Embodied CO$_2$ Evaluation of a Zero Life-Cycle CO$_2$ Home:
A Case Study of an Actual Industrialized Home

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Abstract
Following the experimental homes that used the concept of zero life-cycle-CO$_2$ (LCCO$_2$) that were built in 2008 and 2009, the first zero-LCCO$_2$ home was introduced in the market in 2010. The idea of a zero-LCCO$_2$ home is to reduce the annual energy consumption and increase solar energy use so that photovoltaic (PV) energy generation substantially exceeds the total energy consumption of the home. The remainder of the annual energy balance can be accumulated every year to compensate for the energy required during the manufacturing and construction periods. The annual CO$_2$ absorption by PV generation exceeds the annual CO$_2$ emissions owing to energy use. In other words, the LCCO$_2$ may approach zero over time. In this study, the annual energy use and CO$_2$ balance of the house were carefully simulated. The embodied CO$_2$ of the house was also evaluated using an input–output analysis and accumulation method. The results suggest that the material added for better energy efficiency and CO$_2$ emissions generated during the manufacturing and construction periods have a positive effect on reducing the LCCO$_2$ of homes.

Keywords: Life cycle CO$_2$; Embodied CO$_2$; Input and output table; Zero energy home

1. Introduction
Japan's total greenhouse gas emissions in FY 2013 increased by 1.2% compared with those in FY 2012. This was mainly because of an increase in CO$_2$ emissions from power generation because most of the nuclear power plants are currently not in operation. Although Japan has reached the Kyoto Protocol target of −6% using the Kyoto mechanisms and forest carbon sink measures, emissions may increase from now on. Energy-origin CO$_2$ emissions from the residential sector have increased by 53.4% compared with the base year, whereas emissions from the industrial sector have decreased by 14.7%. CO$_2$ emissions from the residential sector may increase further because people's demand for a better living standard is not yet completely satisfied.

According to the Energy Performance of Buildings Directive in the EU, member states are required to actively promote buildings for which both CO$_2$ emissions and primary energy consumption are low or equal to zero. In June 2010, the Ministry of Land, Infrastructure, Transport and Tourism of Japan also implemented the Basic Act on Energy Policy to enable typical homes built in 2020 to be net zero energy. The Japanese government now has a subsidy program to support the building of zero-energy houses. The definitions of zero energy or zero emissions are not necessarily unified among nations; nevertheless, a zero-energy building is typically defined as one that consumes less energy than it produces through natural resources, such as solar power.

Commercial zero-energy homes have been built since 1997. The Institute for Building Environment and Energy Conservation (IBEC) has certified those homes as the first commercial "zero-energy homes" in Japan. The definition of "zero-energy" at the time was the same as the one stated above, i.e., a house that consumes an amount of energy that is equal to or less than the energy it produces annually from a solar system. According to our survey, the energy balances of such houses built in the middle area of Japan were actually zero. They were also carbon neutral.

Regardless of how effective a zero annual-energy-balance home is in reducing its environmental impact, it would make no sense if the energy required to actually build the home exceeded the energy saved. Some research studies have been performed on embodied energy, embodied CO$_2$, or life-cycle analysis of houses. Regarding the environmental impact, not only is the annual energy balance during the living period important but also the energy and resources consumed during the manufacturing and construction...
periods. In other words, the embodied CO$_2$ must also be carefully considered for a zero life-cycle-CO$_2$ (LCCO$_2$) home. The purpose of this paper is to evaluate the effects of the embodied CO$_2$ in a home targeting zero LCCO$_2$ in Japan.

The embodied energy and CO$_2$ associated with buildings, including residential houses, in Japan have been analyzed in several papers$^{2,13}$. The embodied greenhouse gases in buildings have also been studied internationally, and a number of case studies are available$^{16}$.

An experimental home that targeted zero LCCO$_2$ was first constructed in February 2008 in Asahikawa City, one of the coldest cities in Japan$^{17}$. An experimental home was also built in 2009 in Kameyama City, whose weather is rather warm and humid. Based on the experimental results for these two cities, we introduced the first commercial zero-LCCO$_2$ homes into the market in 2010.

The idea of a zero-LCCO$_2$ home is to further reduce annual consumption so that its photovoltaic (PV) generation substantially exceeds its consumption. The remainder of the annual energy balance can be accumulated to compensate for the energy or CO$_2$ required during manufacturing and construction. In other words, the LCCO$_2$ may reach zero over time.

2. Specification of the Home

2.1 Insulation and Planning

The fundamental insulation specification of a zero-LCCO$_2$ home is augmented in every part of the home. 100-mm-thick glass wool is added to the standard wooden panels, which already contain 75-mm-thick glass wool. The ceiling is insulated with 250-mm-thick glass wool. The foundation and basement floor are insulated with 100-mm-thick styrene foam boards. The underfloor area is also made airtight. The windows are made of plastic sashes with double-glazed, low-emissivity glass containing argon gas between the glass panes. The central ventilation system includes a heat recovery unit with a 70% recovery performance. The heat loss coefficient of the home per unit floor area is calculated as 1.05 W/(m$^2$K), although the highest performance indicated in the Quality Assurance Law of the Performance Indication System is 2.7 W/(m$^2$K). Table 1. shows the specifications and performance of each part.

A house designed by one of the industrialized housing companies in Japan, shown in Fig.1., was actually built in Tokyo. Although the highly insulated home may save heating energy, it may not save cooling energy. Because open planning for wind passage or heat exhaust is very important for minimizing the cooling load, the opening ratio, defined as the ratio of the total window area to the total floor area, is 27.4%, which is 3.8% larger than that of the average home provided by the company. It is also important to enhance the natural ventilation. A floor-level window placed on the north side of the house and a skylight in the roof can be opened automatically by means of a thermostat so that the overheated air in the house can be exhausted by the stack effect. Those windows are connected to a Home Energy Management System (HEMS) so that the windows can be controlled effectively using the outdoor temperature data and air conditioning data as feedback. The cooling effect of wind is usually difficult to simulate because the behavior of occupants related to the opening and closing of the widows is not automated. However, the natural cooling effect of this home can be estimated precisely using the simulation model because the HEMS controls the windows and air conditioners.

![Fig.1. Floor Plan of the Zero-LCCO$_2$ Home](image)

### Table 1. Specifications and Performance of Each Part

| Specification (conventional) | Specification (zero-LCCO$_2$ model) |
|-----------------------------|-------------------------------------|
| Ceiling                     | RW 40 kg/m$^2$ 200 mm              |
|                             | GW 24 kg/m$^2$ 250 mm              |
| Wall                        | GW 16 kg/m$^2$ 75 mm               |
| Basement (Floor)            | GW 16 kg/m$^2$ 75 mm               |
| Window                      | Plastic sash, low-e double glazed   |
|                             | Plastic sash, low-e double         |
|                             | glazed window with Ar gas         |
| Ventilation                 | HR central system (HR coefficient 70%) |
|                             | HR central system (HR coefficient 70%) |

GW: Fine fiber glass wool; PSF: Polystyrene foam; RW: Rock wool; HR: Heat recovery.

2.2 Equipment

The heating and cooling are provided by an air-to-water heat pump system and panel radiators. Table 2. shows the performance of the heating/cooling unit. Heated or cooled water is delivered from the heat pump unit to the radiators through polyethylene pipes coated with an aluminum layer. Panels installed in the living room are controlled by thermostats. The panel radiators, usually used only for heating, can also be used for cooling in summer. The panel radiators are combined with drain pans so that the condensed water

| Table 2. Performance of the Heating/Cooling Unit |
|-----------------------------------------------|
| Rated heating performance                    | 11.5 kW |
| Rated heating consumption                     | 2.95 kW |
| Rated heating COP                            | 3.9 |
| Rated cooling performance                     | 7.0 kW |
| Rated cooling consumption                     | 2.8 kW |
| Rated cooling COP                            | 2.5 |

*1 Outdoor 7°C, heating water 40°C.  
*2 Outdoor 35°C, cooling water 7°C.
created on their surfaces during cooling can be drained out of the home.

Hot water is supplied by a CO$_2$ heat pump system. The system uses inexpensive nighttime electricity to store hot water in a tank. The tank, with a capacity of 460 l, stores hot water at temperatures up to 90°C. The annual water heating efficiency defined in the Japanese Industrial Standards (JIS) is 3.0.

A conventional induction cooker is used for cooking, whereas the exhaust air can be purified and returned to the room, resulting in a ventilation heat load reduction. Light emitting diode (LED) devices are used for the primary lighting equipment in the home. The light emitting performance of an LED is up to seven times higher than that of a conventional light bulb and two times higher than that of a conventional fluorescent lamp. Another advantage is that LEDs have high durability.

2.3 Cascade Solar System

The southern roof of the home is fully covered by the modules of what we call the "cascade solar" PV system. Mono-crystalline PV modules are designed to cover the entire roof area. The generating capacity of the PV system is 9.5 kW. The generated electricity can be converted to alternating current for general use in the home. Because the system is connected to the grid, surplus electricity can be sold to the power company. On rainy days or at nighttime, when more electricity is required than is generated, the difference can be supplied by the power company.

The cascade solar PV modules are fixed 53 mm above the roof boards so that air can flow under them. Because the temperature of the PV modules can become high even in winter, the warmed air under the modules can be collected by a fan and used as a heating source. Each module at the top of the roof is made of clear glass and does not contain any PV cells, so that the air temperature can become sufficiently high below them. Ducts under the top glass modules are connected to the roof, and the warm air is forced by a fan to the underfloor area of the house for floor heating. The underfloor area is insulated at the continuous footing so that warmth can be retained for a long time by exploiting the heat capacity of the basement. The simulated results of the hourly generation and heat collection in typical weather conditions are shown in Fig.3. The simulation was conducted using an originally developed simulation tool\textsuperscript{15}. This tool was developed with a thermal network model, which can simulate the collected heat hourly throughout the season. By collecting heat, the system realizes a 3% improvement in PV generation efficiency because the module temperature may become lower compared with normal non-heat-collecting PV modules. The Center for Better Living, whose main services are building permits and inspection services, has certified the system as the first cascade solar system according to the Quality Housing Components Certification System\textsuperscript{16}.

3. Annual Energy Balance Simulation

The energy consumption for heating, cooling, hot water supply, cooking, lighting, and general electric appliances were simulated using the following methods.

The energy supplied by PV generation and the heat collected by the Cascade Solar system were also simulated according to the climate conditions at the construction site in Tokyo.
child's room, and 23:00–7:00 for the bedroom. In summer, the room temperature and humidity were controlled at 26°C and 50% whenever an occupant remained in the room. The assumed cooling hours were the same as for heating. These assumptions were rather strict compared with those commonly used in Japan. Air exchange by the stack effect was also assumed when the indoor temperature was above 26°C and the outdoor temperature was below 24°C. This assumption was valid because HEMS-controlled windows were installed, as mentioned in Section 2.1. The monthly energy (electricity) consumption was obtained by the simulated heat load and seasonal COPs of the heat pump hot/cold water system.

3.2 Hot Water
The heat load of the hot water supply was based on reference, which contained regional annual energy consumption data. In Japan, the heat load of the hot water supply is rather large compared with the room heating load. The annual heat load data were divided into monthly data based on the monthly city water temperatures, which were provided by the metropolitan waterworks bureau. The monthly COPs of the heat pump based on the outdoor temperature were provided by the manufacturer. Therefore, the monthly energy (electricity) consumption was obtained from the monthly load data and monthly COP of the system.

3.3 Cooking
The cooking load was also obtained from reference. Because the annual data were consumption data rather than load data, the cooking load was first calculated by assuming conventional cooking device performance. The annual load was then simply divided equally to determine the monthly load. The monthly energy (electricity) consumption was obtained from the data and efficiency of the induction cooking heater.

3.4 Lighting and General Electrical Appliances
The electrical loads for lighting and general appliances were also obtained from the database of reference. Because this database does not distinguish lighting from general appliances, the ratio of the electricity load for lighting was assumed, based on reference, to be 21%. The electricity savings from the use of LEDs for lighting could be calculated from this ratio and from the efficiencies of a conventional bulb and an LED.

3.5 PV Generation and Heat Collection by the Cascade Solar System
The amount of PV generation could be calculated by the parametric method. The parameters affecting the generation are module efficiency, converter efficiency, solar irradiation, temperature, and dust or snow accumulation. The simulated results agreed well with the actual data. The heat collected by the cascade solar system could be simulated in detail by our originally developed simulation software.

Fig.4. shows the PV generation and heat collection of the cascade solar system. Although solar irradiation declines during the winter period, the system provides even more heat by collecting unused solar energy.

3.6 Annual CO₂ Balance
Fig.5. shows the annual CO₂ balance depending on the specifications. Energy (electricity) consumptions calculated by the previously mentioned methods are transformed to CO₂ values. The CO₂ intensity of the electricity used for the calculation is 0.476 kg-CO₂/kWh, which is the value reported by the Foundation of Electricity Power Companies of Japan.

Fig.4. Monthly Electricity Generation and Heat Collection

Fig.5. Annual CO₂ Balance Depending on Specifications

4. Embodied CO₂ Analysis
Regardless of how high the energy performance of a house is, the overall impact may not be positive if the embodied CO₂ of the housing materials and the CO₂ released during manufacturing and construction are high. The embodied CO₂ emission intensities of materials are obtained from the latest Japanese input–output table.

Fig.6. shows the weights of the classified components used in building the house. The weight of a house built using conventional specifications is also shown. The zero-LCCO₂ home weighs 106.3 tons, whereas the conventional home weighs 101.6 tons. The additional parts include reinforced insulation, solar shading devices, the cascade solar system, heating/cooling panels, and LED lighting devices. The total weight difference between the homes is 4.7
tons or 4.5%. The weight of the house excluding the foundation is 54.7 tons or 52.4% of the total.

Fig.7. shows the embodied CO₂ evaluated using the specifications of the components. Although the weight of the foundation exceeds 50% of the total, its embodied CO₂ is rather small. The embodied CO₂ difference caused by using additional materials is 11.7 tons or 14%.

Table 4. shows the detailed weights and embodied CO₂ of the materials used in the house. Every component of the house, including equipment, was reclassified into its base material according to the I–O database. Interestingly, the embodied CO₂ of crushed stone, sand, and cement, the main components of the foundation, is not necessarily large, even though the weight of the foundation itself is almost half the total weight.

The energy consumption during the manufacturing and construction periods is also considered: (1) electricity and light oil consumed at the factory; (2) light oil consumption of the trucks that transport materials to the factory and products to the construction site; (3) electricity used at the construction site; (4) light oil consumption by the construction machinery; (5) light oil consumption during the transportation of construction machinery; (6) light oil consumption during the transportation of by products from the site; and (7) energy used during the commutes of the workers. The resulting energy consumption during the manufacturing and construction periods is shown in Fig.8. CO₂ emissions related to transportation account for 56% of the manufacturing and construction emissions. This implies that the efficiency of transportation is as important as the efficiency of the manufacturing process at the gate factory. By contrast, the amount of CO₂ emissions during manufacturing and construction is 4.7%, which is rather small compared to the material-related CO₂.

Fig.9. shows the LCCO₂ transition during the lifetimes of the homes studied. The LCCO₂ of a conventional home increases every year due to the daily energy consumption for living. By contrast, the LCCO₂ of a zero-LCCO₂ home decreases every year because the annual CO₂ balance of the home is less than zero, as shown in Fig.5. The CO₂ emissions related to maintenance are also added to the yearly CO₂ emission value\(^{26}\). According to the calculation, additional CO₂ emissions for the zero-LCCO₂ home during manufacturing and construction can be recovered within two years, as shown in the figure.

In general, the ratio of CO₂ emissions during manufacturing and construction is considered to be rather small. For example, if the lifetime of a conventional home is assumed to be 50 years, the ratio of CO₂ emissions during manufacturing and construction compared to the total is only 16%. However, the ratio of CO₂ emissions during the manufacturing and construction of a zero-LCCO₂ home may become dominating. This result implies that as the energy performance of a home increases, the impact of the embodied CO₂ on the LCCO₂ also increases. It also implies that increasing the energy performance of a

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Additional equipment or materials for energy performance improvements are generally effective for reducing the LCCO$_2$.

5. Discussion

The LCCO$_2$ level may change depending on the climate conditions, living culture, energy performance of the house, CO$_2$ intensity of the electricity, and embodied CO$_2$ emission intensities of the materials. It is clear that reducing the energy load by increasing the energy performance of a home has a high impact on the LCCO$_2$. The amount of solar energy use is also critical for achieving zero LCCO$_2$. Although the LCCO$_2$ reduction potential of PV generation may become even higher when the CO$_2$ intensity of electricity is high, the embodied CO$_2$ emission intensities of major materials may also increase due to the electricity consumed in their manufacture.

6. Conclusion

The performance of the first commercial zero-LCCO$_2$ home in Japan was carefully analyzed. Improving the energy performance of the home and increasing the use of renewable energy such as solar are the keys to achieving zero LCCO$_2$. The ratio of embodied CO$_2$ within the LCCO$_2$ for a zero-LCCO$_2$ home becomes quite high when compared with that of a conventional home. Not only are the operational energy savings during the living period important but the embodied CO$_2$ savings also become quite important in reducing the total CO$_2$ emissions.

Acknowledgments

The author acknowledges Mr. Takashi Kawakami for his dedication to building the heat collection simulation software of the cascade solar system and Ms. Tomoko Nagasaku for her untiring efforts in gathering the material information of the house.

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