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Effect of living in well-insulated warm houses on hypertension and cardiovascular diseases based on a nationwide epidemiological survey in Japan: a modelling and cost-effectiveness analysis

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ABSTRACT

Introduction Cardiovascular diseases (CVDs) are more prevalent in colder homes, partly due to cold-induced high blood pressure (BP). While thermal insulation and heating are rational strategies to mitigate cold exposure, the high initial and running costs pose significant barriers. Therefore, this study aims to evaluate the cost-effectiveness of living in well-insulated warm houses.

Methods An economic model was developed based on the indoor temperature–BP and BP–CVDs relationships. Five scenarios were outlined: a base scenario (Scenario 0: the most prevalent thermal insulation level (Grade 2) and indoor temperature (15°C) in Japan), two scenarios of upgrading insulation and living in warm houses after age 40 years (Scenario 1–1: Grade 4 & 18°C and Scenario 1–2: Grade 6 & 21°C), and two scenarios of retrofitting insulation of entire houses and living in warm houses after age 60 years (Scenario 2–1: Grade 4 & 18°C and Scenario 2–2: Grade 6 & 21°C). Monte Carlo simulations for 100 000 virtual husband–wife pairs were conducted to investigate quality-adjusted life-years (QALYs) and life-cycle costs for thermal insulation work, heating and medical treatments.

Results Regarding the upgrading insulation scenarios, compared with Scenario 0, Scenarios 1–1 and 1–2 increased the life-cycle cost by Japanese yen (JPY) 0.26 and JPY0.84 million, respectively, while extending the combined healthy life expectancy of a husband and wife by 0.31 and 0.48 QALYs. The incremental cost-effectiveness ratios were below the threshold value of JPY5 million/QALY gained. Regarding the retrofitting insulation scenarios, probabilistic sensitivity analyses showed that Scenario 2–2 emerged as the most cost-effective option when the willingness to pay reached JPY6.5 million or more, which is above the threshold.

Conclusions Upgrading insulation and residing in warmer homes could be cost-effective strategies. When conducting insulation retrofitting, lower-cost methods such as partial insulation retrofitting should be considered. These findings support decision-making for residents and policymakers.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Many clinical trials on housing improvement have demonstrated preventive effects on cardiovascular diseases (CVDs).

⇒ These effects may lead to a reduction in economic burdens associated with poor indoor thermal environments.

⇒ Although there are several papers on health economic analyses of housing improvements, such as retrofitting insulation, it is challenging to apply these results to other settings because they are economic evaluations of specific trials or programmes.

WHAT THIS STUDY ADDS

⇒ A mathematical economic model was proposed to assess the cost-effectiveness of living in well-insulated warm houses, using general indices such as indoor temperature and blood pressure, to ensure applicability to various settings.

⇒ Using this framework, the costs (including thermal insulation, heating, and medical expenses for hypertension and CVDs) and effectiveness (measured in quality-adjusted life-years (QALYs)) of five scenarios were evaluated in a case study, drawing on data from a nationwide epidemiological survey in Japan.

⇒ The analysis revealed that upgrading thermal insulation when purchasing new houses and living in warm houses is more cost-effective than retrofitting insulation, yielding an incremental cost-effectiveness ratio below the threshold value of JPY5 million/QALY gained.

INTRODUCTION

Housing is becoming crucial for improving public health. Given that people in the modern age spend more than 50% of their time at home[1–3] and that the over 65

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

- ⇒ For residents, the mathematical economic model of housing and health can support the decision-making process regarding whether they should upgrade or retrofit the thermal insulation of their houses.
- ⇒ For policy makers, they can decide whether they should subsidise housing-related costs to reduce future medical expenditures.
- ⇒ Moreover, as an impact on society, the dissemination of high-quality houses (Sustainable Development Goal (SDG) 11) has positive ripple effects not only on the medical aspect (SDG 3) but also on reduced inequalities (SDG 10) in terms of health and climate changes (SDG 13) by reducing energy consumption.

population, who generally spend more time at home, is estimated to double from 2022 (771 million) to 2050 (1.6 billion),[4] there is an increasing need for healthy housing. In line with the growing importance of healthy housing, the WHO issued the Housing and Health Guidelines in 2018,[5] indicating that improved housing conditions can save lives and prevent diseases. One of the five primary areas in the guidelines is 'low indoor temperatures and insulation', showing that the number of excess winter mortality (EWM) due to cold housing has been estimated at 38 200 per year (12.8/100 000) in 11 European countries.[6] One of the primary causes of EWM is cardiovascular diseases (CVDs), which is partially caused by cold-induced hypertension.

Particularly in Japan, which became the first country experiencing a super-aged society, approximately 30% of 50 million existing houses were not thermally insulated as of 2019. Accordingly, there is concern that low indoor temperatures may greatly affect hypertension. In fact, the nationwide Smart Wellness Housing (SWH) Survey found that the minimum indoor temperature was below 18°C, which is recommended by the WHO, in more than 90% of houses.[7] Authors also revealed that systolic blood pressure (SBP) increased with a decrease in indoor temperature and that older residents, who have a high risk of CVDs, were more vulnerable to low temperatures.[8] There is therefore an urgent need to tackle the housing and health issues in Japan.

To mitigate cold exposure inside houses, the substantial initial costs required for thermal insulation can be a major barrier. Furthermore, given the recent global conditions where household energy costs would spike by 62.6%–112.9% due to recovery from the COVID-19 pandemic and the Russia–Ukraine conflict,[9] the running costs of heating could be a second barrier. However, the benefits of preventing hypertension and CVDs by living in warm houses might outweigh these costs. This is particularly relevant considering that the total medical costs of hypertension and CVDs in Japan exceed US$40 billion annually. Thus, improving the thermal environment of housing has the potential to recoup the costs associated with insulation and heating. Furthermore, it also has the potential to prolong healthy life expectancy, which is one of the most important health indices in recent years.

Based on the background provided, this study posits the following hypotheses: 'Is improving the thermal environment of housing through insulation and heating beneficial in terms of life-cycle costs?' and 'Does it prolong healthy life expectancy?'. Health economic evaluation, typically used in the development of new drugs and treatment methods, was applied to assess the health impacts of housing insulation and heating. This research includes cost-effectiveness analyses to aid in the decision-making process for residents purchasing or operating houses, as well as for policymakers discussing subsidies for the thermal insulation of houses or energy costs.

MATERIALS AND METHODS

Overview of health economic analyses

The analyses were conducted and reported in accordance with the Consolidated Health Economic Evaluation Reporting Standards (CHEERS) statement.[10] Adherence to the CHEERS statement is summarised in online supplemental table S1-1. An economic model combining a decision tree and a Markov model was developed to evaluate the cost and effectiveness of upgrading thermal insulation and living in warm houses. A Monte Carlo simulation was conducted by creating 100 000 virtual husband–wife pairs. The health economic analysis plan is detailed in this paper and its supplement. The model was created from the perspective of a public healthcare payer, using an exchange rate of US$1 = Japanese yen (JPY) 150 as of August 2024. All analyses were conducted using TreeAge Pro Healthcare V.2022 R2.1 (TreeAge Software, Massachusetts, USA).

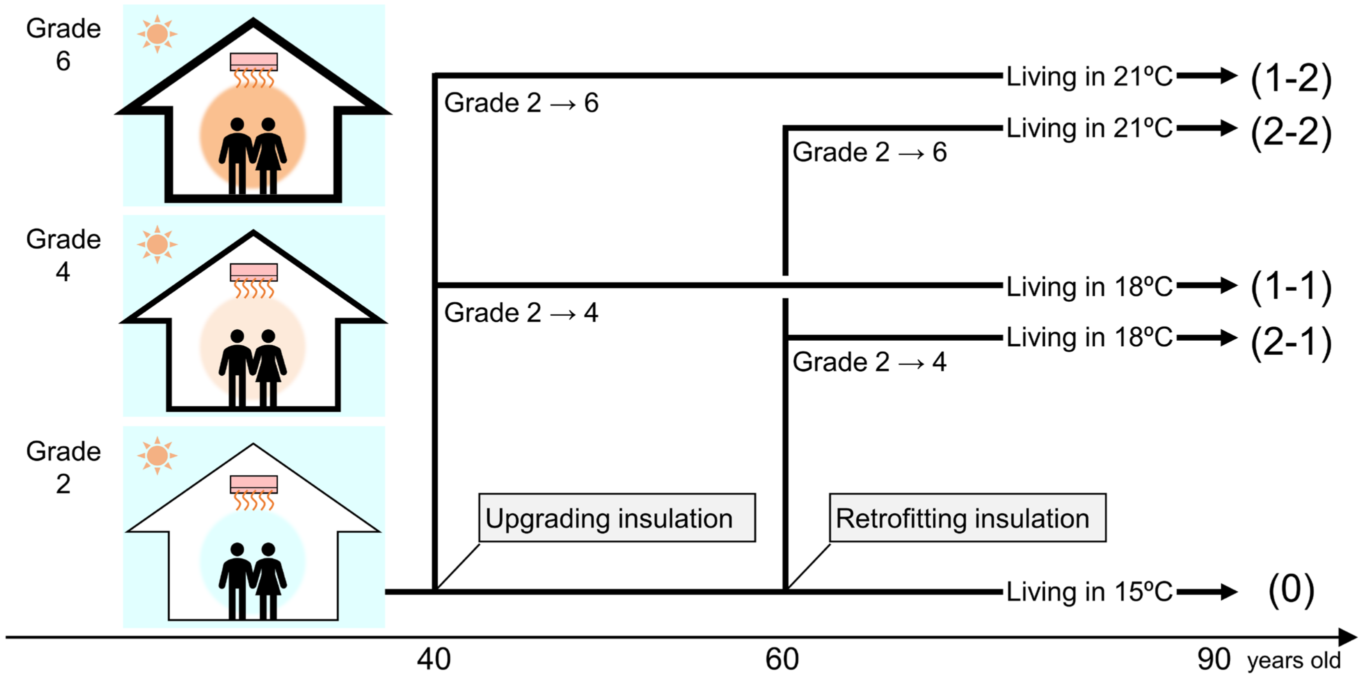
Population

The study area, Japan, was selected because (1) It is facing a super-aged society, and (2) It has many homes with low thermal insulation levels, leading to a prevalent problem of cold homes. The model population was derived from the SWH Survey from Japan. The detailed protocol of the SWH Survey is available in the published paper by Umishio *et al*[8] and at http://www.umin.ac.jp/ctr/ (Trial No. UMIN000030601). The selected characteristics of husband–wife pairs, as shown in online supplemental table S1-2, were based on this survey. To evaluate the preventative effect on hypertension and CVDs from living in warm houses, the association between indoor temperature and morning SBP was used, based on approximately 33 000 data points from 2900 residents of the SWH Survey (online supplemental figure S1-1). For example, when the indoor temperature increased from 10°C to 20°C, SBP decreased by 5.1 mm Hg in 40-year-old men, 7.6 mm Hg in 60-year-old men, and 10.2 mm Hg in 80-year-old men. Under the same conditions, SBP decreased by 6.5 mm Hg in 40-year-old women, 9.1 mm Hg in 60-year-old women, and 11.6 mm Hg in 80-year-old women. The detailed equation can be found in online supplemental table S1-3. The focus on morning data is based on numerous studies indicating a higher frequency of CVDs in the morning,[11–13] and the strong predictive value of morning SBP for cardiovascular events.[14–16]

Scenario setting

Three cases of thermal insulation levels were set: (1) Grade 2 (the most prevalent standard in existing houses in Japan), (2) Grade 4 (the highest standard before 2022), and (3) Grade 6 (newly established standard in 2022). This grading is defined based on the heat loss from the outer skin of houses, with a higher grade indicating a higher level of insulation. Details of the thermal insulation levels are shown in online supplemental tables S2-1, S2-2 and figure S2-1. Additionally, three indoor winter temperature cases were considered: (1) 15°C (the average temperature in about 2000 houses in the morning),[8] (2) 18°C (the minimum temperature recommended by WHO guidelines),[5] and (3) 21°C (a beneficial temperature for health based on a previous systematic review).[17]

Using these thermal insulation levels and indoor temperatures, five scenarios were formulated as illustrated in figure 1. Scenario 0 (the comparative base scenario) involved living in a 15°C environment in Grade 2 houses, which is the most common condition in Japan. Scenario 1 (the upgrading insulation scenario) involved residents upgrading thermal insulation levels when purchasing new houses at the age of 40 years. This age was chosen because the average age for purchasing a first house is nearly 40 years in Japan, according to the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). Specifically, Scenario 1–1 involved living at 18°C in Grade 4 houses, and Scenario 1–2 at 21°C in Grade 6 houses. In Scenario 2 (the retrofitting insulation scenario), residents retrofitted the thermal insulation of their houses at the age of 60 years. This age was also chosen because the average age for conducting such renovations is 60.2 years according to the MLIT. In Scenario 2–1, an insulation retrofit was conducted from Grade 2 to Grade 4 with living conditions at 18°C, while in Scenario 2–2,



Scenario	Description
0: Base Grade 2 & 15°C	The most prevalent thermal insulation level and indoor temperature in Japan
1: Upgrading insulation 1-1: Grade 4 & 18°C 1-2: Grade 6 & 21°C	Upgrading the thermal insulation level when purchasing a new house at the age of 40, and maintaining an indoor temperature of 18°C or 21°C
2: Retrofitting insulation 2-1: Grade 4 & 18°C 2-2: Grade 6 & 21°C	Retrofitting the thermal insulation at the age of 60, and maintaining an indoor temperature of 18°C or 21°C

Figure 1 Five scenarios combining thermal insulation levels and indoor temperatures. 'Grade' refers to the level of thermal insulation of houses in Japan. Grade 2: the most prevalent standard in existing houses in Japan; Grade 4: the highest standard before 2022; Grade 6: the newly established standard in 2022.

the retrofit was conducted from Grade 2 to Grade 6 with living conditions at 21°C.

In Japan, the average lifespan is 85 years. Therefore, the time horizon for the upgrading insulation scenarios was set from age 40 years to 90 years (50 years), and for the retrofitting insulation scenarios, it was set from age 60 years to 90 years (30 years). The model, focusing on the winter season, was developed with 600/360 iterations to calculate a 1 month cycle (50/30 years × 12 months/year). The aforementioned indoor temperatures (15°C/18°C/21°C) were set only for the winter season (November–March), while 24°C was used in spring and fall (April, May, September and October), and 26°C was used in the summer season (June–August) for all scenarios.

Model structure

The structure of a hybrid model, which combines a decision tree and a Markov model, is depicted in online supplemental figures S1-2 and S1-3. Six health statuses were modelled as follows: (1) Normal BP (home SBP <135 mm Hg) and no hospital visit, (2) High BP (home SBP ≥135 mm Hg) and no hospital visit, (3) Normal BP and hospital visit, (4) High BP and hospital visit, (5) Acute complications and (6) Dead. The status '(2) high BP and no hospital visit' represents residents with hypertension who do not seek hospital care, reflecting the nature of hypertension as a 'silent killer', often without subjective symptoms. In '(3) normal BP and hospital visit', it was assumed that once residents visit the hospital, they continue to do so even if their BP returns to normal. 'Acute complications' include coronary artery disease (CAD), stroke, heart failure (HF) and atrial fibrillation (AF). According to a previous study,[18] once residents enter the 'acute complications' status, they either remain in that status or pass away from the complication within 12 months. Subsequently, they may recover from 'acute complications' to 'normal BP and hospital visit/high BP and hospital visit' with a postcomplication tag. This tag indicates a slightly higher mortality rate than natural deaths in patients who have experienced CAD, stroke or HF. It was also assumed that more than one acute complication does not occur simultaneously.

Probabilities

The annual incidence and mortality rates of each complication are summarised in online supplemental table S1-4. Probabilities of natural deaths and hospital visits due to hypertension were modelled based on national statistics (online supplemental figure S1-4). In line with a previous study,[18] both acute and postcomplication (chronic) mortality rates were established for each complication. The annual incidence rates of these complications were adjusted based on BP categories (online supplemental table S1-5). Given that the model operates on a 1 month cycle, these annual rates were converted to their monthly equivalents.

Costs

The costs included the cost of thermal insulation work, heating costs, and medical costs related to hypertension and CVDs. The costs for thermal insulation work on houses were set as follows: (1) JPY1 million (US$6670) for upgrading new houses from Grade 2 to Grade 4, (2) JPY2 million (US$13 300) for upgrading new houses from Grade 2 to Grade 6, (3) JPY3.5 million (US$23 300) for entirely retrofitting existing houses from Grade 2 to Grade 4, and (4) JPY4.5 million (US$30 000) for entirely retrofitting existing houses from Grade 2 to Grade 6. Regarding heating costs, heat load, indoor environment and energy consumption, simulations were performed using the Building Energy Simulation Tool for Housing calculation (BEST-H). The detailed setting for the calculation of heating costs is shown in the online supplemental figures S2-1, S2-2 and online supplemental tables S2-1-S2-3. In response to the recent energy crisis,[9] analyses of heating costs were also conducted, assuming an electricity price of JPY62/kilowatt-hour (kWh) (equivalent to US$0.413/kWh), which is double the current rate of JPY31/kWh (US$0.207/kWh). Since heating costs are incurred at the household level, to avoid double counting, the costs were attributed to the wife, who typically has a longer lifespan than the husband. The medical costs related to hypertension and CVDs were defined in accordance with previous studies. The references for each parameter are shown in online supplemental table S1-4. An annual cost reduction rate of 2% was set in line with the Japanese guideline.[19]

Effectiveness

Effectiveness was evaluated by quality-adjusted life-years (QALYs), an index of healthy life expectancy. The QALYs were calculated by multiplying life expectancy by a utility value assigned to the health status during that period. The utility values range from 0 to 1, where 1 represents perfect health and 0 represents death. Utility values for hypertension and acute complications were referred to from published studies (online supplemental table S1-4). Outcomes were evaluated as the incremental cost-effectiveness ratio (ICER) per QALY gained. Effectiveness, as well as annual costs, were discounted at a 2% rate.[19]

Analysis of uncertainty

Probabilistic sensitivity analyses were conducted to consider the effects of uncertainty. The distributions set for all parameters are shown in online supplemental table S1-6. Typically, a beta distribution was used for probabilities and effectiveness, while a gamma distribution was applied to cost parameters. Distributions that closely aligned with those in a previous study were generated. The distributions of residents' characteristics were assigned based on a nationwide survey in Japan.[8] To demonstrate the uncertainty of the results, 1000 husband–wife pairs were extracted.

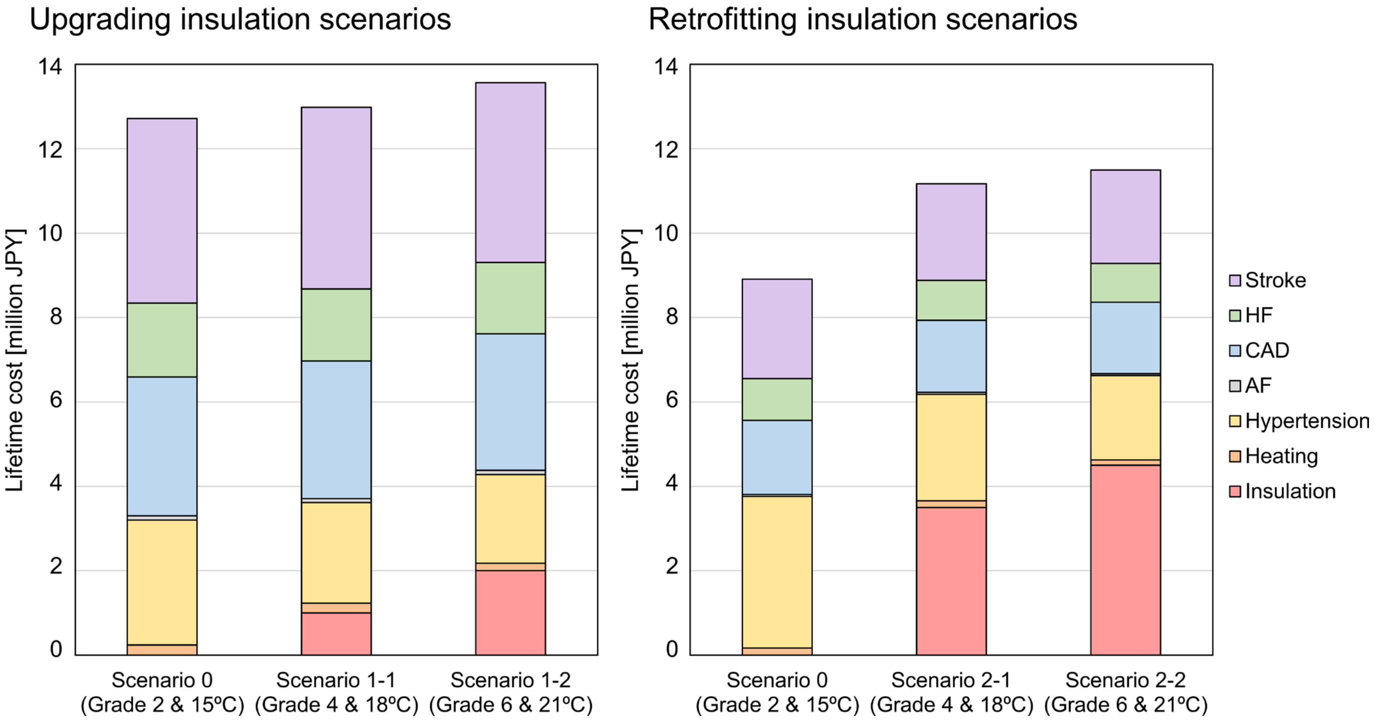


Figure 2 Breakdown of lifetime costs for upgrading and retrofitting insulation scenarios. Bar charts indicate the mean costs of a Monte Carlo simulation of 100 000 virtual husband–wife pairs. AF, atrial fibrillation; CAD, coronary artery disease; HF, heart failure; JPY, Japanese yen.

Patient and public involvement

No patients or members of the public were involved in this study due to a non-disclosure agreement signed among the researchers. On publication, the results will be widely disseminated through symposiums, social media and the efforts of the public awareness team, which is mainly composed of construction companies.

RESULTS

Figure 2 illustrates the breakdown of lifetime costs in each scenario, assuming an electricity price of JPY31/kWh (US$0.207/kWh). While medical costs constituted a significant portion of the expenses, amounting to 59.8%–98.1% of the total costs, the expenditure on heating was comparatively minimal, accounting for less than 2% across all scenarios. In the upgrading insulation scenarios (Scenarios 1–1 and 1–2), the lifetime costs were higher by JPY0.26 million and JPY0.84 million, respectively, compared with Scenario 0. This indicates that 74.1% and 57.9% of the initial costs for thermal insulation work were recouped, mainly through reduced medical costs related to hypertension and CVDs, respectively. In the retrofitting insulation scenarios (Scenarios 2–1 and 2–2), 35.4% and 42.6% of the costs for thermal insulation work were recouped mainly by reduced medical costs.

Table 1 shows the cost-effectiveness of the five scenarios. Regarding upgrading insulation scenarios, compared with the Scenario 0, the sum of the healthy life expectancies of the husbands and wives increased by 0.31 QALYs in Scenario 1–1 and by 0.48 QALYs in Scenario 1–2. The ICERs for Scenarios 1–1 and 1–2 were JPY0.84 million/QALY and JPY1.77 million/QALY, respectively, which were below the threshold value in Japan of JPY5 million/QALY gained. In the retrofitting insulation scenarios, there was an increase in healthy life expectancy of 0.56 QALYs for Scenario 2–1 and 0.86 QALYs for Scenario 2–2. This resulted in ICERs of JPY4.07/QALY and JPY3.00 million/QALY, respectively, both below the threshold value in Japan. The ICERs for Scenarios 1 and 2 slightly decreased when the energy price doubled from JPY31/kWh to JPY62/kWh, due to the lower heating energy requirement achieved through enhanced thermal insulation. However, the overall trend of the results remained consistent, as heating costs constituted only a small portion of the total costs. Consequently, subsequent results were calculated assuming the heating cost was set at the current rate of JPY31/kWh.

The results of the probabilistic sensitivity analyses are shown as incremental cost-effectiveness scatter plots in figure 3. In the context of upgrading insulation scenarios, the probabilities of dominance (being less costly and more effective) and cost-effectiveness (being more costly and more effective, with an ICER of less than JPY5 million/QALY gained) were 21.1% and 72.3% in Scenario 1–1, and 2.4% and 84.4% in Scenario 1–2, respectively. In terms of the retrofitting insulation scenarios, although the probability of dominance was 0% in both Scenarios 2–1 and 2–2, the probability of cost-effectiveness was 29.1% in Scenario 2–1 and 43.3% in Scenario 2–2.

The cost-effectiveness acceptability curves are shown in figure 4. Regarding the upgrading insulation scenarios, when the willingness to pay (WTP) to obtain 1 QALY

Table 1 Cost-effectiveness of upgrading and retrofitting insulation scenarios

Scenario		Cost (million JPY)	Healthy life expectancy (QALYs)	Increment cost (million JPY)	Increment healthy life expectancy (QALYs)	ICER (million JPY/QALY)
(A) Heating cost: JPY31/kWh						
Upgrading insulation scenarios for 40-year-old husband–wife pairs						
0:	Grade 2 & 15°C	12.78	51.38	–	–	–
1–1:	Grade 4 & 18°C	13.04	51.69	0.26	0.31	0.84
1–2:	Grade 6 & 21°C	13.62	51.86	0.84	0.48	1.77
Retrofitting insulation scenarios for 60-year-old husband–wife pairs						
0:	Grade 2 & 15°C	8.94	33.58	–	–	–
2–1:	Grade 4 & 18°C	11.20	34.14	2.26	0.56	4.07
2–2:	Grade 6 & 21°C	11.52	34.44	2.58	0.86	3.00
(B) Heating cost: JPY62/kWh						
Upgrading insulation scenarios for 40-year-old husband–wife pairs						
0:	Grade 2 & 15°C	13.07	51.35	–	–	–
1–1:	Grade 4 & 18°C	13.30	51.66	0.23	0.31	0.76
1–2:	Grade 6 & 21°C	13.83	51.82	0.77	0.47	1.61
Retrofitting insulation scenarios for 60-year-old husband–wife pairs						
0:	Grade 2 & 15°C	9.05	33.55	–	–	–
2–1:	Grade 4 & 18°C	11.30	34.12	2.25	0.57	3.98
2–2:	Grade 6 & 21°C	11.59	34.42	2.53	0.87	2.91

The values indicate the means of Monte Carlo simulations of 100 000 virtual husband–wife pairs.
ICER, incremental cost-effectiveness ratio; JPY, Japanese yen; kWh, killowatt-hour; QALYs, quality-adjusted life-years .

ranged from JPY1 million to JPY2 million, Scenario 1–1 (Grade 4 & 18°C) emerged as the most cost-effective option. As the WTP reached JPY2.5 million or more, Scenario 1–2 (Grade 6 & 21°C) became the most cost-effective. In the retrofitting insulation scenarios, Scenario 2–2 (Grade 6 & 21°C) emerged as the most cost-effective when the WTP reached JPY6.5 million or more, which is above the threshold value of JPY5 million/QALY gained. The discrepancy between the results of the retrofitting insulation scenarios in table 1 and figure 4 (table 1 shows that retrofitting insulation is cost-effective, whereas figure 4 does not) is due to the difference in husband–wife pairs: table 1 includes only pairs with healthy lifestyles, while figure 4 includes some pairs with unhealthy lifestyles. In other words, unhealthy lifestyles progressed hypertension even in warm houses, resulting in a weakened benefit of retrofitting insulation. To realise cost-effective retrofitting for residents with various characteristics, it is necessary to consider lower-cost methods, such as partial insulation retrofitting targeting only the frequently used rooms, although the cost in this study was set assuming insulation retrofitting of the entire house.

DISCUSSION

Economic analyses related to housing and health have been summarised in the WHO guideline[5] and systematic reviews.[20] In New Zealand, cost-benefit analyses were performed to evaluate the effect of retrofitting houses with insulation based on a randomised community-level trial,[21–23] and an insulation subsidy programme.[24] They revealed that the savings achieved by improving health conditions dominated the costs of insulation retrofitting. An earlier analysis on retrofitting insulation in the USA also showed that the benefits including energy savings and productivity benefits outweighed costs.[25] However, these studies do not include the benefits gained from preventing CVDs, which are the leading cause of death globally and are caused by cold temperatures inside the house. Among previous studies addressing CVDs, one published paper[26] estimated the impact of eradicating cold housing on health in Australia, finding that it was comparable to the effects of lifestyle and dietary interventions. However, this study did not provide a detailed quantification of the associated costs. In the UK, a report by the Building Research Establishment estimated the cost-benefit of improving poor housing based on the Housing Health and Safety Rating System, indicating that the savings generated by mitigating hazards in poor housing were £18.5 billion (US$22.4 billion) per year and that improving excess cold contributed to a large amount of the savings.[27] Another study showed that upgrading windows and doors to double-glazed ones and installing wall insulation decreased emergency hospital admissions and generated considerable estimated savings using longitudinal data.[28] However, these two studies showed the evaluation of QALYs as one of their future challenges. Among previous studies that evaluated both the costs and effectiveness (measured in QALYs) related

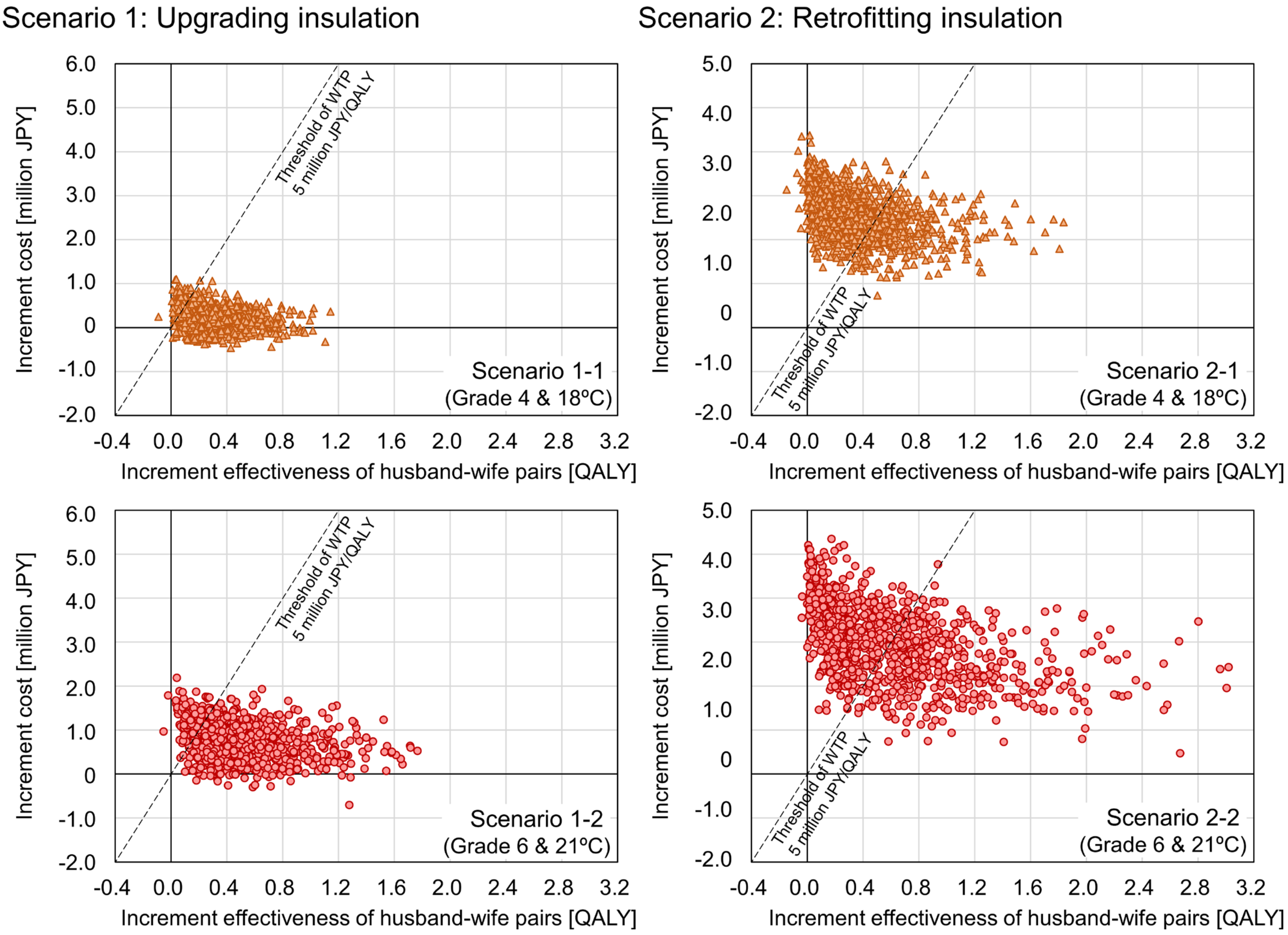


Figure 3 Cost-effectiveness plots in the upgrading and retrofitting insulation scenarios (vs Scenario 0). JPY; Japanese yen, QALYs; quality-adjusted life-years; WTP; willingness to pay.

to CVDs, one study[29] based on mathematical modelling demonstrated the effects of energy efficiency interventions in the UK. According to this study's findings, the impact of investments in home energy efficiency mostly exceeded the ICER threshold in the UK. This may be attributed to the relatively higher indoor temperatures before the interventions in the UK compared with the lower indoor temperatures in Japan, resulting in a diminished effect of temperature increases due to energy efficiency interventions.

In this context, it is necessary to consider whether low indoor temperatures are a problem unique to Japan. According to prior research, cold homes represent a challenge not only in Japan but also in other countries. In a study conducted in Asia, the average morning temperature in 114 Chinese households during winter was 15.3°C.[30] Another study conducted in China revealed indoor temperatures ranging from 0.5°C to 24°C during the winter months in 527 residential buildings.[31] In India, an investigation of 150 vernacular homes across different seasons indicated that mean indoor temperatures were lowest in January, dropping to 13.7°C in Imphal, 15.0°C in Cherrapunjee and 17.2°C in Tezpur.[32] In Oceania, environmental measurements revealed a winter average temperature of 16.5°C in 100 Australian houses.[33] A New Zealand study that monitored indoor temperatures in 397 houses during winter found that the average living-room temperatures during the day and bedroom temperatures at night were 15.8°C and 13.6°C, respectively.[34] In Africa, year-long measurements of 100 houses across five towns in Tunisia revealed minimum indoor temperatures ranging from 4.8°C to 15.7°C.[35] In Europe, the average indoor temperature during winter in 141 Portuguese households was 14.9°C in bedrooms and 16.6°C in living rooms.[36] A study of 43 Greek houses reported an average temperature of 15.9°C.[37] Conversely, a review of measured indoor temperature in UK homes indicated that the average living room temperature in winter ranged between 18°C and 21°C.[38] The Energy Follow-Up Survey 2017, which involved 750 UK dwellings, revealed an average indoor temperature of 18.4°C during the heating season (December to February).[39] In France, the average temperature in 384 houses was reported to be 20.0°C.[40] In the USA, the average temperature across 327 homes in various climate zones during the heating season was 19.6°C.[41] Despite these relatively high averages of indoor temperature, energy poverty remains a prevalent problem even in both Europe and the USA,[42 43]

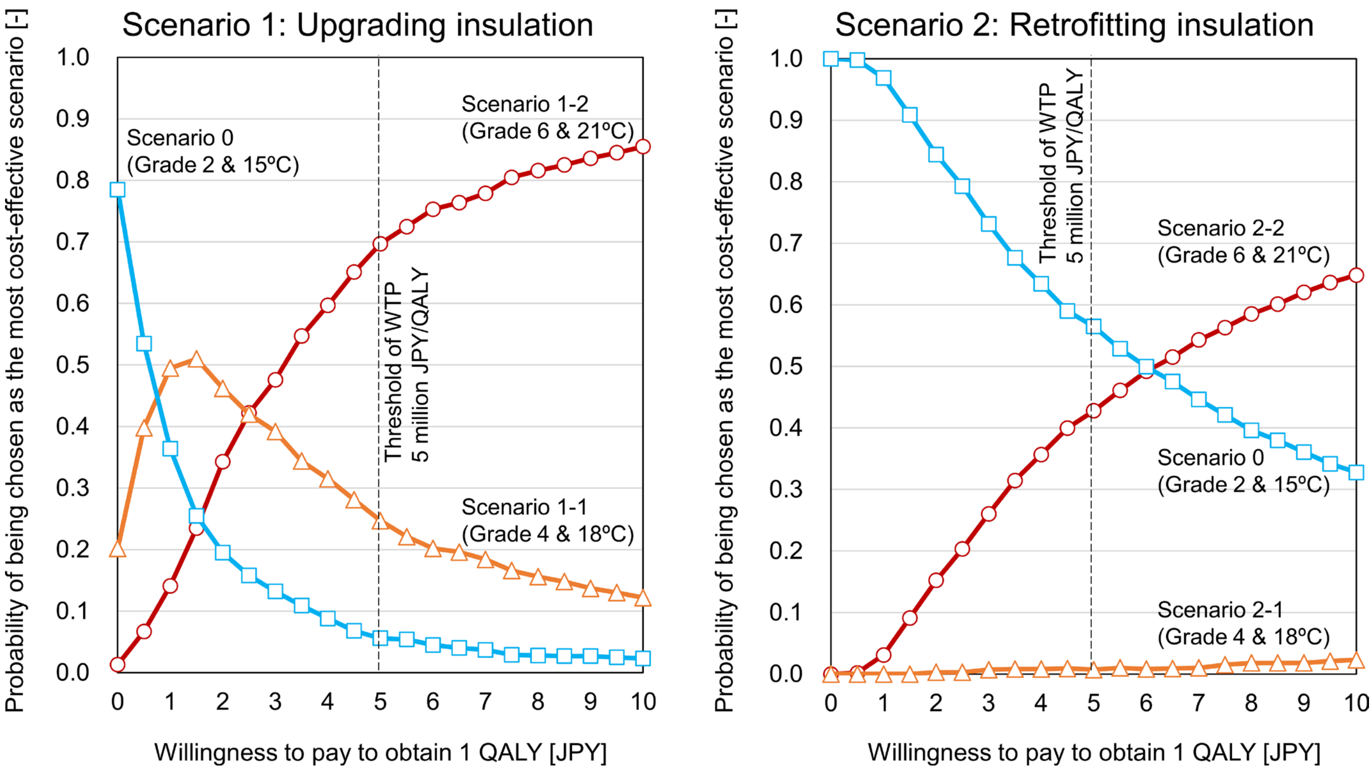


Figure 4 Cost-effectiveness acceptability curve for upgrading and retrofitting insulation scenarios. JPY; Japanese yen, QALYs; quality-adjusted life-years; WTP; willingness to pay, .

leading to the widespread issue of cold homes. Furthermore, the recent surge in energy prices has exacerbated the problem of energy poverty, increasing the global challenge of living in cold homes.[44]

In summary, the results from most previous health economic analyses and the present analysis are generally consistent in showing that thermal insulation work on houses could be beneficial. However, the studies vary widely: some consider only costs, others focus solely on health impacts, and some account for both. Additionally, the health indicators and productivity losses included differ across studies. This variability in prior research, where health improvements can lead to savings that exceed the costs for thermal insulation work on houses, contrasts with our study, which found that these costs were not fully recouped. Furthermore, most previous studies focus on specific insulation programmes in particular areas or countries, which weakens the generalisability of the findings. According to the systematic review,[20] a key limitation of previous analyses is that evidence from one setting is difficult to transfer to another. In contrast, a major strength of the present analysis is that the model is established based on the association between BP and indoor temperature, which are internationally generalisable indices. Through the aforementioned review on indoor temperature, it is evident that the problem of cold homes is prevalent worldwide, thus generalisability is an important aspect. In addition, the causal relationship between hypertension and CVDs is well established based on abundant previous research. Therefore, the framework of the economic model suggested in this paper is expected to be applicable to other situations by adjusting the model inputs.

The present study has several limitations. First, the suggested model only included the health status of hypertension and CVDs. For example, the prevention effect on respiratory diseases, which are also affected by low indoor temperatures, was not included.[5 45–47] This was because quantitative evidence on the association between indoor temperature and generalisable respiratory indices (eg, forced expiratory volume in 1 s and forced vital capacity) is limited at present. A systematic review[48] and a recent study[49] also showed that residents' mental health declines when their houses have disadvantages, or when they can no longer afford to warm their homes. Thus, the inclusion of health statuses not related to hypertension and CVDs is expected to contribute to multiple benefits that support the importance of housing. On the other hand, considering health statuses beyond hypertension and CVDs might lead to increased medical costs for other diseases, such as cancer (the second highest medical expenditure following CVDs in Japan) due to the prevention of CVDs and longer lifespans in upgrading and retrofitting insulation scenarios. Future research should aim to develop a comprehensive model that can evaluate other health statuses and their associated costs once further quantitative evidence becomes available. Second, only a husband–wife pair was included, and other family members (eg, children) were not considered. Given that respiratory diseases are more prevalent in children, this might be one of the causes of underestimation. Third, previous research[50] has shown that reducing ventilation to maintain indoor temperatures during winter can lead to increased indoor radon concentrations, thereby increasing the risk of lung cancer. Therefore, it is necessary to comprehensively assess the living environment, including ventilation.[51 52] In this context, it is also essential to consider $PM_{2.5}$ (particulate matter less than 2.5 micrometers in diameter) as it moves from outdoors to indoors through ventilation, and has a significant impact on health.[53] From the perspective of indoor air quality, the type of heating used warrants further examination. Although the present study focused on non-polluting types of heating devices, there are still heating devices that pollute indoor air in real life settings. In fact, a randomised controlled trial in New Zealand, which involved the installation of non-polluting heaters, showed significant benefits in preventing respiratory diseases.[54 55] Finally, 40-year-old/60-year-old husband–wife pairs in Japan were evaluated as a first step. Therefore, the results may vary when considering populations in other countries. However, the present economic model can consider various conditions flexibly by changing the inputs to the model. For example, although the temperature–BP relationship obtained from the Japanese population was used in this study, it should be adjusted to reflect the relationships in other populations.[56] Of note, although the present study considered the difference between men and women in the indoor temperature–BP relationship, recent papers and guidelines have criticised the treatment of gender as a binary factor (male/female).[57 58] Simplification is a necessary process in creating a health economic model, but the limitation of considering only husband (male)–wife (female) combinations should be noted.

In conclusion, the present study suggested a mathematical economic model to calculate the cost-effectiveness of living in well-insulated warm houses using general indices based on the combination of the indoor temperature–BP relationship and BP–CVD relationship obtained in previous studies. Using this framework, it was indicated that (1) 74.1% and 57.9% of the expenses incurred from upgrading the thermal insulation level from Grade 2 to Grade 4 and Grade 6, respectively, were recouped, mainly due to the reduction in medical costs from living in warmer houses; (2) In a similar manner, 35.4% and 42.6% of the expenses associated with retrofitting thermal insulation from Grade 2 to Grade 4 and Grade 6, respectively, were recouped; (3) When taking the healthy life expectancy of a husband–wife pair into consideration, upgrading the thermal insulation level when purchasing new houses could be cost-effective strategies, with ICERs below the threshold value of JPY5 million/QALY gained; and (4) The probabilistic sensitivity analyses showed that retrofitting insulation in entire existing houses from Grade 2 to Grade 6 and maintaining a temperature of 21°C emerged as the most cost-effective options when WTP reached JPY6.5 million or more, indicating the necessity of considering lower-cost methods such as partial insulation retrofitting.

The authors believe that this feasible modelling study will aid in systematic decision-making on housing and health for several stakeholders. The authors also anticipate that these interdisciplinary findings will facilitate the widespread adoption of well-insulated houses, contributing to sustainable development in terms of not only Sustainable Development Goal (SDG) 3 (health) and SDG 11 (sustainable cities) but also SDG 10 (reduced inequalities) and SDG 13 (climate change).

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Contributors SM is the chief investigator of the Smart Wellness Housing Survey. TI, YF and SA designed the Smart Wellness Housing Survey and developed the protocol. TI, YF, SA and WU were responsible for data collection. WU was responsible for data curation, analysed the effectiveness data with inputs from KK, YF, NK, MS and KS, conducted the long-term cost-effectiveness analysis and wrote the first draft of the manuscript. All the authors contributed to the interpretation of the data and critically reviewed the manuscript. WU and SA directly accessed and verified the underlying data and TI was responsible for the decision to submit the manuscript for publication. All authors approved the final version. WU is responsible for the overall content as the guarantor.

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