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ORIGINAL RESEARCH

Application of renewable energy sources and new building technologies for the Philippine single family detached house

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Abstract The Philippine residential sector consumes a large percentage of the country's generated electricity, and the price of electricity there is one of the highest in Asia. With a government program in renewable energy utilization and energy efficiency, the development of energy efficient houses is important. This paper presents a numerical investigation on how to minimize the house's energy consumption, and the results show that a house's electricity consumption can be supported by the installation of solar photovoltaic panels on its rooftop. A solar thermal collector with an auxiliary biomass water heater could support the hot water requirement of the house. The desiccant dehumidification system combined with evaporative and ground cooling systems can keep the house's indoor temperature below 27 °C with a humidity ratio of less than 11 g/kg year-round. Energy conservation measures such as additional insulation of a concrete house, unplugging of unused electrical appliances and application of light-emitting diode lighting are important to reduce electric energy consumption. The application of new building technologies is having a positive impact on a building's energy consumption and indoor environment conditions. The results of this study are important for the Philippine program in alternative energy utilization and energy efficiency.

Keywords Tropical climate · Detached house · Renewable energy · Building envelope · Energy conservation

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List of symbols

A	Solar collector area (m^2)
C_P	Specific heat (kJ/kg K)
COP	Coefficient of performance
D	Day
E	Electric energy (kWh)
$\dot{E}$	Electric power (kW)
EER	Energy efficiency ratio
$\dot{Q}$	Thermal power (kW)
Q	Thermal energy (kWh)
h	Moist air enthalpy (kJ/kg)
I_R	Solar irradiance (kW/m^2)
$\dot{m}$	Mass flow
t	Time (s)
T	Temperature (°C)
LHV	Low heating value (kJ/kg)
STF	Solar thermal fraction (–)
SEF	Solar electric fraction (–)
FIT	Feed-in tariff
DHW	Domestic hot water
EA	Exit air
SA	Supply air
BA	Back-up heater
EC	Evaporative cooler
AC	Air cooler
PV	Photovoltaic

Symbols

η	Efficiency
₱	Philippine Peso (US$1 ≈ ₱45 at 2013)

Subscripts

1, 2…	HVAC system notation
a, b…	Thermal system notation
APP	Appliances

Aux	Auxiliary thermal/electric energy
CE	Cooling effect
CL	Cooling load
EC	Electric consumption
F	Fuel
GL	Grid line electricity
HC	Heating coil
HL	Heating load
HVAC	Heating, ventilating and air-conditioning system
HW	Hot water
I	Inverter
PV	Photovoltaic
PP	Photovoltaic panel
SA	Supply air
SC	Solar collector
SE	Solar thermal energy, sensible energy
TE	Thermal energy
W	Water

Introduction

In residential buildings, energy conservation through the application of high-performance envelopes [1, 2], ventilation [3, 4], energy efficient lighting [5] and appliances [6] is becoming common in developed countries such as Japan [7, 8]. In some residential buildings, installation of non-conventional energy utilization devices such as solar thermal collector [9, 10], photovoltaic panels [11] and even wind turbines [12] has been done. In other countries such as in Germany, it was demonstrated that the utilization of different renewable energy sources along with the application of new building technologies can make even a whole town energy independent [13]. The Solar Decathlon contest [14] is aimed at developing a house which can itself generate its own energy requirement, by applying the different studies of an energy efficient home (EEH), energy plus home (EPH), zero emission house (ZEH) and others.

Philippines is situated in the Southeast Asian region. The country is bounded on the eastern side by the Pacific Ocean, the western side by the Western Philippine Sea, the northern side by the Bashi Channel and the southern side by the Celebes Sea. The country consists of more than 7100 islands with the two larger ones being Luzon in the northern part and Mindanao in the southern part of the country. The country has a land area of 300,000 km^2, and due to the geographical situation of the country, most of the population lives on large islands and is concentrated in areas with rapid economic development. Figure 1 shows the geographical and climatic map of the Southeast Asian (SEA) region, illustrating the location and climatic conditions of the Philippines. The weather and climatic conditions are affected mainly by the surrounding bodies of water, as it is an island nation. The country has a tropical wet climate with hot and humid outdoor air for the whole year. Figure 2 shows the climatic conditions of the Philippines. It shows a high yearly solar fluctuation due to the effect of cloudy sky, particularly during the rainy season (Fig. 2a). The outdoor temperature of the country is hot and humid, typical of the tropical climate (Fig. 2b, c). The outdoor humidity ratio is high which results in the need for ventilation and air-conditioning (natural and artificial) to maintain the indoor

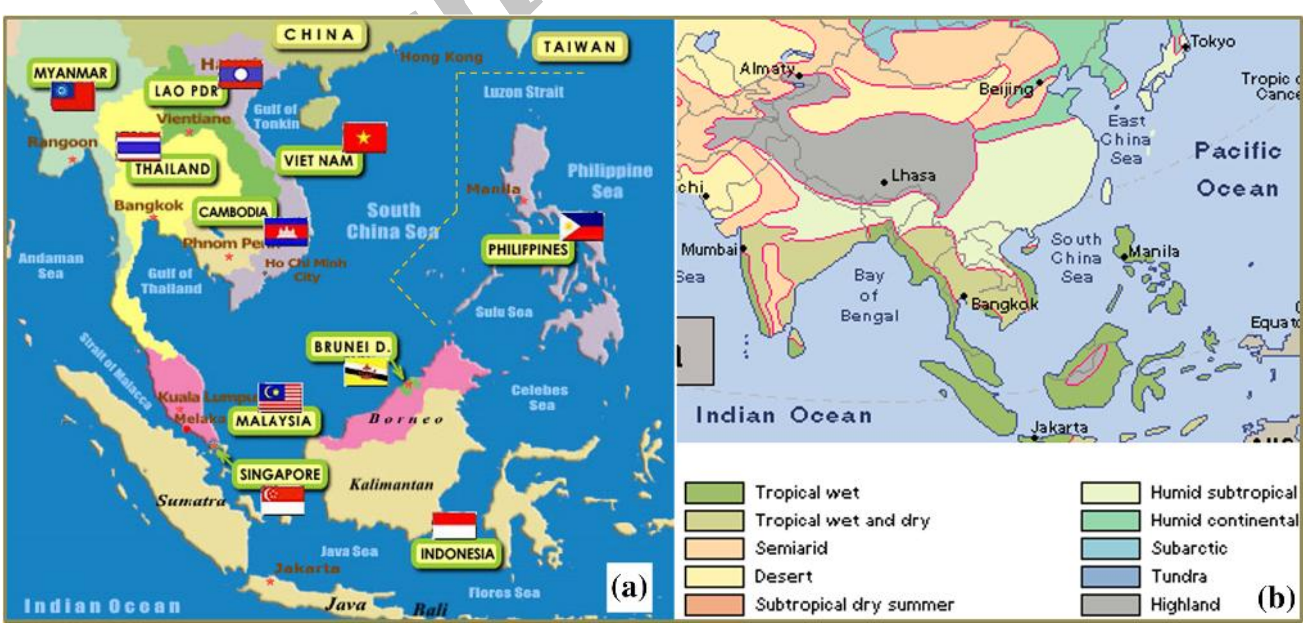


Fig. 1 Association of South East Asian Nations (ASEAN) physical information: **a** Geographical map [15]; **b** climatic map [16]

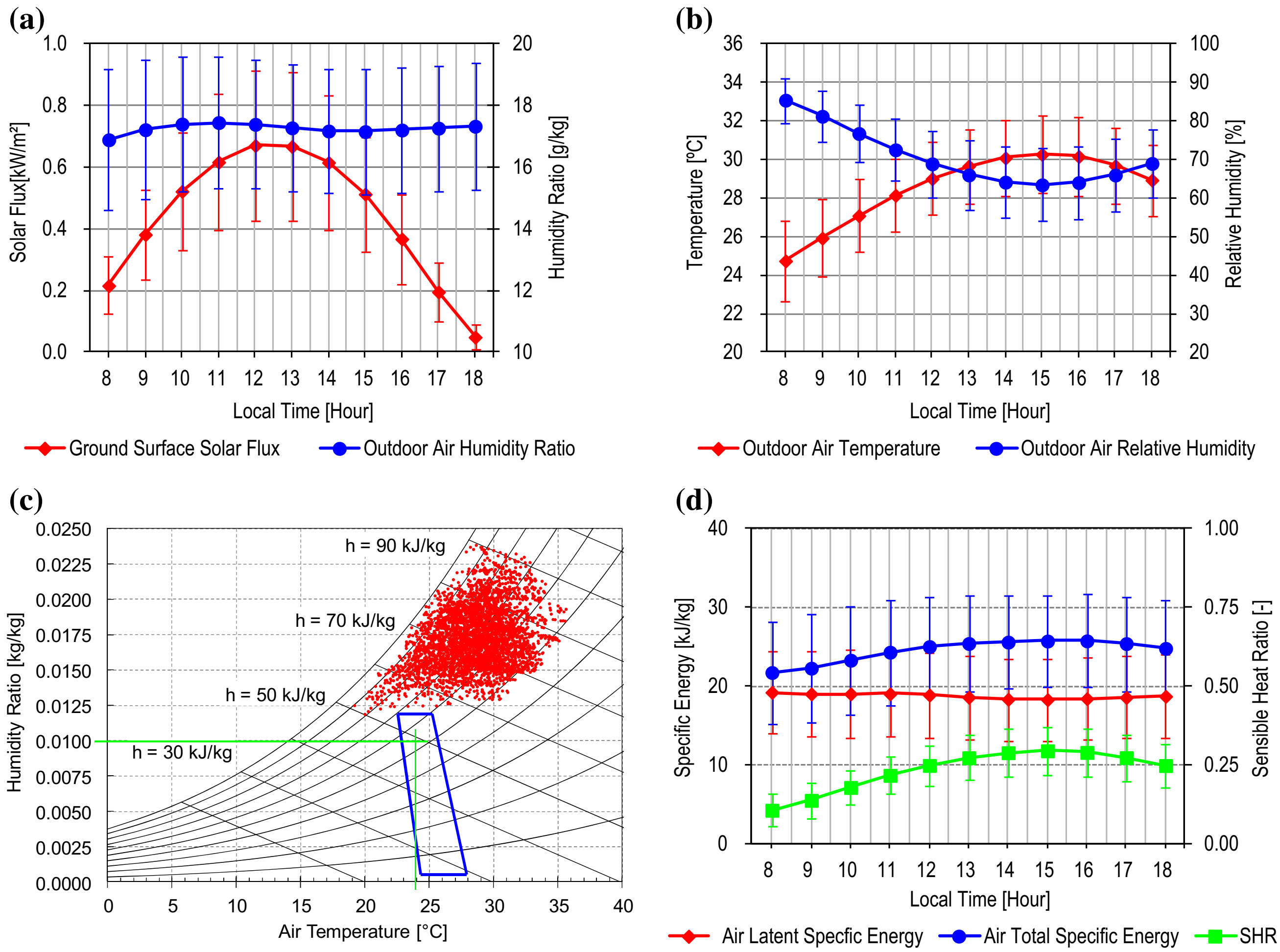


Fig. 2 Philippine climatic conditions: **a** available solar flux; **b** air temperature and relative humidity; **c** outdoor air conditions, and; **d** air energy content at 24 °C and 10 g/kg

thermal condition (Fig. 2b, c). In a conventional air-conditioning system, the air is dehumidified through the condensation process which means that air processed by the air-conditioning system becomes cool and dehumidified. It shows that the air-conditioning process is mainly used to reduce the air moisture content as sensible heat ratio (SHR) is less than 0.4. With the climatic conditions and the demands of the air-conditioning system, maintaining a comfortable indoor environment is an energy intensive operation as is normal in a tropical climate.

As the Philippines is a tropical climate, due to its physical shape, topography and location, there are different seasons in different parts of the country. Figure 3a shows the different wind direction in the Philippines. It shows that from July to September, the Southwest monsoon prevails. The Northeast trades with cool wind from Siberia due to the winter season there are from November to February and caused cool breeze in the Philippines during these months particularly during night time. The four different rainfall patterns of the country show that from July to October, the rainy season occurs in the western section of the country due to the Southwest monsoon. The eastern part of the country has heavy rain affected by the Northeast trades from November to January. The central part of the Philippines is in its dry season from February to April, while most of the southern Philippines (Mindanao Island) have almost constant rainfall for the full year except during the month of April. Figure 3b shows the density and population distribution of the Philippines. It shows that the National Capital Region (NCR) or the central location of the country's political and business world has the highest population density, as expected. It is followed by the central Philippines with the second highest concentration of businesses. It shows that northern, eastern, western and southern Philippines have a low population density due to less economic development in these areas. As presented, the high population density particularly in the country's capital is affected by the Southwest monsoon.

As the Philippines is situated in the typhoon belt region of the Asian Pacific and located in the Pacific ring of fire,

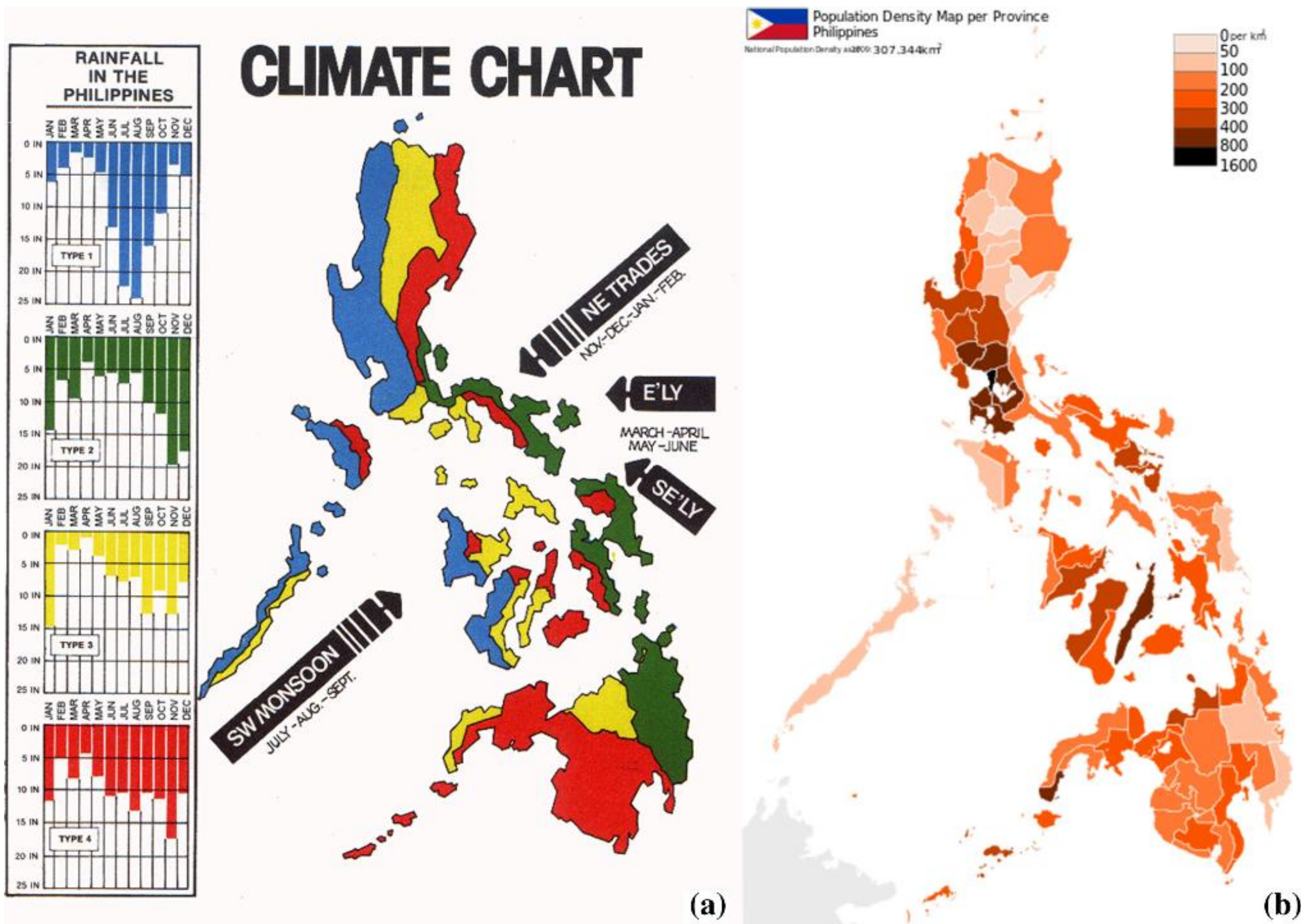


Fig. 3 Philippine physical information: **a** climatic map [17], and **b** population density [18]

the country is always experiencing weak to sometimes strong earthquakes. Hence, in most cases middle to upper class Philippine houses are designed taking these natural phenomena into consideration [19, 20]. Due to the Philippines being one of the rapidly developing economies of Southeast Asia, coupled with its high population growth, and along with government reform, economic expansion is increasing. With the expanding economy and population, energy consumption is also increasing, which results in shortages that often causing a rotating black-out, particularly during summer seasons. As the country has limited and not fully utilized local energy resources, imported carbon-based energy sources augment the country's energy requirement. With the new government policies in alternative energy utilization and energy efficiency, development and application of new technologies to fit the tropical climate have generated interest. Also, as the economy and population are expanding more every year, the demand for new residential buildings is high. Demand is further increased as migration from rural areas to urban areas increases the demand for urban employment. Figure 4 shows the trend of Philippine building construction in

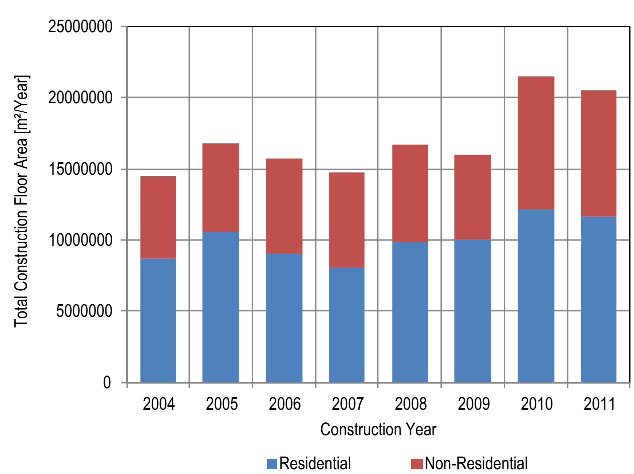


Fig. 4 Philippine building construction in total square meter

which the residential sector is the largest in terms of floor area construction (see Fig. 5) [21].

Philippine residential houses utilize different types of architectural design, following at the same time both Asian and Western building construction. Hence,

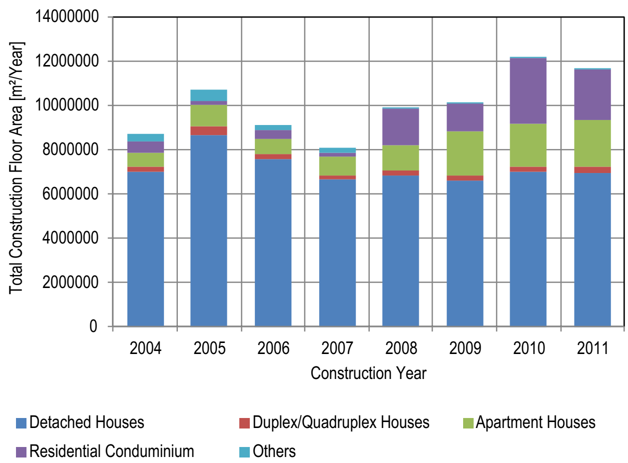


Fig. 5 Philippine different residential construction type in square meter

conditions in this tropical climate are in most cases overlooked during the building design and selection of materials. Figure 6 shows the different typical residential units and houses in the Philippines. So, the Philippine residential sector consumes a sizable amount of conventional energy, and this is expected to increase with urbanization, increasing population and the improving economy. Hence, it is important to develop and utilize alternative energy sources to support the residential sector's energy requirements. It is particularly important for every individual house and unit to generate its own energy requirements since construction of this type of houses is increasing. Most of the urban and large houses are built using typical construction materials and methods which are based on concrete, single glazing windows and corrugated steel roofing. Development and application of a high thermal performance building envelope are important to minimize thermal losses so as to reduce the air-conditioning energy consumption for the houses. Hence, development of a high thermal performance building envelope is important for the Philippine tropical houses. Figure 7 shows the sample typical building construction materials and methods in the Philippine single family detached houses. In addition, energy conservation measures (ECM) by the houses' occupants are also important in the minimization of the houses' energy consumption. In the Philippines, most of the occupants are not fully aware of conservation measures as long as the comfort and cost of the house maintenance can be financially met. However, with the new government tax for residential houses with over 650 kWh electricity consumption per month, it is important for houses to minimize electricity consumption [31]. At the same time, this could contribute to the minimization of the rotating brownouts which occur during the summer season.

There is very little research in residential building, indoor environment or energy consumption in the developing countries of Southeast Asia. For example, in the Philippines, most of the studies are based on a national survey conducted by government agencies [32] and a few universities [33–35]. Comprehensive and detailed studies which are very important to understand the situation of the country's residential building sector are not fully considered. Singapore is a Southeast Asian country which has done serious studies in residential buildings. However, it is difficult to compare the situation of residential buildings in Singapore to the Philippine situation since most of the residential buildings in Singapore are high-rise buildings. In the Philippines, residential constructions are mostly single family detached houses. However, some results from the study in Singapore can be given reference for the Philippine situation which shows that when using a split air-conditioning system in the room in which air is just recirculating, the indoor air quality is low [36]. Therefore, the addition of an exhaust fan is suggested to increase indoor air quality through increased air infiltration. This situation is almost always related to air-conditioned residential houses in the Philippines where most of the upper middle to upper class houses use the split-type and window-type air-conditioning systems. The study of Wong and Huang [37] shows that air-conditioned bedrooms have a higher concentration of CO_2 than the naturally ventilated bedrooms. Furthermore, their study shows that the naturally ventilated bedrooms have higher relative humidity and temperature than air-conditioned rooms. Hence, the result is important to be considered in Philippine air-conditioned and naturally ventilated houses, as most Philippine houses are not aware of the houses' indoor environment and air quality.

In Malaysia, it is shown that the energy consumption for refrigeration is the largest contributor of household energy consumption, closely followed by air-conditioning. Furthermore, it shows that the result of a high energy consumption for the air-conditioning system is due to the low set point temperature and long operating hours [38]. This electricity consumption pattern is similar to the results of a Philippine survey which shows that food preparation is the largest consumer of electricity, and most particularly for refrigeration [32]. In the case of tropical Singapore residential buildings, Wong and Li [39] show that in high-rise residential buildings, location, orientation and envelope play a part in the energy consumption and indoor environment of the buildings. This study is important to Philippine residential houses as most of the houses follow almost the same building envelopes such as concrete walls and single glazing windows. Hence, this paper shows the situation of the Philippine

Fig. 6 Philippine different single family detached houses: **a** photo credit from Ref. [22] and **b** photo credit from Ref. [23] single family mansion; **c** photo credit from Ref. [24] and **d** photo credit from Ref. [25] single family and double storey house; **e** photo credit from Ref. [26] and **f** photo credit from Ref. [27] single family and single storey house and; **g** photo credit from Ref. [28] and **h** photo credit from Ref. [29] single family and double or single storey typical urban and rural house at lower level

single family detached house, the utilization of alternative energy sources to support its energy requirement, the application of new building technologies to utilize different energy sources and to minimize energy consumption. In addition, there are energy conservation measures which can be easily applied in Philippine residential houses such as the unplugging of un-used electrical appliances and replacement of typical fluorescent-based lighting with energy efficient light-emitting diode (LED) lighting. The study also shows the value of ground cooling to provide a lower indoor temperature of the house in case the peak noontime temperature becomes very high.

Methodology

Description

Figure 8 is the layout for a single family double storey detached house in the Philippines. This arrangement is one of the most typical types for the middle class family, which constitutes one of the largest percentages of the Philippine population. Therefore, it is worthwhile to investigate such a house's design and arrangement. The typical Philippine house has a living area, dining area and kitchen on the first floor, along with a toilet and lavatory for visitors. The second floor is normally reserved for bedrooms for the

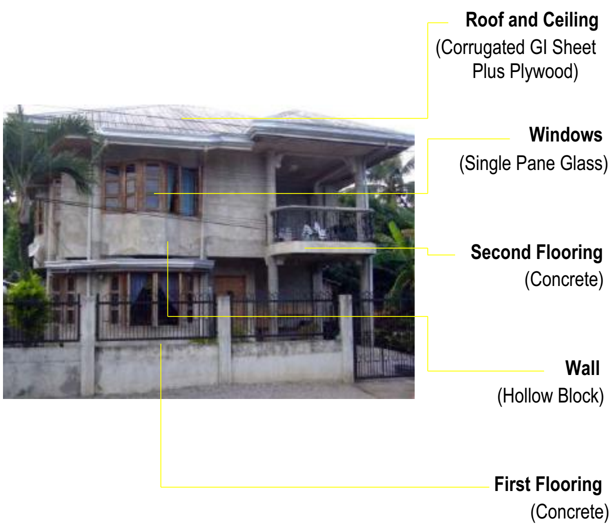


Fig. 7 Philippine construction materials for typical middle to upper class single family detached houses for Fig. 3a–f. Photo credit from Ref. [30]

parents, children and housekeeper in case the housekeeper's room is not on the first floor. In middle to upper class families in the Philippines, it is normal to have a housekeeper. The presented single family detached house in this study has a total floor area of 161.5 m^2. The floor area considered in this paper is within the size of a typical middle class single family house in the Philippines as shown in Fig. 6c, d. The typical house, materials and construction shown in Fig. 6c, d are shown in Fig. 7. Therefore, the house investigated in this study utilizes construction materials of the typical Philippine house as shown in Table 1.

Modeling

The investigated single family detached house in the Philippines is shown schematically in Fig. 8. A numerical model is developed in the transient system simulation (TRNSYS) environment based on the available information on Philippine single family detached houses and families. Figure 9a shows the flow chart of the new air-conditioning system based on desiccant material. It shows that the outdoor air could be dehumidified using the desiccant material naturally. After the air dehumidification, the air could be cooled either evaporative cooling or such as ground cooling method. Enteria and Mizutani [40] and Enteria et al. [41] presented the review and overview of the basic concept and different applications of the desiccant-based air-conditioning systems. The schematic diagram of the house supported by the proposed alternative energy sources coupled with a new air-conditioning system is presented in Fig. 9b. A photovoltaic panel is installed on the house's rooftop and the solar thermal panels are installed on the garage rooftop. The thermal storage tank and auxiliary water heater are installed at the back of the garage.

The auxiliary water heater presented in this study utilizes possible alternative fuels such as liquefied gas (liquefied petroleum gas), kerosene and wood pellets (biomass). The price of kerosene per liter is ₱23 or $0.51. The calculation of the required amount of kerosene is based on the lower heating value (LHV) of 43.1 MJ/kg. The price for liquefied petroleum gas (LPG) is ₱855 per 11 kg or $1.73 per kg. The calculation of the required amount of liquid petroleum gas is based on the 25 m^3 of natural gas equal to 1054 MJ and the lower heating value (LHV) of natural gas is 48.632 MJ/kg. The average price of wood pellets in the Philippines is ₱8100 per 1000 kg or $0.18 per kg. The calculation of mass requirement for biomass (wood pellets) is based on the lower heating value (LHV) of 3100 kWh/m^3. The density of the wood pellets is 650 kg/m^3. A ground heat exchanger is shown to support and augment cooling for the house's interior. As the feed-in tariff law is already approved, the house generated electricity is connected to the grid line. ₱9.68 or $0.22/kWh is the feed-in tariff for the electricity generated from the solar photovoltaic [42]. At present, the FIT is only applicable to generation facilities, but that of a house's generation is currently being discussed.

The specification for the installed photovoltaic panel on the rooftop used in the simulation is presented in Table 2. The installed photovoltaic panel covers the south facing roof and the installed capacity is 8.3 kW. The installed solar thermal collector covers the car garage with the thermal tank at the back of the garage along with the auxiliary water heater. The specifications of the solar thermal system are shown in Table 3. The proposed alternative air-conditioning system as a replacement for the typical air-conditioning used in a tropical climate has the technical specifications shown in Table 4. The effectiveness and efficiency values shown in Table 4 are based on the actual measurement values of the previous systems [43]. Figure 9 shows the schematic diagram of the new air-conditioning system which utilizes different energy sources and separates the handling of latent air and sensible energies [44].

Operation

The numerical operation of the house for the simulation is developed using the information from available Philippine families and houses. Due to the scarcity of research in this field, very seldom is information available. However, the authors made an actual observation of typical Philippine families and houses to be used for the numerical house

Fig. 8 House floor plan and schematic diagram for solar thermal, PV system, ground source cooling, biomass heater and grid-connected electricity

operation. For the typical middle and upper middle class Philippine family, an occupancy schedule is developed as shown in Fig. 10. The family considered has five members—father, mother, 2 children and a housekeeper. During weekdays, the father and the two children go to work and school, while the mother and housekeeper stay at home to maintain the house. With such an arrangement and with the information on electrical appliances and lighting consumption in the Philippines, a house usage model is developed to support the numerical operation of the house. Figure 11 shows the house appliances usage model of the Philippine house, using the most common appliances in middle to upper class Philippine families. Table 5 shows the energy rating for the appliances. To make it more realistic, the operation energy ratings shown in Table 5 are based on the actual appliances in the first author's house. However, standby power ratings are based on estimates when standby ratings are not available. To support the house occupancy and appliances usage models, the house lighting model is developed using the present lighting system usage in Philippine houses. Figure 12 shows the lighting usage model for the Philippine house used in the numerical house operation. In the modeling and operation of the air-conditioning system, 350 m^3/h is the volumetric capacity in which the air flow rate and direction change, depending on the occupancy of the house. For example, when the occupants are in the bedrooms, no ventilation goes to living areas and dining areas; during weekdays, the volumetric flow rate is reduced as the system is expected to support 70 m^3/h for each occupant.

Investigation

In as much as it is difficult to gather detailed information in the Philippine houses' comprehensive energy consumption from different sources due to the scarcity and non-availability of detailed research in this field in the Philippines, actual and personal information with general information

Table 1 House envelope materials, physical and thermal specifications

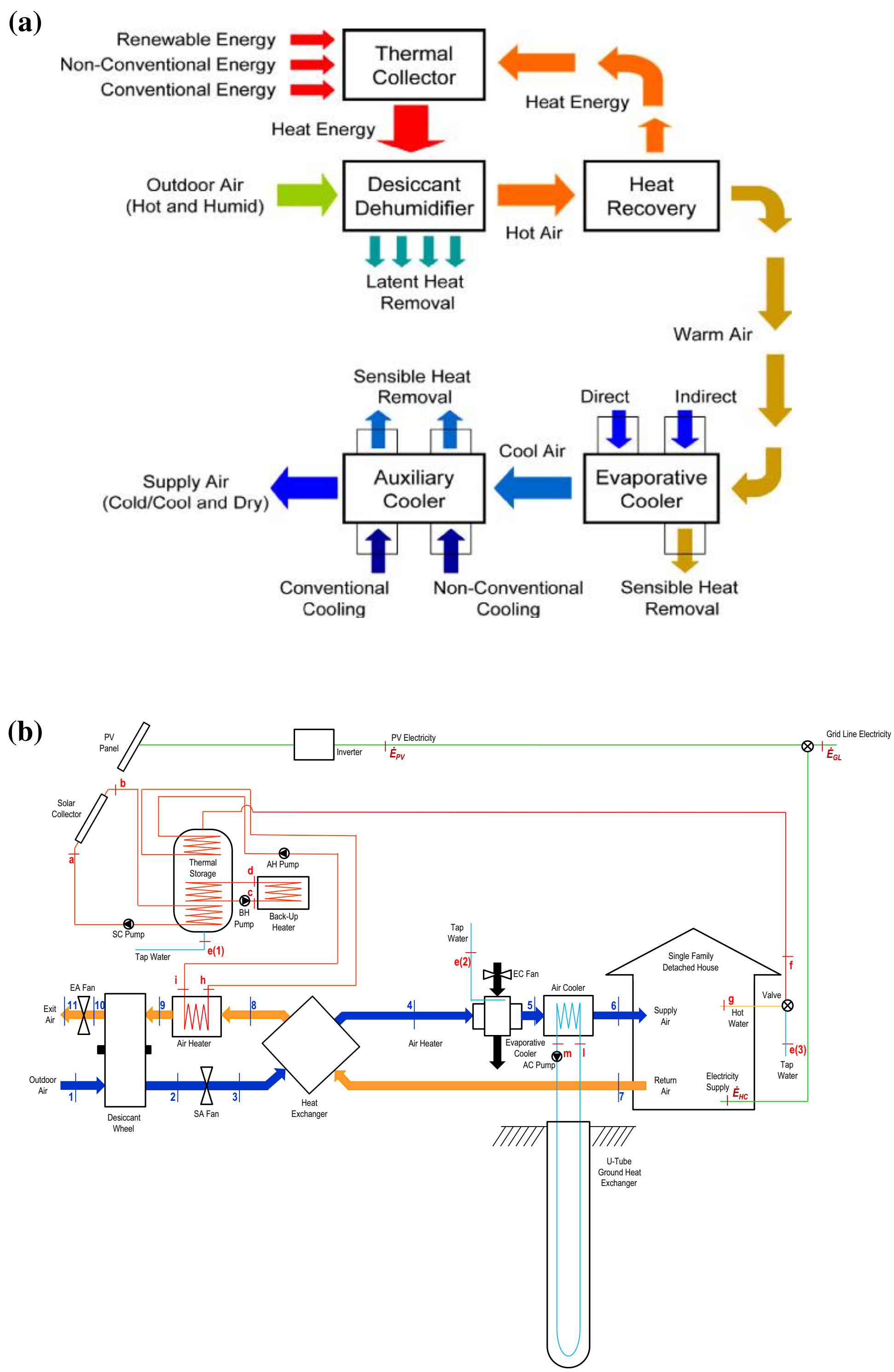
	House specifications
Roofing + ceiling	
Materials	Corrugated GI sheet
	Glass wool
	Ply wood
Thickness (m)	0.056
U value (W/m^2 K)	0.216
Walls	
Materials	Hollow block concrete
	Cement plaster
Thickness (m)	0.12
U value (W/m^2 K)	2.462
Floors	
Materials	Solid concrete
Thickness (m)	0.24
U value (W/m^2 K)	1.561
Windows	
Materials	Single pane glass
Thickness (m)	0.005
U value (W/m^2 K)	5.74
Doors	
Materials	Wood
Thickness (m)	0.05
U value (W/m^2 K)	1.808

from survey of the household energy consumption is used. The developed model presented above is compared to the electricity consumption of the average household based on the census [21]. In the Philippines, the average price of electricity is ₱7.10/kWh ($0.16/kWh). Figure 13 shows the comparison of the numerical results using the model presented in Fig. 6, house information shown in Table 1, occupancy model in Table 2 and usage models for appliances and lighting shown in Figs. 11 and 12. In addition, as there is no detailed hot water consumption in the Philippines, it is assumed that hot water consumption is 55 L per day at 40 °C. Hot water in the Philippines is mostly used for half bathing before bedtime. Based on the numerical model assumption with the available Philippine household electricity consumption, it shows that the developed model can be used for further investigation of the house.

In the Philippines, air-conditioned houses utilize the typical vapor-compression system to maintain the indoor temperature and humidity level either using split-type or window-type systems. In the Philippines and in other parts of tropical Southeast Asia, it is typical to cool the houses' indoor temperature at around 23 °C. Hence, as the study investigates the application of an alternative air-conditioning system, Fig. 14 shows the three different types of air-conditioning systems for application in Philippine houses. Figure 14a is the typical vapor-compression system widely installed in the Philippine houses, Fig. 14b is the hybrid vapor-compression system with desiccant dehumidifier [45]. The system is already available in Japanese market and expected to be available in tropical countries. Figure 14c is the desiccant dehumidifier with an evaporative ground cooling system [40]. Ground cooling utilization is possible due to the lower temperature of subsurface and ground in Philippines at around 19.4 °C [46]. In addition, ground cooling is applied and studied in neighboring countries of the Philippines with almost the same temperature at deep of 12 m [47, 48]. Also, the concept is already evaluated in the single family detached house in Japanese conditions [44]. Figure 15a shows that the typical air-conditioning system (Fig. 14a) consumes a large amount of electricity to support the indoor environmental conditions of the house. The typical air-conditioning system has the lowest coefficient of performance (COP) of 3 or energy efficiency ratio (EER) of 10.2 as base case. In the Philippines, the air-conditioning system should have an EER of 8.7 for a cooling capacity of less than 12,000 kJ/h and 7.8 for a cooling capacity greater than 12,000 kJ/h [49]. Also, utilizing the hybrid system's (Fig. 14b) separate handling of latent and sensible energy contents, electricity consumption is reduced from 5000 to 2900 kWh or 42 %. In addition, the coefficient of performance is increased to 5.2, or equivalent to 17.7 energy efficiency ratio (EER). To further reduce electricity consumption using the new air-conditioning system (Fig. 14c), electricity consumption is reduced to 2200 kWh or 56 %. In addition, the coefficient of performance is 5.1 or 17.4 EER. In terms of indoor temperature maintenance, the typical air-conditioning system and hybrid system can maintain the lower temperature of the house at 22.5 °C rather than the new system with a temperature of 26.5 °C shown in Fig. 15b. In terms of the humidity ratio, the new system can support a lower humidity ratio compared to the other system as it relies fully on desiccant dehumidification compared to the typical system of dehumidification by condensation. Figure 15c shows the relative humidity of the house. It demonstrates that the relative humidity using the new system is lower than that of the other systems. Hence, with the new system (Fig. 14c), the required indoor environmental comfort is met.

With the evaluation model (Fig. 9) and the performance evaluation of the new air-conditioning system (Fig. 14), an evaluation of the house building envelope is conducted to determine which building envelope provides more comfort and lower energy consumption for the air-conditioning system. Table 6 shows the different types of houses built with different construction materials. House A is the typical house in the Philippines as discussed above; House

Fig. 9 Application of alternative energy sources and new building technologies: **a** desiccant-based air-conditioning system [40], and **b** photovoltaic panel roofing, ground source air cooling, solar thermal collector in garage roof, biomass-fueled water heater and grid connection electricity



B is the highly insulated house common in temperate climate; House C is the wooden house also common in lower middle class houses in the Philippines; House D is the improved House A using additional insulation, and House E is the improved House C using additional insulation. Figure 16 shows the average overall heat transfer coefficient for the different houses.

To further investigate the house in the case of the Philippines, test cases for energy conservation measures (ECM) are evaluated. Table 7 shows typical energy conservation measures that could be easily applied to minimize electricity consumption and to improve the indoor thermal conditions of the Philippine house. The unplugging of unused electrical appliances is the simplest saving method

Table 2 Photovoltaic panel specification (installed capacity: 8.3 kW)

Parameter	Value	Unit
Module size	1535 × 280	mm
Number of modules in series	223	
Number of modules in parallel	1	
Number of cells wires in series	12	
Module short circuit current (reference conditions)	5.4	A
Module open circuit voltage (reference conditions)	13.3	V
Reference temperature	298	K
Reference isolation	1000	W/m^2
Module voltage at maximum power point (reference conditions)	10.5	V
Module current at maximum power point (reference conditions)	4.9	A

which can be applied in the Philippines, as at present it is seldom applied. The second method is the usage of the high-efficiency lighting system. Based on the national survey, most houses have installed either a fluorescent tube or a compact florescent lamp (CFL). However, the new light-emitting diode (LED) is the best option as a 4 W LED lamp could provide the equivalent of 13 W CFL.

Energy performance

The total thermal power supplied to the system is

$$\dot{Q}_{\mathrm{TE}} = \dot{Q}_{\mathrm{SE}} + \dot{Q}_{\mathrm{Aux}} \tag{1}$$

The collected solar thermal power is

$$\dot{Q}_{\mathrm{SE}} = \dot{m}_{\mathrm{SC}} C_{P_{\mathrm{W}}} (T_b - T_a) \tag{2}$$

The available solar power in the collector is

$$\dot{E}_{\mathrm{SE}} = A_{\mathrm{SC}} I_{\mathrm{R}} = \dot{Q}_{\mathrm{SE}} / \eta_{\mathrm{SC}} \tag{3}$$

The thermal power provided by the auxiliary heater is

$$\dot{Q}_{\mathrm{Aux}} = \dot{m}_{\mathrm{Aux}} C_{P_{\mathrm{W}}} (T_d - T_c) \tag{4}$$

The available power supplied to the auxiliary heater is

$$\dot{E}_{\mathrm{Aux}} = \dot{m}_{\mathrm{F}}\,(\mathrm{LHV}) = \dot{E}_E = \dot{Q}_{\mathrm{Aux}} / \eta_{\mathrm{Aux}} \tag{5}$$

The total consumption of thermal power presented is

$$\dot{Q}_{\mathrm{TE}} = \dot{Q}_{\mathrm{HW}} + \dot{Q}_{\mathrm{HC}} \tag{6}$$

The thermal power for hot water production is

$$\dot{Q}_{\mathrm{HW}} = \dot{m}_{\mathrm{HW}} C_{P_{\mathrm{W}}} \left(T_f - T_{e(1)}\right) \tag{7}$$

The thermal power for the heating coil during summer is

$$\dot{Q}_{\mathrm{HC}} = \dot{m}_{\mathrm{HC}} C_{P_{\mathrm{W}}} (T_h - T_i) \tag{8}$$

The thermal power for heating coil during winter season is

$$\dot{Q}_{\mathrm{HC}} = \dot{m}_{\mathrm{HC}} C_{P_{\mathrm{W}}} \left(T_j - T_k\right) \tag{9}$$

The supplied electricity from the photovoltaic is shown as

$$\dot{E}_{\mathrm{PV}} = \dot{E}_{\mathrm{PP}} \eta_{\mathrm{I}} \tag{10}$$

Since the installed photovoltaic panels are connected to the grid line, there are two scenarios by which electricity flows. The first scenario shows that when the photovoltaic electricity is not enough to support the house electricity consumption, grid line electricity supports it.

$$\dot{E}_{\mathrm{PV}} + \dot{E}_{\mathrm{GL}} = \dot{E}_{\mathrm{EC}}\ (\text{if } \dot{E}_{\mathrm{PV}} < \dot{E}_{\mathrm{EE}}) \tag{11}$$

In the second scenario, when electricity consumption is less than of the electricity generated by the photovoltaic panels, the excess electricity is transferred to the grid line through the feed-in tariff mechanism.

$$\dot{E}_{\mathrm{PV}} = \dot{E}_{\mathrm{EC}} + \dot{E}_{\mathrm{GL}}\ (\text{if } \dot{E}_{\mathrm{PV}} > \dot{E}_{\mathrm{HC}}) \tag{12}$$

The house's electricity consumption is distributed to the appliances, lighting and the HVAC system shown as

$$\dot{E}_{\mathrm{EC}} = \dot{E}_{\mathrm{App}} + \dot{E}_{\mathrm{Lights}} + \dot{E}_{\mathrm{HVAC}} \tag{13}$$

The sensible power component of the total cooling load of the air-conditioning system is

$$\dot{Q}_{\mathrm{SE(CL)}} = \dot{m}_{\mathrm{SA}} h_{\mathrm{Lat}} (x_1 - x_6) \tag{14}$$

The cooling load of the air-conditioning system is

$$\dot{Q}_{\mathrm{CL}} = \dot{m}_{\mathrm{SA}} (h_1 - h_6) \tag{15}$$

The sensible heat ratio for the cooling load of the air-conditioning system is

$$\mathrm{SHR}_{\mathrm{CL}} = \int_d^{365} \dot{Q}_{\mathrm{SE(CL)}} \mathrm{d}t \bigg/ \int_d^{365} \dot{Q}_{\mathrm{CL}} \mathrm{d}t \tag{16}$$

The sensible power component of the total cooling effect of the air-conditioning system in the house is

$$\dot{Q}_{\mathrm{SE(CE)}} = \dot{m}_{\mathrm{SA}} h_{\mathrm{Lat}} (x_7 - x_6) \tag{17}$$

Table 3 Solar collection and thermal storage specifications

Component	Parameter	Value	Unit
Flat plate collector			
	Collector area	20	m^2
	Collector inclination	15	O
	Fluid specific heat	4.187	kJ/kg K
	Tested flow rate	120	kg/m^2 h
	Intercept efficiency	0.594	
	Efficiency slope	16.2	kJ/h m^2 K
	Efficiency curvature	0	
Thermal storage tank			
	Tank volume	0.74	m^3
	Tank height	1.4	m
	Tank perimeter	1.82	m
	Height of water inlet	Tank Bottom	
	Height of water outlet	Tank Top	
	Tank loss coefficient	0.92	W/m^2 K
	Fluid thermal conductivity (water)	0.6	W/m K
	Height of first HX inlet (from bottom)	0.5	m
	Height of first HX outlet	Tank Top	
	Height of second HX inlet (below tank top)	0.5	m
	Height of second HX outlet	Tank Top	
	Height of third HX inlet (above tank middle)	0.5	m
	HX tube inlet diameter	0.01	m
	HX tube outlet diameter	0.012	m
	HX fin diameter	0.022	m
	HX surface area	1	m^2
	HX tube length	20	m
	HX wall thermal conductivity	401	W/m K
	HX material conductivity	401	W/m K
Water pump			
	Power coefficient	1	kJ/h
	Number of power coefficient	1	
	Motor heat loss fraction	0	
	Total pump efficiency	0.6	
	Motor efficiency	0.9	
Water pipe			
	Inside diameter	0.02	m
	Outside diameter	0.025	m
	Pipe length (collector loop, desiccant loop)	20	m
	Pipe length (auxiliary loop)	5	m
	Pipe thermal conductivity	0.24	W/m K
	Fluid thermal conductivity	4	kJ/h m K
	Insulation thickness	0.04	m
	Insulation thermal conductivity	0.043	W/m K
	Outer surface convective coefficient	3	kJ/h m2 K
Back-up water heater			
	Rated capacity	5	kW
	Set point temperature	65	°C
	Boiler efficiency	0.8	

Table 4 Desiccant-based air dehumidification with evaporative and ground cooling system

Component	Parameter	Value	Unit
Air heating coil			
	Effectiveness	0.8	
Desiccant wheel			
	F1 effectiveness	0.235	
	F2 effectiveness	0.8	
Heat exchanger			
	Sensible effectiveness	0.85	
Ground heat exchanger			
	Borehole deep	15	m
	Outer radius of U-tube pipe	0.01664	m
	Inner radius of U-tube pipe	0.01372	m
	Pipe thermal conductivity	1.512	kJ/h m K
	Fluid specific heat	4.19	kJ/kg K
Evaporative cooler			
	Secondary air flow rate	1/2 of Primary air flow rate	kg/h

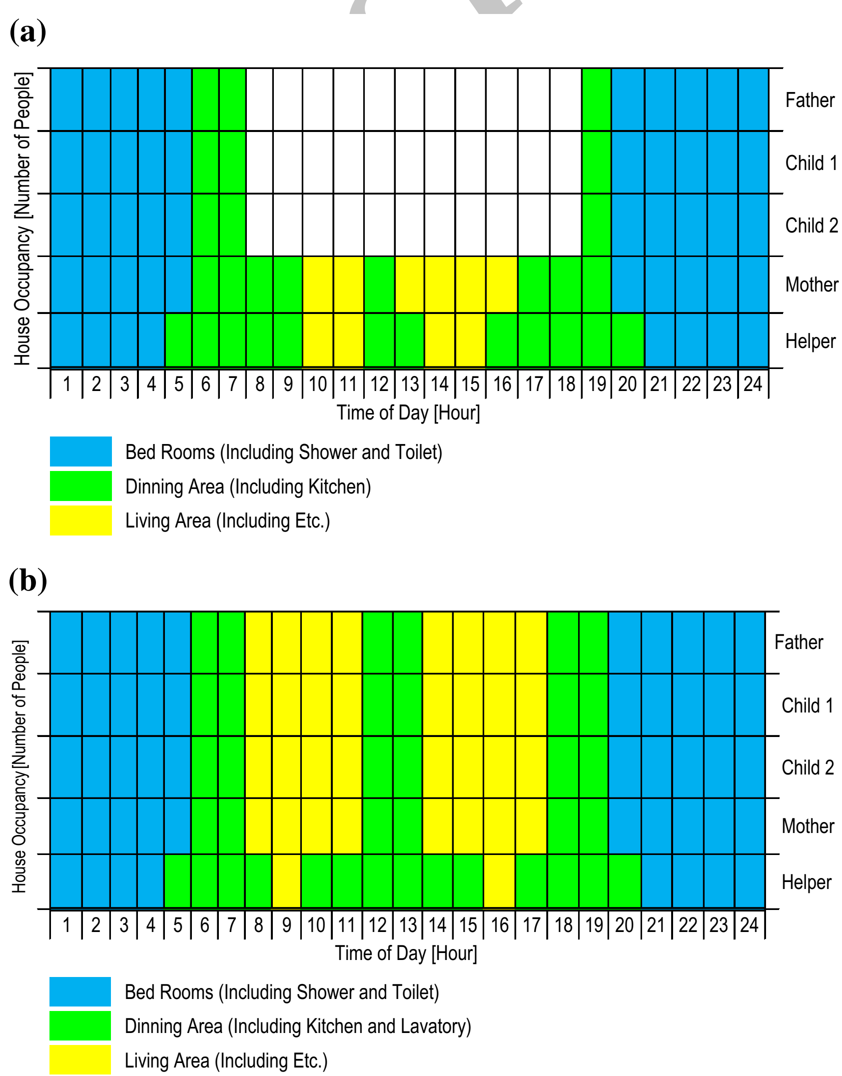


Fig. 10 House occupancy schedule: **a** weekdays and **b** weekends

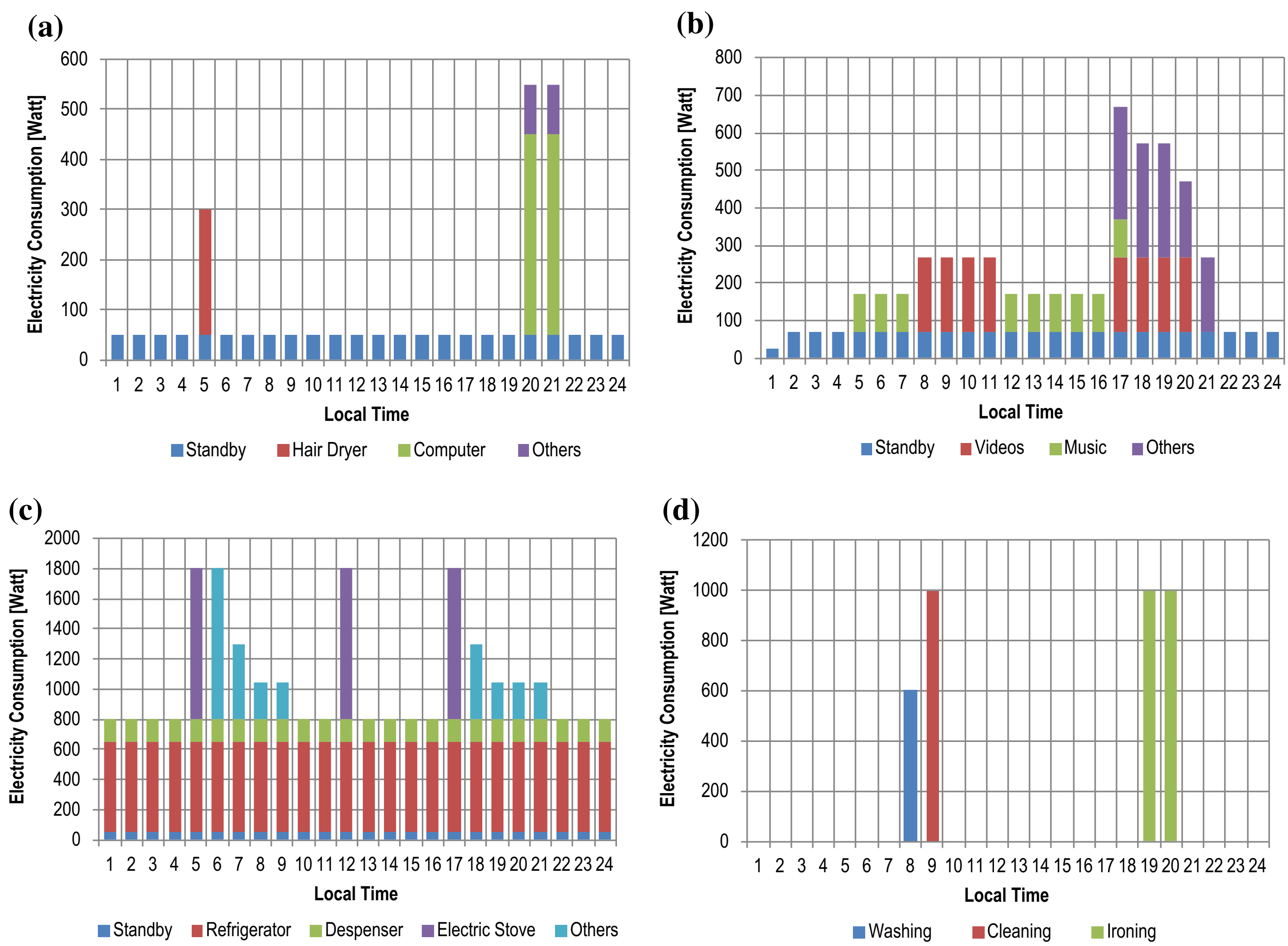


Fig. 11 House appliances usage schedule: **a** master and children rooms, **b** living areas, **c** dinning areas, and **d** lavatory and cleaning

The cooling effect of the air-conditioning system in the house is

$$\dot{Q}_{\mathrm{CE}} = \dot{m}_{\mathrm{SA}}(h_7 - h_6) \tag{18}$$

The sensible heat ratio for the cooling effect of the air-conditioning system is

$$\mathrm{SHR}_{\mathrm{CL}} = \int_d^{365} \dot{Q}_{\mathrm{SE(CE)}}\mathrm{d}t \Bigg/ \int_d^{365} \dot{Q}_{\mathrm{CL}}\mathrm{d}t \tag{19}$$

The coefficient of performance (COP) of the air-conditioning system is

$$\mathrm{COP} = \int_d^{365} \dot{Q}_{\mathrm{CL}}\mathrm{d}t \Bigg/ \int_d^{365} \dot{E}_{\mathrm{HVAC}}\mathrm{d}t \tag{20}$$

The equivalent energy efficiency ratio (EER) of the air-conditioning system is

$$\mathrm{EER} = 3.412(\mathrm{COP}) \tag{21}$$

The contribution of solar energy for the thermal energy requirement of the house is

$$\mathrm{STF} = \int_d^{365} \dot{Q}_{\mathrm{TE}}\mathrm{d}t \Bigg/ \left(\int_d^{365} \dot{Q}_{\mathrm{SE}}\mathrm{d}t + \int_d^{365} \dot{Q}_{\mathrm{Aux}}\mathrm{d}t \right) \tag{22}$$

The contribution of solar energy for the electric energy requirement of the house is presented as

$$\mathrm{SEF} = \int_d^{365} \dot{E}_{\mathrm{EC}}\mathrm{d}t \Bigg/ \left(\int_d^{365} \dot{E}_{\mathrm{HC}}\mathrm{d}t \pm \int_d^{365} \dot{E}_{\mathrm{GL}}\mathrm{d}t \right) \tag{23}$$

This means that when it is negative, the photovoltaic panels are generating more than the house electricity consumption. In the case of a positive sign, the generated electricity from the installed photovoltaic panels is not enough to support the house's electricity consumption.

Results and discussion

Indoor environment

Figure 17 shows the indoor thermal environment of the different houses presented in Table 6. Figure 17a shows the yearly average temperature of the houses. It shows that the highly insulated house has the lowest indoor temperature as it minimizes thermal losses. It also shows that the typical house (House A) has a higher average temperature together with the other houses. In terms of the humidity ratio, the high thermal performance house has the lowest humidity ratio, while the other houses have a higher humidity ratio. This means that House B is the most thermally efficient house as it is designed for temperate climates. Hence, it shows that the insulation of the typical tropical houses in Philippines (House A and House C) needs improvement. Figure 17c shows the average equivalent relative humidity inside the house. To determine which of the houses, aside from the high-performance one, has the higher thermal performance, the product of the indoor temperature and the humidity ratio is used as shown in Fig. 17d. It shows that House B is expected to have the lowest value: House D has the next lowest value followed by House C. Hence, improving the typical Philippine house (House A) wall insulation has an impact on the indoor thermal environment. The next higher thermal efficient house is House C, which is the typical wooden construction house in the Philippines. Hence, the U value for the wooden house wall is lower than that of the improved wooden house (House E) U value.

Table 5 Typical electrical appliances energy rating use in the numerical analysis

	Operating (W)	Standby (W)
Washing and cleaning		
Washing machine	1200	10
Flat iron	1000	–
Vacuum cleaner	1000	–
Food preparation		
Electric stove	1000	5
Rice cooker	1000	5
Water dispenser	150	–
Bread toaster	1000	5
Coffee maker	1000	5
Microwave oven	1000	5
Refrigerator	600	5
Entertainment		
TV	200	20
Components	100	10
Radio	25	5
CD player	50	5
Cable modem	10	–
Internet modem	10	–
Personal		
Computer	200	20
Printer	150	15
Hair dryer	800	–
Electric fan	500	–
Mobile phone	50	2

Figure 18a shows the cooling load and cooling effect of the air-conditioning system for different houses. For comparison, the cooling load is almost double that of the cooling effect. It means that high energy in the air (latent and sensible) is removed to provide a cooler and more dehumidified air supply to provide an acceptable indoor thermal environment. It shows that at 350 m^3/h air ventilation flow rate for five household occupants resulted to 70 m^3/h-person, the total energy removed from the air is around 11,200 kWh; on the other hand, the cooling effect, or the cooling to support the indoor thermal environment or energy absorbed by the ventilation air is around 600 kWh. Based on the sensible heat ratio or the ratio of sensible air energy to total air energy, the air removed by the air-

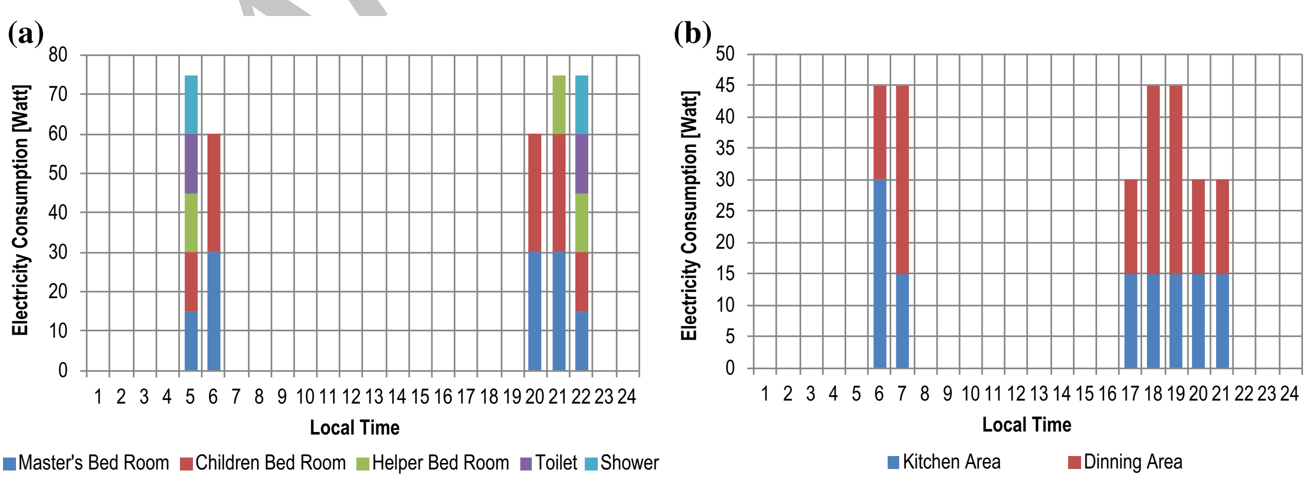


Fig. 12 House lighting switching-on schedule: **a** master and children bed rooms and **b** dinning areas

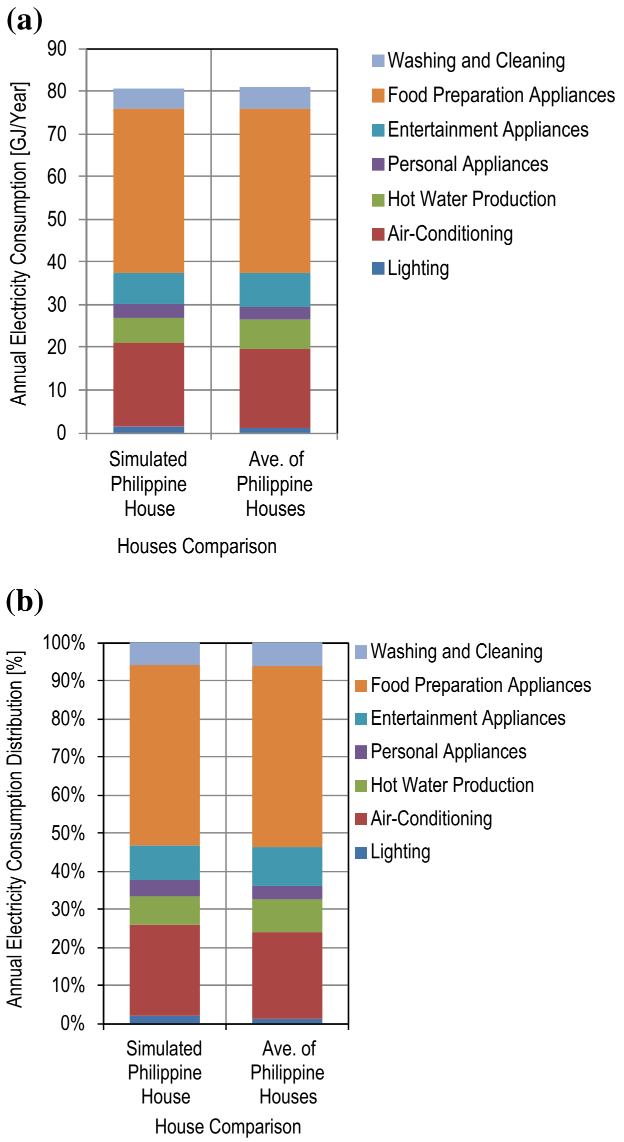


Fig. 13 Comparison of the developed house model and the average of the Philippine household electricity consumption considered: **a** distribution of the house electricity consumption and **b** percent distribution of the electricity consumption

conditioning system is mostly latent or moisture. This is to be expected for the air in a tropical climate. On the other hand, inside the house, the sensible heat ratio in the air for the cooling effect is a majority of sensible energy. As shown in the results, the sensible heat ratio decreases (SHR_{CE}) as the house envelope overall heat transfer coefficient is improved. It means that the building envelope contributed to the effect of sensible energy on the house ventilation. Figure 18b shows the electricity consumption of the house air-conditioning system, along with the performance coefficient of the air-conditioning system. It shows that the consumption is around 2200 kWh. With the

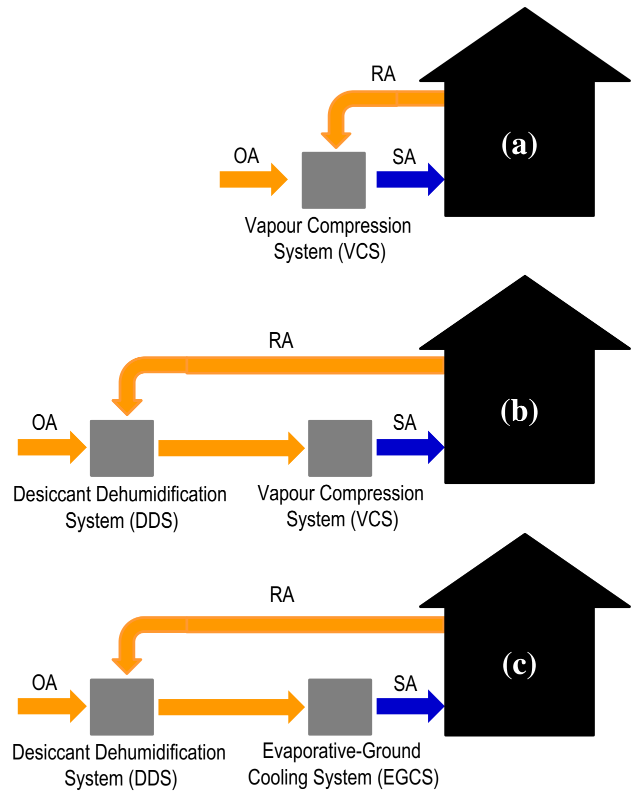


Fig. 14 Comparison of the different air-conditioning system: **a** typical vapor-compression system (typical air-con); **b** hybrid air-conditioning system (hybrid air-con) and **c** new air-conditioning system (new air-con)

cooling load of the air-conditioning system to support the cool and dehumidified air supply which supports the indoor thermal environment, the coefficient of performance is above 5.

Figure 19 shows the effect of the air-conditioning system on the average indoor air temperature and humidity ratio. Figure 19 shows how the average of the overall heat transfer coefficient for different houses shown in Fig. 16 affects the performance of the air-conditioning system to support the indoor temperature and humidity ratio. Based on the result, the highly insulated house (House B) has a higher value than the lower insulated house typical in the Philippines (House A). On the other hand, improvement of House A through wall insulation and use of double glass windows improved the performance. Hence, the Philippine concrete house (House A) construction method could be improved. In addition, it shows that wooden Philippine houses (House C) are better than house A. This is due to the fact that the overall heat transfer coefficient for the wooden house is lower. Hence, additional insulation or using double glazing glass has an effect on improving the house performance for the air-conditioning system.

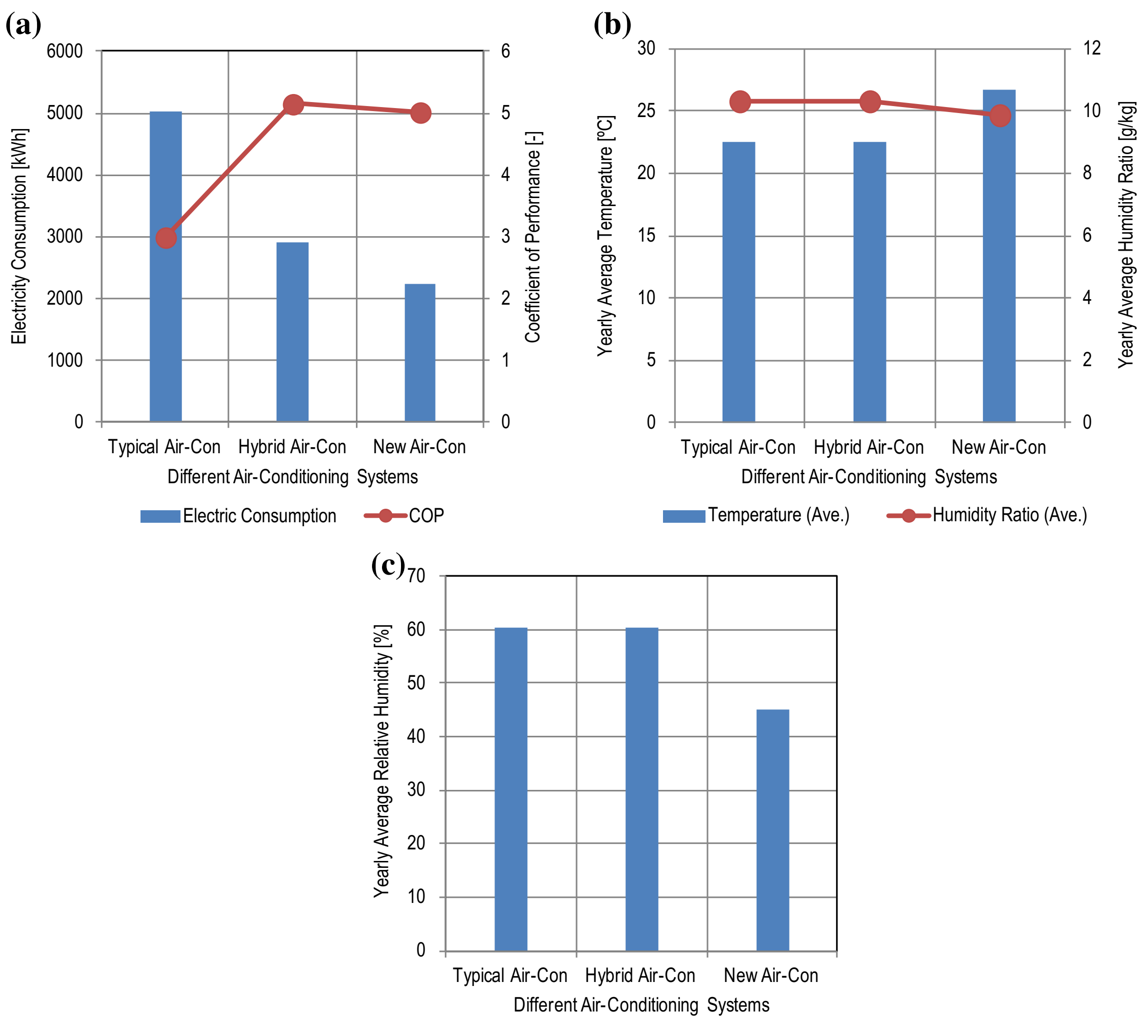


Fig. 15 Performance comparison of different types of air-conditioning system applied in single family detached house: **a** electricity consumption and coefficient of performance; **b** indoor yearly average temperature and humidity ratio and **c** indoor yearly equivalent relative humidity

Energy performances

Figure 20 shows the contribution of solar thermal energy to support the thermal energy requirement for the air-conditioning system and hot water production. It shows that the installed solar thermal collector on the garage rooftop of 20 m^2 with 0.74 m^3 tank can support up to 72 % of the requirement. The remaining thermal energy required can be from the auxiliary water heater supported by kerosene, liquefied gas or biomass fuel. In the case of transforming a house into a renewable energy supported house, it shows that the biomass-fueled heater would be a good option. Figure 20 shows the contribution of solar energy to support the electricity requirement of the house. In total for the full year, there is electricity that could be fed to the grid line as the installed photovoltaic panel has an excess yearly electricity generation. It does not mean that grid electricity is not needed; hence, grid-connected photovoltaic system is needed such as during the nighttime. However, during the daytime, excess electricity from photovoltaic is sold to a grid line through the feed-in tariff mechanism.

Figure 21a shows the annual total energy supply for the different houses. It shows that 32,000 kWh is supplied to the houses together with the excess electricity fed to the grid line. In Fig. 21b, it shows that the installed photovoltaic panels supplied up to 60 % of the total energy. Solar thermal energy provided up to 27 % of the total energy. Furthermore, the low-grade geothermal energy contributed up to 2 % of the house's cooling requirements. In general, an installation of 8.2 kW of photovoltaic panel, enough to cover the south facing roof with a 20 m^2 flat plate solar collector, can provide 87 % of the energy generated by the house. Furthermore, with the biomass-fueled heater, the thermal energy requirement of the house is supported. Hence, with the utilization of low-grade geothermal energy, the cooling requirement of the house is supported.

Table 6 Different houses specifications—materials, dimensions and thermal properties

	Concrete house [House A]	High insulation house [House B]	Wood house [House C]	Concrete house plus insulation [House D]	Wood house plus insulation [House E]
Roofing + ceiling					
Materials	Corrugated GI sheet Glass wool Ply wood	Bricks Ply wood Glass wool Air space Ply wood	Corrugated GI sheet Glass wool Ply wood	Corrugated GI sheet Glass Wool Ply wood	Corrugated GI sheet Glass wool P l y wood
Thickness (m)	0.056	0.466	0.056	0.056	0.056
U value (W/m2K)	0.216	0.085	0.216	0.216	0.216
Walls					
Materials	Hollow block concrete Cement plaster	Bricks Ply wood Glass wool Gypsum board	Wood Air space Ply wood	Hollow block concrete Cement plaster Glass wool Ply wood	Wood Glass wool Ply wood
Thickness (m)	0.12	0.465	0.13	0.145	0.155
U value (W/m2K)	2.462	0.096	0.229	0.886	0.187
Floor					
Materials	Solid concrete	Concrete Polyurethane Insulation	Solid concrete	Solid concrete	Solid concrete
Thickness (m)	0.24	0.456	0.24	0.24	0.24
U value (W/m2K)	1.561	0.556	1.561	1.561	1.561
Windows					
Materials	Single pane glass	Double pane glass with gas	Single pane glass	Double pane glass with gas	Double pane glass with gas
Thickness (m)	0.005	–	0.005	–	–
U value (W/m2K)	5.74	0.68	5.74	0.68	0.68
Doors					
Materials	Wood	Wood insulation	Wood	Wood	Wood
Thickness (m)	0.005	–	0.05	0.05	0.05
U value (W/m2K)	1.808	0.845	1.808	1.808	1.808

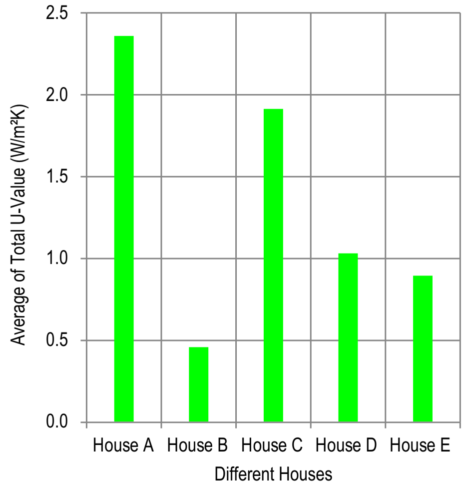


Fig. 16 Average of the house envelope overall heat transfer coefficient [W/m^{2}K]

Figure 22 shows the investigated house's energy consumption. The house's energy consumption is around 149 kWh/m^2. The house's appliances consumed a large amount of energy, 93 kWh/m^2 or 60 % of the total. 46 % of the house's energy consumption is for food preparation (refrigeration, cooking and others). Thermal energy consumed for the regeneration of the desiccant dehumidification is the second largest use of energy in its thermal form. It accounted for 17 % of the total energy consumption. Electric lighting for the houses consumed only 2 % of the total energy consumption. In general, it shows that the house consumed around 112 kWh/m^2 of electricity per year to support its operation while 34 kWh/m^2 is the amount of thermal energy. In terms of comparison with different houses it did not much affect the house's energy consumption since most energy consumption is for the electrical appliances. Almost 1500 kWh per year of the electricity is back to the grid line to support the electricity requirement of other houses or establishment.

Figure 23a shows the mass fuel requirement in the cases of the different types of water heater to be used to support the auxiliary thermal requirement of the house. It shows that when using liquefied petroleum gas (LPG), 250 kg is the yearly requirement. The use of a kerosene water heater results in the kerosene mass requirement of 280 kg per year. The application of a biomass-fueled heater results in a 700 kg requirement, or more than double the mass requirement of the previous two fuels. In terms of monetary benefits, Fig. 23b shows that using the gas heater or liquefied petroleum heater, the operational cost is \$530 per year. The kerosene fueled heater results in a cost of \$180 per year. Using the biomass fuel, cost is \$160 per year. However, as shown in the result, using the feed-in tariff mechanism, the excess electricity supplied to the grid line can earn \$300

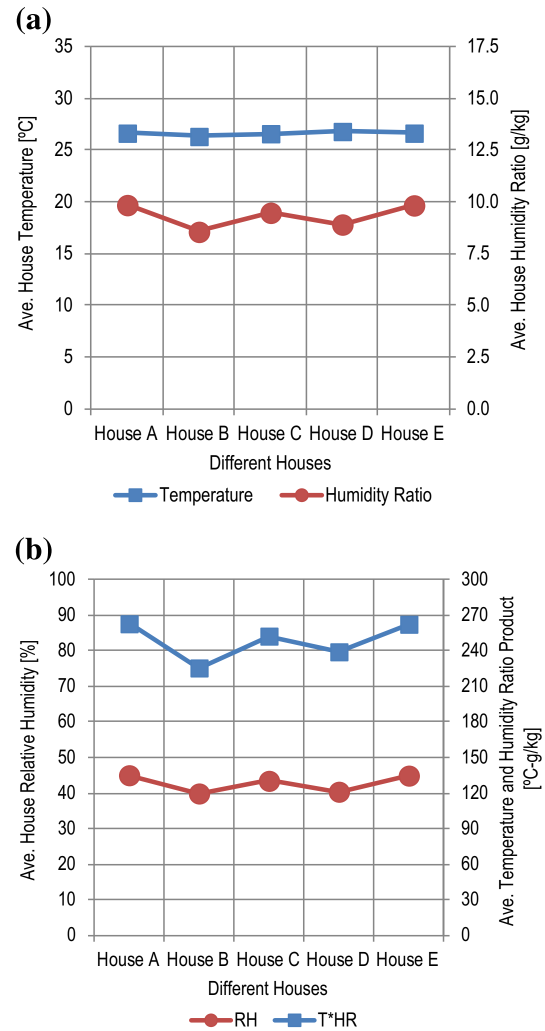


Fig. 17 Different houses indoor environment: **a** yearly average temperature and humidity ratio, **b** yearly average relative humidity and product of the indoor temperature and humidity ratio ($Y_H = (T_H X_H)$)

Table 7 Test cases for energy conservation evaluation

	House D	House F = House D +	House G = House F +	House H = House G +
Conditions	Base case	Unplugging of appliances	Using LED lights	High overall U value for first flooring

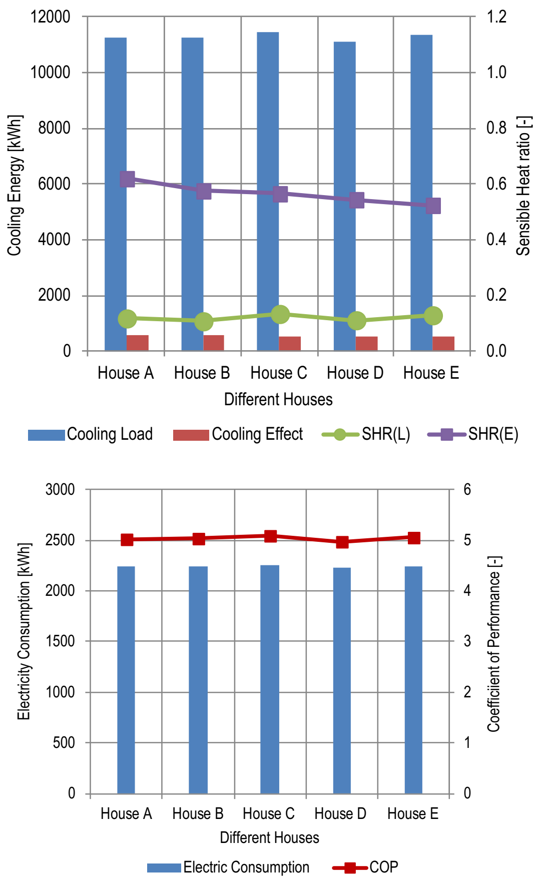


Fig. 18 New air-conditioning system performances: **a** cooling load and cooling effect produced and **b** electricity consumption and the coefficient

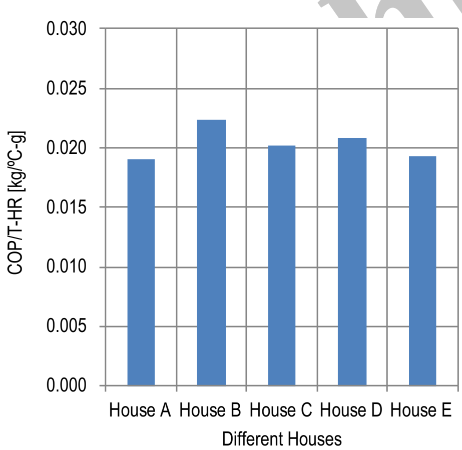


Fig. 19 Ratio of the yearly coefficient of performance to the product of the yearly indoor temperature and humidity ratio

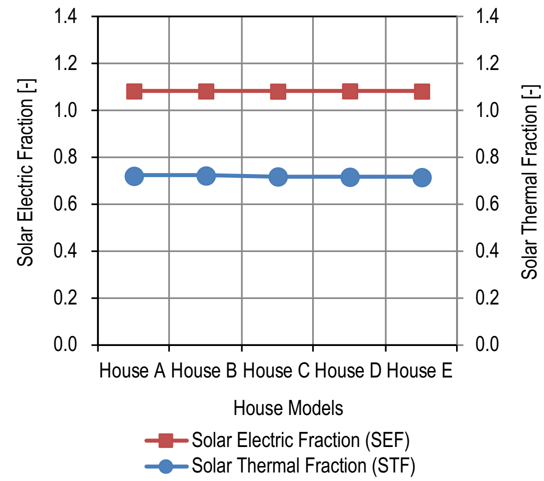


Fig. 20 Solar energy contribution in building energy requirements: yearly solar thermal fraction, and yearly solar electric fraction

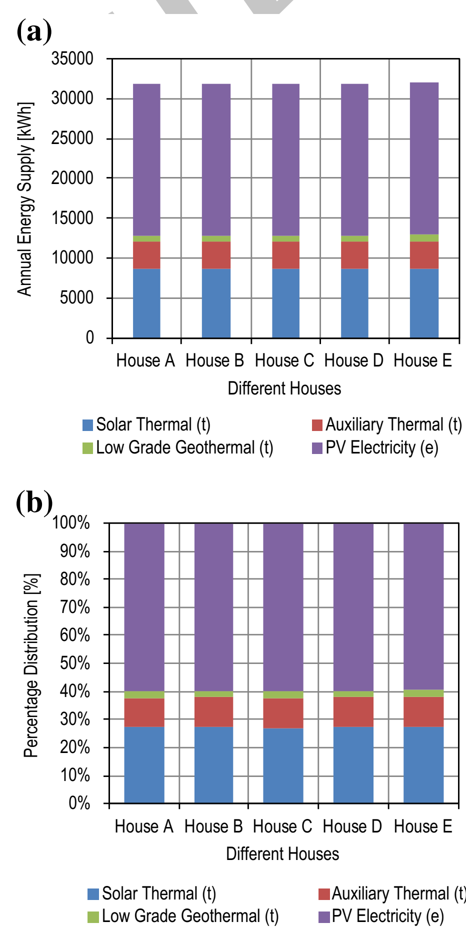


Fig. 21 Annual energy supply to different houses: **a** amount of energy supply (kWh) and **b** percentage distribution of different energy supply (%)

per year. The earned electricity in the grid line can support the operation of the auxiliary water heater using either the kerosene or biomass fuels. However, when the environmental factor is considered, it would be preferable to use the renewable energy sources such as biomass. Hence, by employing the above mechanism, the house is earning an income.

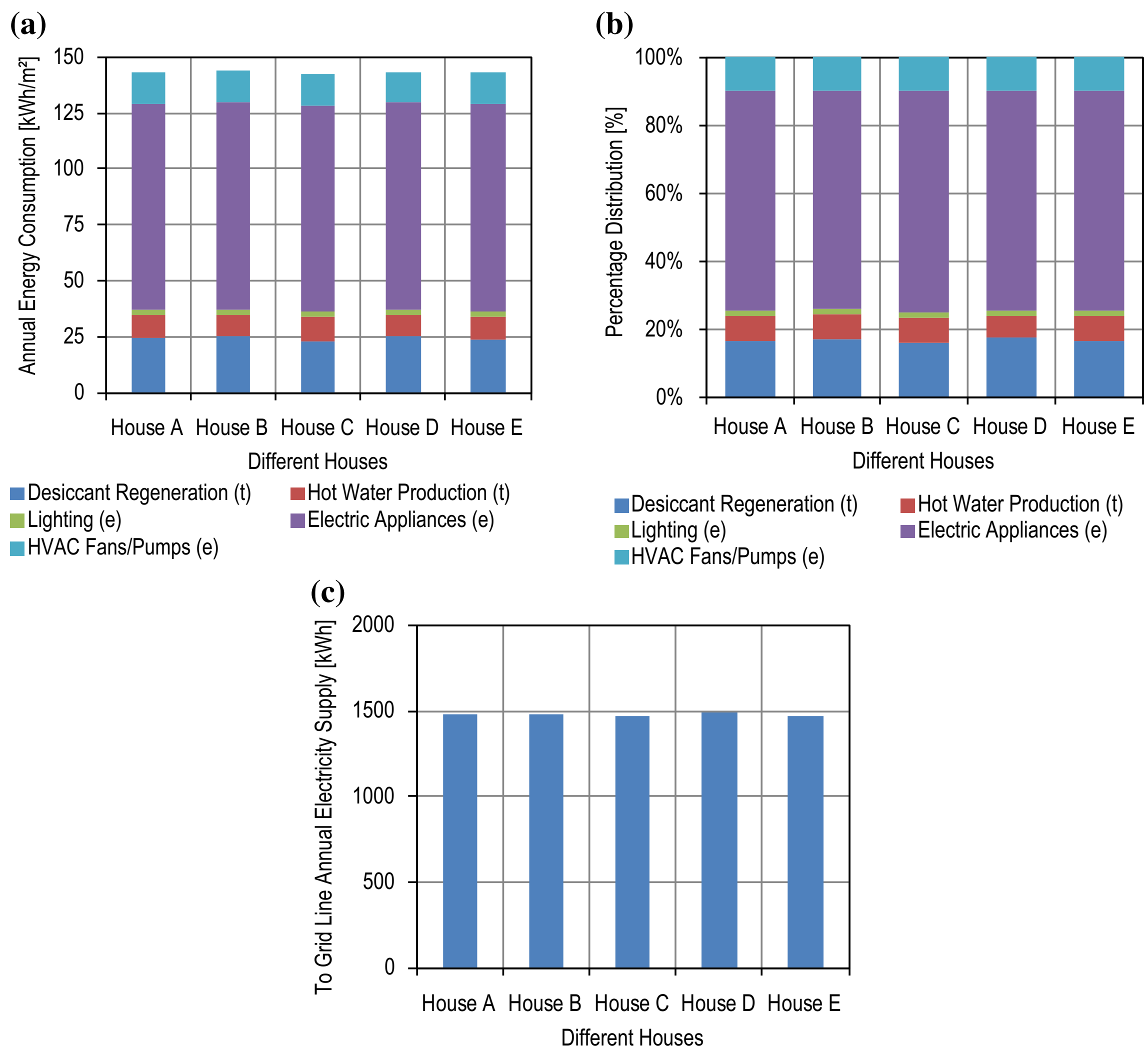


Fig. 22 Annual energy consumption of different houses: **a** amount of energy consumption (kWh/m^2), **b** percentage distribution of different energy consumption (%), and **c** to grid line electricity (kWh)

Case analysis

Figure 24 shows the energy supplied by the installed different alternative energy sources in the different houses shown in Table 7. It shows that the house is generating its own energy of 32,000 kWh per year for different cases. Figure 25 shows the amount of energy consumed by the houses together with the electricity supplied to the grid line. Based on the base house (House D), the energy saving measure of unplugging the un-used electrical appliances amounted to 9.3 kWh/m^2 per year or a decrease by 10.3 % of the house electricity consumption, thus demonstrating that the unplugging of electrical appliances not just turning them off is important. In addition, there is a reduction of air cooling of supply air by geothermal cooling as the sensible cooling effect is reduced by 0.41 kWh/m^2 per year or 10 % as the thermal gain from appliances is reduced. Hence, the electricity saving operation for the air fans and the geothermal pump is reduced by 0.04 kWh/m^2 per year or 0.3 %. In addition, using light-emitting diode (LED) lighting as a replacement for the compact fluorescent lamp (CFL) a saving of 1.61 kWh/m^2 per year or 69 % is possible. Hence, the promotion of an energy efficient lighting system is very important as one of the energy conservation measures for the houses. In addition, using a high overall heat transfer coefficient first flooring material increases the heat transfer between the cool ground and the house interior which resulted in the reduction of 0.63 kWh/m^2 per year or 18 % compared to House G. Furthermore, pump and fan power is reduced by 0.06 kWh/m^2 per year or 0.5 % using these energy conservation measures. In Philippine houses, the flooring is usually covered by wood tiles, vinyl tiles or carpet.

Figure 26 shows the case analysis for the application of different alternative energy sources for water heating.

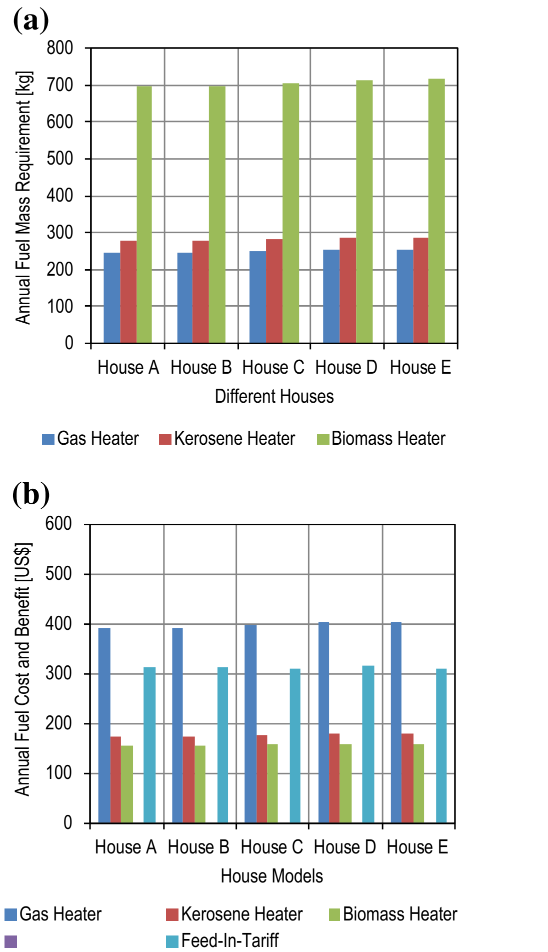


Fig. 23 Auxiliary heater fuel cost and benefits: **a** fuel costs for different heaters and **b** cost and benefits from auxiliary heater and feed-in tariff electricity

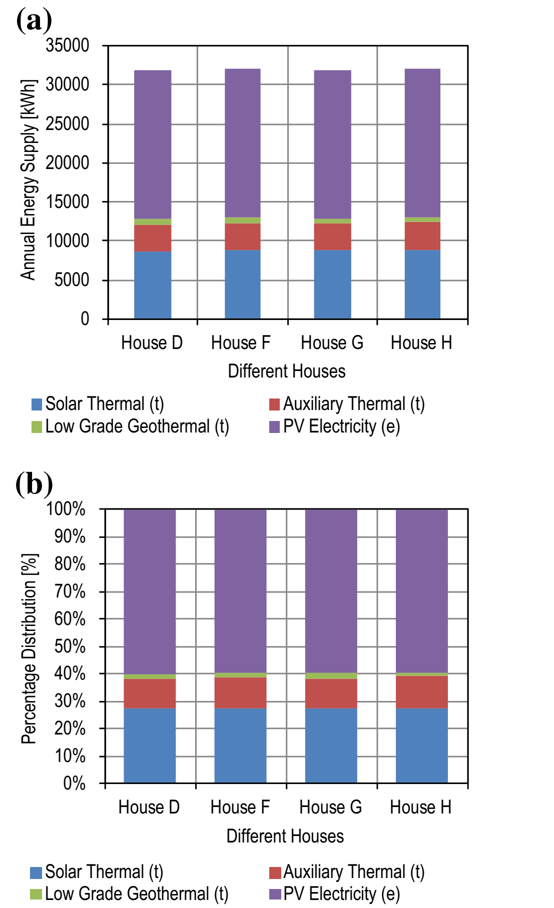


Fig. 24 Annual energy supply to different houses: **a** amount of energy supply (kWh) and **b** percentage distribution of different energy supply (%)

Based on the fuel mass requirement, it shows that using a liquefied petroleum gas (LPG) gas heater requires 260 kg per year. Using the other typical Philippine household fuel, kerosene, it needs around 300 kg per year. On the other hand, using the renewable biomass fuel which is not yet fully applied in the Philippine household, needs around 750 kg per year as shown in Fig. 26a. These different fuel masses are basically based on different lower heating values (LHV). However, in terms of energy and environmental factors, it is important that the renewable energy type for the auxiliary heater, biomass, be used. The cost of the auxiliary heater fuels mentioned shows that using the gas or the LPG is more expensive which is above $400 per year compared to the less than $200 per year for kerosene or biomass. However, when selecting either kerosene or biomass, the environmental factor is the key consideration. Using the feed-in tariff mechanism in the Philippine case, the earned money for House D is enough to support the fuel requirement for a biomass-fueled water heater. As an electricity saving for Houses D to H, it shows that there is more than enough saving when using different fuels for the auxiliary heater. However, using the biomass-fueled heater, more saving is possible for the house with which it can support other household utility requirements such as water consumption or internet and cable television signals. Figure 26b shows the cost and benefits of using different auxiliary water heater fuels when the feed-in tariff mechanism is applied to defray fuel cost using different energy saving measures for Houses D to H.

Figure 27 shows the contribution of the installed rooftop photovoltaic panel and the solar thermal collector on the garage rooftop for the needed energy for the house. Based on the base house, House D, the improved Philippine house such as when appliance saving measures are employed, as shown in Table 7, 19 % of the generated electricity from the photovoltaic panel could be fed to the grid line. Using the energy efficient lighting measure in House G (Table 7), 21 % of the generated electricity could be fed to the grid line, as is the case of House H. This means that there is

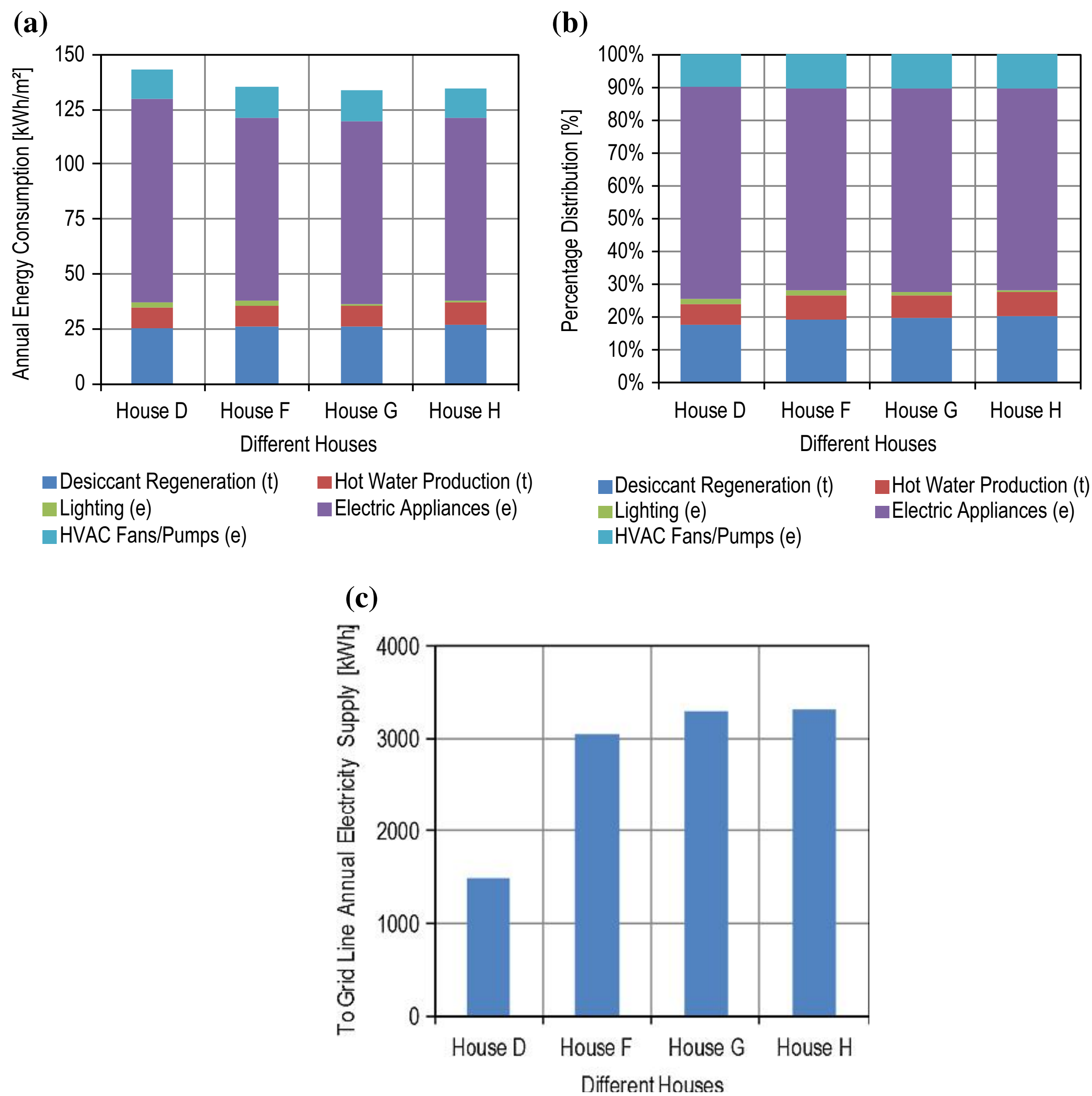


Fig. 25 Annual energy consumption of different houses: **a** amount of energy consumption (kWh/m^2) **b** percentage distribution of different energy consumption (%), and **c** to grid line electricity (kWh)

more electricity to be fed to the grid line to support the house's other utility requirements. On the other hand, it could lessen the burden of the peak load which frequently happens in the Philippines. However, the solar energy contribution for the house's thermal requirement is 70 %. It means that the auxiliary heater is needed to support the remaining 30 % which can be supported by biomass fuel when building a renewable energy supported house.

Figure 28 shows the reduction of electricity consumption using different energy conservation measures (ECM) with respect to the Philippine base house used in this study (Fig. 13). As presented in Fig. 28a, using the new air-conditioning system (Fig. 14c), the space conditioning energy consumption is reduced from 19.35 GJ/year (0.12 GJ/m^2 year) to 8.03 GJ/year (0.05 GJ/m^2 year) as presented by House D. By the unplugging of un-used electrical appliances as presented by House F, the house appliance electricity consumption is reduced from 49.1 GJ/year (0.30 GJ/m^2 year) to 43.5 GJ/year (0.27 GJ/m^2 year). By the use of energy efficient light-emitting diode (LED) as presented by House G, the lighting energy consumption is reduced from 1.36 GJ/year (0.0084 GJ/m^2 year) to 0.42 GJ/year (0.0026 GJ/m^2 year). The effect of a high overall heat transfer coefficient for the first floor material to the space conditioning energy consumption is minimal as it is only lowered from 8.00 GJ/year (0.0495 GJ/m^2 year) to 7.97 GJ/year (0.0493 GJ/m^2 year) as presented by House H. Based on Fig. 28b, it is shown that house electricity consumption is reduced 21.54 % when using the new air-conditioning system (Fig. 14c) coupled

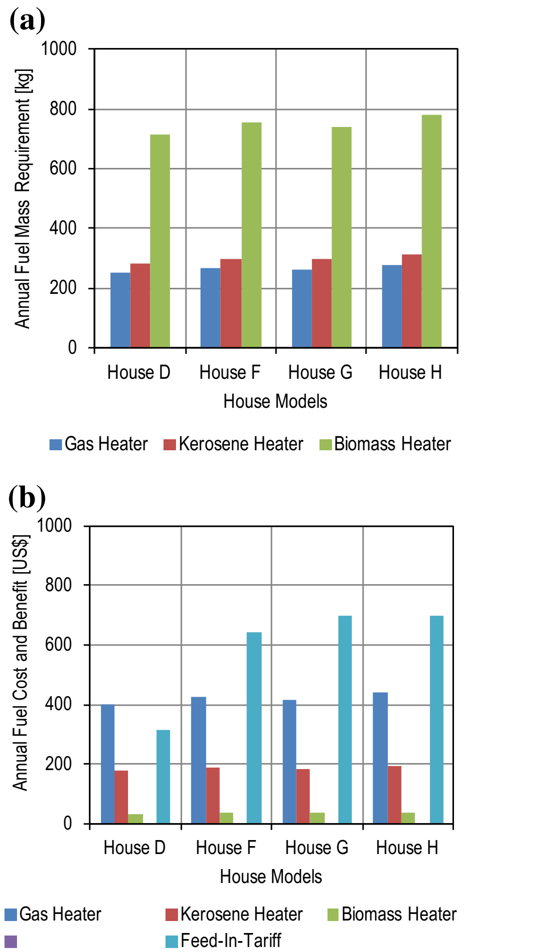


Fig. 26 Annual auxiliary heater fuel cost and benefits: **a** fuel costs for different heaters and **b** cost and benefits from auxiliary heater and feed-in tariff electricity

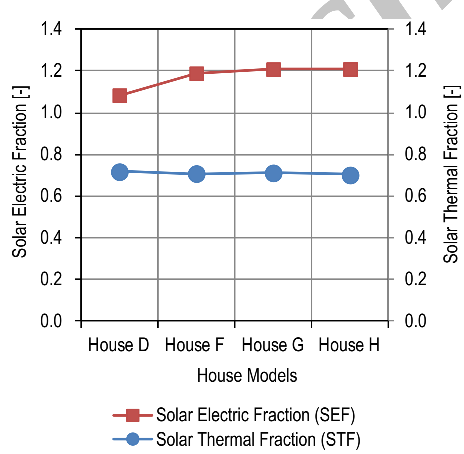


Fig. 27 Solar energy contribution in building energy requirements: **a** yearly solar thermal fraction and **b** yearly solar electric fraction

with hot water production from solar thermal and auxiliary water heater (House D). Unplugging of un-used electrical appliances reduced the house electricity

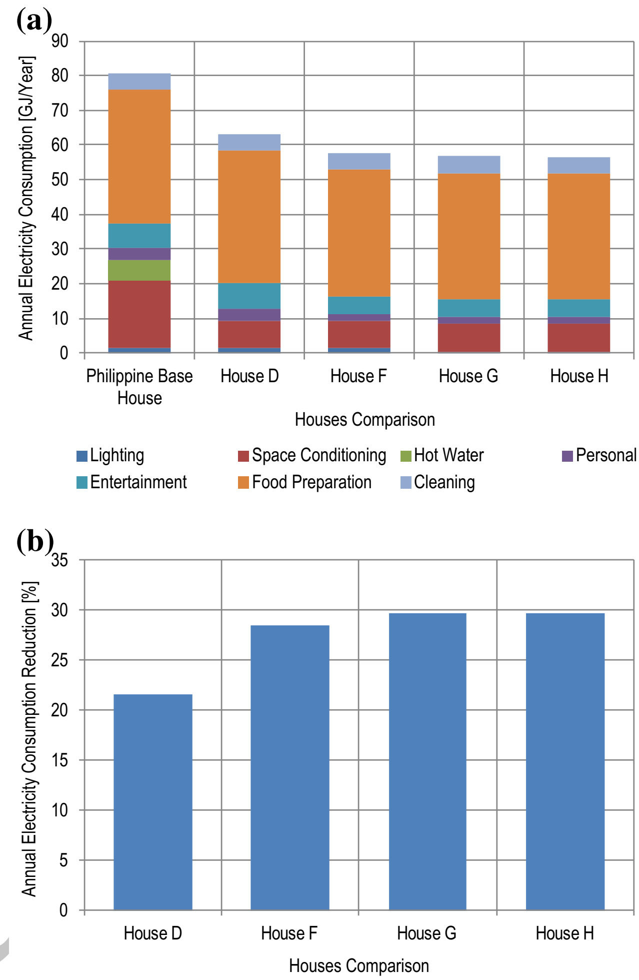


Fig. 28 Annual electricity consumption of different energy conservation measures for houses with respect to Philippine base house: **a** amount of electricity (GJ/year) and **b** percentage electricity consumption reduction for different energy conservation measures with respect to Philippine base house (%)

consumption by 28.46 % as shown by House F. Using light-emitting diode (LED) lighting, the total house electricity consumption is reduced by 29.63 % as shown by House G. Using a high overall heat transfer coefficient on the first floor for ground cooling as shown by House H, the house's total electricity consumption is reduced by 29.68 %. Based on the presented results, the application of a new air-conditioning system aided much to the reduction of the house electricity consumption as it utilizes minimal electricity because other energy is generated from solar, auxiliary heater and low-grade geothermal sources. In addition, unplugging of electrical appliances after use has contributed to the reduction of the house's electricity consumption. Hence, the above energy conservation measures are more important compared to the application of energy efficient lighting and high overall heat transfer coefficient first floor material.

Conclusions

Typical Philippine single family detached concrete and wooden houses were evaluated based on house occupancy, appliances usage, lighting usage and electricity consumption. The gathered information was used to develop a numerical model in a transient system simulation (TRNSYS) environment to investigate the Philippine typical house and possibly improve them in terms of house envelopes and energy conservation measures using alternative energy sources and technologies.

1. House A has the highest overall heat transfer coefficient house envelope—wall, roof and windows compared to the wooden Philippine house, House C. However, house A could be retrofitted to reduce its house envelope U value through the addition of insulation as presented in the case of House D (Fig. 13). On the other hand, using the new air-conditioning system (Fig. 14c) compared to the typical Philippine air-conditioning system (Fig. 14a), electricity consumption of the house intended for the air-conditioning system could be reduced as presented in Fig. 16. Hence, using the new air-conditioning system, alternative energy sources could also be used, particularly thermal energy sources from solar and biomass resources.
2. In terms of the new air-conditioning system (Fig. 14c), the performance coefficient of the air-conditioning system in the houses with respect to the maintenance of the indoor temperature and humidity (Fig. 19), the highly insulated house (House B) has the higher performance. When compared to the result for the typical Philippine concrete house, House A shows that it has the lowest performance. Therefore, retrofitting or adding insulation to House A, as presented by House D would make it more efficient. However, comparing House C, the Philippine wooden house, it is more efficient than by adding insulation to the wooden house as presented by House E. This is due to the fact that House E wall overall heat transfer coefficient is lower than for the House C overall heat transfer coefficient (See Table 6). Double walling for those ordinary Philippine single family wooden detached houses which use an air-conditioning system, is important to lower electricity consumption used for air-conditioning.
3. By installing photovoltaic panels to the house rooftop and a solar thermal collector to the garage rooftop (Fig. 5), it is shown that the house can support its own electricity requirement annually as the solar electric fraction (SEL) is above 1 (Fig. 20). It means that some of the generated electricity could be fed to the grid line. At present, the feed-in tariff law is already approved and its application for houses is being prepared. The installation of photovoltaic panels to individual houses of the community could lessen the peak load during summertime. This is a serious problem in the Philippines where a large percentage of power generation is from hydroelectric power plants. On the other hand, the installed solar thermal collector cannot fully support the thermal energy requirement of the house, being able to support only 70 % of it. Hence, auxiliary thermal sources most particularly a biomass water heater could augment the thermal energy supply.
4. It is shown that the house electrical appliances—personal appliances such as computer, printer and others; entertainment appliances such as television, music, radio and others; food preparation appliances such as refrigerator, ovens, and stoves, and cleaning appliances such as a washing machine or vacuum cleaner contributed to a high house electricity consumption. The results show that electrical appliances represented 60 % of the total house energy consumption for different house cases shown in Fig. 22. However, using the electricity generated by the installed photovoltaic panel, the house could still feed the grid line the amount of 6 % of the photovoltaic electricity generated. Using the feed-in tariff mechanism in the Philippines, the excess electricity supplied to the grid line is enough to support the energy cost for the auxiliary heater fuel, particularly when using biomass as a water heater fuel (Fig. 23).
5. The energy conservation measures (ECM) in Table 7 show that in test case House F, the unplugging of unused electrical appliances could lower the electricity consumption of the house by 10 %. As 60 % of the house energy consumption is for electrical appliances, unplugging them rather than just simply turning off the switch has a significant effect on the house's electricity consumption. Awareness of this habit is very important to Philippine household owners. Furthermore, using an energy efficient lighting system, particularly the light-emitting diode (LED) lamp could save lighting electricity consumption by up to 69 % as represented by House G. In the Philippine middle to upper class houses, most of the lightings are the florescent-based lamps. In terms of prices, the current price of LED light bulb is around ₱85 per watt ($1.9/W) compared to ₱10 per watt ($0.2/W). However, in terms of lamp lifespan, the LED light is 30,000 h compared to 8000 h for the CFL. Hence, price is another factor for mass application of LED lighting. Using a high overall heat transfer coefficient material on the first floor could help support

the cooling requirement of the house. The house saves fan and pump energy consumption from the low-grade geothermal cooling of the air supply. Hence, these energy conservation measures have an effect on the energy consumption of the house and are important for the development of energy efficient houses for tropical Philippines. Based on the study's overall results, the present Philippine single family house (House A) needs more improvement in its thermal performance and energy conservation measures. In addition, utilization of alternative energy sources and application of new air-conditioning technologies are important to minimize the house's energy supply from the grid line and maximize energy conservation. Energy conservation measures (ECM) such as unplugging of un-used electrical appliances are important and are the simplest way to save electricity. Another important measure is to use a high energy efficient lighting system to save more energy for the lighting requirement.

The result of this study is an important contribution toward minimizing the energy consumption of the residential building sector in the Philippines. Based on the census, more than half of the construction in the Philippines is for the residential sector and more than 50 % of that is for single family detached houses. In addition, almost 30 % of the country's electricity generation is intended for the residential sector. As most electricity generated, more than 70 %, comes from carbon-based fuels, energy conservation in the residential sector utilizing alternative energy sources and application of new technologies coupled with energy conservation measures are important for the minimization of the residential sector's contribution to the total energy consumption of the country, and indirectly to the amount of greenhouse gas emissions. With this, it could contribute to the Philippine government's plan to tap alternative energy sources and to implement energy conservation programs [50]. However, there is a scarcity of information for making a more detailed evaluation of Philippine houses such as the detailed lifestyle, varying energy consumption and implementation of other standards in the Philippine building code, it is very important to pursue further research so as to better understand the details in this field. From this research, more comprehensive evaluations of Philippine houses could be affected.

Conflict of interest The authors declare that they have no conflict of interest.

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