RESEARCH ON UNDERFLOOR DUCTED HEATING HOUSES WITH AIR-BASED PVT PANEL ON THE ROOFS

～INVESTIGATION OF COST-EFFECTIVE FOUNDATION INSULATION SPECIFICATIONS～

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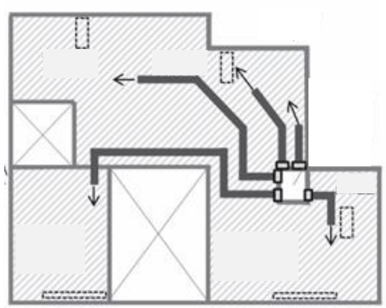
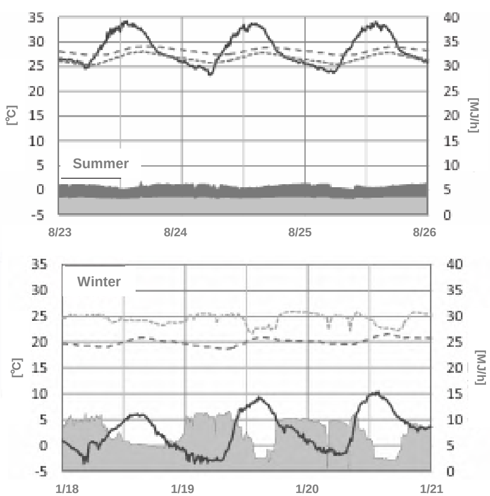
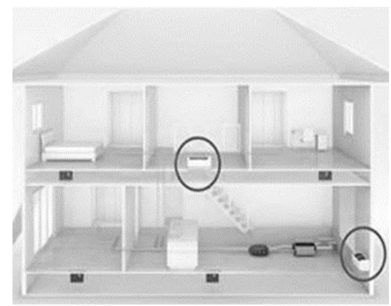
Research background

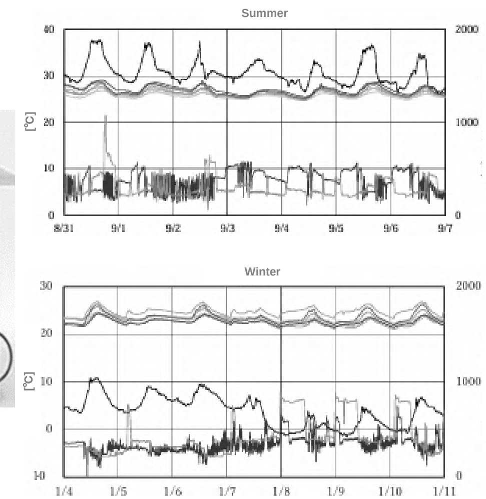
Demand for comfort, health, and energy conservation in housing has increased,
and many houses are being built with insulation performance that exceeds energy conservation standards.





Demonstrated the effectiveness of floor chamber air conditioning in the highly insulated detached house.[1)]



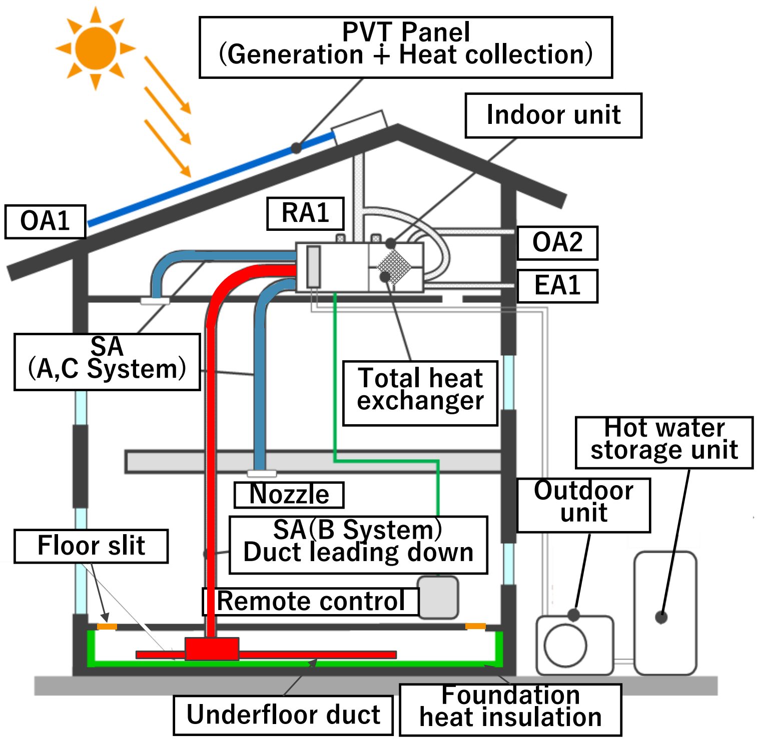


The good indoor environment can be achieved in the ductless whole-house air conditioning system using the wall-mounted air conditioner[2)]

In the detached house with the large floor area, the temperature difference between rooms is expected to be large, and the ductless whole-house air-conditioning system may not be sufficient to ensure the comfortable thermal environment.

1)：Iguchi, M., et al.：Verification of Air Distribution Thermal Environment and Energy Consumption in an Existing Detached House
A methodology for designing the air-conditioning system using floor-chambers in a residence Part 4.
2)：Iwasaki, Y., et al. : Study on a Ductless Central Air-conditioning System Utilizing Crawl Space as Supply Chamber
Part 1 Overview of the System and Verifications by Measurements, technical papers of annual meeting.

Whole-house air conditioning system under study



System overview

System specification

Type	Item	Data
Heating	Standard heating capacity[kW]	4.0
	Standard power consumption for rated heating[kW]	0.905
	Rated low-temperature heating capacity[kW]	4.7
	Rated low-temperature heating power consumption[kW]	1.700
	Coefficient of Performance(COP)[-]	4.42
Air volume	Rated supply air fan airflow[m³/h]	930
	Rated power consumption of indoor blower fan[W]	215
Ventilation	Rated ventilation airflow[m³/h]	200
	Rated power consumption[W]	65
	Temperature exchange efficiency[%](winter)	90
	Total heat exchange efficiency[%](winter)	85
Hot water supply	Tank capacity[L]	370
	Winter peak power consumption[kW]	1.35
	Intermediate period standard power consumption[kW]	1.06

The ducted air-conditioning system under the floor (hereinafter referred to as "this system") was studied, which is expected to realize the thermal environment with less temperature difference between rooms by uniformly heating the under-floor space through the use of under-floor ducts.

This system is also expected to reduce the heating load by using HP (Heat Pump) and roof PVT (PhotoVoltaic and Thermal collectors) panels together.

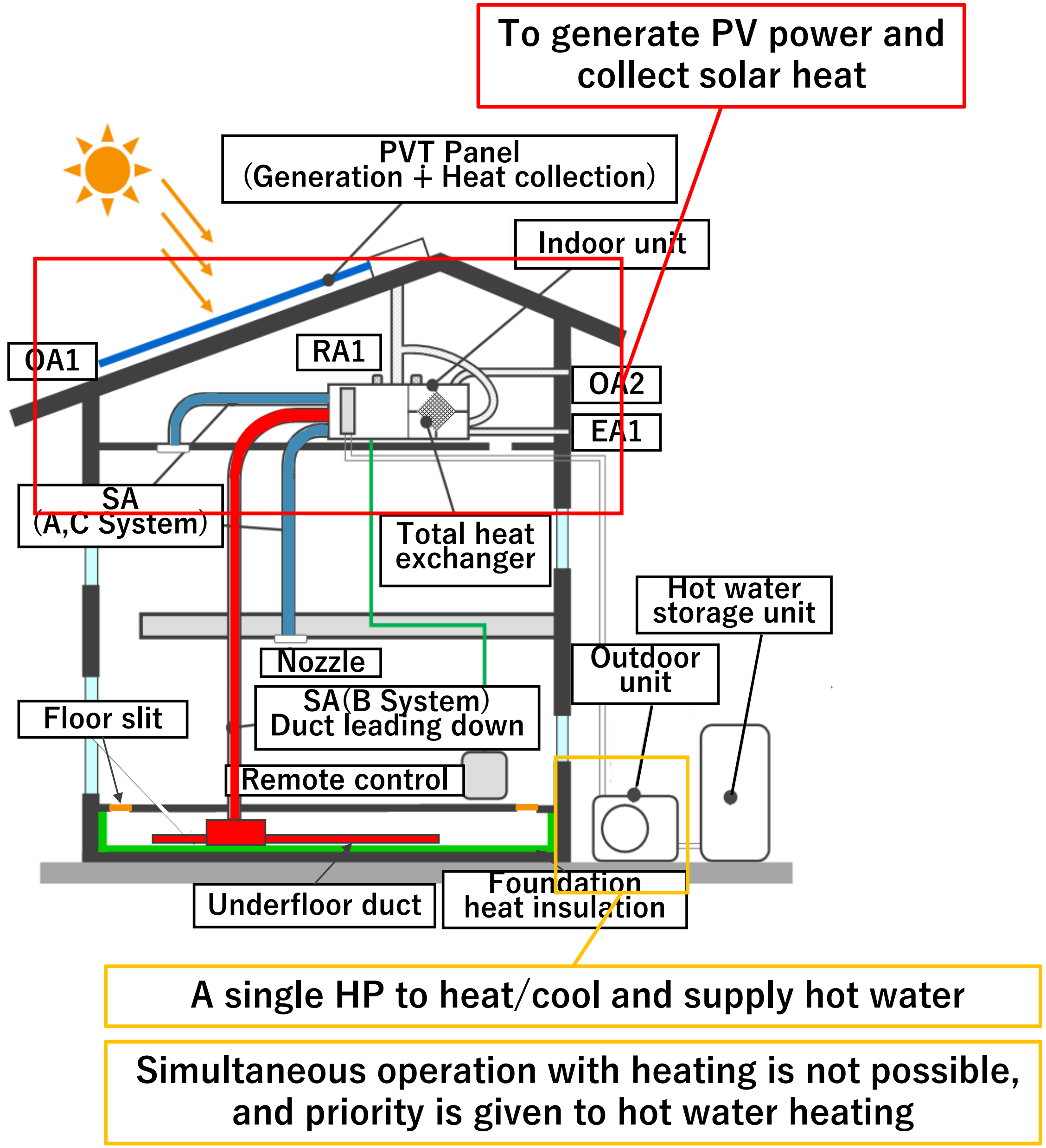
This system is designed for continuous operation, heat capacity of the foundation is not expected, and full insulation over the earthen floor is the standard installation method. However, this installation method is **time-consuming and expensive**.

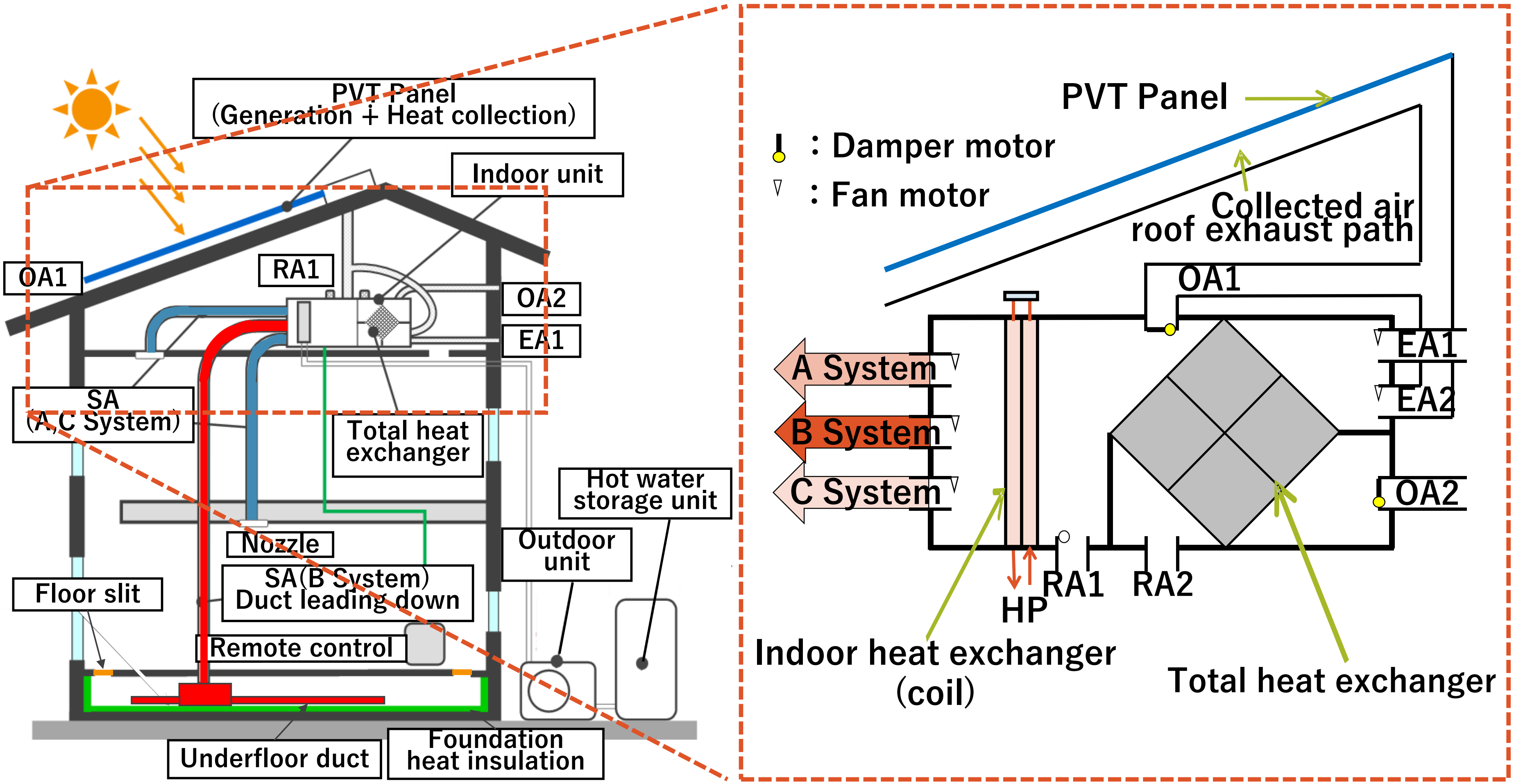
＜Research purpose＞

1. **To understand the amount of under-floor heat loss**
2. **To calculate effective target values for foundation insulation performance**

In this study, the following items were compared using simulations

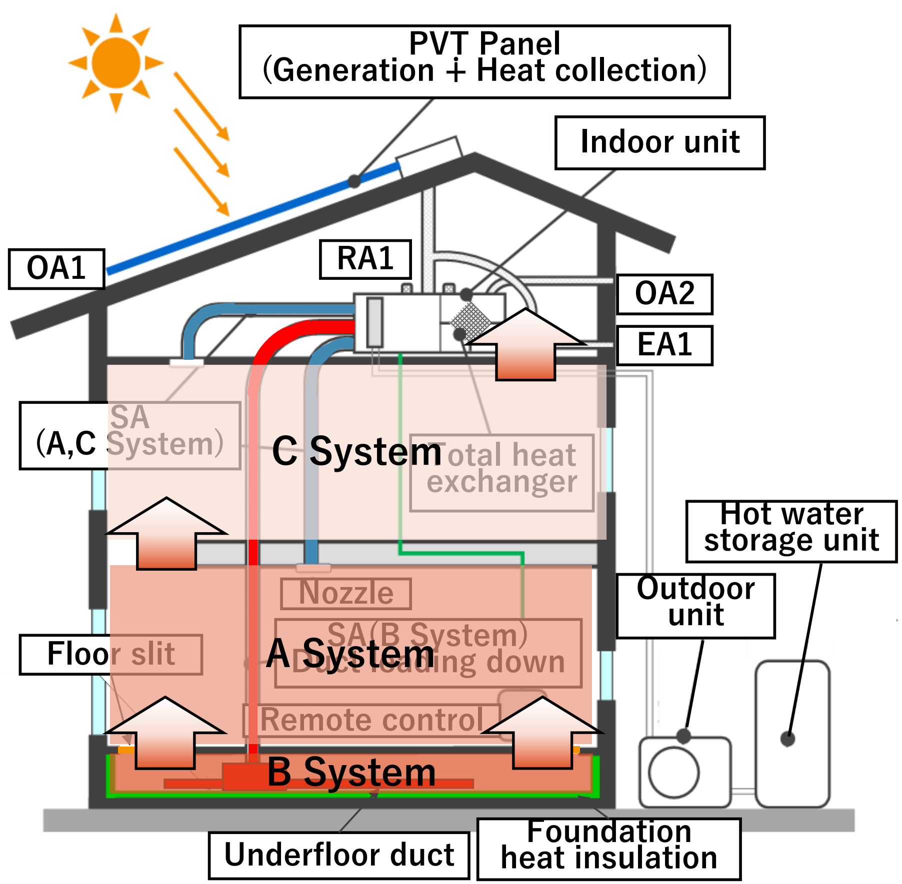
・The thermal environment
・Underfloor heat loss
・Cost

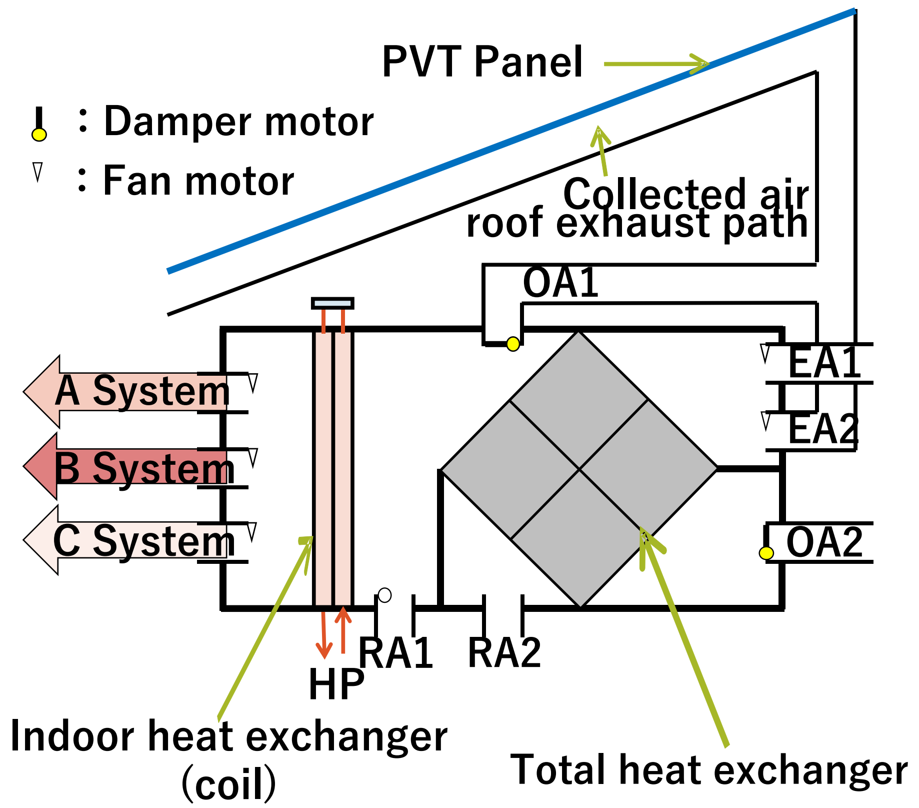

To generate PV power and collect solar heat
PVT Panel
(Generation + Heat collection)
Indoor unit
OA1
RA1
OA2
EA1
SA
(A,C System)
Total heat exchanger
Hot water storage unit
Outdoor unit
Nozzle
SA(B System)
Duct leading down
Floor slit
Remote control
Underfloor duct
Foundation heat insulation
A single HP to heat/cool and supply hot water
Simultaneous operation with heating is not possible, and priority is given to hot water heating



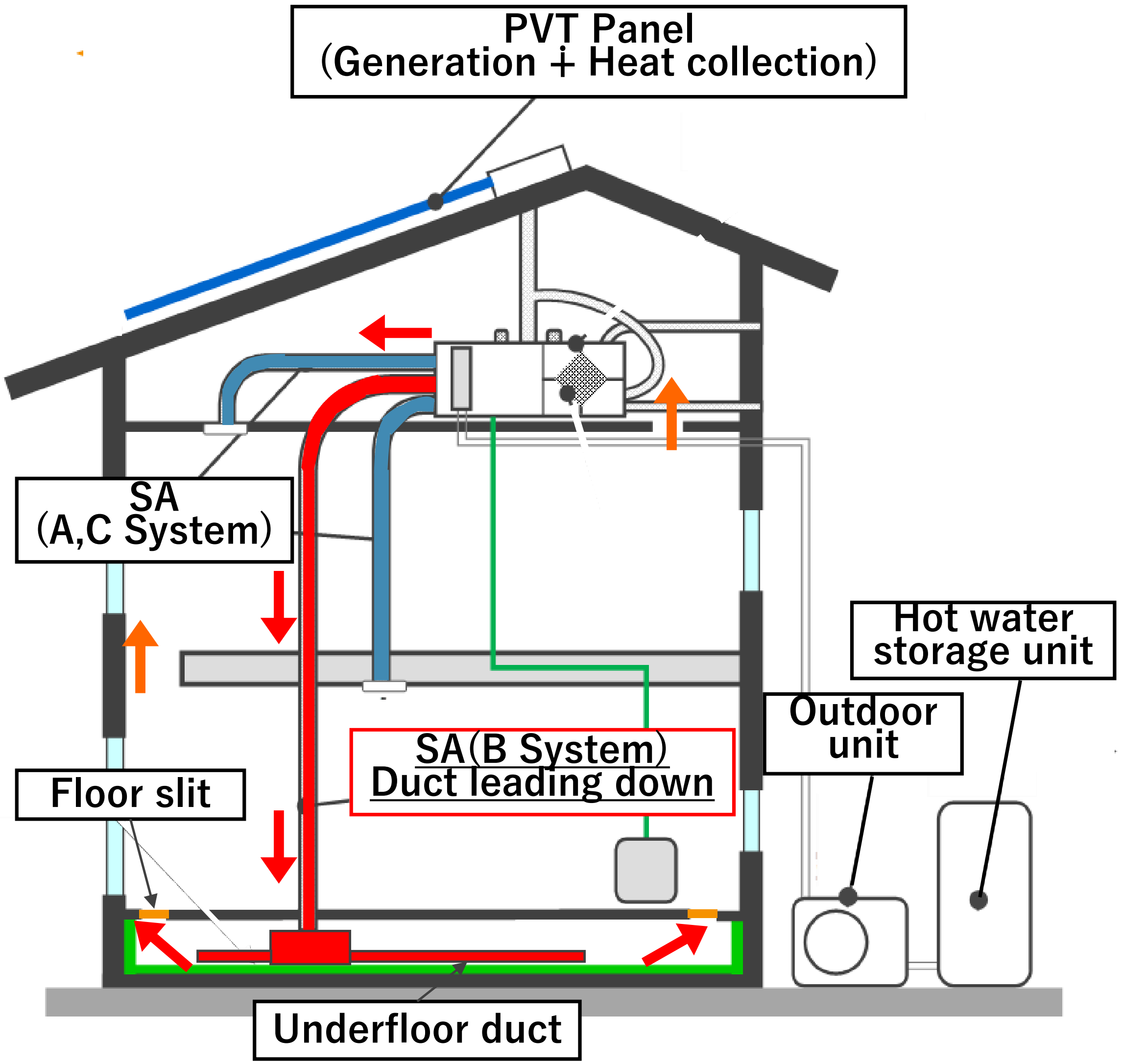
The indoor unit of this system has the built-in total heat exchange ventilation.

- A system：1st floor　B system：Under floor　C system：2ed floor

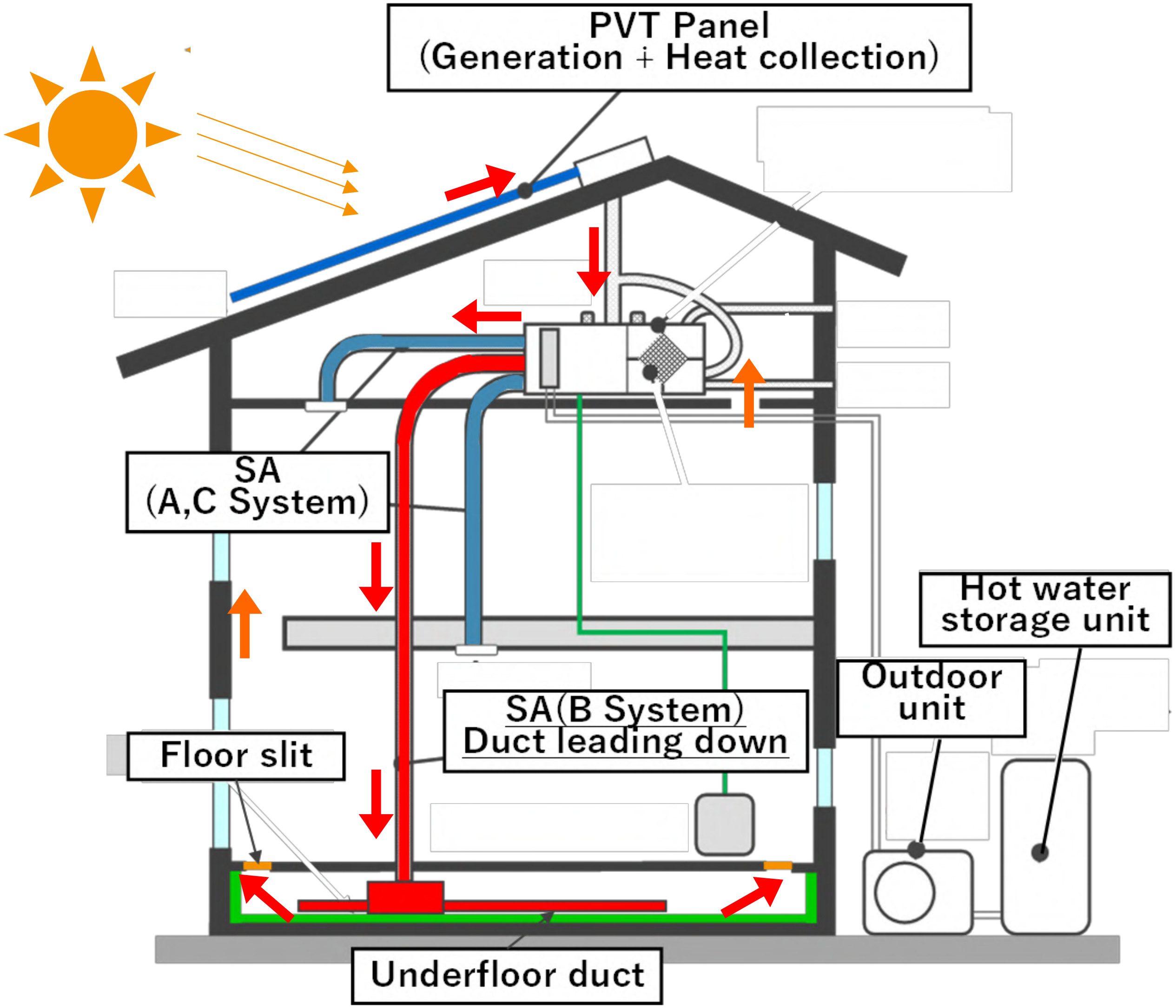




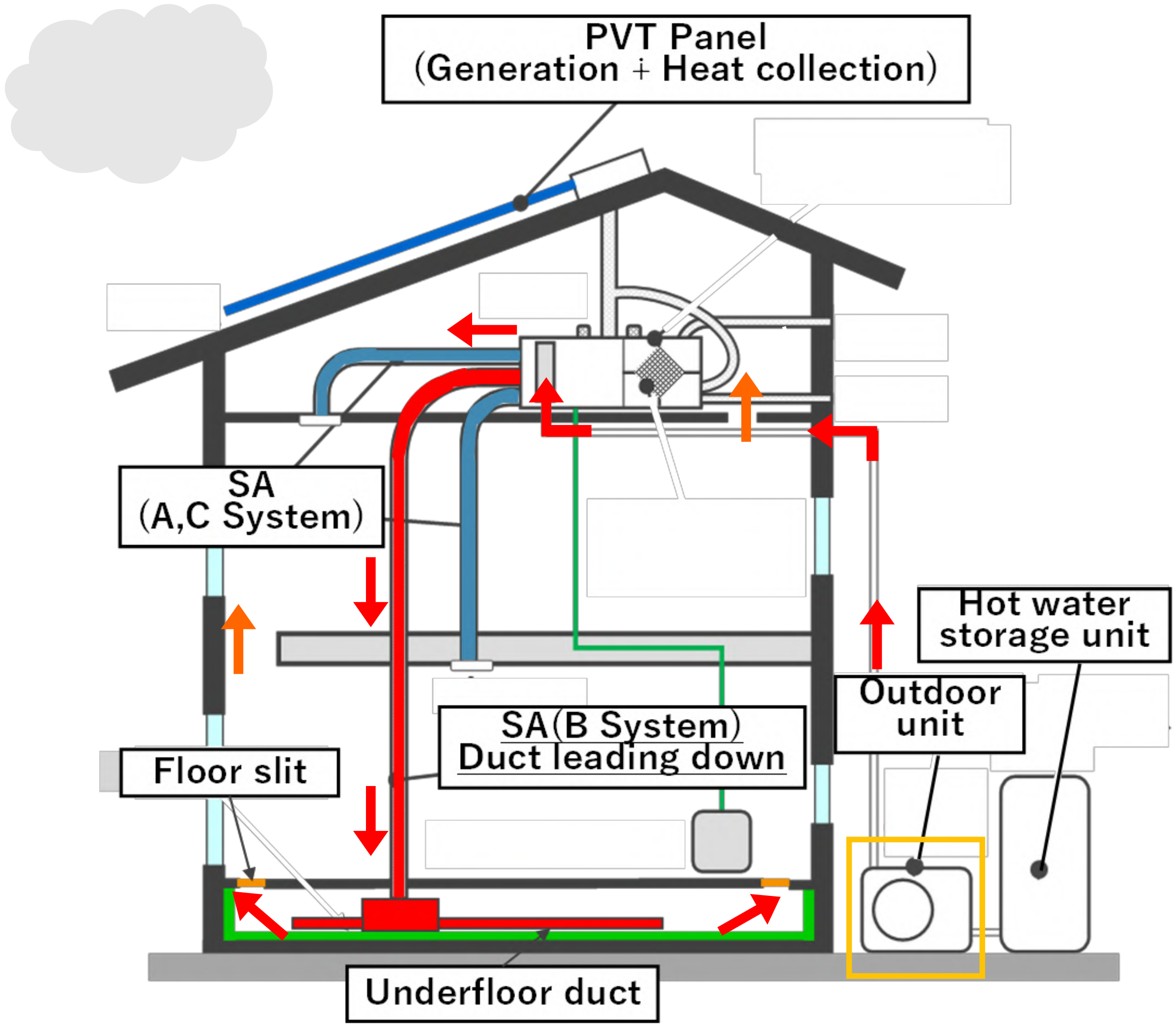
Supplied air is then returned to the indoor unit installed in the back of the shed through the ceiling vents via the atrium and stairwell and circulates throughout the dwelling unit.



In winter, warm air is supplied under the floor mainly from the B system and blown into the room from each floor slit.



On sunny days, heating is provided by solar heat collection by PVT panels,
and if the amount of collected heat is insufficient, it is supplemented by HP heating.



At night and on cloudy days, heating is provided by HP.

1, Introduction

・Research background and purpose
・System overview

2, Construction of simulation method to reproduce this system

・Reproduce this system behavior and organize simulation conditions
・Consistency verification from simulation results

3, Case study with simulation

・Calculate cost-effective foundation insulation performance for underfloor heating based on comparison of thermal environment, underfloor heat loss, and cost

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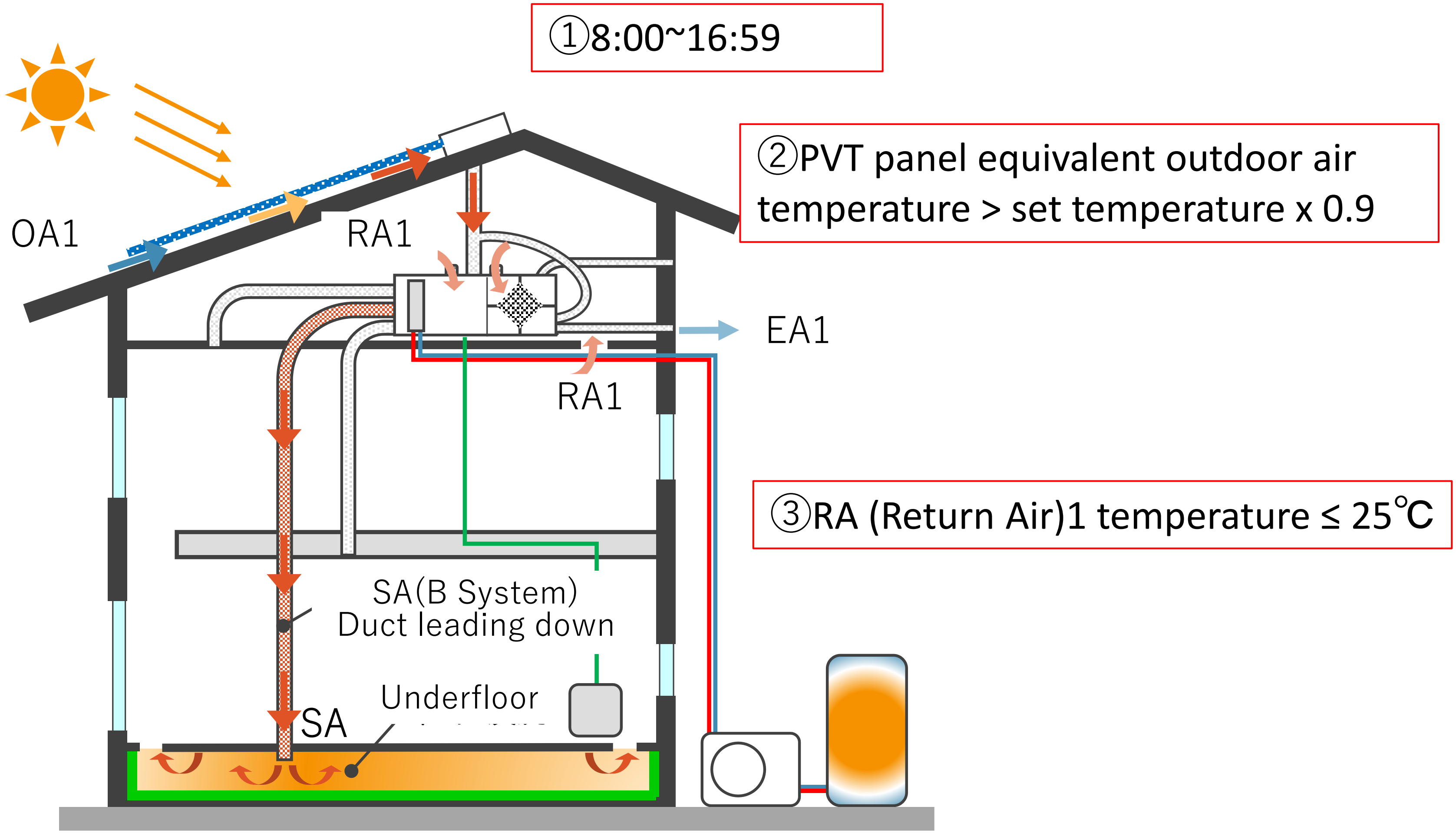
Heating operation control in this study



The operating conditions for solar heating were defined as when conditions ①②③were met.
In estimating the heat collection temperature of the PVT panels and the amount of electricity generated by the PV panels, calculations were made based on previous studies[1) 2)]

1) Udagawa, M., et al. : Simulation of roof integrated solar collector for space and DHW heating systems, Part 1 Simulation model, technical papers of annual meeting.
2) Satoh, M., et al. : Simulation of roof integrated solar collector for space and DHW heating systems,
Part 2 Example results of space and DHW heating system for residential house using solar air collector, technical papers of annual meeting.

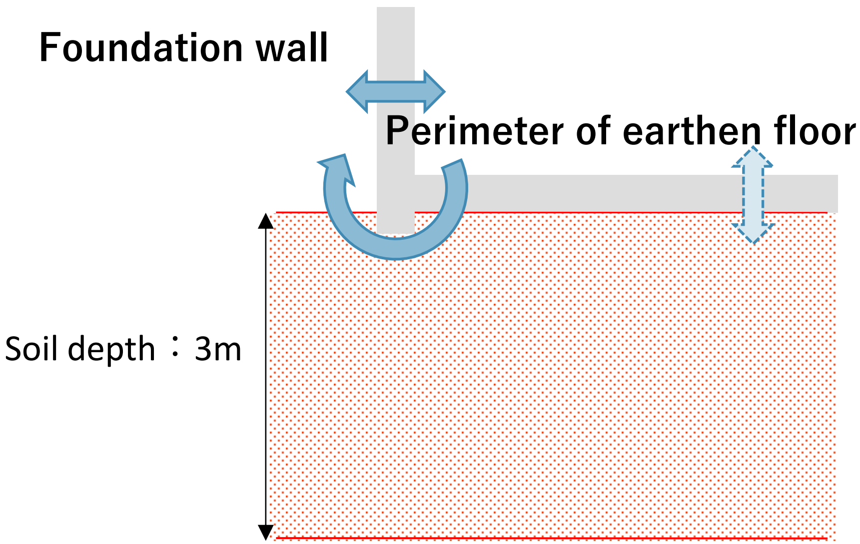
<Calculation Methods in Calculation Methods in this Study>

Heat Transfer Calculation

・2D steady heat conduction

Soil properties

・Thermal conductivity：1.0W/(m・K)



＊No heat loss calculation for the center of earthen floor

<Calculation Methods in this Study>

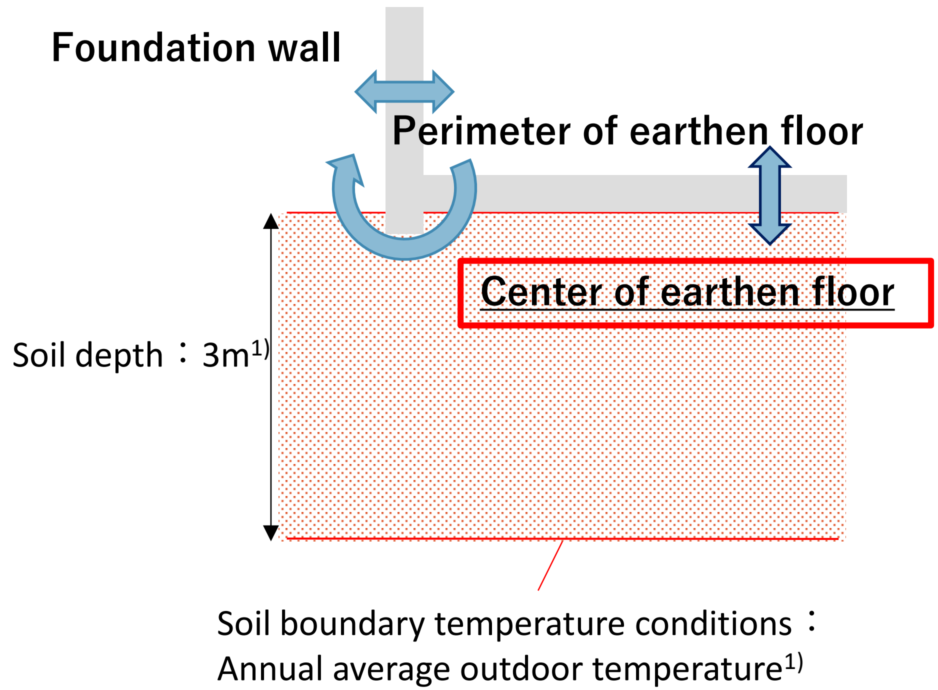
Heat Transfer Calculation

・1D unsteady heat conduction

Soil properties

・Thermal conductivity：1.0W/(m・K)

・Specific heat by volume：3340J/(m^3・K)[2]

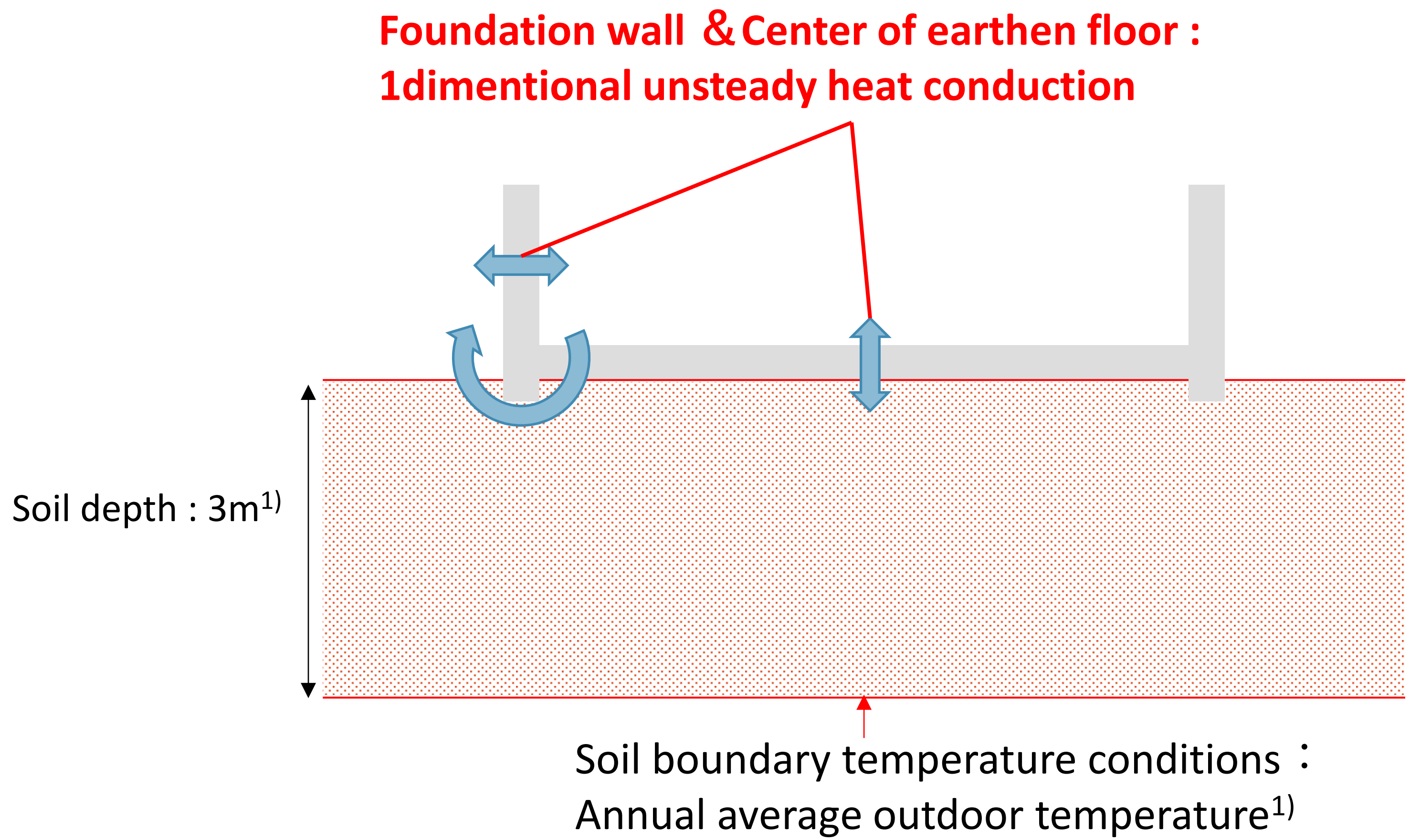


1) Satoh, M., et al. : Study on the evaluation method of heat transfer via the ground on detached houses with insulated foundation, technical papers of annual meeting
2) The Society of Heating, Air-Conditioning and Sanitary Engineers of Japan : Try and Learn Thermal Load HASPEE, 2012.

Calculation of **under-floor heat loss** in this study

Aiding period[1)] 1 year in this study

Soil properties[2)] Thermal conductivity：1.0W/(m・K)
Specific heat by volume：3340J/(m^3・K)



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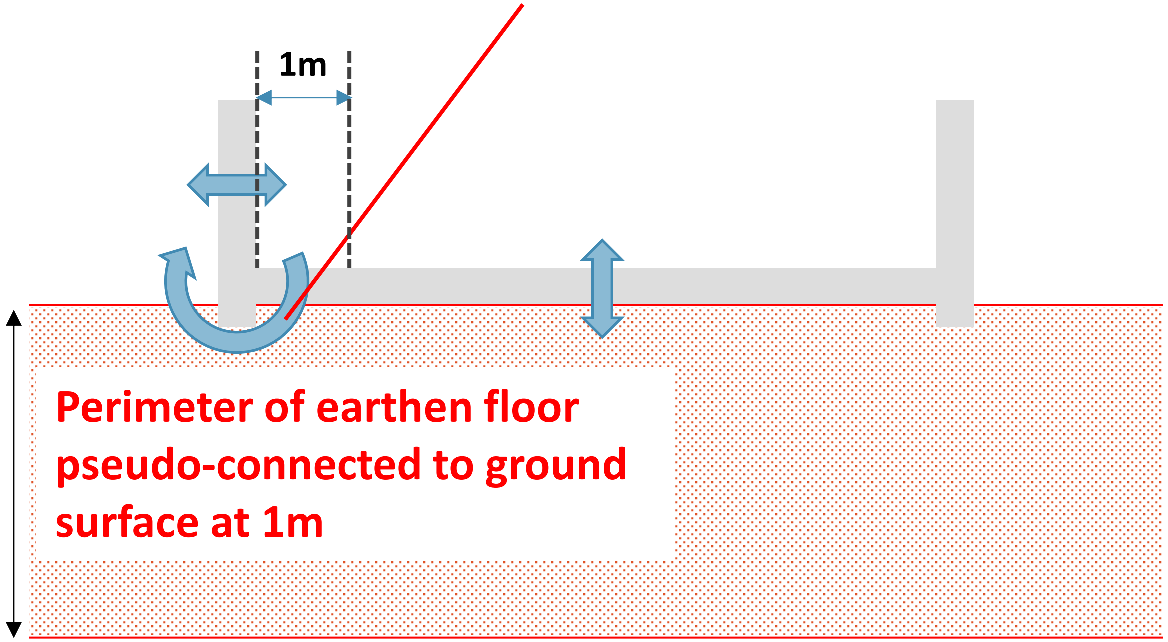
Calculation of **under-floor heat loss** in this study

Aiding period[1)]   1 year in this study

Soil properties[2)]   Thermal conductivity：1.0W/(m・K)
Specific heat by volume：3340J/(m^3・K)

Perimeter of earthen floor :
Approximated by 1dimentional unsteady heat conduction

Soil depth : 3m[1)]



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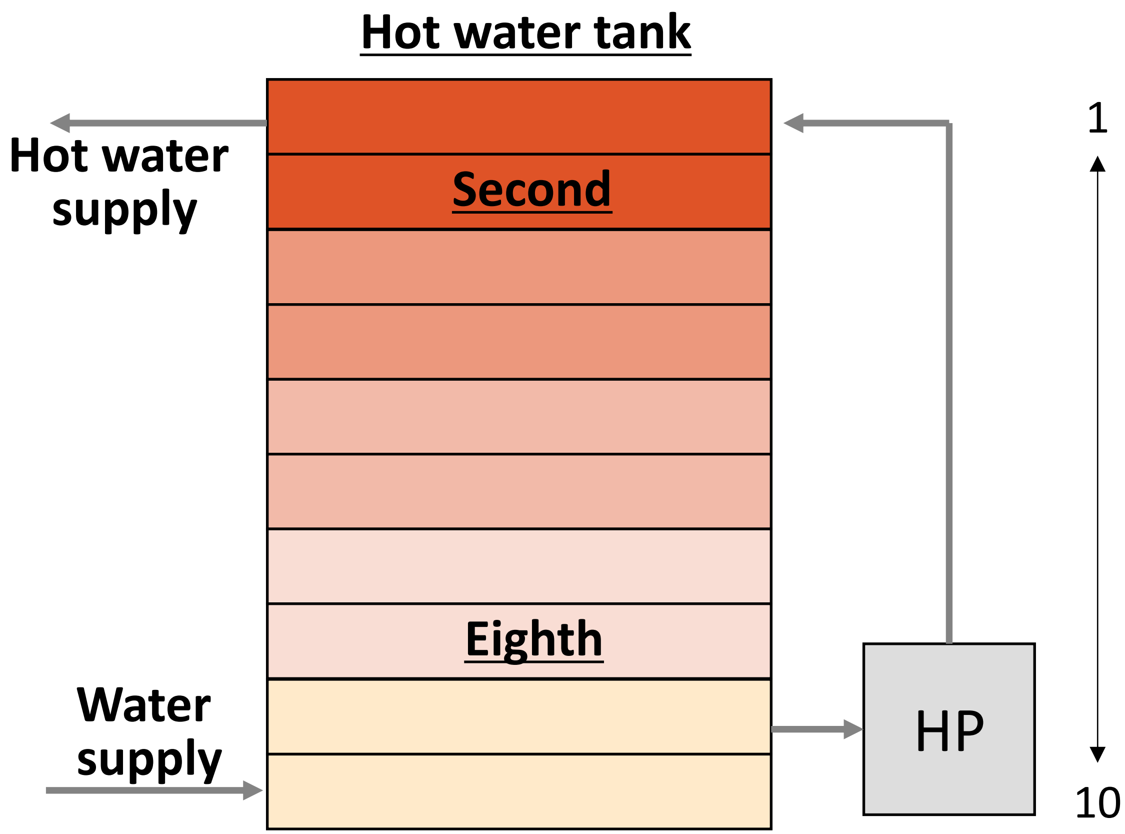
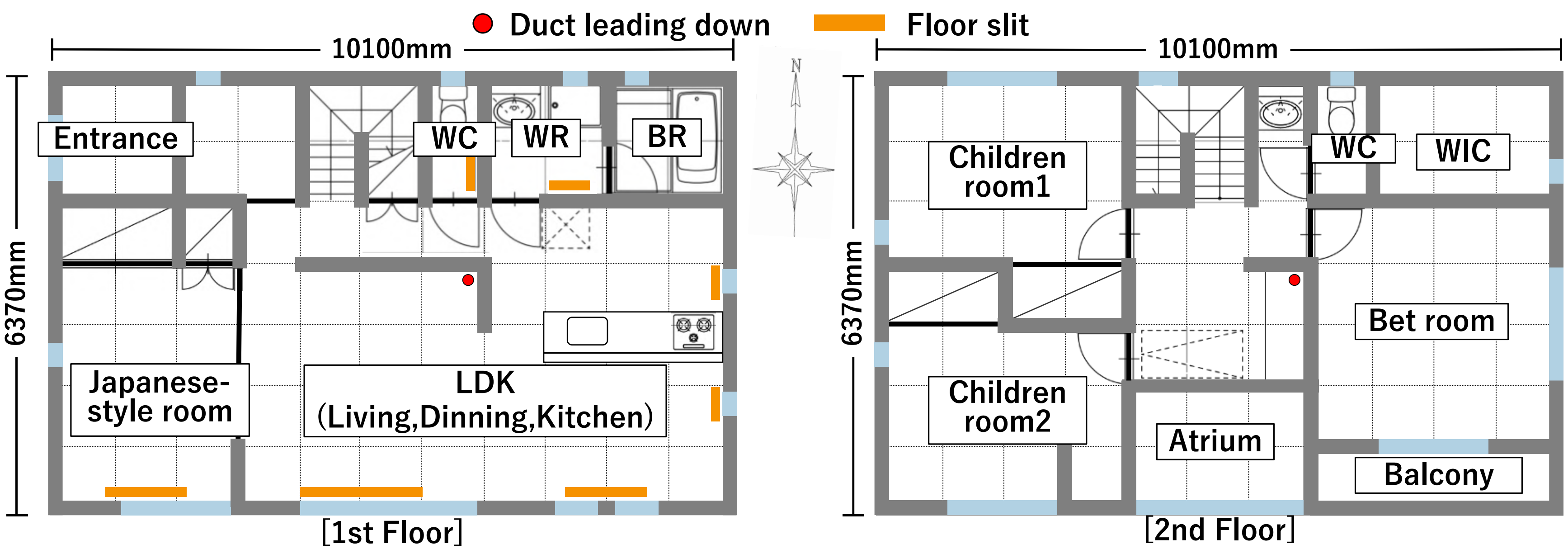
Hot water supply operation control in this study



The storage tank was divided into 10 blocks, and the control model was set up so that HP hot water heating would start and HP heating would stop when the eighth block fell below 65℃ from 12:00 to 15:59 or when the second block fell below 45℃ from 20:00 to 23:59.

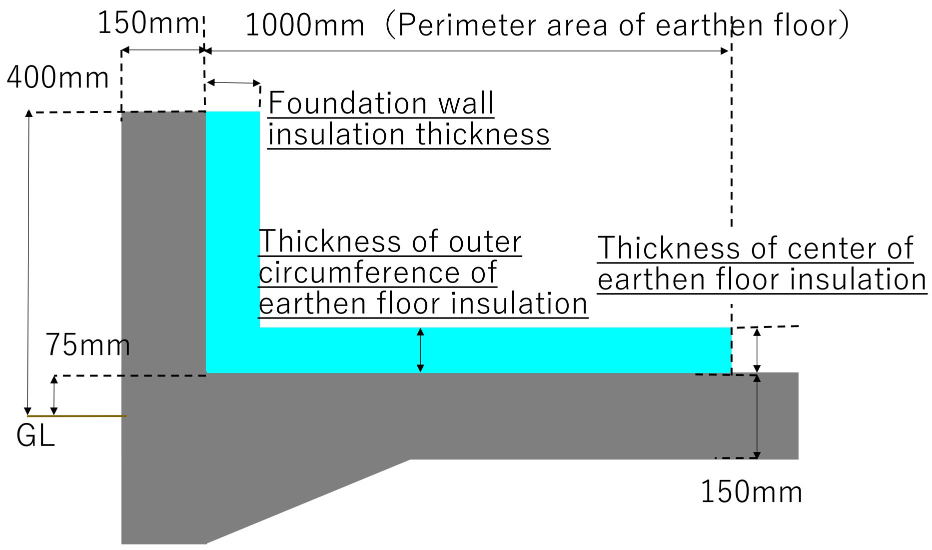
Building outline

Type	Data
Building Model	Passive standard plan
Building Structure	Two-story wooden house
Roof[Method/Slope(cm)/Eaves length(mm)]	Gable roof/12.1/600
Address	Tokyo 23 wards(Region 6)
U_A value/ η_{AC} value	0.46/1.9
PVT panel(kW)	8.2
U value(W/m²K)[Roof/Wall/ Window]	0.13/0.39/2.33

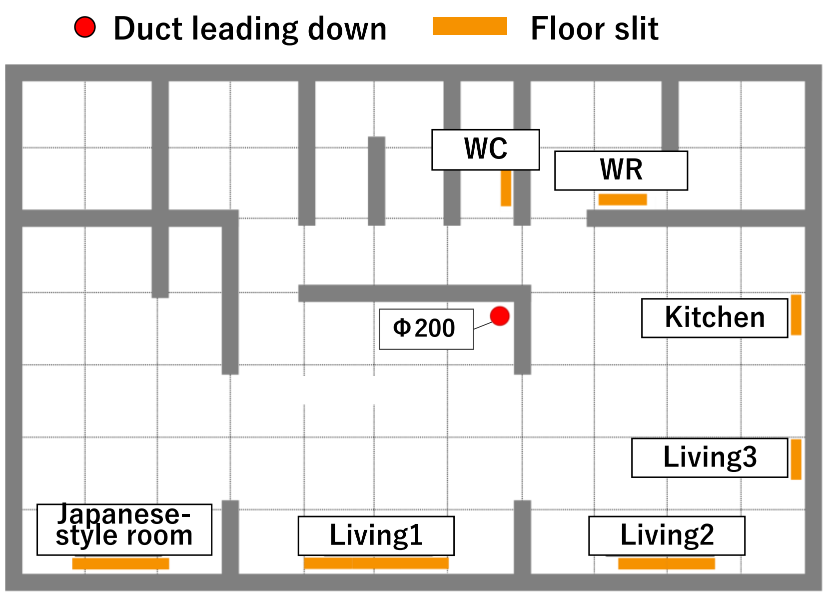


Using passive standard plans [1] that are common in the shape and scale of the houses.

1) Taniguchi, K., et al. : New Passive Standard Plan Proposal, Self-Sustaining Circulation Project Symposium, 2020.



Cross section of foundation



Underfloor plan

The foundation insulation material is
extruded polystyrene foam insulation type 3 bA (λ = 0.028 W/mK).

Thermal network calculation conditions

Type	Data
Thermal network calculation software	EESLISM7.2
Meteorological data	Standard year extended AMeDAS weather data 2010 Tokyo
Analysis period and interval	10/1~4/31(preparatory period：1year)・1hour
Ventilation operation	Air volume：always 200m³/h　Temperature exchange efficiency：85%
Solar heating operating conditions	8:00~16:59 PVT equivalent outside temperature>Set temperature×0.9 Return air temperature≦25℃
HP hot water heating operating conditions	Dividing the hot water storage tank into 10 blocks, the 8th is less than 65° C at 10:00~14:00 or the 2nd is less than 45° C at 20:00~24:00
Conditions of use for hot water supply	Based on the energy conservation standard M1 standard 4-person mode weekday (medium)
Internal heating conditions	Based on criteria for residential project builders

Calculation conditions in the simulation

Thermal network calculation conditions

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- The weader data used was the standard year extended AMeDAS weader data 2010 Tokyo.
- For ventilation operation, the ventilation rate of 200 m³/h was always, and the temperature exchange efficiency of 85% was used.

Thermal network calculation conditions

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Internal heating conditions	Based on criteria for residential project builders

- The operating conditions for heating and hot water heating were reproduced from this system's controls, while other settings were made assuming general conditions.

CFD Analysis conditions(Used as part of thermal network calculations)

Type	Data
Analysis software	FlowDesigner2022
Total number of meshes	5.8 million mesh
Turbulence model	Standard k- ε model
Convergence criterion	(stationary)1.0×10^-3.5
Outside temperature/Soil temperature	-0.3°C/18.6°C
Inflow conditions (SA from B system)	Airflow：437m³/h　Blowoff temperature：49.3°C
Outflow conditions (RA)	437m³/h from unit location

- The outdoor air temperature was set to the lowest outdoor air temperature in January of the standard year's extended AMeDAS weather data.
- The soil temperature was set to the annual average outdoor air temperature of the standard year's AMeDAS weather data.

Calculation conditions in the simulation

CFD Analysis(Used as part of thermal network calculations)

Type	Data
Analysis software	FlowDesigner2022
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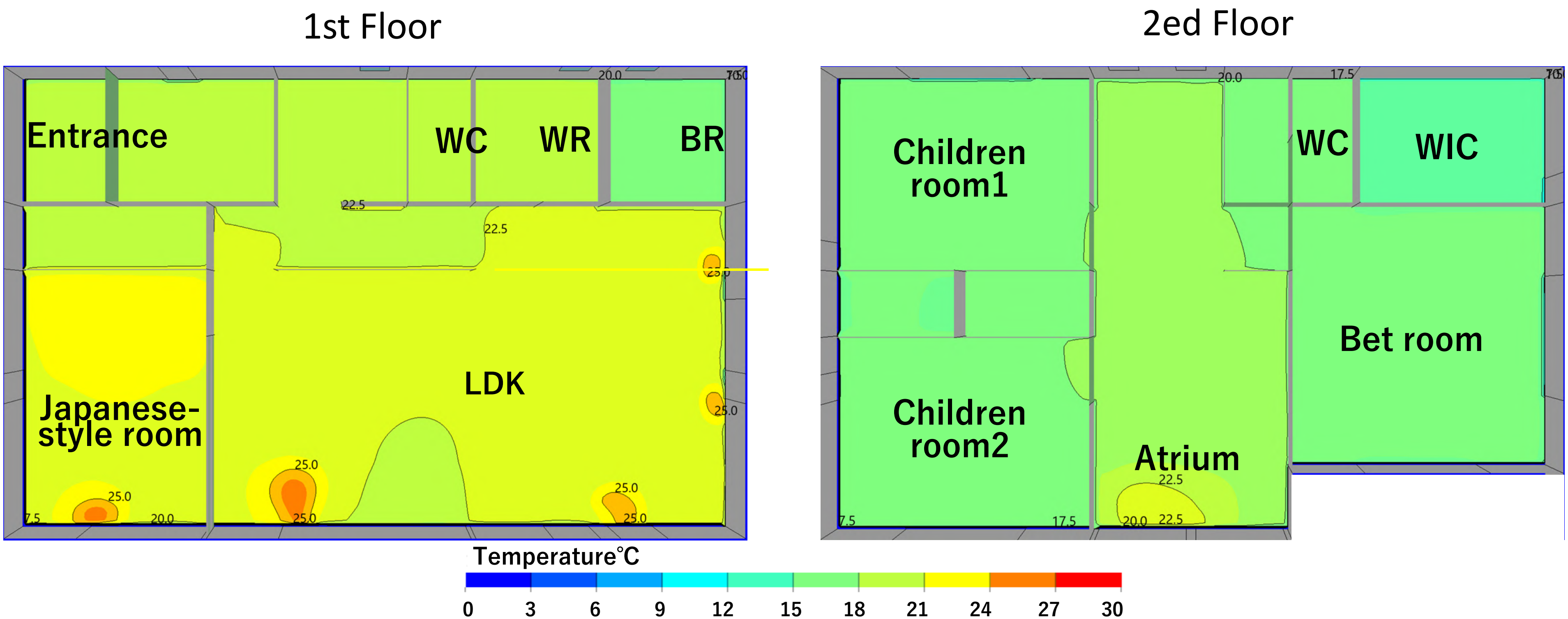
Outflow conditions (RA)	437m³/h from unit location

- The blowout temperature was calculated using the following formula, assuming an indoor temperature of 22℃.

$$t_D = t_R + \frac{q_s}{0.34 \times Q_{AC}}$$

t_D : Blowoff temperature[℃]　t_D : Indoor temperature[℃]
q_s : Maximum heat load determined by thermal network calculation[W]
Q_{AC} : Airflow[m^3/h]

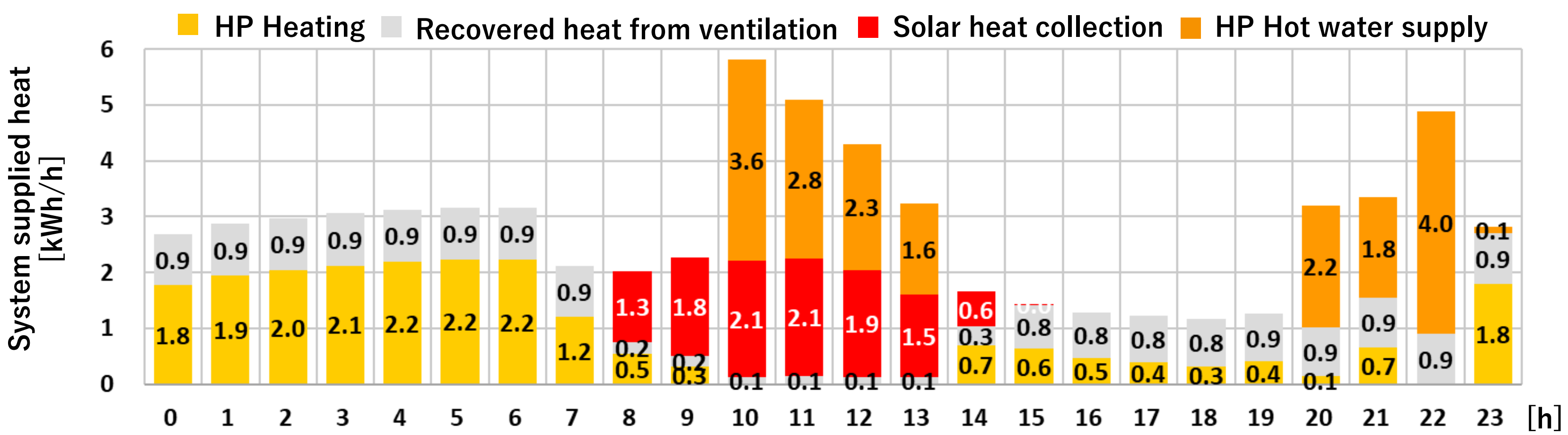
- Room temperature distribution

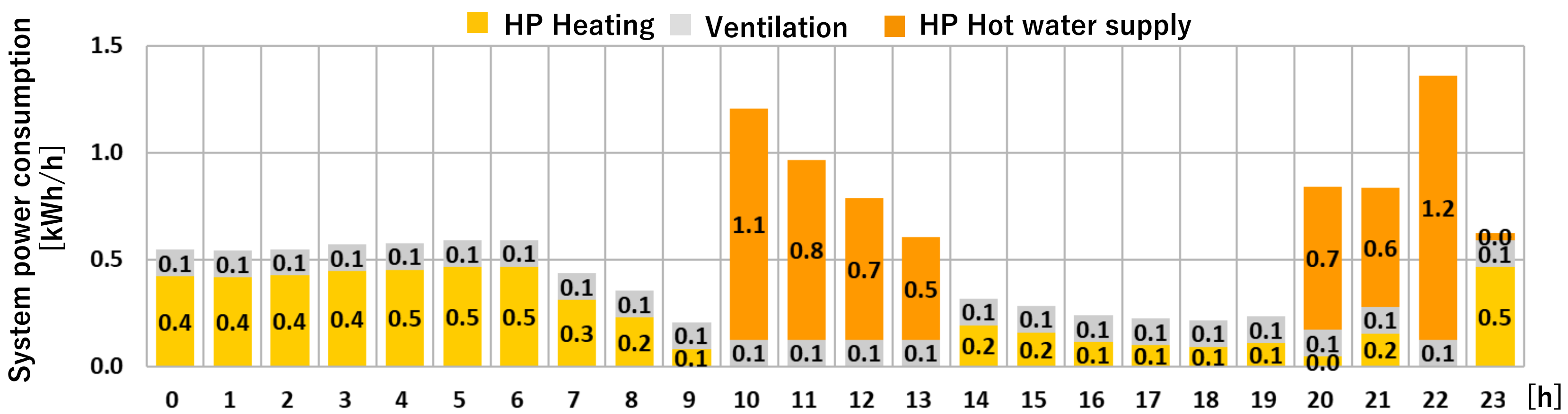


the room temperature in LDK is about 23℃, which is around the set temperature of 22℃.

→This was judged to be generally appropriate and set on thermal network calculations.

- Average system supplied heat and power consumption by time of day in January

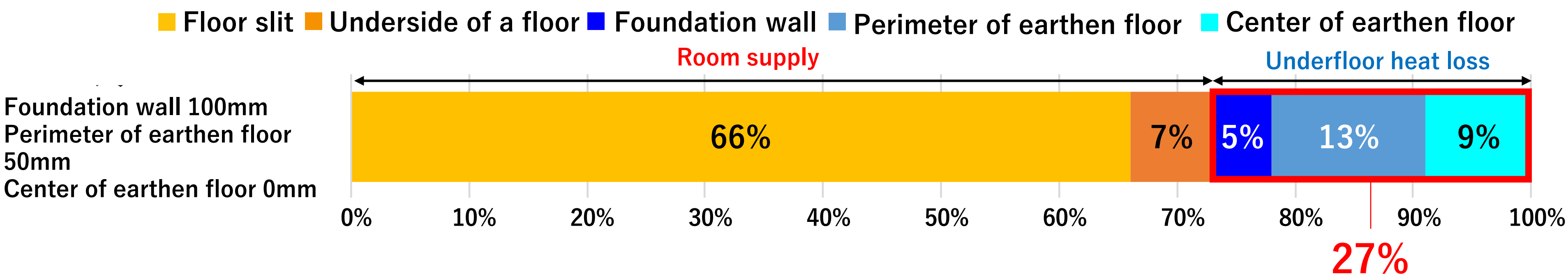




During the daytime, the HP is used to heat water supply, and the heating is done only by solar heat collection, and no heating power consumption was generated by HP.

Simulation results

- Percentage of heat supplied under the floor to be allocated to



The amount of heat loss under the floor in relation to the amount of heat supplied under the floor was **5% for the foundation wall**, **13% for the perimeter of the earthen floor**, and **9% for the center of the earthen floor**.

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Influence of differences in basic thermal insulation performance by regional classification

In this section the authors look at the impact of differences in basic thermal insulation performance targeting energy conservation region classifications 5 and 6.

Region5(Sendai) **Region6(Tokyo)**	×	**Grade4** **Grade5** **Grade6**	×	**Thermal insulation performance** **12Case**

<u>In this section the authors look at the impact of differences in basic thermal insulation performance targeting energy conservation region classifications 5 and 6.</u>

Region5(Sendai)

Region6(Tokyo)

×

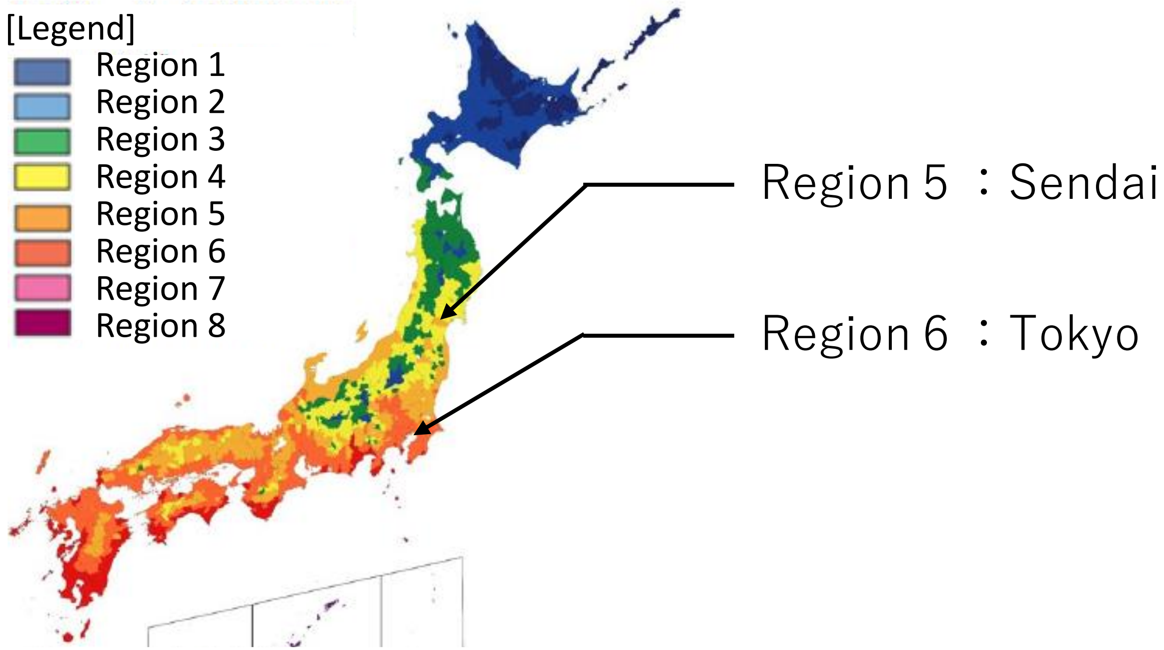
Grade4

Grade5

Grade6

×

Thermal insulation performance 12Case



Targeting **<u>Tokyo in region 6</u>** and **<u>Sendai in region 5</u>**

In this section the authors look at the impact of differences in basic thermal insulation performance targeting energy conservation region classifications 5 and 6.

Region5(Sendai) **Region6(Tokyo)** × **Grade4 Grade5 Grade6** × **Thermal insulation performance 12Case**

Insulation grade(U_A value)[W/m²K]	Region 5(Sendai)	Region 6(Tokyo)
Grade 2	1.67	1.67
Grade 3	1.54	1.54
Grade 4	0.87	0.87
Grade 5	0.60	0.60
Grade 6	0.46	0.46
Grade 7	0.26	0.26

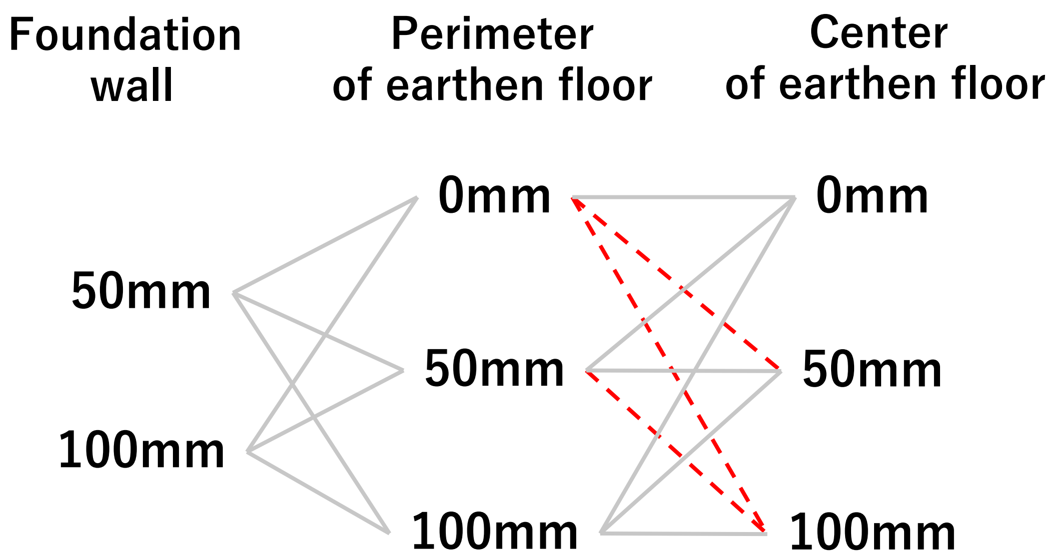
In Japan, insulation **grade 4** is used as the value for energy conservation standards.

In this section the authors look at the impact of differences in basic thermal insulation performance targeting energy conservation region classifications 5 and 6.

Region5(Sendai) × Grade4 × Thermal insulation performance

Region6(Tokyo) Grade5 12Case

Grade6

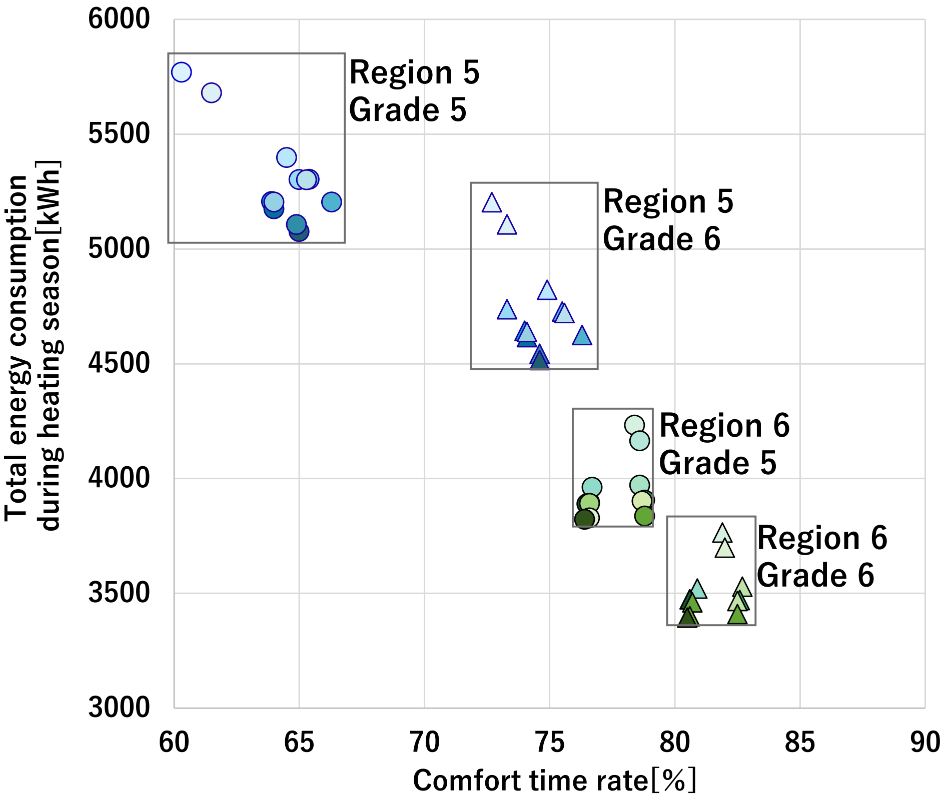


Foundation insulation performance, 12 cases were considered, excluding the red line.

Energy consumption and comfort considerations

$$C_{time} = \frac{OT_{20\sim24}}{d \times 24 \times r} \times 100[\%]$$

C_{time}: Comfort time rate d: Number of days of period covered r: Number of target rooms(Living room, etc.)
$OT_{20\sim24}$: Number of hours within the target room operating temperature of 20~24° C



- ○ Grade5 △ Grade6
- Blue Region5(Sendai) Green Region6(Tokyo)
- As the insulation becomes thicker, the color is made darker.

Foundation wall	50mm	100mm
Perimeter of earthen floor	0mm	100mm
Center of earthen floor	0mm	100mm

The comfort time rate was defined using the above equation with a comfort temperature range of 20-24℃.

$$C_{time} = \frac{OT_{20\sim24}}{d \times 24 \times r} \times 100[\%]$$

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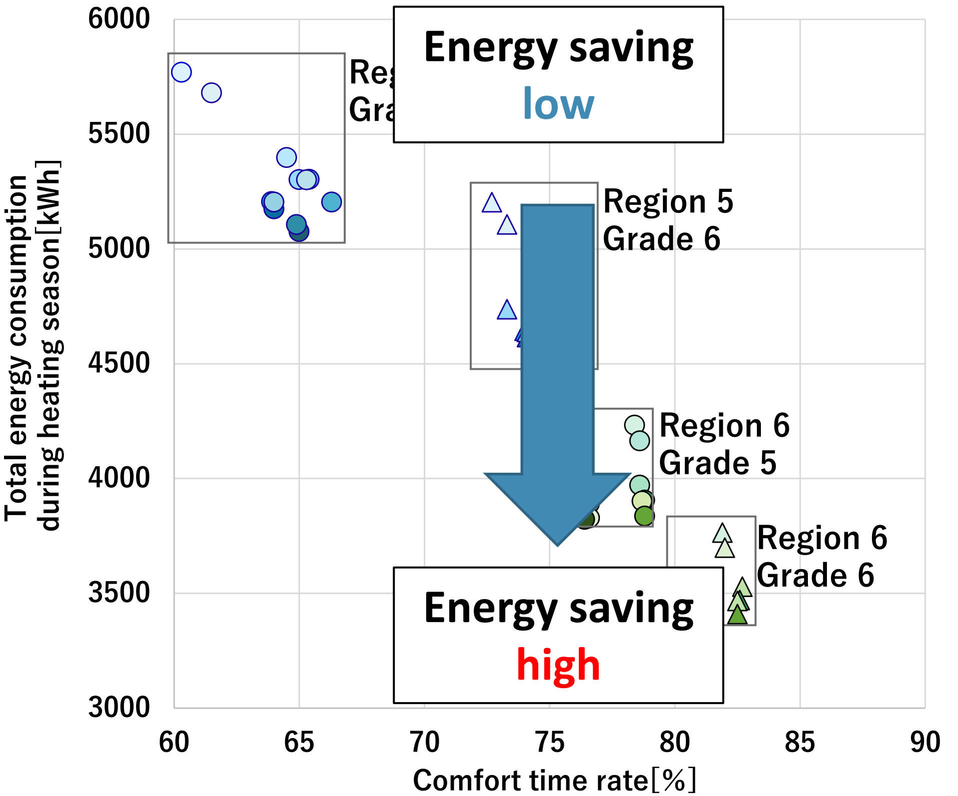

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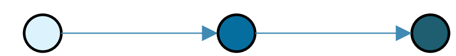

Foundation wall	50mm	100mm
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Center of earthen floor	0mm	100mm

The lower the energy consumption, the higher the energy savings.

Energy consumption and comfort considerations

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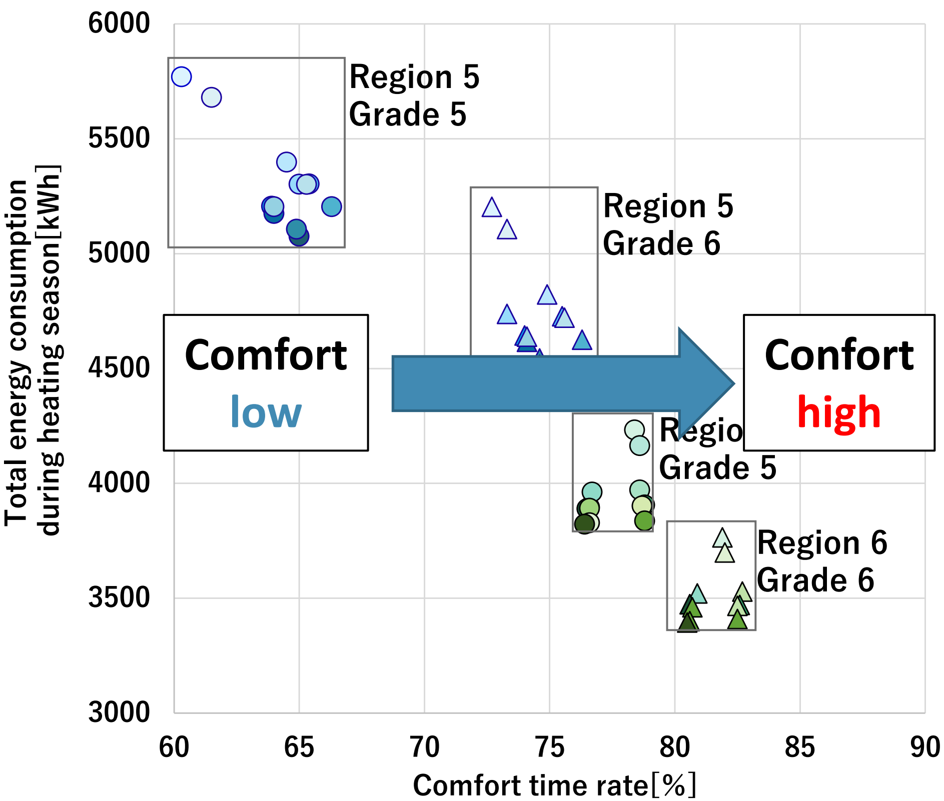

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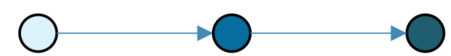
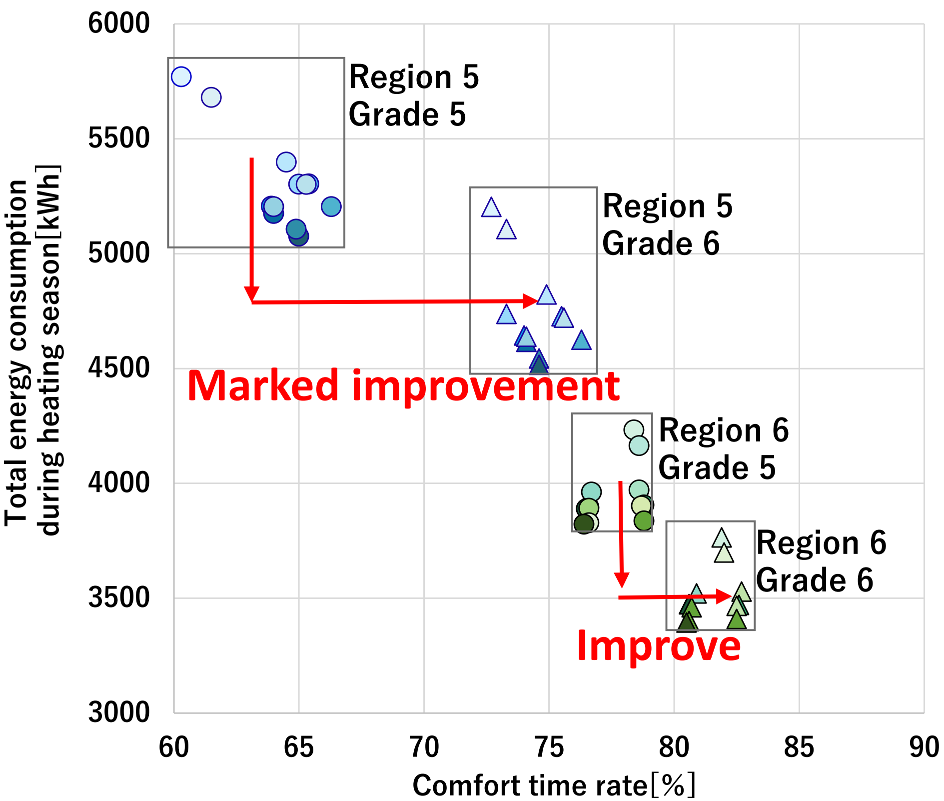


Foundation wall	50mm	100mm
Perimeter of earthen floor	0mm	100mm
Center of earthen floor	0mm	100mm

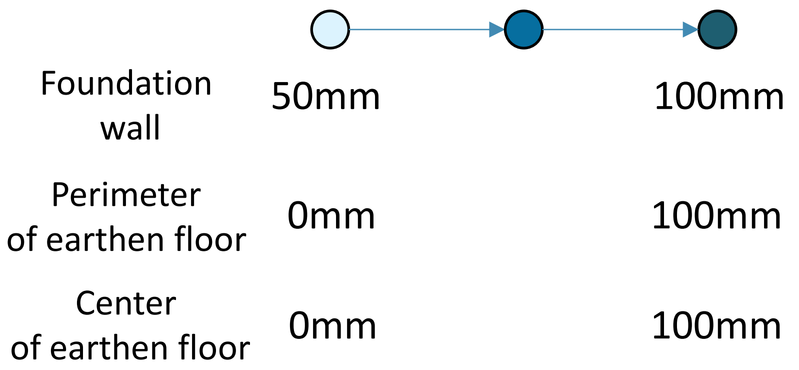
Region 6 is more energy efficient and more comfortable than region 5.

$$C_{time} = \frac{OT_{20\sim24}}{d \times 24 \times r} \times 100[\%]$$

C_{time}: Comfort time rate d: Number of days of period covered r: Number of target rooms(Living room, etc.)
$OT_{20\sim24}$: Number of hours within the target room operating temperature of 20~24° C



- ○ Grade5 △ Grade6
- Blue Region5(Sendai) Green Region6(Tokyo)
- As the insulation becomes thicker, the color is made darker.

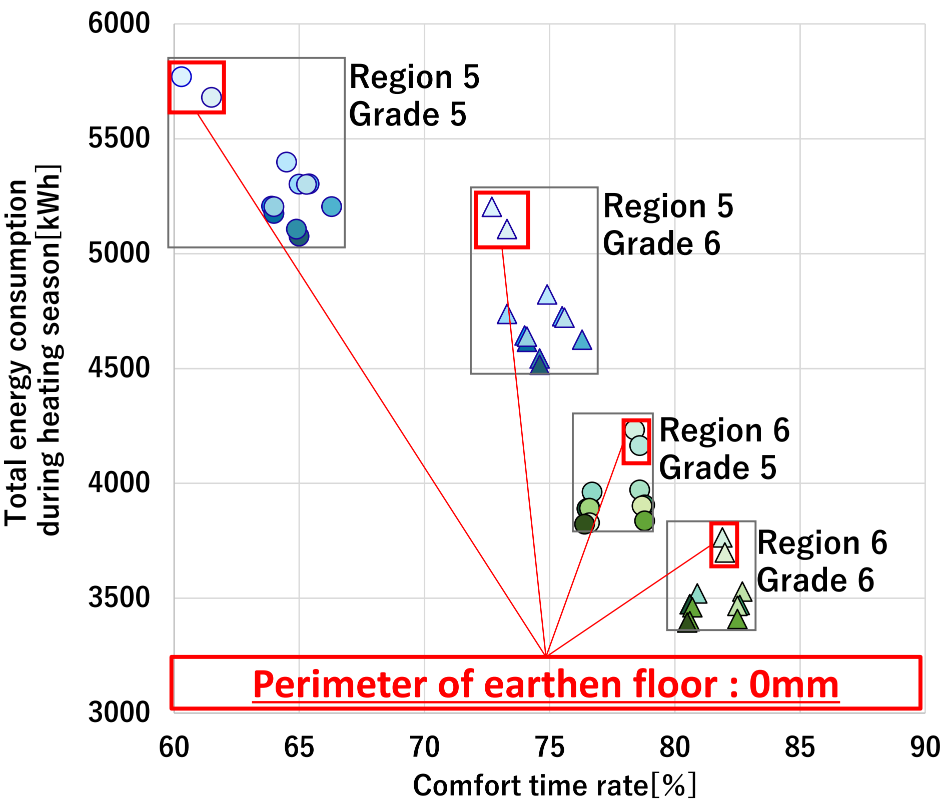


The energy efficiency and comfort improved in both the regions 5 and 6 by changing the insulation grade from 5 to 6.

➡A grade 6 level of insulation is needed in region 5.

$$C_{time} = \frac{OT_{20\sim24}}{d \times 24 \times r} \times 100[\%]$$

C_{time}: Comfort time rate d: Number of days of period covered r: Number of target rooms (Living room, etc.)
$OT_{20\sim24}$: Number of hours within the target room operating temperature of 20~24° C



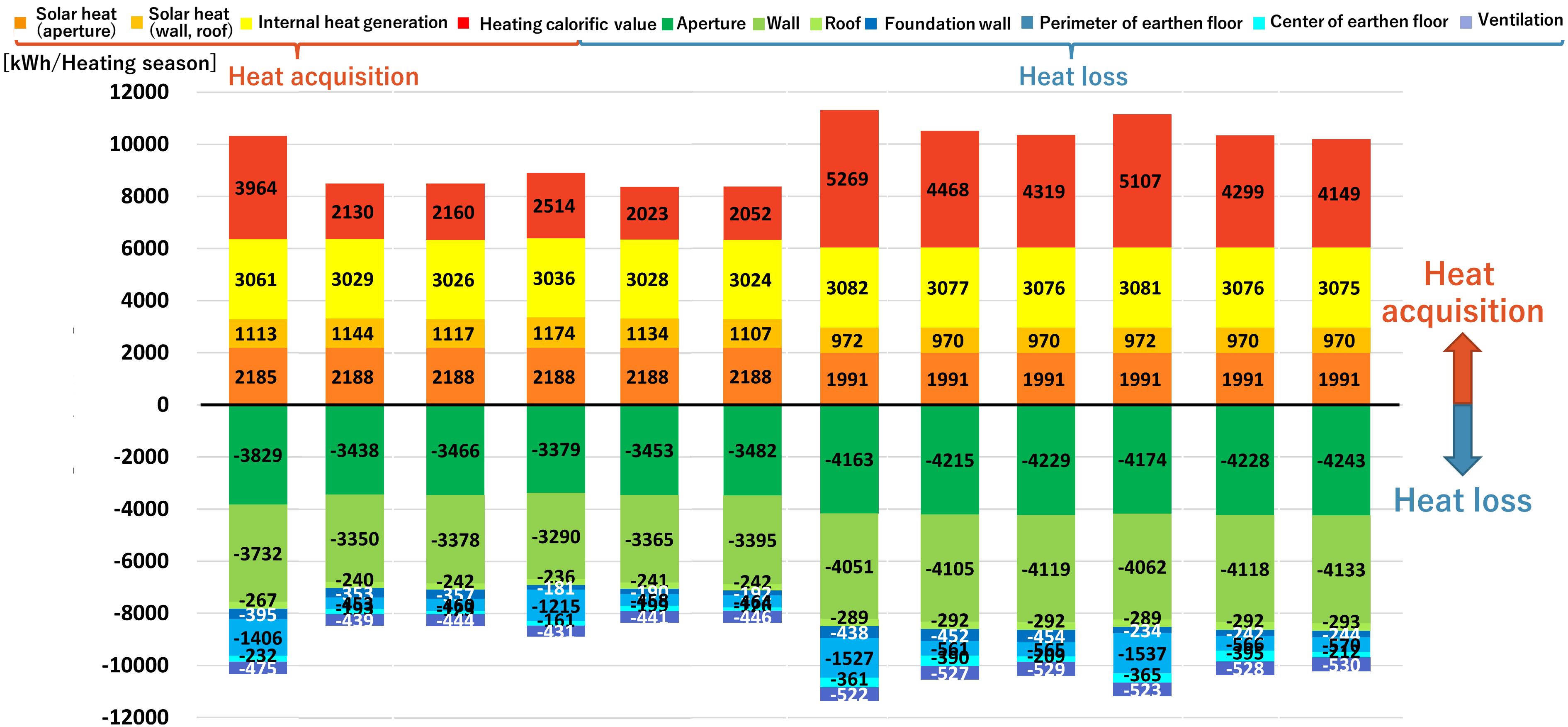
- ○ Grade5 △ Grade6
- Blue Region5(Sendai) Green Region6(Tokyo)
- As the insulation becomes thicker, the color is made darker.

Foundation wall	50mm	100mm
Perimeter of earthen floor	0mm	100mm
Center of earthen floor	0mm	100mm

The perimeter of the earthen floor is not insulated, **the higher energy consumption in each region and insulation grade, and the lower comfort level especially in region 5.**

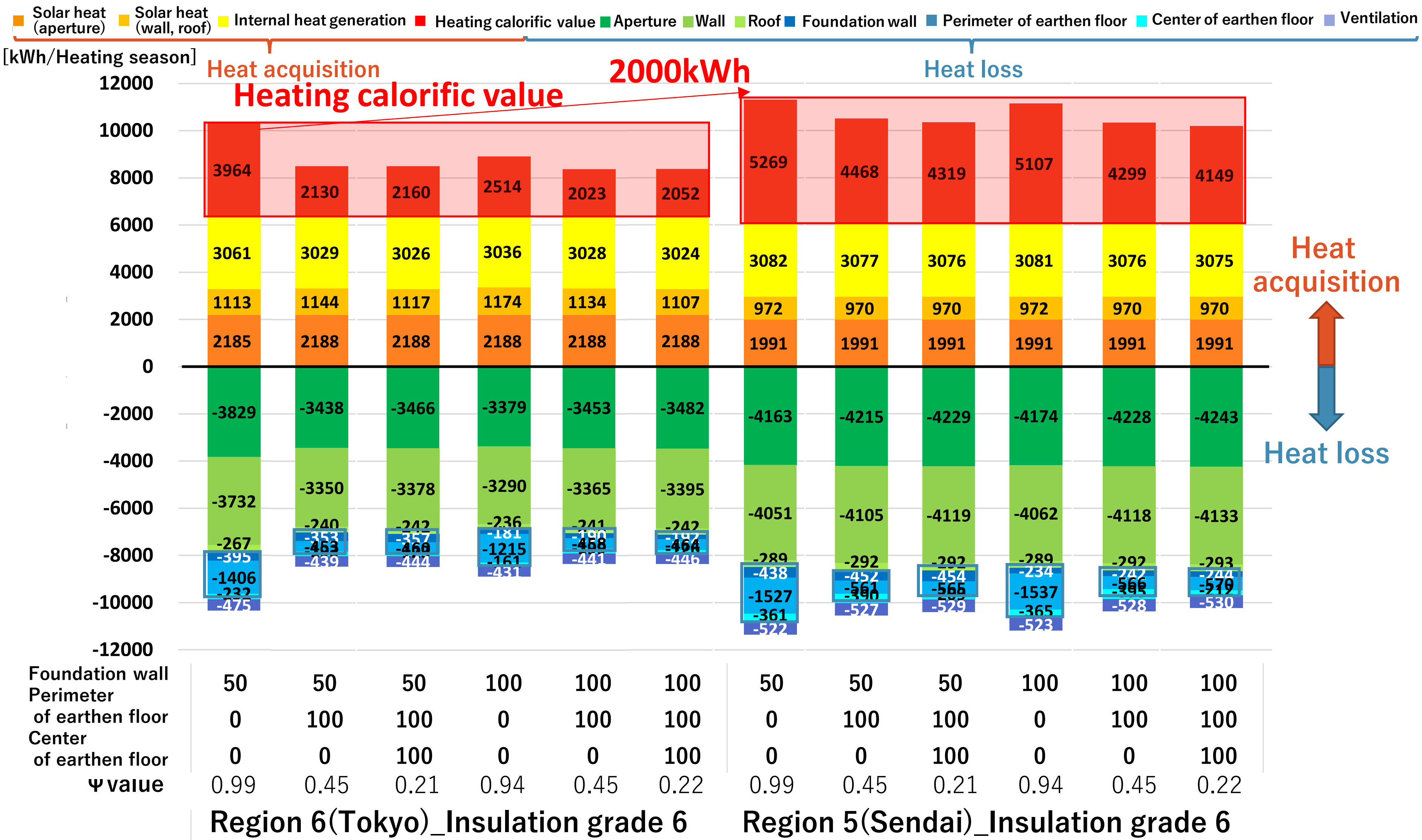
➡The perimeter of the earthen floor is effective for underfloor heating.

Study of under-floor heat loss

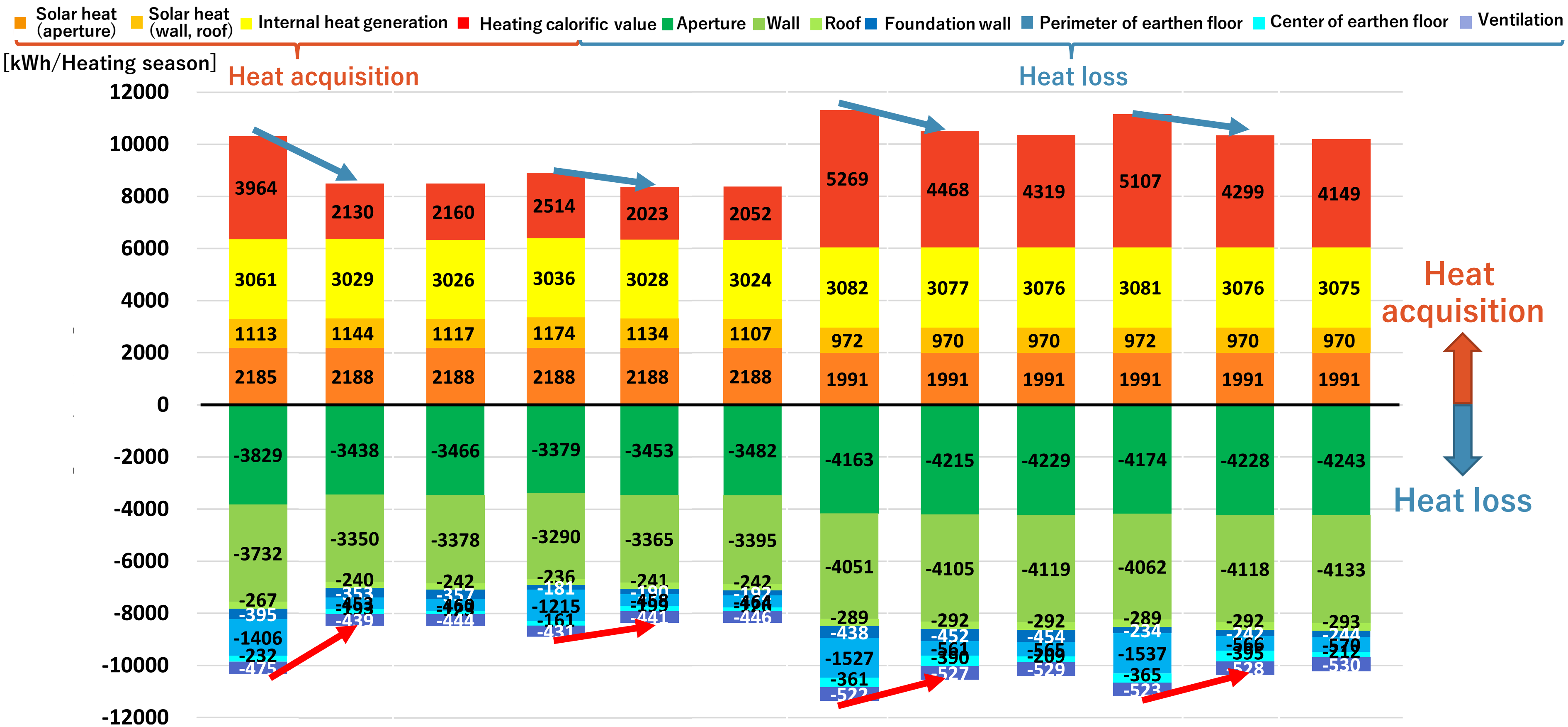


Foundation wall	50	50	50	100	100	100	50	50	50	100	100	100
Perimeter of earthen floor	0	100	100	0	100	100	0	100	100	0	100	100
Center of earthen floor	0	0	100	0	0	100	0	0	100	0	0	100
Ψ value	0.99	0.45	0.21	0.94	0.45	0.22	0.99	0.45	0.21	0.94	0.45	0.22
	Region 6(Tokyo)_Insulation grade 6						Region 5(Sendai)_Insulation grade 6					

The underfloor heat loss for each case during the heating season (November to April).



Compared to region 6, **the amount of heating heat increased by about 2000 kWh in region 5**.

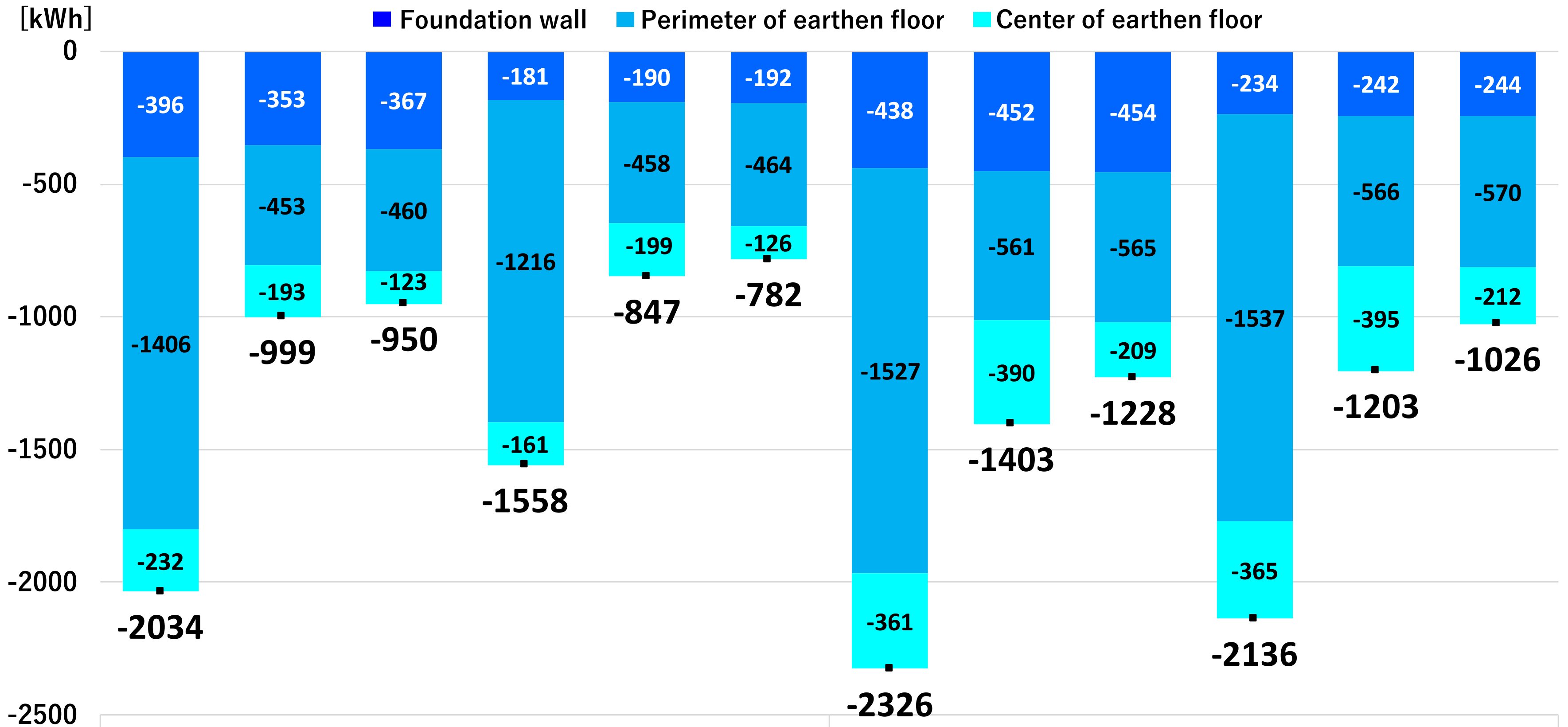


Foundation wall	50	50	50	100	100	100	50	50	50	100	100	100
Perimeter of earthen floor	0	100	100	0	100	100	0	100	100	0	100	100
Center of earthen floor	0	0	100	0	0	100	0	0	100	0	0	100
Ψ value	0.99	0.45	0.21	0.94	0.45	0.22	0.99	0.45	0.21	0.94	0.45	0.22
	Region 6(Tokyo)_Insulation grade 6						Region 5(Sendai)_Insulation grade 6					

By installing insulation around the perimeter of the earthen floor,

The amount of both heating heat and underfloor heat loss was significantly reduced.

Study of under-floor heat loss

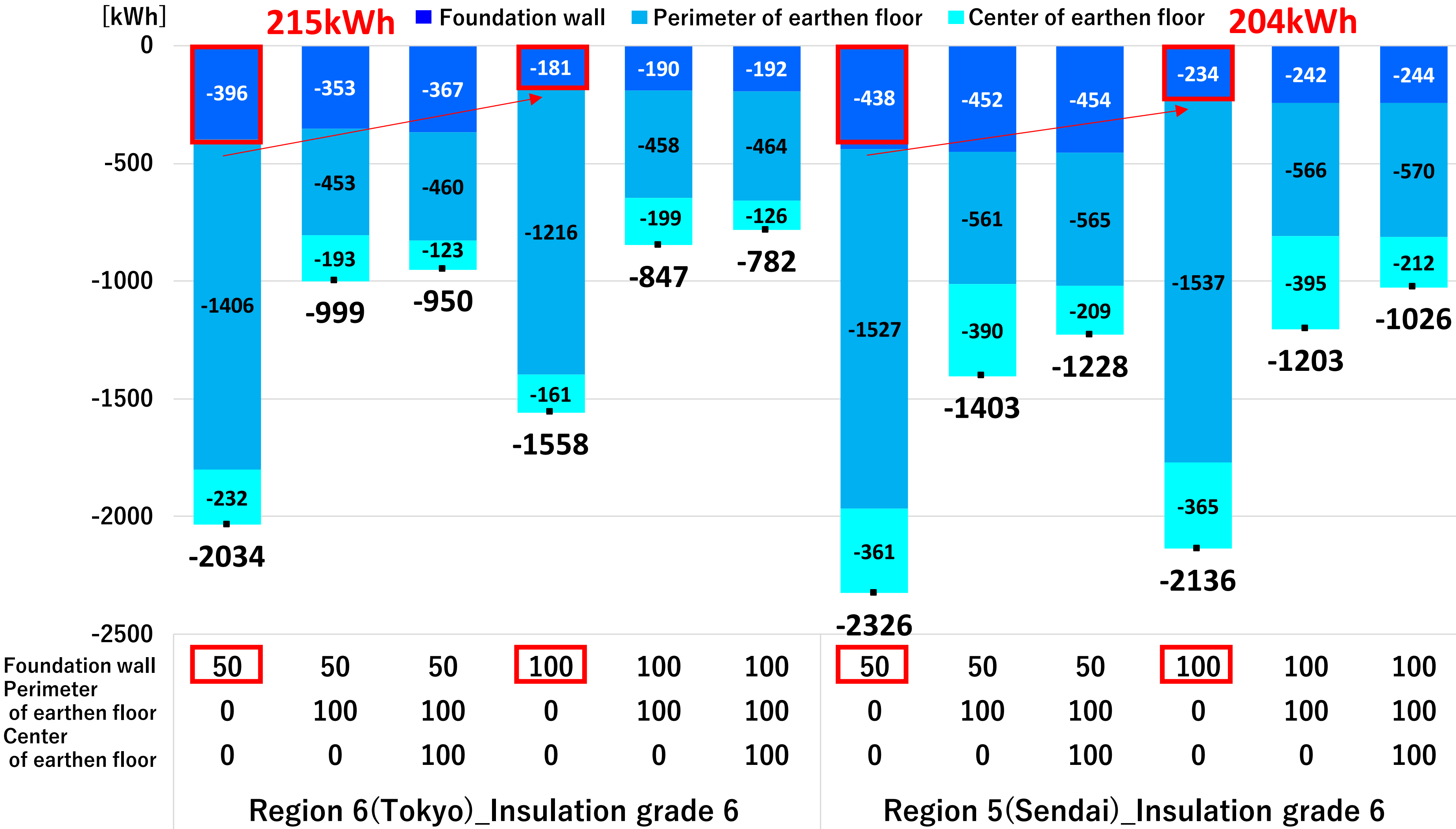


Foundation wall	50	50	50	100	100	100	50	50	50	100	100	100
Perimeter of earthen floor	0	100	100	0	100	100	0	100	100	0	100	100
Center of earthen floor	0	0	100	0	0	100	0	0	100	0	0	100
	Region 6(Tokyo)_Insulation grade 6						Region 5(Sendai)_Insulation grade 6					

<u>Confirm where foundation insulation can more effectively reduce underfloor heat loss</u>

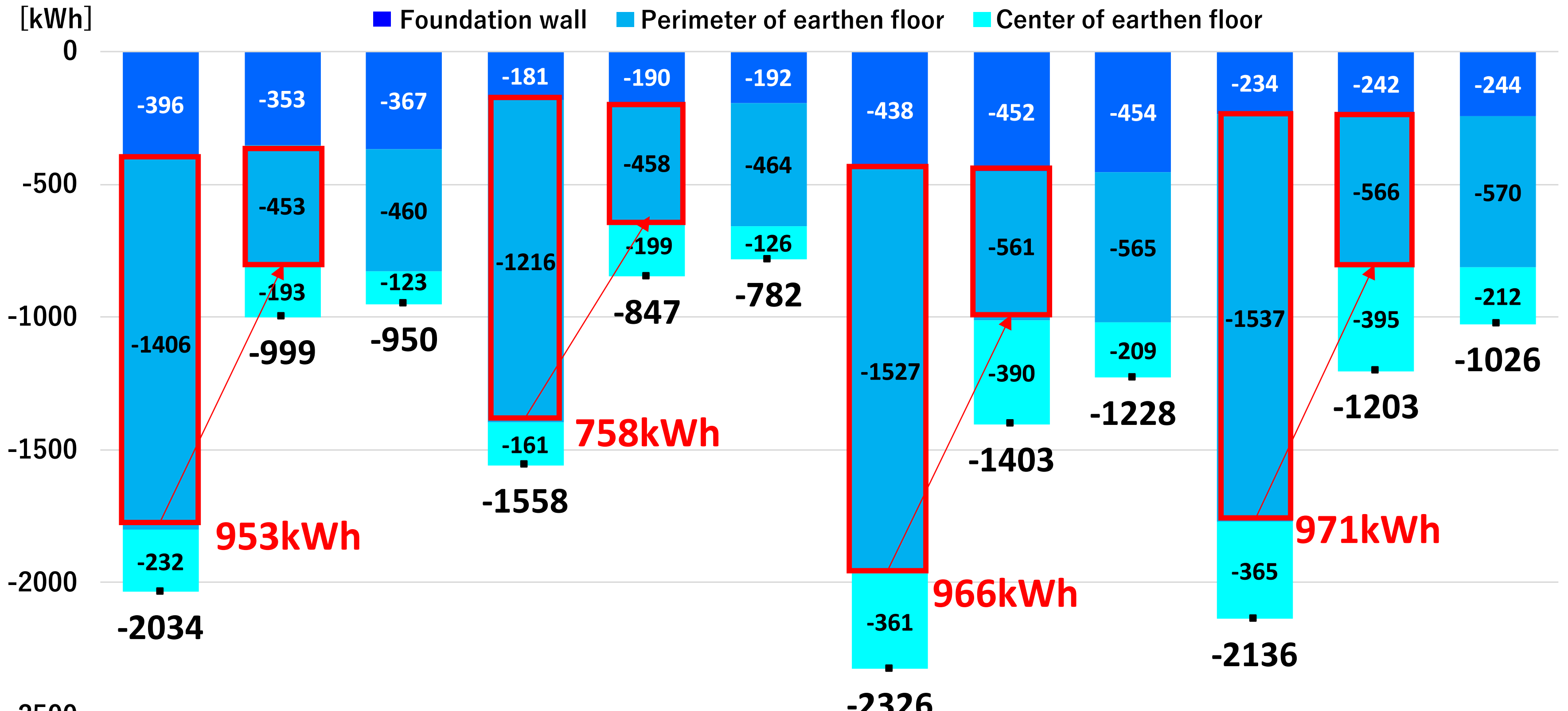
: foundation walls, perimeter of earthen floor, or center of earthen floor.

Study of under-floor heat loss



By increasing the thickness of the foundation wall insulation from 50 mm to 100 mm,
the underfloor heat loss decreased by about 200 kWh in each region.

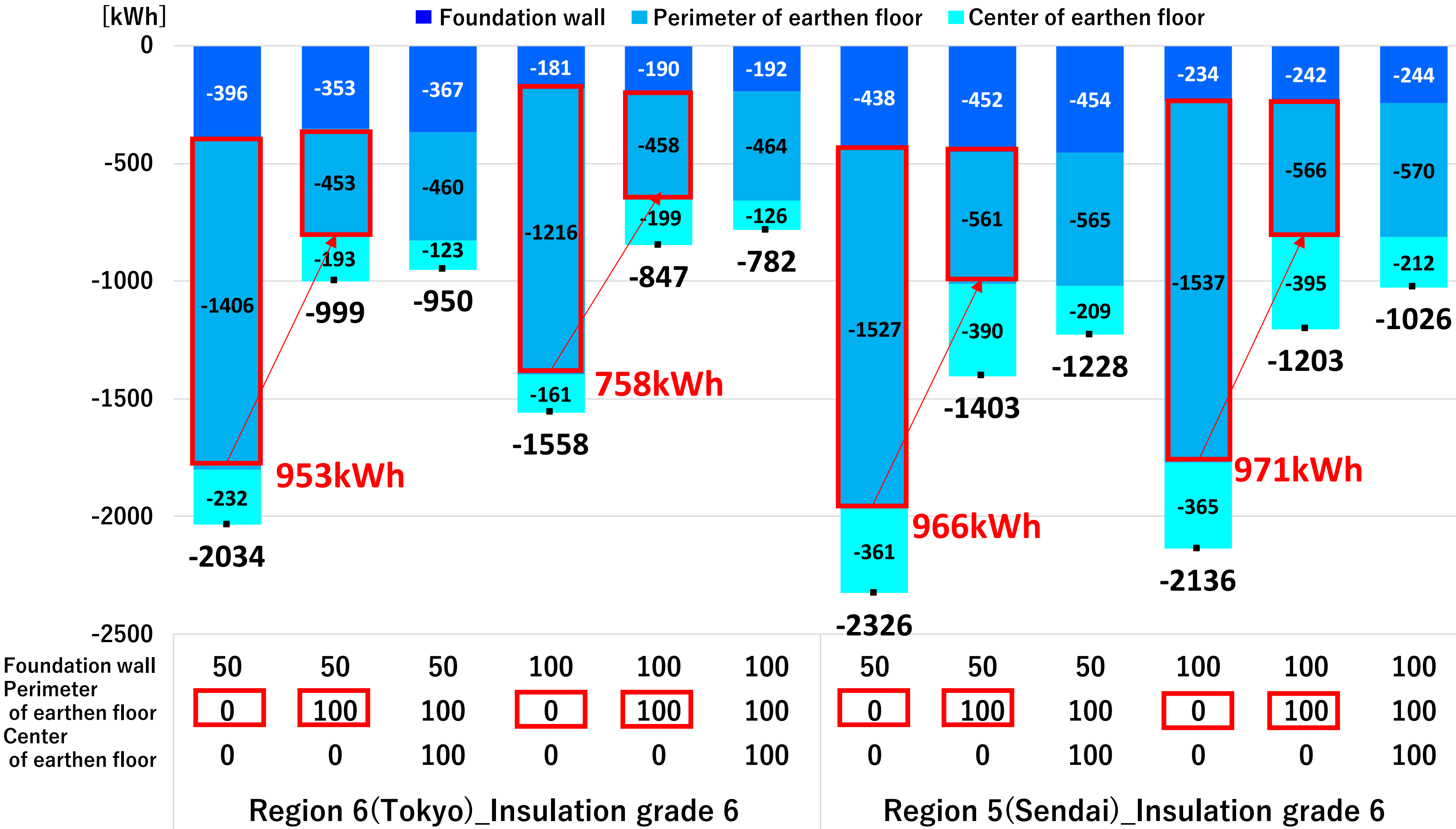
Study of under-floor heat loss



Foundation wall	50	50	50	100	100	100	50	50	50	100	100	100
Perimeter of earthen floor	0	100	100	0	100	100	0	100	100	0	100	100
Center of earthen floor	0	0	100	0	0	100	0	0	100	0	0	100
	Region 6(Tokyo)_Insulation grade 6						Region 5(Sendai)_Insulation grade 6					

By increasing the thickness of the perimeter of earthen floor insulation from 0 mm to 100 mm, **the underfloor heat loss decreased by about 700~900 kWh in each region.**

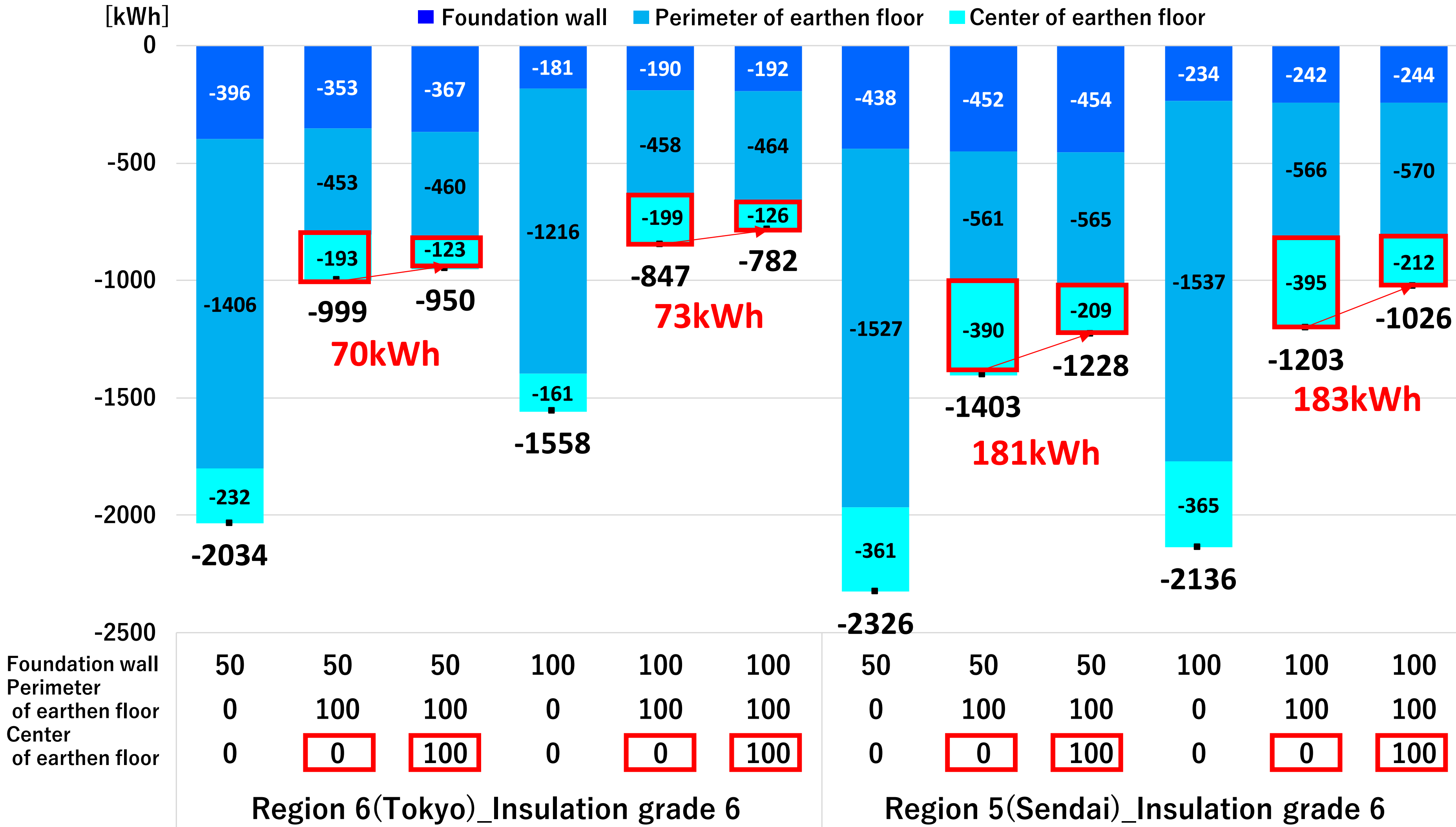
Study of under-floor heat loss



Underfloor heat loss was significantly reduced by installing perimeter of earthen floor insulation.

Demonstrated effectiveness of insulating the perimeter of earthen floor.

Study of under-floor heat loss



By increasing the thickness of the cebter of earthen floor insulation from 0 mm to 100 mm,

the underfloor heat loss decreased by about 70 kWh in region 6 and 180kWh in the region 5.

Initial and running cost consideration

$$P_{time} = \frac{\textbf{Construction cost for each insulation specification} - \text{Construction cost for insulation at the base case}}{\text{Heating season electricity charges for the base case} - \textbf{Heating season electricity rates for each insulation specification}}$$

＜The material cost for insulation[1]＞

Type	Item	The lumer cost[yen/m²]
Heat insulating material	High-performance glass wool 10K 100mm	960
	High-performance glass wool 16K 155mm	2,140
	High-performance glass wool 24K 120mm	2,120
	High-performance glass wool 20K 105mm	2,210
	Phenol foam Class 1 No. 2 63mm	3,530
	Extruded polystyrene foam Class 3 bA 50mm	1,623
Aperture	Diagonal move	54,773
	FIX	53,424
	Sliding window	11,817

＜Calculation of Electricity Rates＞

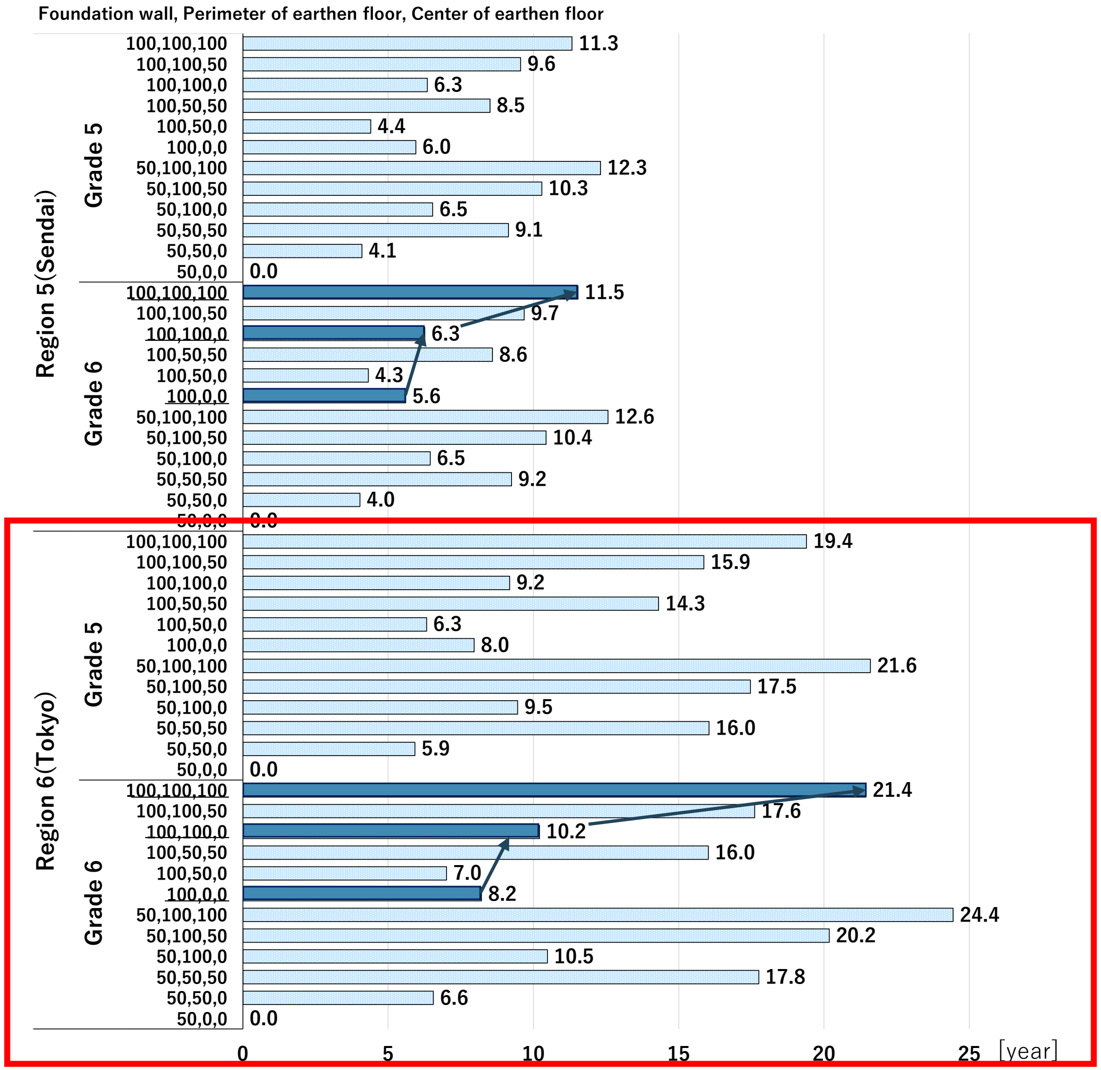
・in consideration of the FIT system, the electricity sales rate is calculated as 16 yen/kWh for the first 10 years, and 8 yen/kWh after the 10th year, when the FIT period ends.

・The purchase price of electricity was set at 40 yen/kWh in consideration of recent electricity prices.

1) Building Construction Research and Development : Accumulation Pocket Notebook, Residential Construction Edition 2021, Economic Research Council, 2021.

Payback time calculation result

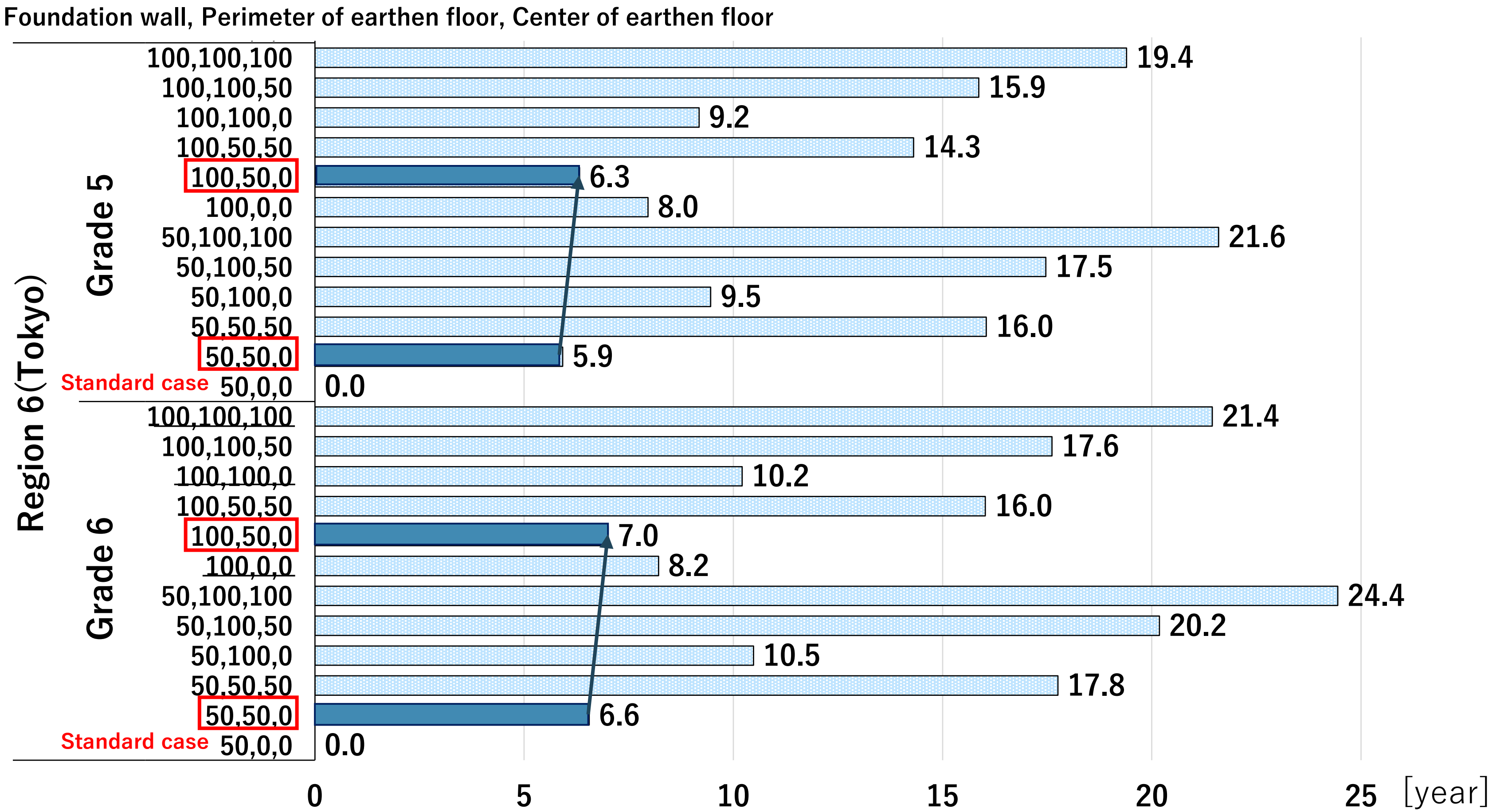
$$P_{time} = \frac{\textbf{Construction cost for each insulation specification} - \text{Construction cost for insulation at the base case}}{\text{Heating season electricity charges for the base case} - \textbf{Heating season electricity rates for each insulation specification}}$$



Indicates for Region 6

Payback time calculation result—Region 6(Tokyo)

$$P_{time} = \frac{\text{Construction cost for each insulation specification} - \text{Construction cost for insulation at the base case}}{\text{Heating season electricity charges for the base case} - \text{Heating season electricity rates for each insulation specification}}$$

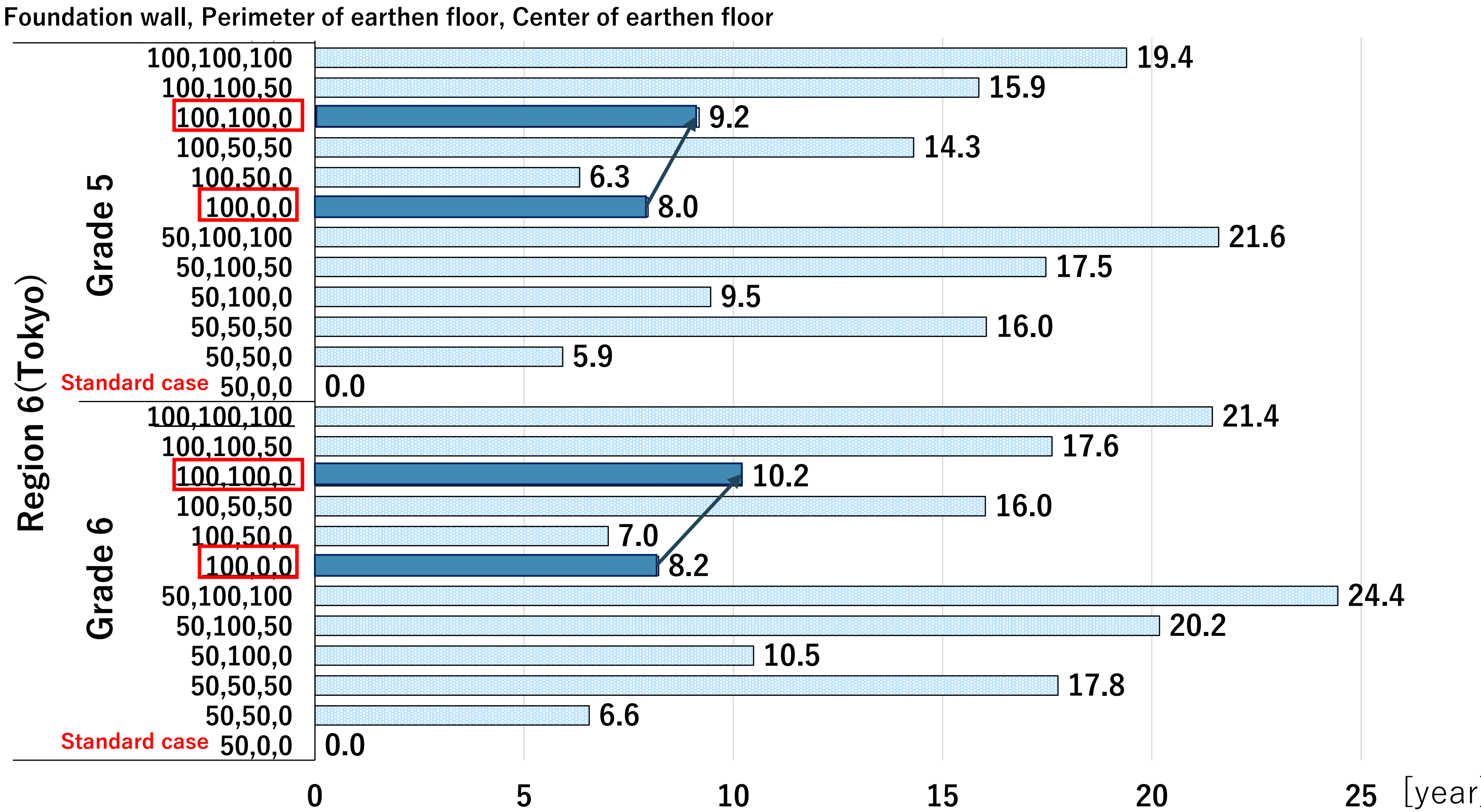


The initial cost could be recovered within one year

when the thickness of the foundation wall insulation material was increased from 50 to 100 mm.

Payback time calculation result—Region 6(Tokyo)

$$P_{time} = \frac{\text{Construction cost for each insulation specification} - \text{Construction cost for insulation at the base case}}{\text{Heating season electricity charges for the base case} - \text{Heating season electricity rates for each insulation specification}}$$

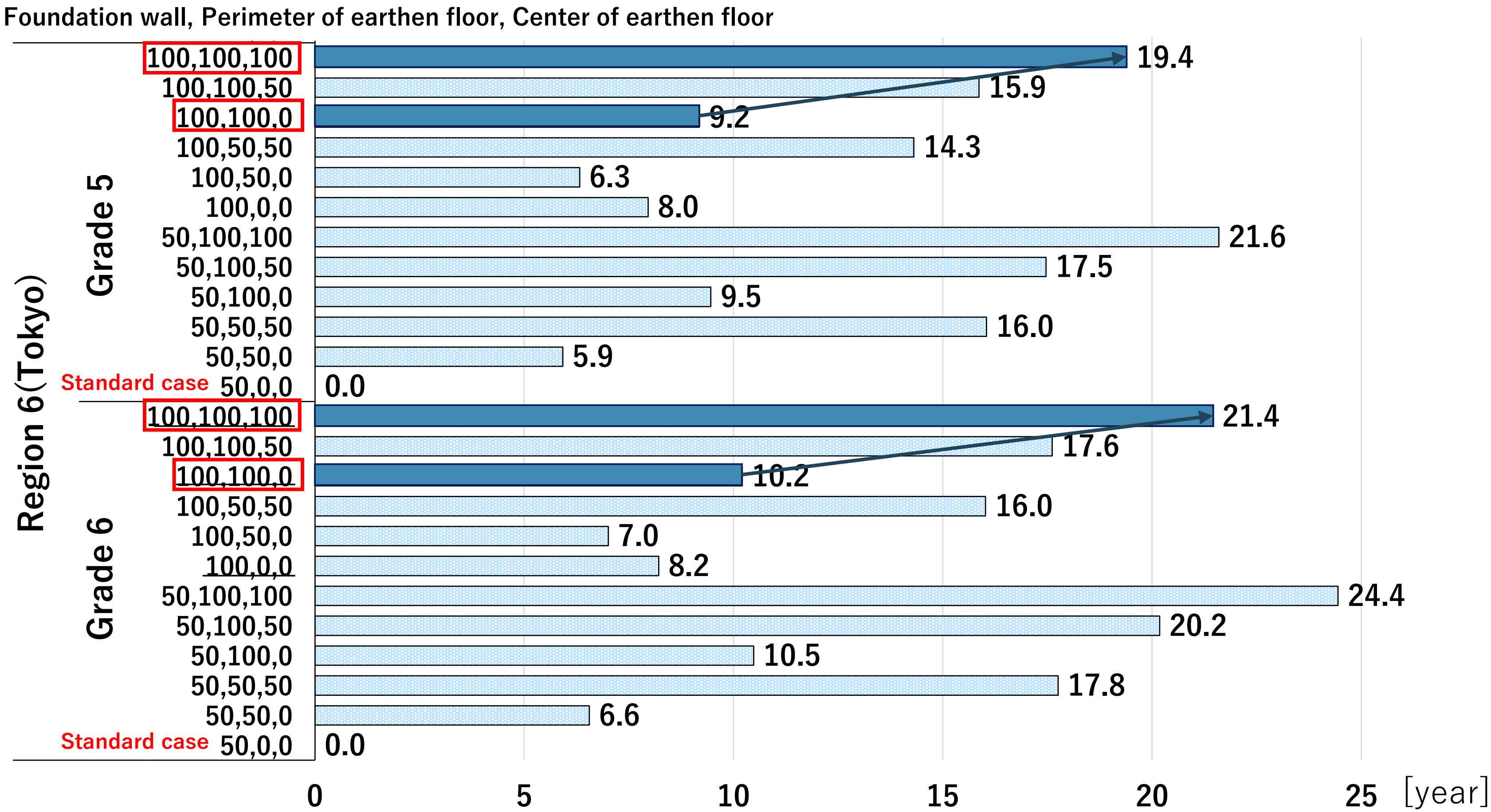


When the insulation thickness of the earthen floor perimeter was increased from 0 to 100 mm, the difference was only about 1 to 2 years.

➡The cost-effectiveness of the insulation in the earthen floor perimeter is high.

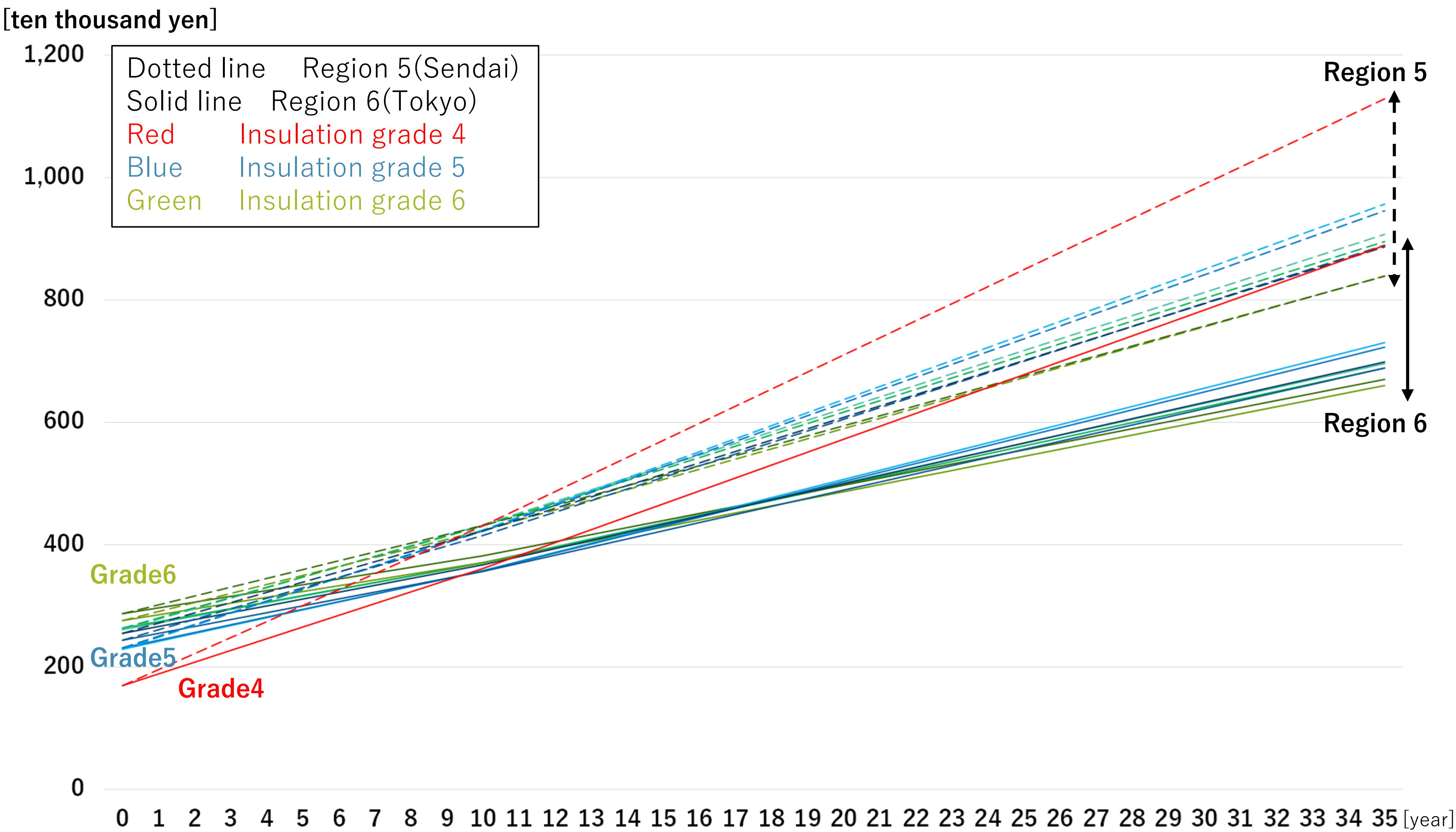
Payback time calculation result—Region 6(Tokyo)

$$P_{time} = \frac{\text{Construction cost for each insulation specification} - \text{Construction cost for insulation at the base case}}{\text{Heating season electricity charges for the base case} - \text{Heating season electricity rates for each insulation specification}}$$



In the center of the earthen floor, when the insulation thickness was increased from 0 to 100 mm, the payback time was longer about 10 years.

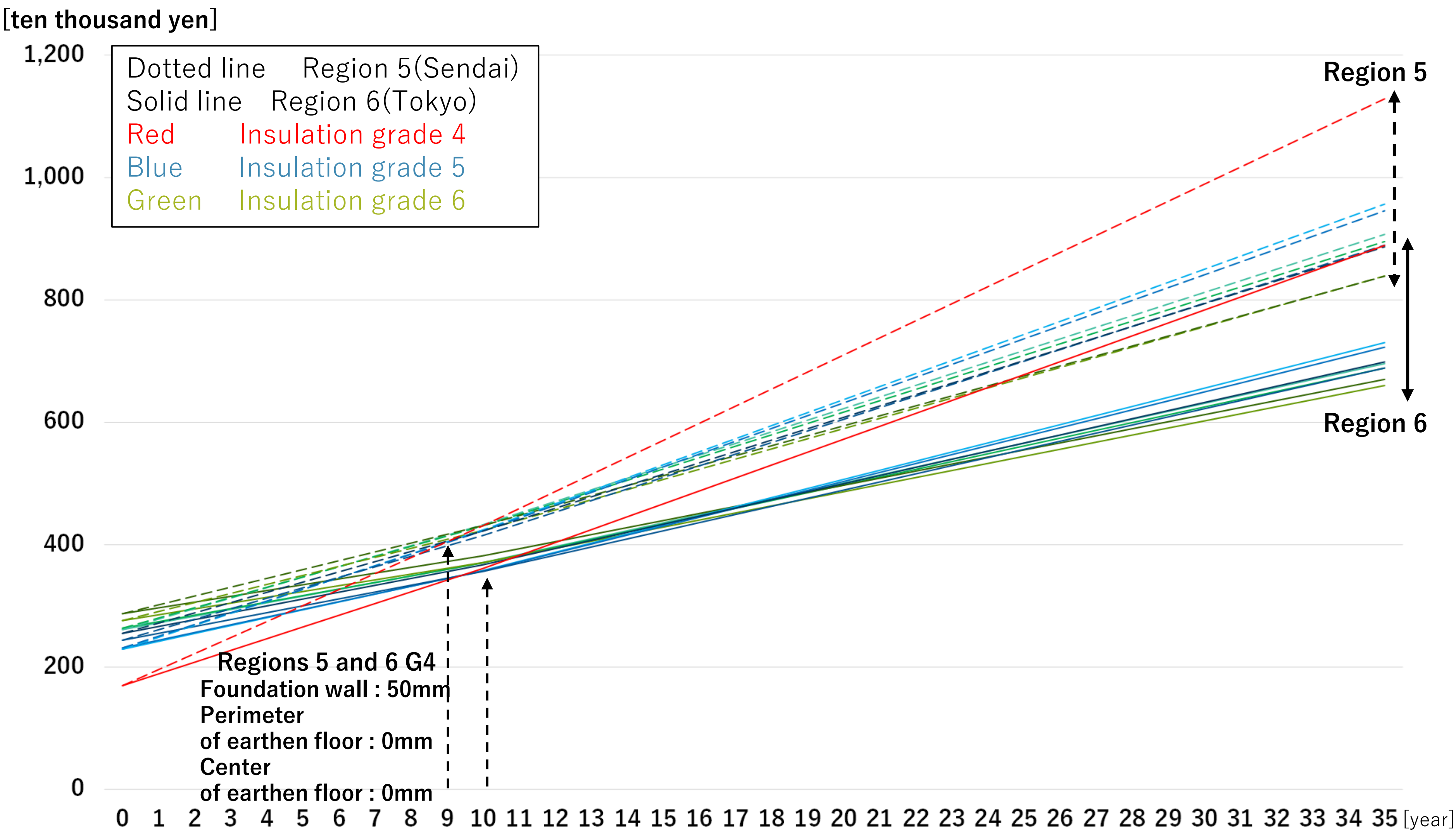
Total cost ＝ the initial cost of the insulation work ＋ the running cost during the heating season



A case of grade 4 (energy conservation standard) was also included in the study.

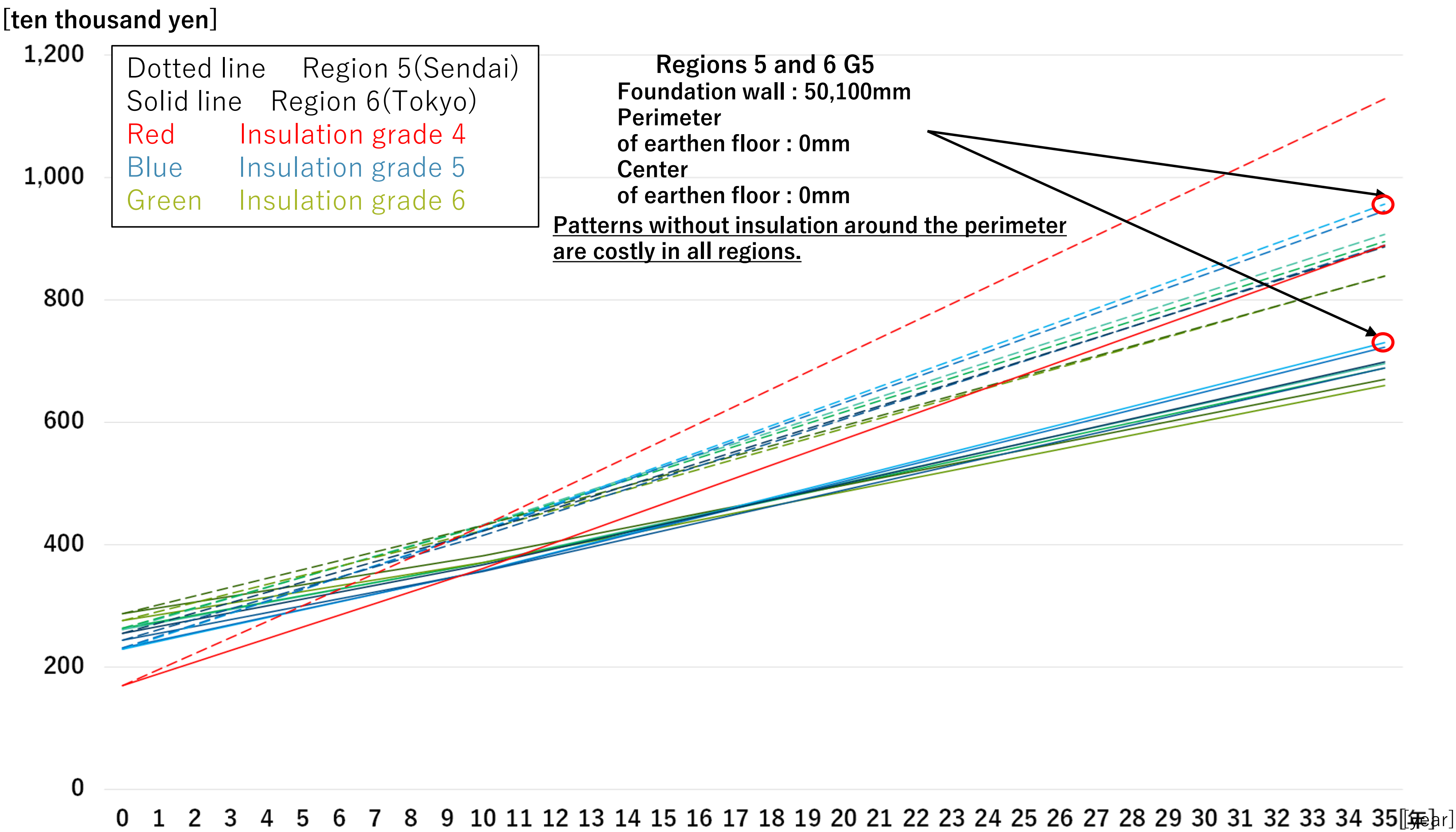
The integrated cost transition during the heating period for each insulation performance

Total cost = **the initial cost of the insulation work** + **the running cost during the heating season**



The material and labor costs for insulation work in insulation grade 4 are small, **the total lifetime cost in both regions 5 and 6 are larger than in the other cases after about 10 years.**

Total cost ＝ **the initial cost of the insulation work** ＋ **the running cost during the heating season**

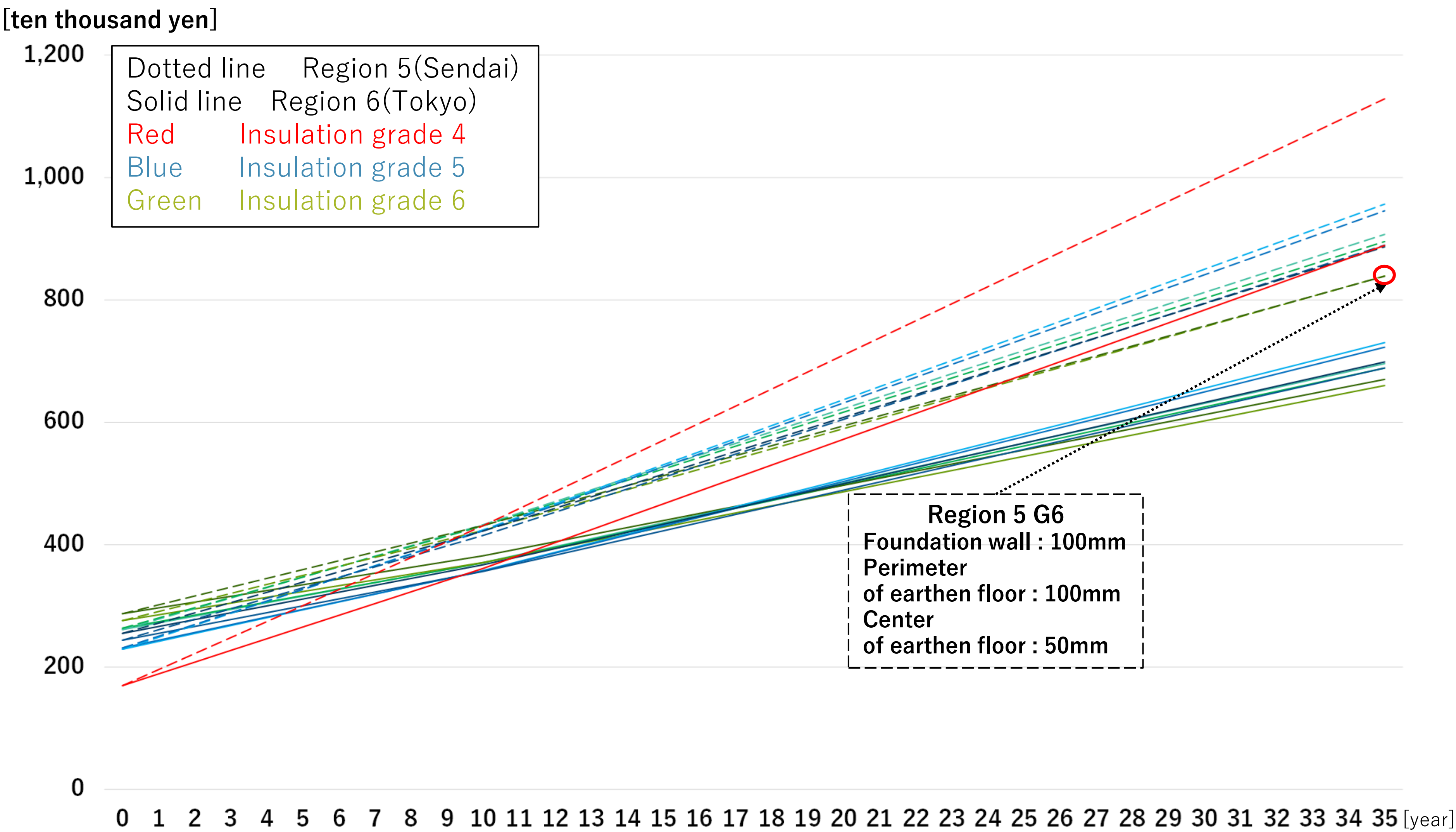


Insulation was not installed at the perimeter and center of the earthen floor,

the lifetime cost was found to be higher in both regions 5 and 6.

The integrated cost transition during the heating period for each insulation performance

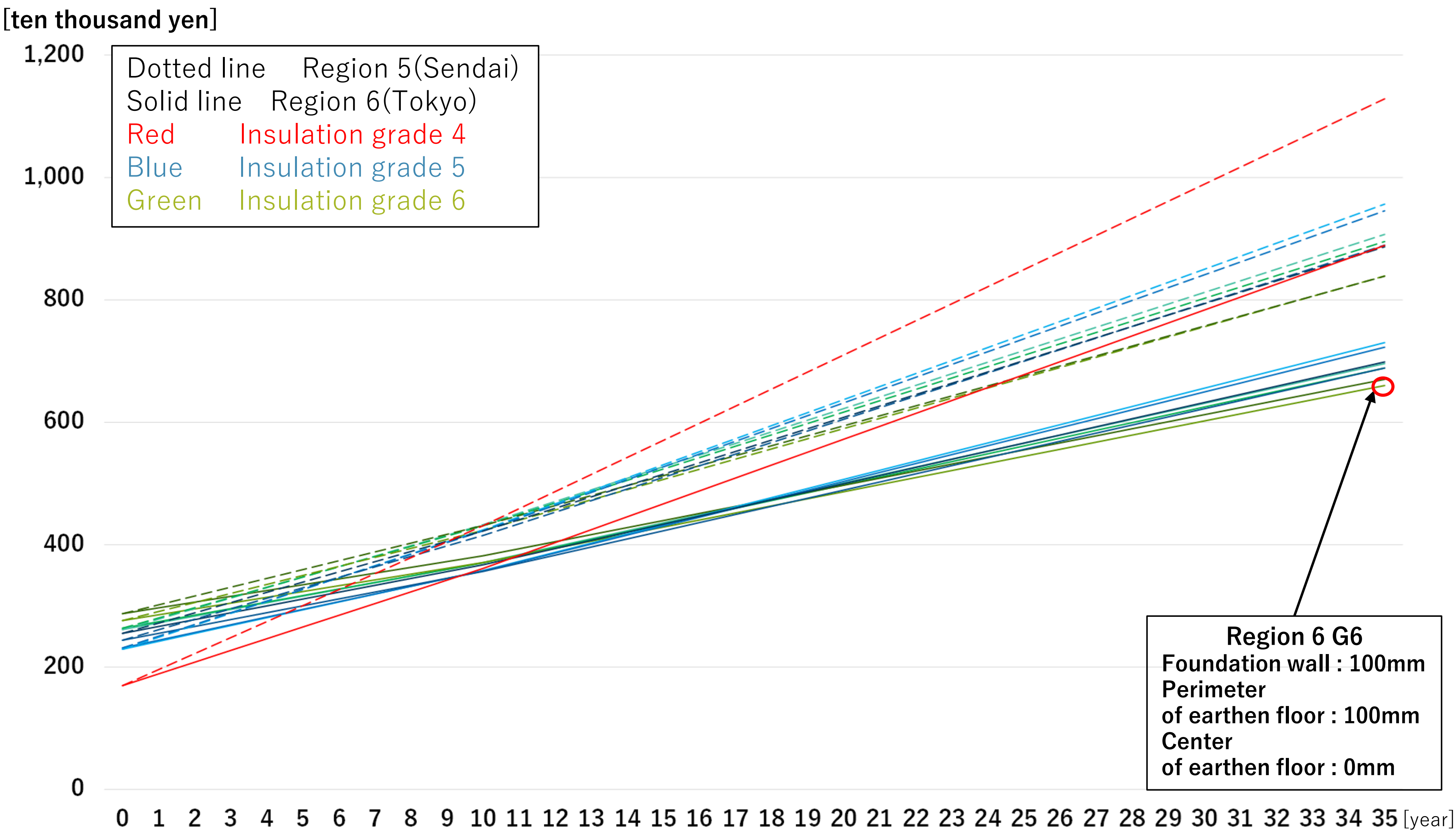
Total cost = the initial cost of the insulation work + the running cost during the heating season



The lowest-lifetime cost insulation specifications in the region 5

Foundation wall→100mm , Perimeter of earthen floor→100mm , Center of earthen floor→50mm

Total cost = the initial cost of the insulation work + the running cost during the heating season



The lowest-lifetime cost insulation specifications in the region 6

Foundation wall→100mm , Perimeter of earthen floor→100mm , Center of earthen floor→0mm

Conclusions

This study examined the effect of different foundation insulation performance in energy conservation area classifications 5 and 6 used passive standard plans.

Here is what authers found out

- Changing the insulation grade from 5 to 6 in both regions improved energy efficiency and comfort.
- Insulating the perimeter of the earthen floor is effective for underfloor heating.
- The lowest-lifetime cost insulation specifications in each regions.

Tipe	Region 5	Region 6
Foundation wall	100mm	100mm
Perimeter of earthen floor	100mm	100mm
Center of earthen floor	50mm	0mm

・The effectiveness of insulation around the perimeter of the earthen floor was demonstrated in both regions 5 and 6.

・In region 5, it was found that the center of the earthen floor should also be laid.