178 (7.44%)
		6	178 (7.44%)
		7	474 (19.82%)
		8	518 (21.66%)
		9	920 (38.46)
	Confirming Electricity charge when paying	1	36 (1.51%)
		2	48 (2.01%)
		3	57 (2.38%)
		4	84 (3.51%)
		5	246 (10.28%)
		6	274 (11.45%)
		7	407 (17.02%)
		8	437 (18.27%)
		9	803 (33.57%)
	Participating in energy saving program	1	342 (14.30%)
		2	138 (5.77%)
		3	186 (7.78%)
		4	158 (6.61%)
		5	414 (17.31%)
		6	283 (11.83%)
		7	298 (12.46%)
		8	234 (9.78%)
		9	339 (14.17%)
	Considering fuel cost in heating and cooling	1	40 (1.67%)
		2	27 (1.13%)
		3	40 (1.67%)
		4	68 (2.84%)
		5	228 (9.53%)
		6	255 (10.66%)
		7	561 (23.45%)
		8	461 (19.27%)
		9	712 (29.77%)
	Multi-tap usage	1	57 (2.38%)

Table A1 (continued)

Variables	Contents	Level	Number of respondents (%)
		2	40 (1.67%)
		3	60 (2.51%)
		4	79 (3.30%)
		5	252 (10.54%)
		6	263 (10.99%)
		7	436 (18.23%)
		8	433 (18.10%)
		9	772 (32.27%)
	Turn-off the unnecessary light	1	19 (0.79%)
		2	18 (0.75%)
		3	38 (1.59%)
		4	53 (2.22%)
		5	156 (6.52%)
		6	215 (8.99%)
		7	437 (18.27%)
		8	480 (20.07%)
		9	976 (40.80%)
Energy efficiency improvement experiences	Adopting appliances with high energy efficiency	Yes	1725 (72.12%)
		No	667 (27.88%)
	Replacing windows and doors	Yes	1248 (52.17%)
		No	1144 (47.83%)
	Setup insulator	Yes	1861 (77.80%)
		No	531 (22.20%)

In level column, 1 indicates "not at all," whereas 9 "really does."

Appendix 2 Survey questions to elicit the implicit discount rate

This is a question related to your energy efficiency investment decision making.

there are devices with general efficiency (A) and devices with high energy efficiency (B). The purchase price of device A is 300,000 KRW, and the annual energy cost is 100,000 KRW. The purchase price of device B is 400,000 KRW, and the annual energy cost is 80,000 KRW.

- Between the two devices, except for the difference in purchase price and annual energy cost, all other conditions are the same, the lifetime of home appliances is generally 10 years. This means that no matter which device you choose, you will be using this appliance for 10 years.
- If you use a low-purchase general efficiency device (A), you will pay more energy costs than the high-energy-efficiency device (B) every year for 10 years. Energy cost can be reduced compared to device (A). For example, if you purchase a high energy efficiency device (B) instead of a general efficiency device (A), you can save an energy cost of 20,000 KRW annually for the next 10 years by investing an additional 100,000 KRW.

Q1. (All respondents) If you purchase an energy-efficient TV (Air conditioner, Dehumidifier, Air cleaner), the purchase price is 100,000 KRW more expensive than a regular-efficiency TV (Air conditioner, Dehumidifier, Air cleaner), but you can save 5.1 (3.3, 4.3) million KRW in energy costs annually for the next 10 years. This means that by investing 100,000 KRW initially, you get an interest rate of 50

(30, 40)%. Do you want to buy a high-efficiency TV (Air conditioner, Dehumidifier, Air cleaner)?

1. Yes (Purchase) – go to Q2
2. No (Do not purchase) – go to Q4

Q2. (Respondent who answered that they purchase in Q1.) If you purchase an energy-efficient TV (Air conditioner, Dehumidifier, Air cleaner), the purchase price is 100,000 KRW more expensive than a general-efficiency TV (Air conditioner, Dehumidifier, Air cleaner), but you will save 2.8 (2.0, 2.4) million KRW in energy costs annually for the next 10 years. can. This means that by investing 100,000 KRW initially, you get an interest rate of 25 (15, 20)%. Do you want to buy a high-efficiency TV (Air conditioner, Dehumidifier, Air cleaner)?

1. Yes (Purchase) – go to Q3
2. No (Do not purchase)

Q3. (Respondents who answered that they purchase in Q2.) So, are you willing to purchase at the lowest energy saving cost listed above?

* Since you answered in Q2 that you are willing to purchase if there is a cost savings of 2.8 (2.0, 2.4) KRW, you must respond with an amount of 2.8 (2.0, 2.4) KRW or less.

Q4. (Respondent who answered no in Q1.) Then, you can save 100,000 KRW (6.1, 8.1) in energy costs annually for the next 10 years. This means that by investing 100,000 KRW initially, you get an interest rate of 100 (60, 80)%. Do you want to buy a high-efficiency TV (Air conditioner, Dehumidifier, Air cleaner)?

1. Yes (Purchase)
2. No (Do not purchase) – go to Q5

Q5. (Respondent who answered no in Q4.) So, do you have no intention of purchasing a high-efficiency TV (Air conditioner, Dehumidifier, Air cleaner) at all?

1. Not at all
2. Yes(purchase) – go to Q6

Q6. (Respondents who answered that they intend to purchase in Q5.) So, are you willing to purchase at the lowest energy saving cost listed above?

* Since you answered in Q4 that you do not intend to purchase even if there is a cost savings of KRW 100,000 (6.1, 8.1), you must respond with an amount exceeding KRW 100,000 (6.1, 8.1).

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