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Evaluation of Energy-Saving and Improvement of the Thermal Environment of the House with High Thermal Insulation, Heat Storage Performance, and Fitting Adjustment

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Abstract: In this study, we assessed a lifestyle in which occupants adjust the fittings based on climate, weather, and time, in terms of energy efficiency and thermal conditions. The proposed solution is a Zero Energy House (ZEH) with high thermal performance. The thermal performance of the building envelope can be adjusted by changing the operation of fittings based on the indoor and outdoor environments, as well as air conditioning usage. Many studies have achieved zero energy by increasing the thermal performance of an envelope and using highly efficient energy-saving facilities; however, uniquely, here we focus on occupant behavior to change the building envelope condition. In this paper, numerical analysis was used to investigate the effect of adjusting the fittings on buildings with different thermal performances of the envelope. The analysis demonstrates that, while more research into measures is needed in the summer, the adjustment of fittings and thermal storage properties in the winter season can reduce the heating load by 48–59% compared to the normal ZEH and improve the indoor environment. In terms of the heating and cooling load throughout the year, the results also showed that applying fittings adjustment and heat storage to an ordinary house can provide nearly the same energy-saving effect as a highly insulated house.

Keywords: Zero Energy House; fitting adjustment; thermal environment; air conditioning load; skylight; thermal storage

Citation: Uehara, Y.; Uno, T. Evaluation of Energy-Saving and Improvement of the Thermal Environment of the House with High Thermal Insulation, Heat Storage Performance, and Fitting Adjustment. *Energies* **2022**, *15*, 6728. https://doi.org/10.3390/en15186728

Academic Editors: Hom Bahadur Rijal and Manoj Kumar Singh

Received: 20 July 2022
Accepted: 6 September 2022
Published: 14 September 2022

1. Introduction

1.1. Background of Zero Energy Houses

The Japanese government has stated in its long-term strategy based on the "Paris Agreement," which was approved by the Cabinet in October 2021, that it aims to reduce greenhouse gas emissions by 46% from 2013 fiscal levels by 2030 and to achieve carbon neutrality by 2050 [1]. To meet these targets, it is necessary to further reduce energy consumption. Household carbon emissions account for approximately 15.9% of the total Japanese emissions [2], and energy consumption for cooling and heating account for 18.5% of the total household energy consumption [3]. Thus, the spread of Zero Energy Houses (ZEH), in which zero energy is achieved by improving building and equipment performance, is being promoted as an energy-saving measure in the residential construction sector, especially reducing energy consumption for air conditioning.

1.2. Energy-Saving by Increasing Thermal Performance of the Buildings

Many studies have been conducted to achieve energy savings for air conditioning by increasing the building envelope. Remy et al. [4] showed the reduction in heating energy by a switching insulation system, which controls the window shades and thermal resistances of walls. Benjamin et al. [5] proposed a dynamic insulation material for increasing the thermal performance of building envelopes and demonstrated their high performance. Thus, most studies show that the solution for energy saving is to develop the equipment or materials and control the building envelope. However, we address the issue from an entirely different perspective, that is, the occupant's behavior in changing the operation of the fitting adjustment, which is a simpler solution based on traditional Japanese living styles.

Owada et al. [6] studied the effect of insulated fitting adjustments and ventilation partitions on the thermal environment in an environmentally symbiotic housing. They showed the effect of the fittings' operation through measurements. However, the study focused on the partitions rather than the envelope, and they were not high performing. Doi et al. evaluated the results of partial insulation remodeling in Kyomachiya [7,8]. Taikobari shoji screens, which are made of Japanese paper and stretched across both sides of a wooden frame, are used as insulated fittings, but their thermal performance is not significantly different from that of ordinary ones. Although they improve the thermal environment, they are not as effective as the fitting adjustments used in this study.

1.3. Occupant behavior

Occupant behavior has received attention in addition to improvements in building and equipment performance. Okuaki et. al. investigated differences in energy consumption related to occupant behavior as well as architectural methods [9]. They have demonstrated that, in terms of occupant behavior, daily energy-conscious actions by residents, such as turning off lights frequently and closing curtains during air conditioning, can have the same effect as insulation retrofitting or replacing appliances with high-performance ones.

In addition to daily activities such as using opening and closing windows, there is a long-established custom in Japan of changing the fitting adjustments seasonally. Fitting adjustments, for example, are replaced twice a year in Kyomachiya (traditional Kyoto houses), once in the summer and once in the winter [10] (pp. 21, 22, 74, 75, 94, 95). In summer, winter fitting adjustments such as sliding doors and shoji screens are replaced with summer fitting adjustments such as bamboo blinds to let in cool breezes and create an open space, while in winter, winter fitting adjustments are re-replaced to prevent heat loss. In modern times, however, fitting adjustments or changes as an annual event are declining even in traditional homes, and the system has not been adapted to modern homes at all. Environmental control in modern homes is accomplished by adjusting interior curtains and blinds, but changes in envelope thermal performance are minor.

2. Purpose of This Study

We had proposed a Zero Energy House (hereafter ZEH) (The ZEH, named Kisekae House, is a model house proposed and constructed by Mukogawa Women's University in the Competition of Energy Management House 2017 [11]). It has devices that allow occupants to control the thermal performances of the building envelope and it was built to the regional classification 6 [12]. The thermal performance of the proposed ZEH was 0.45 W/m2K, which is higher than the standard level in this area and exceeds the level of the HEAT 20 G2, which is the required thermal performance of the high-level house (Table 1).

Table 1. U_A value of the national standard in Japan and ZEH.

Regional Classification		**1 2**	**3**	**4**	**5**	**6**	**7**
Degree day [°C day]		>4500	3000–3500	2500–3000	2000–2500	1500–2000	500–1500
Building Energy Conservation Law		0.46	0.56	0.75	0.87	0.87	0.87
ZEH		0.4	0.5	0.5	0.5	0.6	0.6
ZEH+ [13]		0.3	0.3	0.4	0.4	0.4	0.5
Heat 20 [14]	G1	0.34	0.38	0.46	0.48	0.56	0.56
	G2	0.28	0.28	0.34	0.34	0.46	0.46
	G3	0.20	0.20	0.23	0.23	0.26	0.26

The thermal performance level of the ZEH can be changed by controlling the fitting adjustment in the room based on indoor and outdoor environmental conditions. Additionally, solar photovoltaic power and high-efficiency equipment were installed in the house. We evaluated the performance of the ZEH by measuring the environmental conditions and energy consumption in winter, in a demonstration experiment, to confirm that the system achieves zero energy consumption [12].

In this paper, we focus on the changing of fittings done by the occupants. We used numerical analysis to evaluate the performance of adjusting the fittings on the energy-saving effects and environmental improvement in a ZEH. In addition, we evaluated the effectiveness of installing the system into an ordinary house to compare the results of ZEH.

3. Methods

3.1. Objectives

3.1.1. Building Condition of Proposed ZEH

A plan and section, and general information on the proposed ZEH in this study are shown in Figure 1 and Table 2. The ZEH consists of a space called EN with a skylight (Figures 2 and 3a) and large openings on the south side (Figure 2), a living room, and a bedroom (Figure 1). The EN is a thermal buffer space between the outside and the living spaces. There are openings on both the north and south sides, with a sliding door in each. Wind can flow in the north-south direction of the building when all windows and partitions are opened.

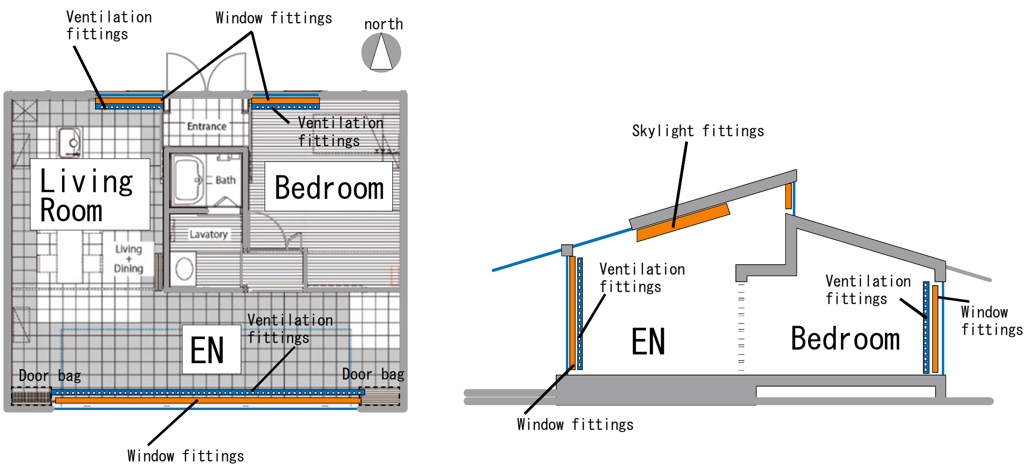

Figure 1. Plan and section of proposed ZEH [12].

Table 2. Outline of proposed ZEH.

Construction Site	Osaka City
Construction	Wooden, 1F
Total Area	66.25 m^2
Regional classification	6
U_A Value	0.45 W/m^2 K

High insulated fitting adjustments are installed under the skylight and inside each window (Figure 3a,b, hereafter the skylight fittings and window fittings, respectively). By operating a cable in the room, the skylight fittings can be fully opened and closed like in the Figure 1 right. In addition, ventilation fitting adjustments (hereafter the ventilation fittings) are installed inside each window to allow ventilation while shielding the windows from solar radiation (Figure 3c). The window fittings and the ventilation fittings can be fully opened or fully closed, and when not in use, they are stored in a door bag on either side of the window. In winter, solar energy from the skylight and the south opening of the EN was stored in the mortar floor and mud walls facing the EN and was dissipated at night. Occupants can adjust these devices to change the environment.

Figure 2. South façade of proposed ZEH.

(**a**) (**b**) (**c**)

Figure 3. Photo of the fitting adjustments. (**a**) skylight and skylight fittings. (**b**) window fittings. (**c**) ventilation fittings.

The layer composition and U value of the ZEH envelopes are explained in Section 3.2.1. The occupants operate the fitting adjustment depending on the season and time shown in Figure 4.

3.1.2. Modification of Components of the ZEH for Numerical Analysis

Several conditions were changed for this study because the ZEH was constructed only for the event and was measured during the winter.

This calculation considers the solar shading devices outside the skylight that was not constructed. A modified composition to the common style of the floor was used.

3.1.3. Condition of an Ordinary House

The ordinary house (OH) was considered for comparison with the ZEH. The space formation and plan of the OH were the same as that of the ZEH (Figure 1). The overall U value of the OH was 0.87 W/m^{2}K, which is same as the standard value of the Building Energy Conservation Law in region classification 6 listed in Table 1. The composition of the envelope was arranged according to the standard and is shown in Table 3.

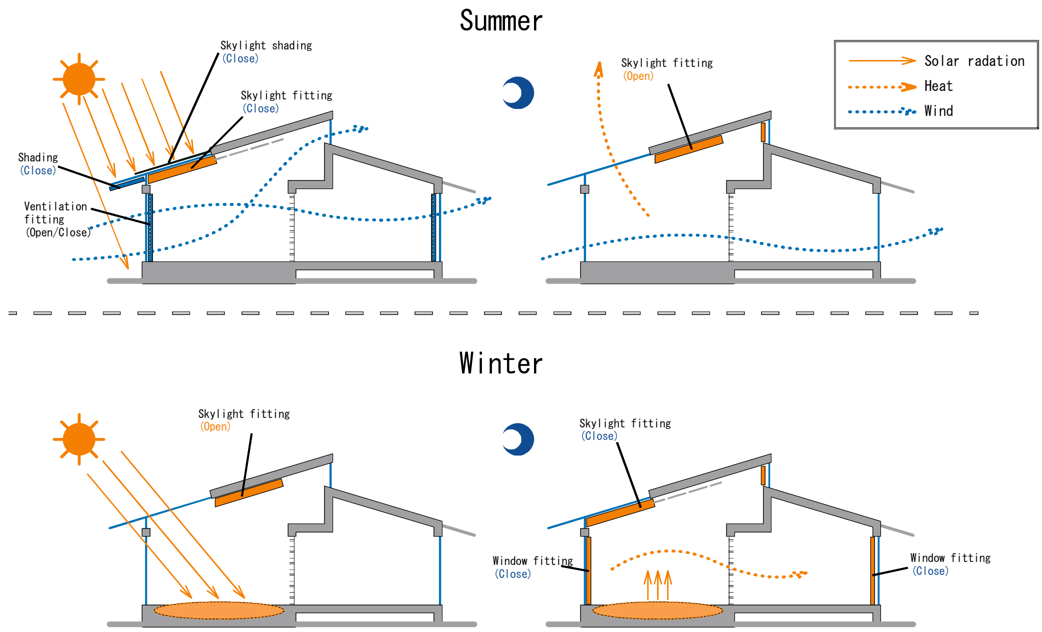

Figure 4. Operation of the fitting adjustments depending on season and time.

Table 3. Envelope specifications.

		ZEH (U Value [W/m^{2}K])	OH (U Value [W/m^{2}K])
Floor	EN	100 mm-Insulation, 150 mm-concrete slab, 80 mm-mortar, 9 mm-tile (0.328)	45 mm-Insulation, 9 mm-tile, 12.5 mm-wooden panel, 3 mm-mortar (0.624)
	Other room	100 mm-Insulation, 45 mm air, 12 mm-wooden panel, 9 mm-tile (0.305)	
Outside Wall		0.3 mm-steel panel, 15 mm-insulation, 15 mm air gap, 40 mm-insulation, 12 mm-wooden panel, 105 mm-GW, airgap, 12.5 mm-plaster board (0.185)	0.3 mm-steel panel, 15 mm air gap, 15 mm-wooden panel, 100 mm-GW, 12.5 mm-plaster board (0.433)
Window		Low-E double (FL5 + Ar12 + FL5) (1.70)	Double (FL3 + A16 + FL3) (4.07)
Roof		0.3 mm-steel panel, 9 mm-wooden panel, 90 mm-insulation, 12 mm-wooden, 105 mm-insulation, 9 mm-wooden panel (0.180–0.182)	0.3 mm-steel panel, 12.5 mm-wooden panel, 160 mm-insulation, air gap, 9 mm-wooden panel (0.291–0.293)
Skylight		Low-E double (FL3 + Ar12 + FL3) (1.60)	Double (FL5 + A12 + FL5) (2.90)

3.2. Analysis Condition

The heating and cooling load, which corresponds to the energy consumption for heating and cooling, as well as the room temperature, were evaluated. The thermal environment simulation software program AE-Sim/Heat (the Architectural Environmental Solutions Simulation Program for Dynamic Heat Load, http://www.ae-sol.co.jp/_src/sc278/AESimH.pdf, accessed 15 August 2022) was used. This deals with the multi-room heat load calculation program using the thermal network.

The external conditions were determined using standard meteorological data from Osaka City (Figure 5) [15]. The validity of the analytical model has been shown in previous studies [16].

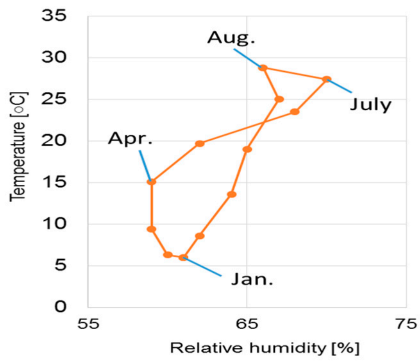

Figure 5. Climate of Osaka [15].

3.2.1. Building Condition and Operation

1. Envelope

Table 3 lists the specifications of the envelopes and their overall heat coefficient used in this analysis. Table 4 lists the solar radiation shading factors of the skylight and windows. The UA values of the ZEH and the OH were 0.45 and 0.87 W/m^{2}K, respectively. The envelope detail of the OH was based on the Next Generation Energy Conservation Standard regional classification 6 specification for a typical conventional wooden house model [17].

Table 4. Radiation shading factor compared between the ZEH and OH.

	ZEH [-]	**OH [-]**
Window	0.44	0.45
Skylight	0.86	0.91

2. Fittings adjustments

The skylight fittings made of 175 mm-thick polystyrene foam (R = 5 m^{2}K/W) were installed under the skylight of ZEH (Figure 3a). The window fittings made of 50 mm-thick polystyrene foam (R = 2.35 m^{2}K/W) were also installed inside the north-south windows (Figure 3b). The ventilation fittings (Figure 3c) were used for the windows to provide ventilation while shielding the windows from solar radiation. In the calculation, the condition with the ventilation fittings has a higher airflow ratio than the condition without the ventilation fittings.

3. Shadings

An awning (*sudare*) was installed under the eaves as an environmental control option. The awning's visible light transmittance and reflectance were set at 17% and 36%, respectively [18].

The ventilation fittings can also be used to prevent solar radiation penetration. The visible light and solar radiation transmission characteristics and reflectance were 17% and 20%, 8%, respectively, and a solar radiation shielding factor was 0.79. In the case of solar shading outside the skylight, the solar reflectance, solar transmittance, and visible light transmittance were set to 90%, 5%, and 20%, respectively. The U value of the ventilation fitting was 5.38 W/m^{2}K.

In the calculation for the skylight shading (+s) in summer, shading was added on the outside of the skylight to prevent solar radiation from entering the skylight. The solar reflectance of the shadings was set to 90%.

4. Ventilation

The difference in ventilation frequency, calculated using the "Judgment Sheet for Measures to Ensure Ventilation," indicated the amount of ventilation (Ver. 0.06) [19]. When ventilation was provided by fully opening the windows (without ventilation fittings), the ventilation frequency was calculated to be ACH 30.52 (EN), 16.70 (DL), and 13.82 1/h (bedroom), respectively. When ventilation fittings were used, it was calculated to be ACH 13.69 (EN), 6.79 (living room), and 6.89 1/h (bedroom), respectively, because the ventilation rate would be lower than when the doors were opened. The ventilation rate with the openings closed was ACH 0.5 1/h.

5. Air condition

For this calculation, the living room and bedrooms were air conditioned, whereas the EN was not. The summer cooling period was set from May to September, the winter heating period from October to April, and no intermediate period was set. The cooling temperature was set at 28 °C and the heating temperature was set at 20 °C. The Table 5 shows the conditions of the fittings under air conditioned.

Table 5. Condition of fittings in the cases air-conditioned.

	Skylight Fittings		Window Fittings	
Term	**May to September (Cooling)**	**October to April (Heating)**	**May to September (Cooling)**	**October to April (Heating)**
Daytime 6:00–18:00	Close	Open	Open	Open
Nighttime 18:00–6:00	Open	Close	Open	Close

3.2.2. Distribution of Solar Heat

The heat storage element was the floor mortar and mud partition walls. In the analysis, the energy of the solar radiation entering through the window was distributed to each surface according to the distribution ratio. The floor surface absorbed 50% of the radiation energy, whereas the remaining 50% was absorbed by other surfaces depending on their sizes.

3.2.3. Case Study

Four cases (Table 6) with and without environmental adjustment in ZEH and OH, were compared. The environmentally adjusted type includes a skylight, thermal storage components, and fitting adjustments to promote solar heat utilization. The skylight and fittings are not installed in ZEH without environmental adjustments.

Table 6. Calculation cases.

Name	House Type	Fitting Adjustment
Case1 OH-nFC	OH	×
Case 2 ZEH-nFC	ZEH	×
Case 3 OH-FC	OH	O
Case 4 ZEH-FC	ZEH	O

The following cases, heating, and cooling load (issue I; energy-saving) and natural room temperature (issue II: thermal condition) were studied in this paper. For the energy evaluation of (issue I), the case in which a solar shading was added, such as Case 3 C-FC+s and Case 3 Z-FC+s, was calculated. The evaluation of the thermal condition (issue II) was considered with fully opened ventilation (+w), with ventilation and awning (*sudare*) (+ws), and with ventilation fittings and awning (*sudare*) (+wss).

In the calculation of natural temperature without air conditioning, the typical condition of fittings was changed like in Figure 5.

4. Results and Discussion

In summer, the average of the highest and lowest values (average maximum and average minimum temperatures) for three days, including the highest temperature day of the year in Osaka City, were compared for the three days being evaluated. In the winter, the same comparison was made for three days, including the coldest day of the year.

4.1. Heating and Cooling Load (Issue I)

Figure 6 shows the daily mean cooling and heating load in the living room (left) and in the bedroom (right). Compared to Case1-OH-nFC, Case4-ZEH-FC had approximately 20% lower cooling load and 77% lower heating load in the living room, and approximately 32% lower cooling load and 70% lower heating load in the bedroom. The Case3-OH-FC saved the heating load by 59% and 48% in the living room and bedroom compared to the normal ZEH (Case 2), respectively. The reason of the larger reduction of the heating load in the living room was that the living room was greatly affected by the environmental condition in the EN compared to the bedroom, which was separated by the insulated partitions thus the effect of changing the fitting adjustment become larger.

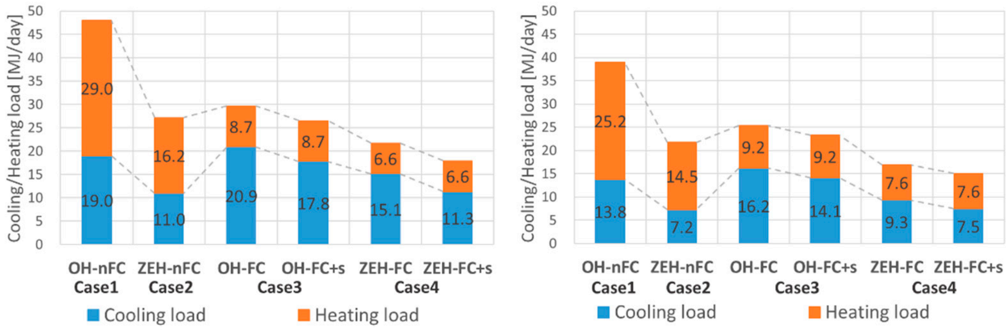

Figure 6. Daily mean cooling and heating load (left: living room, right: bedroom).

The cooling load was lowest in Case2-ZEH-nFC. Assuming air conditioning, Case2 was more effective than Case4-ZEH-FC. This was due to the significant influence of solar radiation heat transfer from the skylight, and even with the insulated fitting adjustments, the solar radiation transmitted through the skylight increased the air temperature between the fittings and the skylight glass, resulting in a heating load to the room. As a result, we investigated the effect of solar radiation shielding outside the skylight (+s) and discovered that the cooling load could be reduced to the same level as in Case2.

In the total heating and cooling load, the reduction with the fitting adjustments was large; it was shown that fitting adjustments can produce the same effect as increasing thermal insulation performance of the building.

4.2. Thermal Environment (Issue II)

Figure 7 depicts the calculated results for natural room temperature in summer and winter. The three-day averages for the highest and lowest values for the living room, bedroom, and EN are shown.

Natural room temperatures exceeded 34 °C at the maximum in both cases without skylight (Cases 1 and 2) and with skylight (Cases 3 and 4). It became clear that the appropriate use of air conditioning was necessary during this period and that changing the fitting adjustments alone were not enough for the situation. For comparative purposes, this section clarifies the relative effectiveness of changing the fitting adjustments such as ventilation, solar shading, and ventilation fittings.

In Figure 7, in summer, the maximum temperatures in the cases with fitting adjustments (Cases 3 and 4) were higher than in the case without fitting adjustments (Case 1 and 2). As in Section 4.1, this was because of solar radiation heat from the roof surface. In winter, however, both daytime and nighttime temperatures were kept high in Case4-ZEH-FC, and the temperature was 3 to 5 °C higher than in Case2-ZEH-nFC. Case3-OH-FC overheated during the day, whereas Case4-ZEH-FC was suppressed due to heat storage. In the summer, the temperature can be controlled by adjusting the fittings to ensure ventilation and sun protection. The study's findings are shown below.

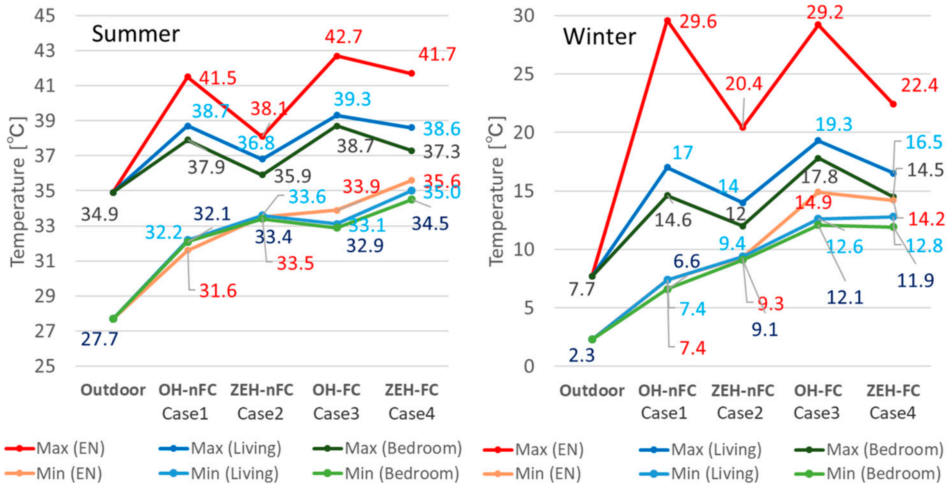

Figure 7. Max and Min temperatures (left: summer, right: winter).

Figure 8 shows the calculation results in the case of the fully opened ventilation, the ventilation and awning, and the ventilation fittings. In the case of only fully opened ventilation (+w), a temperature drop of about 6 °C was obtained at the maximum temperature in the EN in both Case 3 and 4, and the temperatures in the living room and bedrooms dropped accordingly. When awnings and ventilation were provided (+ws), temperatures dropped, albeit slightly.

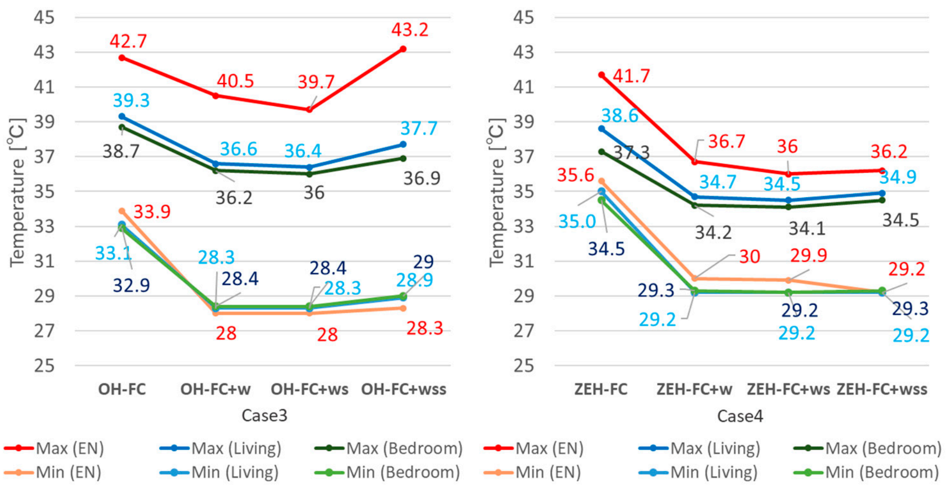

Figure 8. Max and Min temperatures depending on fitting adjustments (left: OH, right: ZEH).

When ventilation fittings were installed (+wss), the sun shading effect increased compared to ventilation alone, but the amount of ventilation was reduced. Thus, the temperature in the Case4-ZEH-FC+wss increased compared to the case of awning and ventilation (Case4-ZEH-FC+ws). In the case of the OH, the solar radiation shading performance of the skylight was not enough, and the temperature increase could not be controlled by the ventilation. The shading of the skylight was absolutely necessary. Further study is needed to determine the balance between sun shading and ventilation.

5. Conclusions

We investigated the effects of a lifestyle, in which residents adjust fittings based on their environment, on energy conservation and indoor environmental performance in this study. Numerical analysis was used to evaluate the ZEH and an ordinary house. In terms of heating and cooling loads throughout the year, the calculation results showed that applying fitting adjustments and heat storage to an ordinary house can produce energy-saving effects nearly equivalent to those of a highly insulated house. The results indicated also that fitting adjustment and thermal storage properties provide energy savings in heating load and improved indoor environment in winter. During the summer, in addition to shielding the exterior of the building from solar radiation, fitting adjustments that ensured ventilation could suppress the rise in room temperature, with the effect being greater in buildings with higher insulation performance. However, further study is needed on the specifications of skylights.

Author Contributions: Y.U. and T.U. As a primary author, Y.U. contributed to the data curation, calculation, analysis, and original manuscript writing. T.U. gave advice on the data analysis, and contributed to the manuscript writing, project administration and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by JSPS KAKENHI Grant Number 18K04509-1.

Acknowledgments: I would like to thank several companies and stakeholders for their cooperation in the design, construction, and disclosure of this KISEKAE HOUSE. I would also like to thank all the teammates and teachers who worked on this project.

Conflicts of Interest: The authors declare no conflict of interest.

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