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Economic and energy consumption analysis of smart building – MEGA house

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ABSTRACT

Energy efficiency and carbon reduction of new buildings are key objectives of policies that aim to decrease electric use nationwide, particularly during the summer, when electricity usage is at its highest. A case study was developed to test the energy-conservation performance and economic feasibility of the creative and intelligent open building “MEGA House”. MEGA House focuses on making improvements in four key areas: (a) Material, (b) Electronic, (c) Green Building, and (d) Automation. This paper focuses on applications in the areas of Electronic and Green Building. The economic analysis in this paper of electricity consumption and of the potential energy-savings is based on the use of energy conservation equipment such as earth tubes and solar chimneys, situation simulations, field measurements at four experimental stages, and economic calculations.

According to the results of measurement and economic analysis, the MEGA House demonstrated optimal energy conservation performance. Using an earth tube (fan) and a solar chimney (exhaust fans) in the MEGA House lowered the indoor temperature about 1~2 °C in summer, while using an earth tube (fan) instead of an electric heater increased the indoor temperature as much as 3–4 °C. In terms of economic benefits, the using the energy-conservation facilities installed in MEGA House reduced electricity expenditures by NT$8537.76 and decreased CO_2 emissions by around 1288.83 kg per year.

1. Introduction

Because of Taiwan's location near the tropics, electricity usage increases significantly during the summer. Based on energy statistics published by the Taiwan Power Company and Bureau of Energy, Ministry of Economic Affairs, R.O.C., air-conditioning accounts for the highest proportion (41%) of the year-round electricity consumption of households and commercial buildings [1]. Therefore, the electricity used for the air-conditionings is overvalued. A 1 °C increase in indoor temperature reduces electricity consumption by 6%, the equivalent of over 300,000,000 kW H in savings nationwide in one summer [2].

Buildings are major energy consumers in modern society and thus have a critical role to play in saving energy and reducing greenhouse gas emissions. Improvements in general building construction have raised popular awareness of energy consumption in buildings and increased the willingness of the general public to seek further energy-saving solutions [3]. One of the primary ways to improve energy conservation in buildings is to incorporate the best energy-saving designs and renewable energy systems into new buildings. Recently, there have been significant studies to analyze the energy consumption in buildings and to find effective control strategies for saving energy through various ways to make better thermal comfort in different climate conditions (such as hot and humid climate) and building types (such as home and residential, etc.) [4–8]. Especially, to achieve the thermal comfort and energy-saving conditions, comfort natural ventilation has been recommended as the one of the most effective cooling strategy for buildings in hot and humid climates [9]. Besides, the “Energy-Saving” building in Paris, France produces its own energy for heating, lighting, and air-conditioning. The cooling system for this building pumps cold water from the Seine River throughout the building, which eliminates the need for air-conditioning, and uses state-of-the-art insulation to prevent heat transmission. The systems used in this building reduce electricity consumption to 16 kW

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per square meter per year [10]. In Taiwan, the Architecture and Building Research Institute commissioned the National Taiwan University of Science and Technology research team to develop the open-building MEGA House to explore the effects of various energy efficiency and carbon reduction measures [11]. The open-building (OB) concept integrates construction life-cycle information. The OB philosophy has been applied in an increasing number of construction projects based on its successful minimization of waste and of the need for building reconstruction [12].

The creative and intelligent open-building "MEGA House" addresses the four key areas of: (1) Materials, (2) Electronics, (3) Green Building, and (4) Automation, with each implemented across the MEGA House life cycle. This paper focuses on the application of Electronics (E) and Green Building (G) and combines the smart control mechanism [13] to find the highest performance combination of energy-saving equipment at different times and conditions. In this paper, "Electronics" refers to electronic facility networks. This project employed RFID technology for door entrance control systems, door plates, and air-conditioning sensors and integrated a smart control system to increase occupant safety, decrease energy consumption, and store essential data. "Green Building" refers to the use of green building design concepts. The green-building facilities used in this project include: 3-in-1 solar panels, insulation glass, a solar chimney, and an earth tube. The solar panel was used to provide clean energy for the building; insulation glass was installed to deflect excess sunlight away from the building; the solar chimney achieved fresh air circulation at lower power consumption; and the earth tube used thermal conduction exchange to stabilize indoor temperatures [14]. Different from the many studies that discuss the saving of energy in buildings by reducing the energy requirements for air conditioning [15,16] through the adjustment of the thermal environment in buildings [17–22] and the use of earth tubes [23–25]. Furthermore, there are various evaluation methods are available for using the energy-saving equipments or renewable energy in the buildings. It also possible performs on-site simulations and measurements of the energy-saving use by the various buildings [8,9,26–28]. This paper focuses on applying energy-saving technology in "MEGA House" open-building project. Using a smart control system to coordinate the smart control mechanisms and energy-saving equipment helps obtain the necessary measurement parameters and the best testing settings in order to evaluate the effects in terms of carbon reduction and economic benefits.

2. Design of experiments

The proposed design for experiments in this paper takes the open-building "MEGA House" as the case study and considers the daily habits of the inhabitants and the probable delayed thermal effects to produce situation simulations. The design of experiments conducted actual measurements over four stages separated in different living day during the course of one year (the durations cover summer (Jul.–Sep.) and winter (Jan.–Mar.)). Besides, the experiments of each stage would be conducted separately in similar environmental conditions (temperature and humidity). Thus, in order to obtain the *reasonable samples in each* measurement,the 3 similar climatic days per month from all measured data would be selected by sampling analysis during the summer (or winter). Therefore, the total measured periods are 9 days as small samples in each simulation and measurement during the summer (or winter).

2.1. Studied buildings

This paper concentrates on the creative and intelligent open-building (OB) "MEGA House" project that was completed in November 2009. The OB MEGA House (hereafter, MEGA House) is a three-storey building designed to meet specific eco-awareness and energy saving objectives. The total floor area of this building is 357.02 square meters (see section drawing in Fig.1).

The term MEGA is an acronym for the integration of sustainable Materials, Electronic management, Green building design, and construction Automation. This project constructs a creative and intelligent open-building MEGA House that addresses the major objectives of energy efficiency and carbon reduction over the construction life cycle through the use of information technology and green design. MEGA House (shown in Fig. 2) integrates innovative technologies that include: (a) nano-coatings, (b) sensor network system, (c) RFID doorplates (d) an RFID door control system, (e) insulation glass, (f) earth tube, (g) solar chimney, (h) 3-in-1 solar panels, and (i) RFID-LIMS (Laboratory Information Management System), among other technologies. The following subsection clarifies the purpose of the energy-saving equipment used in MEGA House. Each technology is illustrated in the model below along with its associated aspect (E, G).

2.2. Description of energy-saving equipment

2.2.1. Electronics ("E")

Electronics refers to electronic facility networks. The electronic equipment required for the present experiment includes: RFID-controlled air-conditioning sensors, smart control system, and smart meters. This experiment employed RFID-controlled air-conditioning sensors to detect the temperature, humidity, and thermal radiation associated with MEGA House. Besides, the wireless sensor network (see Fig. 3(a)) was integrated with the smart control system to open/close windows automatically and to adjust venetian blinds, air-conditioning, and lights based on the current environmental conditions inside MEGA House in order to minimize energy consumption. Smart meters were used to monitor the electricity consumption information of MEGA House.

A. RFID-controlled air-conditioning sensors

The experiment employed several RFID-controlled air-conditioning sensors in MEGA House to detect temperature, humidity, and thermal radiation. This sensor array was linked into a wireless sensor network environment, which consisted of spatially distributed autonomous devices that used sensors to cooperatively monitor physical and environmental conditions at different locations at the MEGA House site.

In addition to one more sensors, each node in the sensor network was equipped with a radio transceiver or other wireless communication device, a small microcontroller, and a battery. Therefore, the results of several nodes were aggregated through the sensor network to capture and record the environmental information of MEGA House. Tmote Sky manufactured by Moteiv was the brand of RFID-controlled air-conditioning sensors used in this experiment (see Fig. 3(b)). The range of detection for the temperature sensors was −40 to 123.8 °C and the range of detection for the humidity sensors was 0–100% RH.

B. Smart control system

The smart control system is an interactive LCD touch screen device that provides integrated access in MEGA House to all lighting controls, air-conditioning controls, window shades controls, ventilator controls, and earth tube compressor controls. The system responds to four different inputs: temperature sensors, humidity sensors, CO_2 intensity sensors, and thermal radiation sensors,

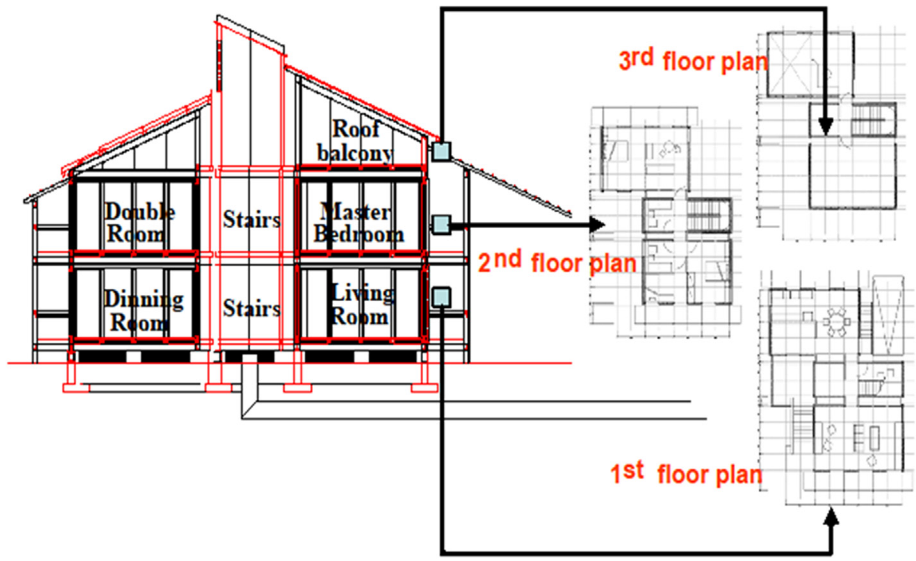
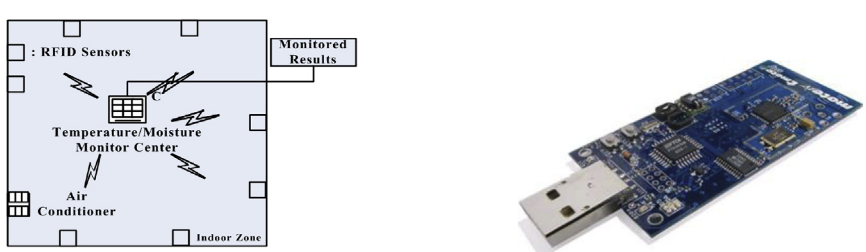


Fig. 1. MEGA House section drawing.

Fig. 2. Creative and intelligent open-building MEGA House.



(a) sensor network framework (b) RFID-controlled air-conditioning sensor (Tmote Sky)

Fig. 3. RFID sensor network system.

whether installed in indoors or outdoors. After receiving the inputs, the smart control system then controls the related energy-saving equipment automatically based on the environmental control logic (smart control mechanism [13] (see Fig. 4)) in order to maintain the optimal level of comfort within MEGA House. The system monitors these inputs constantly and responds to the changing demands of the environment by adjusting/shutting down equipment as appropriate.

C. Smart meters

Smart meters were installed into the MEGA House to monitor the electricity information related to the earth tube compressor, air-conditioning system, and LEDs. This information, including the

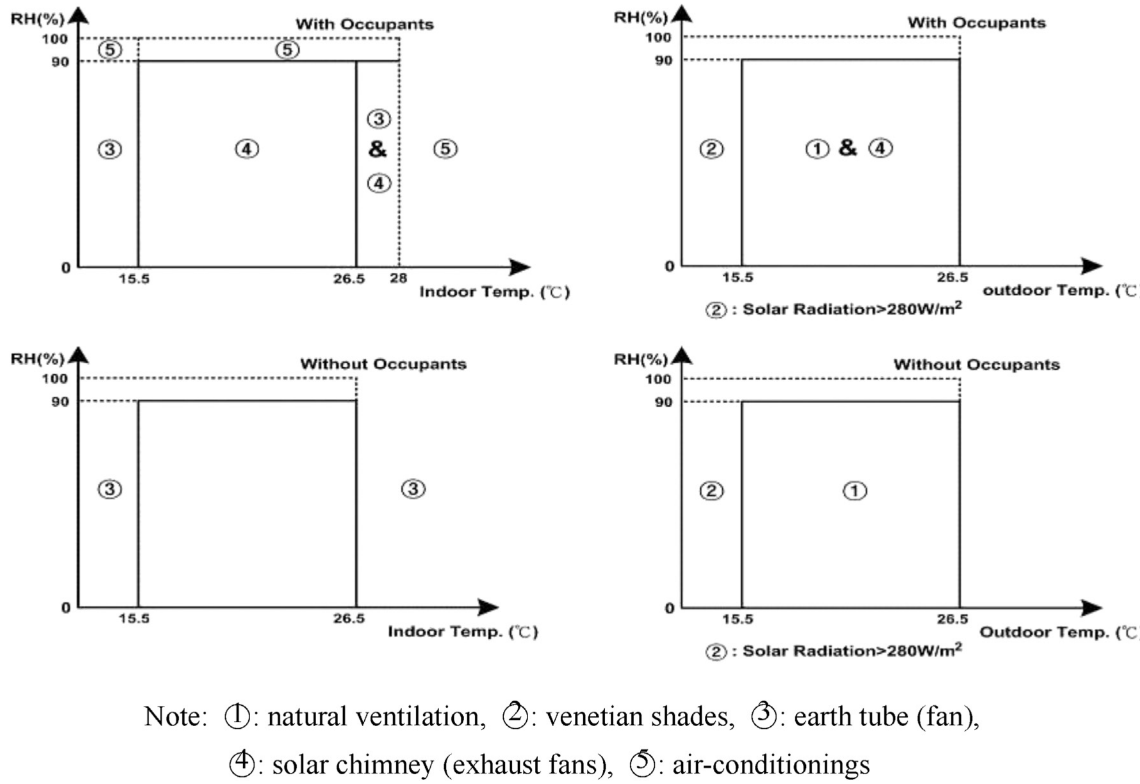


Fig. 4. The smart control mechanism [7].

real-time and historic data and daily and monthly power demand, was communicated via ZigBee and used as the basis for the economic analysis conducted in this experiment. Additionally, MEGA House users may easily access the website to simultaneously monitor all of the smart meters and manage the power consumption.

2.2.2. Green building ("G")

Green building refers to "green" building design concepts. In this experiment, the basic set of green building equipment includes: a solar chimney (paired with exhaust fans) and an earth tube. A solar chimney and earth tube were incorporated into the MEGA House (shown in Fig. 5). The solar chimney circulates fresh air using minimal power and the earth tube uses thermal conduction exchange to stabilize indoor temperatures. This experiment conforms to energy conservation design requirements as follows: (a) collect simulation parameters; (b) validate and implement network system based on monitoring and response feedback; and (c) adjust the MEGA House facility to strike an optimal balance between comfort and energy use.

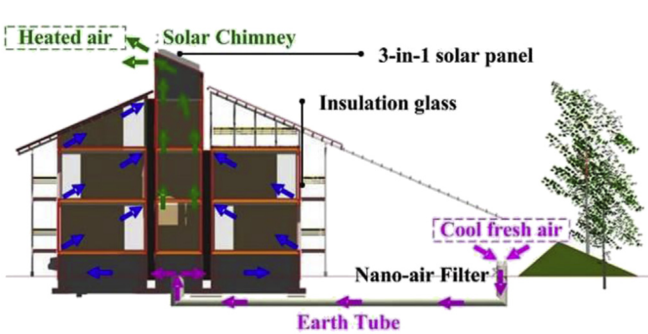


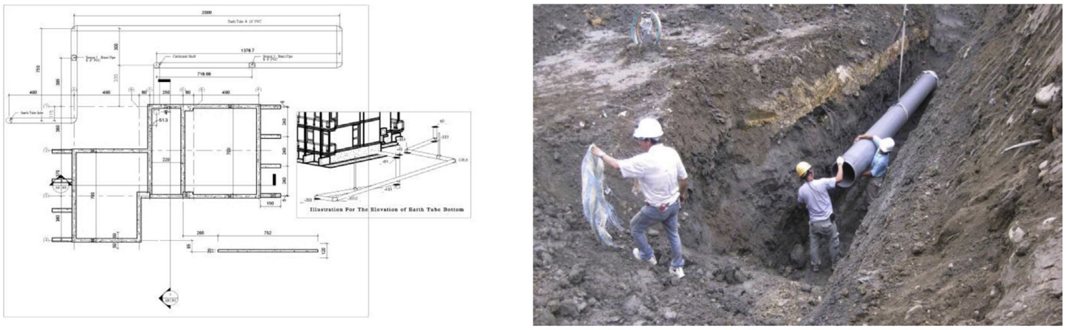
Fig. 5. Air circulation mechanism.

A. Earth tube

An earth tube is a heat exchanger arrangement in which a pipe or tube is buried to facilitate the transfer of geothermal energy with air [29]. In MEGA House, a 40 cm diameter earth tube system was installed beneath the ground to a depth of 4.2 m. The system travels beneath the ground outside of Mega House for about 50 m before passing through two shafts (shown in Fig. 6). This earth tube is mainly comprised of a PVC piping material that impregnated with a nano-coating on the interior surface. A windmill that is installed on the intake end facilitates air convection. This system is designed to utilize the near-constant ground temperature to either extract or reject heat energy to or from the incoming air stream with the ground. Outside ambient air passing through the earth tubes is either heated or cooled before entering MEGA House. In the summer, the earth is cooler than the outside air temperature and the air is thus cooled as it passes through the tubes; the opposite occurs in the winter.

B. Solar chimney (exhaust fans)

Pollution and the desire to use alternative energy sources have led to a new environmental approach to MEGA House design. A simple description of a solar chimney is a vertical shaft that utilizes solar energy to enhance natural stack ventilation through a building. A solar chimney directs warm air inside the chimney causing it to rise out the top and drawing air in from the bottom through a earth tube to ventilate the MEGA House (see Fig. 5). Natural ventilation can be created by providing vents in the upper level of MEGA House to allow warm air to rise by convection and escape to



(a) earth tube direction (b) earth tube buried

Fig. 6. MEGA House earth tube.

the outside. At the same time cooler air can be drawn in through vents located in the lower level.

A solar chimney with exhaust fans enhances the natural ventilation process. The chimney structure must extend higher than the roof level and be constructed on the wall facing the direction of the sun. Furthermore, the openings of vents in the chimney should face away from the direction of the prevailing wind. The added advantage of this design in MEGA House is that the system may improve ventilation rates in the summer and provide a reverse effect during the winter to provide solar heating.

2.3. Situation simulations and experimental layout

Based on the above purposes of the energy-saving facilities in MEGA House, the present experiment designs a series of simulations and measurements to validate the benefits of energy conservation. This experimental design is divided into four stages, as described in the following subsections.

2.3.1. The 1st experimental stage

In order to simulate a normal living environment, MEGA House was naturally ventilated to balance the initial difference between indoor and outdoor temperatures prior to starting the energy-saving equipment in the morning.

A solar chimney and earth tube were incorporated into the first experimental stage. Natural ventilation was created by providing vents in the upper level of MEGA House to allow warm air to rise by convection and escape to the outside. However, in order to enhance the convection effects, the earth tube fan or solar chimney exhaust fans were operated using mechanical energy to reduce the temperature and power consumption throughout the day. Measurements in this experimental stage were conducted over a 23-h period started from 8:00 AM to the following morning 7:00 AM and the temperature were recorded every 20 min. Next, these results are compared with the results that used different equipment sets to gain the best efficiency combination as an opening condition.

- Testing combinations:
  a. Earth tube + Solar chimney: No starting the earth tube fan and solar chimney exhaust fans.
  b. Earth tube (fan) + Solar chimney: Starting the earth tube fan and the solar chimney exhaust fans are closed.
  c. Earth tube + Solar chimney (exhaust fans): Closing the earth tube fan and the solar chimney exhaust fans are operated.
  d. Earth tube (fan) + Solar chimney (exhaust fans): Both earth tube fan and solar chimney exhaust fans are operated.
- The required sensor numbers:

The sensor layouts in the experimental design are shown in Fig. 7. The required sensors in the first stage are as follows - living room: no.13 and no.16, dining room: no.21, master bedroom: no.52 and no.53, bedroom (202): no.62, air vent of earth tube: no.31.

2.3.2. The 2nd experimental stage

Based on the best efficiency combination in the first experimental stage, the second stage notifies the smart control system to initiate the best combination and lower the indoor temperature first via a text message or app before the MEGA House user returns home. The purpose of this experimental stage is to understand clearly the best time to engage the energy-saving combination time prior to returning to MEGA House in order to lower the temperature and conserve power prior to starting air-conditioners. The required sensors in the second stage are the same as those in the first experimental stage (see Fig. 7). The following section describes the process for this experimental stage:

Step 1: Time assumption for returning home

This experiment assumes a normal work schedule and so sets the time of arrival at MEGA Home as 6:00 PM. Therefore, there is no one in MEGA House prior to 6:00 PM and no energy-saving equipment is thus running earlier than this time. In other words, the house is in a natural ventilation condition with a solar chimney and earth tube.

Step 2: Set up the measuring time

In accordance with the above conditions, this experiment proposes to lower indoor temperature first before the resident returns home. For this reason, the experiment sets several moments (the measured time interval is 1 h) prior to the return-home time of 6:00 PM in order to assess the relative benefits of energy conservation. These are: 1 h prior, 2 h prior, 3 h prior, and 4 h prior.

Step 3: Record temperature and power consumption data at each testing time.

This experiment lasts for a 4-day period. The best efficiency combination in the first experimental stage operates at 5:00 PM, 4:00 PM, 3:00 PM, and 2:00 PM respectively on each day, then gains the temperature curves and power consumption in these four

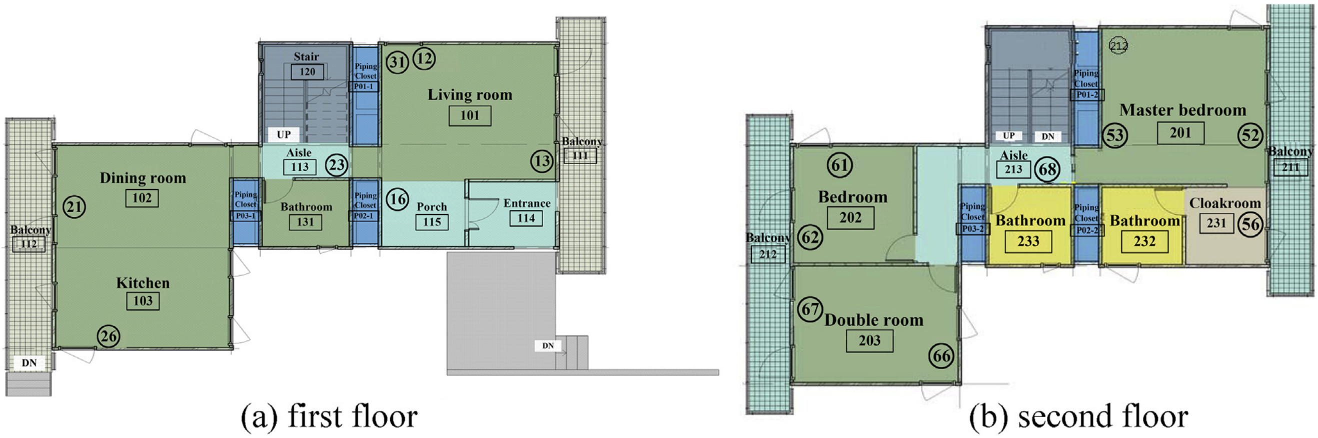


Fig. 7. Sensor layouts.

days.

2.3.3. The 3rd experimental stage

This stage discusses the cooling and heating conditions after the resident returns home to MEGA HOUSE.

A. Cooling test in summer

Continuing the previous situations, the indoor temperature remains uncomfortable at the time the resident returns home. The MEGA House resident chooses whether to use the earth tube compressor or the air-conditioner to lower indoor temperature. Hence, the testing approach is divided into two parts: (1) start the earth tube (fan) and earth tube compressor set and (2) start the indoor air-conditioner. This section then discusses which equipment combination serving two or three spaces conserves more energy and then verifies the relative benefit of choosing to use the earth tube. One measurement in the cooling stage lasts 2 h after 6:00 PM (recorded every 20 min) and the experimental locations include the living room, dining room, and master bedroom. The sensors required in this stage are the same as those used in the first experimental stage (see Fig. 7).

- Testing combinations (see Table. 1 and Table. 2):

B. Heating test in winter

- Experimental group (master bedroom) (see Fig. 7(b)): Served by earth tube and solar chimney.
- Control group (bedroom (202)) (see Fig. 7(b)): Served without earth tube and solar chimney.

Because houses need to be kept warm during winter, the earth tube fan is operated during this season as a heater to provide warmth when a MEGA House resident returns home. However, the solar chimney exhaust fans are not used during this stage because the solar chimney exhaust fans may quickly discharge the warm air and lower temperatures indoors. For this reason, the warming effect of using the earth tube in the master bedroom was observed for the heating test (the master bedroom and bedroom (202) doors are all closed), with one measurement period lasting for a 4-h period after 6:00 PM (recorded every 20 min).

- Testing combinations:
  a. No energy-saving equipment was operated during the winter: To compare the temperature consistency between the master bedroom and bedroom (202).
  b. When the outdoor temperature is less than 20 °C: Assess the warming effects of master bedroom served by earth tube fan.
  c. When the outdoor temperature is less than 10 °C: Assess the warming effects.
- The required sensor numbers (see Fig. 7):

Master bedroom: no. 52 and 53, bedroom (202): no. 62, and air vent of earth tube: no. 31.

2.3.4. The 4th experimental stage

This stage integrates the smart control mechanism (see Fig. 4) into the MEGA House smart control system and operates energy-saving equipment to adjust indoor environmental conditions, including temperature, humidity, and illumination, automatically through the system. The power consumption may be calculated based on full-day measurement data to provide an index to the energy conservation benefits and to the conditions under which the smart control mechanism is used. Therefore, the measurement time in the 4th experimental stage lasted 15 h from 8:00 AM to 11:00 PM and all data were recorded every 20 min.

- Testing combinations:
  a. Operate the energy-saving equipment according to the smart control mechanism
  b. Operate the equipment without using the smart control mechanism: Run the air-conditioner all day.

Table. 1
The testing combinations for two spaces.

Combination no.	Equipment combinations and serving spaces
(1)	Earth tube fan + earth tube compressor (for living room and dining room)
(2)	Indoor air-conditionings (for living room and dining room)

Note: Control the indoor temperature at 26 °C.

Table. 2
The testing combinations for three spaces.

Combination no.	Equipment combinations and serving spaces
(3)	Earth tube fan + earth tube compressor (for living room, dining room, and master bedroom)
(4)	Earth tube fan + earth tube compressor (for living room and dining room) + an indoor air-conditioning (for master bedroom)
(5)	Indoor air-conditionings (for living room, dining room, and master bedroom)

Note: Control the indoor temperature at 26 °C.

- The needed sensor numbers (see Fig. 7):

The sensors required during the 4th stage are as follows: living room: no. 13, dining room: no. 21, master bedroom: no. 52, bedroom (202): no. 62, air vent of earth tube: no. 31.

3. Field measurements and analyses

In order to evaluate the energy and economic performance of MEGA House presented in Subsection 2.3, situation simulations and energy conservation measurement were carried out on the basis of the experimental designs. The design aims to elicit the behavior related to using energy-saving equipment and to identify the optimal usage combination. A testing analysis was thus carried out in this chapter based on field measurements to investigate the benefits of the energy-saving equipment.

3.1. Measured energy consumption at the 1st stage

Table. 3 will show the main temperature difference between master bedroom and bedroom (202) for the earth tube and solar chimney under investigation. The majority of the cold air supplied to the master bedroom came from earth tube and solar chimney, which demonstrated better temperature-control performance than bedroom 202.

The average temperature difference between the master bedroom and bedroom (202) under combination (a) is 0.17 °C (see Table. 3). The master bedroom gained a lower air temperature from the earth tube and the solar chimney, whereas bedroom 202 had a higher temperature because these two pieces of equipment were not available. Combination (a), which used neither mechanical forces nor electricity, achieved a limited temperature-reduction effect. Combination (b), the earth tube fan and solar chimney, was used in the master bedroom and achieved an overall average temperature of 29.44 °C, which was below the temperature of bedroom (202). The difference between the two situations reached as high as 0.54 °C (see Table. 3). This result supports that using a mechanically driven earth tube fan enhances the temperature-reduction effect. By the same token, the temperature-reduction effects in the master bedroom were good for combination (c) and combination (d) (see Table. 3). However, the margin of temperature reduction reached as high as 1.09 °C in combination (d) due to the concurrent use of the earth tube fan and solar chimney exhaust fans to enhance the convection and ventilation effects.

Furthermore, in order to select the optimal combination in the experimental stage, this study calculated the efficiency ratio under each combination according to the average temperature differences and the average power consumptions, as shown in Table. 3. The results show that combination (d) delivered the best performance (efficiency ratio = 3.39) in lowering ambient indoor temperature. Therefore, combination (d) is used in the analysis conducted in the following experimental stage. Based on the smart control mechanism shown in Fig. 4, the operating conditions of combination (d) were defined as:

- When the indoor temperature >15 °C: the solar chimney exhaust fans are turned on;
- When the indoor temperature <15 °C and the indoor temperature >26.5 °C: the earth tube fan is turned on.

3.2. Measured energy consumption at the 2nd stage

The second experimental stage was just carried out in accordance with the combination conditions of the earth tube fan and solar chimney exhaust fans as described in the 1st stage. This testing was set up over four time intervals, with data on temperature reduction and power consumption recorded each hour and then converted into an efficiency ratio (shown in Table. 4). The results indicate that the temperature reduction is more obvious during the first hour of each testing time and reaches the higher efficiency ratio of 4.72 °C/kWh at 5:00 PM. Therefore, we obtained a preliminary conclusion at the second experimental stage: MEGA House residents may engage the earth tube fan and solar chimney exhaust fan together 1 h prior to returning home (at 5:00 PM) to

Table. 3
The relative utilization efficiency of energy-saving combinations.

Testing combinations	Average temperature (average 9 samples) (°C)			Power consumption (Avg.) (kWh)	Efficiency ratio (°C/kWh)
	Experimental group	Control group	Difference (master bedroom -based)		
	Master bedroom (in service)	Bedroom 202 (no service)			
a. Earth tube + Solar chimney	30.15	30.32	−0.17	0	–
b. Earth tube (fan) + Solar chimney	29.44	29.98	−0.54	0.184	2.93
c. Earth tube + Solar chimney (exhaust fans)	31.43	31.89	−0.46	0.138	3.33
d. Earth tube (fan) + Solar chimney (exhaust fans)	29.12	30.21	**−1.09**	**0.322**	**3.39**

Note: 1. Select the 3 similar climatic days per month during summer (Jul.–Sep.) (9 samples).
2. Efficiency ratio (°C/kWh) = Avg. temperature difference (°C)/Avg. power consumption (kWh).

Table. 4
Results for temperature reduction at each time interval.

Testing time	Temperature reduction (°C)				Total temperature reduction	Total power consumption	Efficiency ratio
(18:00-based)	14:00–15:00	15:00–16:00	16:00–17:00	17:00–18:00	(°C)	(kWh)	(°C/kWh)
1 h ago	–	–	–	1.51	**1.51**	**0.322**	**4.72**
2 h ago	–	–	1.27	0.10	1.37	0.64	2.14
3 h ago	–	0.61	0.30	0.12	1.03	0.97	1.06
4 h ago	0.81	0.25	0.23	0.37	1.66	1.29	1.29

Note: This test averaged the results of four days under similar environmental conditions.

Table. 5
Power requirements of different systems to achieve a 1.51 °C reduction in temperature 1 h prior to getting back home.

A Drop of 1.51°C	Earth tube (fan) + solar chimney exhaust (fans)	Three air-conditioners
Working time	1 h	20 min
Power consumption (kWh)	0.322 (1)	1.24 (2)
Power consumption savings (kWh)	**0.918** ((2)–(1))	

Table. 6
The efficiency ratio in cooling test.

Space amounts	Equipment combinations	Temperature reduction (°C)	Avg. Power consumption (kWh)	Efficiency ratio (°C/kWh)
Two spaces	Earth tube fan + earth tube compressor (for living room and dining room)	**1.13**	**0.376**	**3.01**
	Indoor air-conditionings (for living room and dining room)	1.86	1.16	1.60
Three spaces	Earth tube fan + earth tube compressor (for living room, dining room, and master bedroom)	**1.02**	**0.376**	**2.71**
	Earth tube fan + earth tube compressor (for living room and dining room) + an indoor air-conditioner (for master bedroom)	1.37	0.956	1.43
	Indoor air-conditioners (for living room, dining room, and master bedroom)	1.86	1.74	1.07

obtain optimal energy efficiency.

Table. 5 estimates the required working time and power consumption of the three air-conditioners to achieve the drop in temperature by 1.51 °C achieved by the earth tube fan and solar chimney exhaust fans. The result indicates that using the earth tube fan and solar chimney exhaust fan combination 1 h prior to getting back home uses 0.918 kWh less power than using the three air-conditioners in order to lower the temperature by 1.51 °C. This power savings (0.918 kWh) is used in the next section as an estimated value.

3.3. Measured energy consumption at the 3rd stage

3.3.1. Results of cooling test (in summer)

This study was conducted under an assumption of a standard indoor temperature of 28–29 °C. Therefore, average power consumption values (shown in Table. 6) were measured under the following environmental setting modes: (a) the outdoor temperature is between 28 and 29 °C, (b) the initial indoor temperature is 28 °C (if the indoor temperature is higher than 28 °C, it will be reduced to 28 °C first using indoor air-conditioners), and (c) the temperature settings of indoor air-conditioners and earth tube compressor are all 26 °C. For the above reasons, the results show that although the temperature reductions are smaller through the use of the earth tube fan and earth tube compressor combination, the power consumption is relatively lower, which provides this approach with the higher efficiency ratio (3.01 °C/kWh) in the two-spaces case. The three-spaces case shows a similar result in favor of the earth tube fan and earth tube compressor combination.

Table. 6 presents the differences in power consumption between operating the earth tube fan and earth tube compressor combination and operating the indoor air-conditioner. In the two-spaces case, the difference in power consumption is 0.784 kWh. In the three-spaces case, the difference is as much as 1.364 kWh. These results are applied in the next chapter as inputs in the economic analysis.

3.3.2. Results of heating test (in winter)

This test was conducted to compare the conserved electric quantity of using earth tube fan with heater in accordance with the smart control mechanism (see Fig. 4) in winter. Considering residents feel colder indoors in temperatures below 20 °C, this test evaluated the potential use of the earth tube fan as a heater and carried out related analysis of power consumption and efficiency.

A. All energy-saving equipment switched off (natural ventilation: earth tube + solar chimney)

Fig. 8 shows the influence of natural ventilation on MEGA House during winter. The temperature trend measurements were taken in

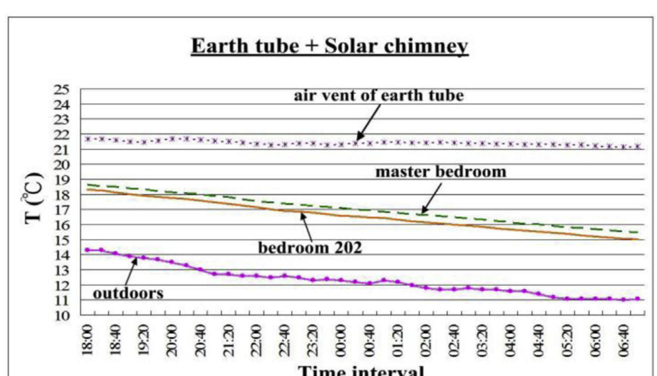


Fig. 8. Average temperature curves under natural ventilation conditions.

the master bedroom, bedroom 202, outdoors, and the air vent of earth tube, with results compared to the each other. One finding is that when the outdoor average temperature was about 12.5 °C on the testing day in winter, the earth tube exchanged the warm air (about 21.5 °C) from below ground into MEGA House, with the solar chimney used to enhance the indoor temperature of the master bedroom. Another finding is that the average temperature of the master bedroom was similar to bedroom 202, which was not served by the earth tube and solar chimney. This finding demonstrates that the effect of the temperature rise is limited in the natural ventilation condition.

B. Outdoor temperature below 20 °C

The simulation time was set from 6:00 PM to 7:00 AM on the testing day and both indoor and outdoor temperatures were observed. Fig. 9 shows a clear temperature trend. When the outdoor temperature dropped from 20 °C to 13 °C, the fresh air drawn in through the earth tube fan maintained the indoor temperature above 20 °C and maintained an average temperature in the master bedroom of 21 °C. On the other hand, the average temperature at bedroom 202, which was not served by the earth tube fan, had temperature than the master bedroom that was lower by about 2 °C. This result supports the good performance of the earth tube in MEGA House of keeping indoor temperatures warm when the outdoor temperature dropped below 20 °C. Therefore, in these relatively cold outdoor conditions, an earth tube (fan) may replace the need for indoor electric heaters in winter.

C. Outdoor temperature below 10 °C:

This test was conducted on a day when the outdoor temperature dropped below 10 °C. Fig. 10 shows that the average temperature difference may be as much as 3–4 °C between the master bedroom and bedroom 202. Although the temperature at the air vent of earth tube dropped to a low of 16.5 °C, it still averaged 7.5 °C higher than the lowest outdoor temperature. This difference indicates an obvious effect of temperature rise in using the earth tube (fan) at lower outdoor temperatures. The difference in temperature between the outdoor air and earth tube air makes the earth tube (fan) a viable alternative to an electric heater in colder weather.

According to the above heating test results, the higher temperature effect of using an earth tube (fan) is similar to using an electric heater (temperature set as 20 °C) when the range of outdoor temperatures ranges between 15.5 °C and 20 °C. Furthermore, Table. 7 compares the difference in power consumption between

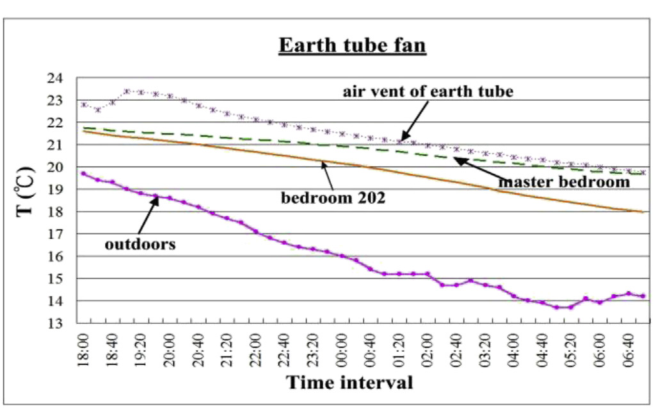


Fig. 9. The warming effect of using an earth tube fan.

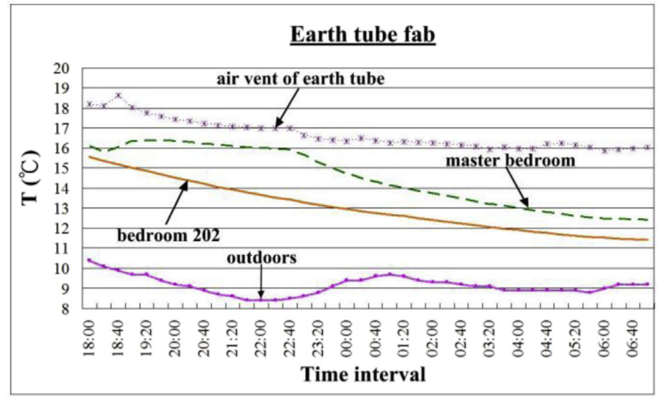


Fig. 10. The utility of using earth tube fan in cold current.

using an earth tube fan and a general electric heater in accordance with the smart control mechanism (shown in Fig. 4) and conducted using the smart control system in three spaces. This demonstrates that the earth tube fan may replace the general electric heater to heat the three indoor spaces in a colder environment during winter. This approach has the potential to save about 2.64 kWh/year in power consumption. A detailed economic analysis follows in the next section.

3.4. *Measured energy consumption at the 4th stage*

The experimental stage assumes MEGA House residents remain in the building for the entire day and turn on each equipment combination as directed by the smart control mechanism (see Fig. 4) in order to validate the start times for using energy-saving equipment and to obtain the power consumption values generated when using and when not using the smart control mechanism. The experimental conditions were set as follows:

a. Operating time: 8:00 AM to 11:00 PM;
b. Outdoor temperature ranges: 28–35 °C; indoor temperature maintained at 26 °C;
c. When the smart control mechanism was not used, indoor air-conditioners were in use all day;
d. The testing place is the living room (one-space condition) and no use is made of the earth tube compressor.

As shown in Table. 8, the main starting equipment combinations in the stated testing environment were combination (e) and combination (h), with a total power consumption of 18.877 kWh/day. Thus, about 0.637 kWh/day may be saved in that hot climate in comparison with using indoor air-conditioners all day.

4. Economic analysis

4.1. *Analytical methodology*

The actual cost of electricity and carbon reduction were estimated on the basis of the results that were measured in Section 3 while the financial cost of CO_2 emissions were calculated based on emissions trading. Therefore, the cost estimates were initially carried out in accordance with their equivalent unit values for electricity and CO_2 emissions in this subsection. For these reasons, the financial cost of CO_2 emissions and of electricity is evaluated in the following subsections. However, the cost of electricity is estimated in accordance with the electrovalence provided by Taiwan Power Company.

Table. 7
The difference of power consumption between an earth tube fan and an electric heater.

Heater equipment (rise in temperature to 20 °C)	Power consumption (kWh)/hr	Difference of power consumption (kWh)/hr
Earth tube fan	0.184	2.636
General electric heater (NP-15ZL)	2.82	

Table. 8
Evaluating MEGA House power consumption (energy–saving equipment).

Tested combinations	Power consumption (kWh/day)	Operating time (%)
Regulated using the smart control mechanism		
a. Natural ventilation	–	–
b. Natural ventilation + Solar chimney (exhaust fans)	–	–
c. Earth tube (fan)	–	–
d. Solar chimney (exhaust fans)	–	–
e. Earth tube (fan) + Solar chimney (exhaust fans)	1.445	31.1
f. Earth tube (fan) + Earth tube compressor	–	–
g. Earth tube (fan) + Earth tube compressor + Solar chimney (exhaust fans)	–	–
h. Air-conditioners	17.432	68.9
Total power consumption	18.877	
Without using the smart control mechanism		
Air-conditioners	19.514	100

Note: All venetian shades were opened during each combination stage.

4.1.1. Cost of CO_2

According to the Emissions Trading Exchange, the European Union Greenhouse Gas Emission Trading Scheme (EU ETS) is the most widely referenced emissions trading scheme worldwide. Therefore, the Council for Economic Planning and Development, R.O.C uses the European Union Allowances (EUAs) value of USD 22/TON to calculate Taiwan's trade volumes in the carbon market. As a result, the value of emissions trading is exchanged based on an equivalent unit value of 0.66 NTD/kg, based on a USD:NTD exchange rate of 1:30.

The emission coefficient for electrical power of 0.636 kg CO_2e/kWh was published by the Bureau of Energy, Ministry of Economic Affairs, R.O.C. in 2008, which generated the value of 0.42 NTD/kWh for CO_2 used in this paper. The formula used is:

$$Value\ of\ CO_2 = (0.66\ NTD/kg)\cdot(0.636\ kg) = 0.42\ NTD/kWh \quad (1)$$

4.1.2. The cost of electricity

MEGA House is a model residential building designed to consume an average of 308 kWh per month per family [2]. Because peak power consumption occurs during the summer, it is reasonable to assume that power consumption may exceed 500 kWh from June to September (summer). The Taiwan Power Company charges 4.51 NTD/kWh during Jun.–Sep. and 3.55 NTD/kWh during Dec.–Mar Table. 9 presents the total cost of electricity during the summer and winter, as estimated from CO_2 emissions and the actual electricity charges from the Taiwan Power Company.

4.2. Results of economic analysis

In this paper, an economic analysis was carried out to evaluate the amount of energy conserved by using energy-saving equipment instead of indoor air-conditioners in MEGA House. The economic efficiency was calculated based on the situation simulations described in Section 2 and the results reported in Section 3. In the following subsections, the economic efficiency will be assessed based on two different time periods: prior to returning home (before 6:00PM) and after returning home (6:00PM and later).

4.2.1. Prior to returning home

According to the measuring and analytical results in Section 3, the indoor temperature was reduced by 1.51 °C by turning on the earth tube fan and the solar chimney exhaust fans at 5:00PM, 1 h prior to MEGA House residents returning home (see Table. 4). The resultant savings in power was about 0.918 kWh (see Table. 5), which is the equivalent to a total savings of 4.93 NTD/kWh in comparison with the situation in which indoor air-conditioners are used to reduce the indoor temperature. Therefore, Table. 10 estimates the economic efficiency of starting energy-saving equipment prior to returning home during the summer on a basis of the conversion forms shown in Table. 9. As shown, CO_2 emissions total 52.55 kg and a total of 407.3 NTD/kWh may be saved prior to residents returning to the MEGA House during the summer.

4.2.2. After returning home

A. Economic efficiency of the cooling test (in summer):

Table. 9
The conversion forms for summer and winter.

	CO_2 emissions			Electric bill (NTD/kWh)	Total cost(NTD/kWh)
	CO_2e/kWh (kg)	Emissions trading valuation (NTD/kg)	Monetary value of CO_2 (NTD/kWh)		
Summer (Jun.–Sep.)	0.64	0.66	0.42 (1)	4.51 (2)	**4.93** (1) + (2)
Winter (Dec.–Mar.)				3.55 (3)	**3.97** (1) + (3)

Table. 10
Result (I) of economic efficiency.

Prior to returning home during the summer	Power saved (kWh)	CO_2 emissions (kg)	CO2e value (NTD/kg)	Cost of electricity (NTD/kWh)	Total cost (NTD/kWh)
Transform value	1.00	0.64	0.42	4.51	4.93
One hour ago	0.918	0.59	0.39	4.14	4.53
One month	27.54	17.52	11.56	124.21	135.77
Summer (Jul.-Sep.)	**82.62**	**52.55**	**34.68**	**372.62**	**407.30**

Table. 11
Result (II) of economic efficiency.

Cooling test in summer (outdoor temperature: 28~29 °C)	Power saved (kWh)	CO_2 emissions (kg)	CO2e cost (NTD/kg)	Cost of electricity (NTD/kWh)	Total cost (NTD/kWh)
Transform value	1.00	0.64	0.42	4.51	4.93
for two spaces					
Per hour	0.784	0.50	0.33	3.54	3.86
Every day (avg.)	2.76	1.76	1.16	12.45	13.61
One month (avg.)	82.84	52.69	34.77	373.62	408.39
Summer (Jul., Aug., Sep.)	**248.53**	**158.06**	**104.32**	**1120.86**	**1225.18**
for three spaces					
Per hour	1.367	0.86	0.57	6.13	6.70
Every day (avg.)	4.79	3.05	2.01	21.60	23.61
One month (avg.)	143.71	91.40	60.32	648.12	708.44
Summer (Jul., Aug., Sep.)	**431.12**	**274.19**	**180.97**	**1944.35**	**2125.32**

Table. 12
Result (III) of economic efficiency.

Heating test in winter (outdoor temperature: 15.5~20 °C)	Power saved (kWh)	CO_2 emissions (kg)	CO2e cost (NTD/kg)	Cost of electricity (NTD/kWh)	Total cost (NTD/kWh)
Transform value	1.00	0.64	0.42	4.51	4.93
for three spaces					
Per hour	2.64	1.68	1.11	9.37	10.48
Every day (avg.)	16.81	10.69	7.06	59.67	66.72
One month (avg.)	504.24	320.70	211.66	1790.05	2001.71
Winter (Jan.-Mar.)	**1512.72**	**962.09**	**634.98**	**5370.16**	**6005.14**

This part discusses the economic efficiency of using an earth tube fan with an earth tube compressor instead of air-conditioners to condition air in two and three spaces (see Table. 11). The results show that if MEGA House occupants take the former approach for two spaces, there will be a decrease of about 158.06 kg in CO_2 emissions and a total cost of 1225.18 NTD/kWh for cooling during the summer. When the same approach is used for three spaces, the savings is even greater: a decrease of about 274.19 kg in CO_2 emissions and a total cost of 2125.32 NTD/kWh for cooling during the summer. From the above results, using the combination of the earth tube fan and the earth tube compressor to condition the air of three spaces in MEGA House is more economically efficient than using air conditioners to achieve the same cooling results.

B. Economic efficiency of the heating test (in winter):

Based on the above-mentioned results, this subsection assesses the economic efficiency of using an earth tube (fan) as an electric heater to condition the air in three spaces of MEGA House during winter. As summarized in Table. 12 , atotal of 6005.14 NTD/kWh is saved on heating expenditures during the winter while 962.09 kg in CO_2 emissions are eliminated.

5. Conclusions

The scope of the present paper is limited to the creative and intelligent open building "MEGA House". We analyzed the power consumption and CO_2 emissions related to the use of the energy-saving facilities that were installed in MEGA House. Because the use of the air-conditioners used more power than the minimum requirements for the building during the summer, a four-stage experiment was set up to simulate, measure, and assess the economic efficiency and the potential for conserving energy. This section summarizes the research procedures used and the results obtained, with conclusions as follows:

1. The energy conservation facilities in MEGA House hold the strong potential to enhance the energy conservation efficiency of "green" buildings.
2. The energy conservation performance achieved by activating an earth tube fan and solar chimney exhaust fans 1 h prior to residents returning home in MEGA House in order to lower the indoor temperature is better than the performance achieved by using air-conditioners.
3. Activating the combination of earth tube fan and earth tube compressor in order to reduce the indoor temperature after returning home achieves good energy conservation performance when the temperature outdoors is in the range of 27–29 °C. Furthermore, MEGA House residents may operate the earth tube fan instead of an electric heater to raise indoor temperatures.
4. Using the smart control mechanism to operate the earth tube fan and solar chimney exhaust fans lowers the indoor temperature in MEGA House about 1–2 °C during the summer. Using

the earth tube fan increases the indoor temperature up to 3–4 °C during the winter.

5. In terms of economic efficiency, MEGA House regularly saves about 8537.76 NTD/year in electricity expenditures and decreases CO_2 emissions by around 1288.83 kg/year (sums given in Tables. 8–10).

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