Research Article

Life Cycle Cost and Energy Analysis of Roof Systems for a Single-Family House

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Abstract

In this study, the life cycle cost (LCC) and energy consumption of a residential home were evaluated to find the lowest LCC among 12 roof systems. EnergyPlus 8.3 program was employed to estimate the annual cooling requirements of a two-storey house with total area of 240 m^2. The analysis was carried out for four types of roof insulation (aluminum foil, fiberglass, polystyrene and polyurethane) and three types of roof tires (concrete, ceramic and fiber cement). The concrete roof tiles without insulation were set as the baseline case. Results show the concrete roof tiles with fiberglass insulation provide the highest energy saving in the air conditioning system at 10.98%. However, the roof using fiber cement roof tiles with polystyrene insulation was found to be the most cost effective roof system. It shows the lowest LCC with the reduction in LCC by 3.31%.

***Key Words*:** Roof tile; Insulation; EnergyPlus; Life cycle cost

Introduction

Thailand is located in the Tropics where the sun travels with high altitude for most of the daytime. As a result, heat transfer through roofs are important components of cooling load in houses and share 26.5% of the total heat transfer through house envelope (Boonyatikarn and Chindavanig, 1993). Reduced heat transfer through roofs decreases the cooling load in air-conditioned areas and improves thermal comfort in non-air conditioned areas. Due to the significance of roof on energy consumption, selecting a suitable roof tile and roof insulation materials is important and a number of studies have been carried out thus far. Al-Sallal (Al-Sallal, 2003) conducted the simulation study using RENCON program to investigate the impact of polystyrene and fiberglass roof insulation on heating and cooling energy in Texas and Minnesota. (Al-Obaidi et al., 2014) reviewed physical characteristics of roofs in modern tropical houses in Southeast Asia. The results show that implementing reflective and radiative approaches in roofing systems reduces the annual cooling loads significantly. However, building type, the occupancy patterns, and weather conditions are major factors to be considered. Insufficient information for both designers and building users are found to be the major reasons in selecting an inappropriate roof system which may result in an unpleasant indoor environment.

The objective of this study is to investigate the variation of energy consumption caused by the roof tiles and roof insulations commonly used in modern houses of Thailand. The calculation of energy consumption is provided by using the building simulation software EnergyPlus version 8.3. The life cycle cost of different roof types which is important information to the decision making is also studied.

Methods

Simulation Software

An energy simulation program, EnergyPlus version 8.3, was used for the simulations. EnergyPlus is a whole-building energy simulation program developed by DOE (Crawley et al., 2001). EnrgyPlus was selected because it is currently used for calculating cooling loads in ASHRAE standard (ASHRAE, 2005).

Description of the Simulated House

A two-story house located in Bangkok, Thailand with the floor of 240.44 m^2 was used in this study. The design of the simulated house is provided online by

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the Department of Public Works and Town & Country Planning of Thailand, 2015. The schematic overview of EnergyPlus simulation model is illustrated in Figure 1. The house is south-oriented and only the living room, the bedroom 1 and the bedroom 2 are air-conditioned rooms (see Figure 2 and 3). Figure 4 illustrates top view of the roof which has the total roof area of 191.36 m^2.

Coefficient of performance (COP) of the air-conditioner used in Bedroom 1 is 3.92 while COP of the air-conditioners used in the living room and Bedroom 2 are 3.90. The operating schedules of the air-conditioners are shown in Table 1. The indoor temperature set-point for cooling was set at 25ºC.

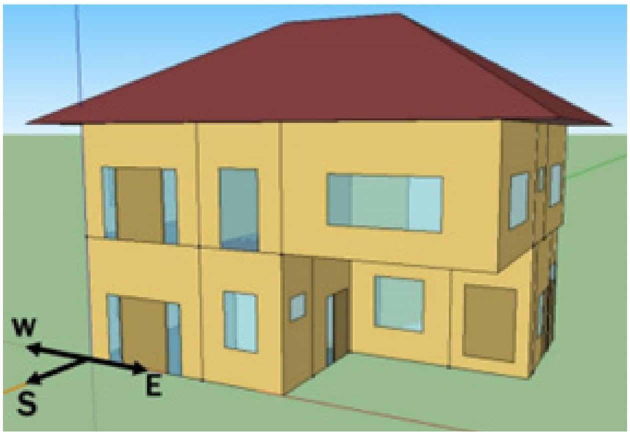

Figure 1 Simulation model

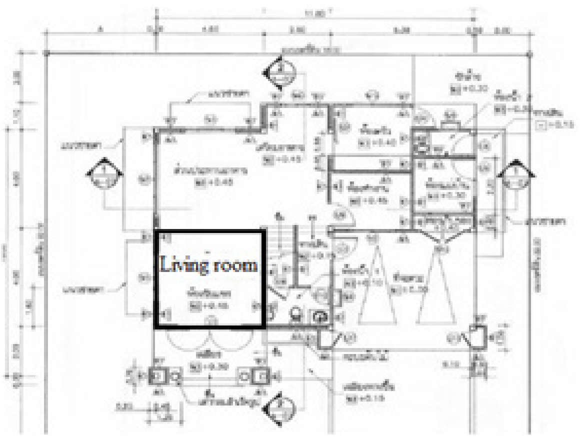

Figure 2 Plan view of the first floor of the simulated house (The Department of Public Works and Town & Country Planning of Thailand, 2015).

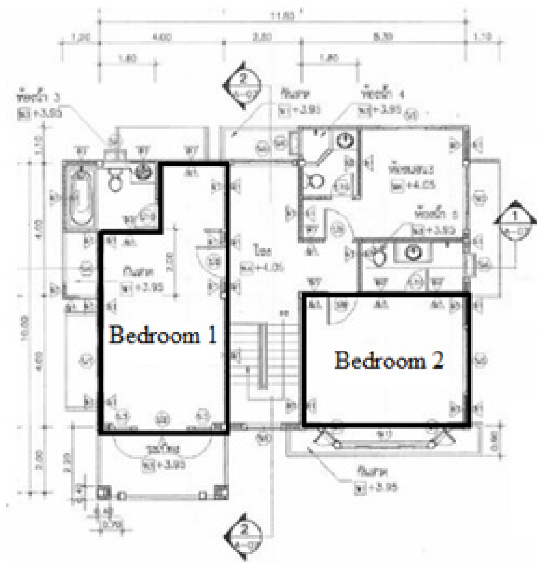

Figure 3 Plan view of the second floor of the simulated house (The Department of Public Works and Town & Country Planning of Thailand, 2015).

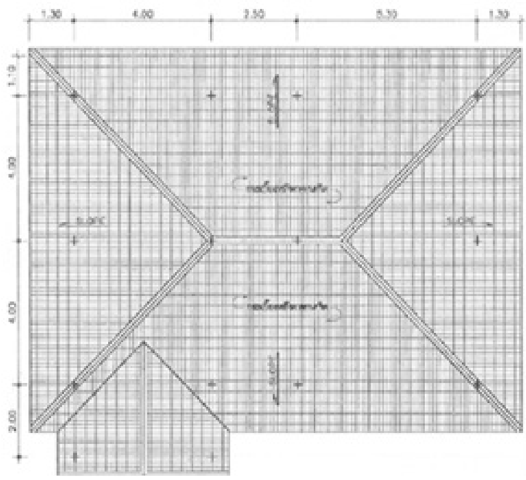

Figure 4 Roof plan (The Department of Public Works and Town & Country Planning of Thailand, 2015).

Table 1 Operating hours, floor area and occupant number in air-conditioned area.

Room	Operating hours	Area (m^2)	Occupant number
Living room	19:00-22:00	16.00	4
Bedroom 1	22:00-06:00	28.40	2
Bedroom 2	22:00-06:00	21.20	2

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In the simulation, Building materials and lamp types were used according to the details given in the house design (The Department of Public Works and Town & Country Planning of Thailand, 2015). The walls made of brick and mortar. The types of lamps and equipment used in each area of the houses along with their schedules are provided in Table 2 and 3.

Table 2 Lamp types and schedules of lighting

Room	Light fixture	Power(W/unit)	Unit	Schedule
Living room	Compact fluorescents	11	4	18.00-21.00
	Fluorescent lights	32	1	
Kitchen	Fluorescent lights	36	1	06.00-07.00, 18.00-19.00
Bedroom1	Compact fluorescents	11	7	06.00-07.00, 21.00-22.00
	Fluorescent lights	32	2	
Bedroom2	Compact fluorescents	44	4	06.00-07.00, 21.00-22.00
	Fluorescent lights	32	1	
Toilet1	Incandescent lights	40	1	06.00-07.00, 20.00-21.00
Bathroom3	Incandescent lights	40	1	06.00-07.00, 20.00-21.00

The analysis was carried out for three types of roof tires (concrete, ceramic and fiber cement) and four types of roof insulation (aluminum foil, fiberglass, polystyrene and polyurethane). The concrete roof tiles without insulation were set as a baseline case. There are total of 13 cases in this study including base case and another 12 cases of variation in roof tiles and roof insulations as shown in Table 4. Gypsum board was used as ceiling for all cases. Table 5 summarizes the thermal properties of roof tiles, ceiling and roof insulations used in this study which were chosen from the materials that are commonly used and available in the market.

The weather data of Bangkok, Thailand was used for the simulation which was directly provided by EnergyPlus official webpage (U.S. Department of Energy, 2015).

Table 3 Types and schedules of equipment

Room	Equipment	Power (W)	Schedule	
			Weekday	Weekend
Living room	TV	80	19.00-21.00	09.00-12.00, 13.00-18.00, 19.00-21.00
	Computer	500	20.00-21.00	20.00-21.00
	Printer	200	20.00-21.00	20.00-21.00
Kitchen	Fan	60	06.00-07.00, 18.00-19.00	06.00-07.00, 12.00-13.00, 18.00-19.00
	Microwave	1000	06.20-06.30, 17.30-17.40	06.20-06.30, 17.30-17.40
	Refrigerator	100	00.00-24.00	00.00-24.00
	Electric hot pot	600	06.00-6.30, 17.30-18.00	06.00-06.30, 17.30-18.00
	Rice cooker	700	06.00-6.30, 17.30-18.00	06.00-06.30, 17.30-18.00
	Washing machine	700	-	07.00-09.00
Bed room1	TV	60	21.00-22.00	21.00-22.00
	Iron	750	-	13.00-15.00
Bed room2	TV	60	21.00-22.00	21.00-22.00
	Computer	500	21.00-22.00	21.00-22.00
Bath room3	Water heater	4400	06.00-07.00, 20.00-21.00	06.00-07.00, 20.00-21.00

The simulation results from EnergyPlus providing energy consumption of the house using different roof tiles and insulations were used to calculate electricity cost by using the normal tariff (type 1.2) for household with consumption exceeding 150 kWh per month (The Metropolitan Electricity Authority of Thailand, 2015) as shown in Table 6. The life cycle cost of each case was evaluated by assuming the project life time at 20 years and 10% interest rate. The life cycle cost accounts material and installation costs of roof tiles, roof insulation, and ceiling, and energy cost.

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Table 4 Types of roof tiles and roof insulation in simulation cases

Simulation cases	Roof tile	Roof insulation
Base case	Concrete	-
case 1	Concrete	Aluminum foil
case 2	Concrete	Polystyrene foam
case 3	Concrete	Polyurethane foam
case 4	Concrete	Fiber glass
case 5	Ceramic	Aluminum foil
case 6	Ceramic	Polystyrene foam
case 7	Ceramic	Polyurethane foam
case 8	Ceramic	Fiber glass
case 9	Fiber cement	Aluminum foil
case 10	Fiber cement	Polystyrene foam
case 11	Fiber cement	Polyurethane foam
case 12	Fiber cement	Fiber glass

Table 5 Thermal properties of roof tiles, ceiling and roof insulation (ASHRAE, 2001, KMUTT, 1998, Bribián et al., 2011)

Materials	Thickness (mm)	Thermal conductivity (W/m.K)	Density (kg/m^3)	Specific Heat Capcity (J/kg.K)
Concrete tile	50.0	0.9930	2400	920.0
Ceramic tile	27.0	1.0000	2000	800.0
Fiber cement tile	5.0	0.5000	1800	1071.5
Aluminum foil	9.0	0.0395	2740	896.0
Polystyrene foam	50.8	0.0350	16	1210.0
Polyurethane foam	50.8	0.0240	24	1590.0
Fiber glass	152.4	0.0360	16	960.0
Gypsum board	9.0	0.1910	880	1090.0

Table 6 Electricity cost (The Metropolitan Electricity Authority of Thailand, 2015)

Energy Charge (Baht/kWh)	
First 150 kWh ($0-150^{th}$)	2.7628
Next 250 kWh ($151^{st}-400^{th}$)	3.7362
Over 400 kWh (401^{st} and over)	3.9361
Service chart (Baht/month)	38.2200
Ft (price in Jan.-Apr. 2015) (Baht/kWh)	0.5896

Results and Discussions

Baseline Case

The electrical energy consumption in lighting, equipment and air-conditioning systems of the baseline case are shown Figure 4. The electricity consumption of equipments accounts for 50%, followed by the cooling load of 45% and the lighting load of 5%. The monthly variation of electricity consumption occurs mainly due to variation of cooling load which varies with the weather. Cooling load is high in summer or pre-monsoon season which lasts from middle of February to middle of May (Thai Meteorological Department, 2015). The highest cooling load occurs in April which is the hottest month in Bangkok (Thai Meteorological Department, 2015). During winter or northeast monsoon season, between mid-October and mid-February, electricity consumption of air-conditioners is low as shown in Figure 5.

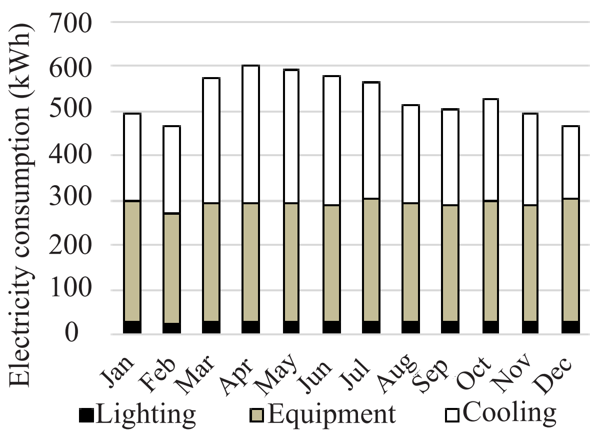

Figure 5 Monthly electricity consumption in lighting, equipment and air-conditioning systems

Analysis of Energy Saving

In all cases of this study, roof tiles and roof insulation materials affect only on cooling load while lighting and equipment loads were unvarying. Figure 6 shows saving in cooling load of different roof systems. Types of roof tiles did not show significant effect on cooling load, while insulation types show major influence on cooling energy consumption. The fiber glass insulation shows the maximum energy saving due to thickness of fiber glass insulation is much higher than other insulations, resulting in high thermal resistance. The results showed that using of concrete roof tiles with fiber glass insulation (case 4) reduces electricity

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consumption of air-conditioners through the whole year by 10.98%.

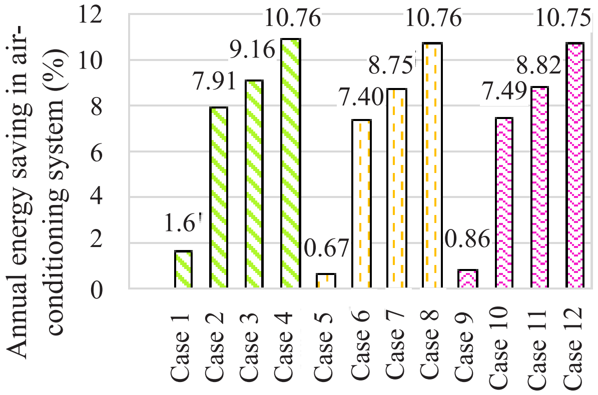

Figure 6 Annual energy saving in air-conditioning system

Analysis of Life Cycle Cost

The material and installation costs of roof tiles, ceiling and roof insulations used in this study are summarized in Table 7. Figure 7 illustrates initial costs of each case. The results show that case 12 has the lowest initial cost due to low tile installation cost and low insulation cost. The LCC of the roofs that use ceramic tiles (case 5-8) is higher than the LCC of another roof tiles considerably (see Figure 8) due to the high material cost of ceramic tiles as shown in Figure 7. Size of fiber cement tile is bigger (0.5 m × 1.2 m) than other tiles (0.33 m × 0.42 m) so it requires less manpower for installation. As a consequence, installation cost of fiber cement tiles is low; resulting in low LCC for the roofs that use fiber cement tiles.

Even though fiber glass insulation shows the highest energy saving in Figure 6 which represents the lowest energy cost, its life time is short. Fiber glass insulation needs to be changed every 5 years while other materials can last 20 years. Therefore, polystyrene insulation provides the lowest LCC among the four types of insulations. As a results of the analysis, the roof that uses fiber cement tiles with polystyrene insulation (case 10) show the lowest LCC among all cases.

Table 7 Material cost and installation cost

Materials	Material cost (Baht)	Installation cost (Baht)
Concrete tile	31,575.00	75,780.00
Ceramic tile	159,067.25	68,910.00
Fiber cement tile	38,962.00	20,240.00
Aluminum foil	49,410.00	1,500.00
Polystyrene foam	43,320.00	1,500.00
Polyurethane foam	72,000.00	1,500.00
Fiber glass	23,136.00	1,500.00
Gypsum board	10,480.00	1,500.00

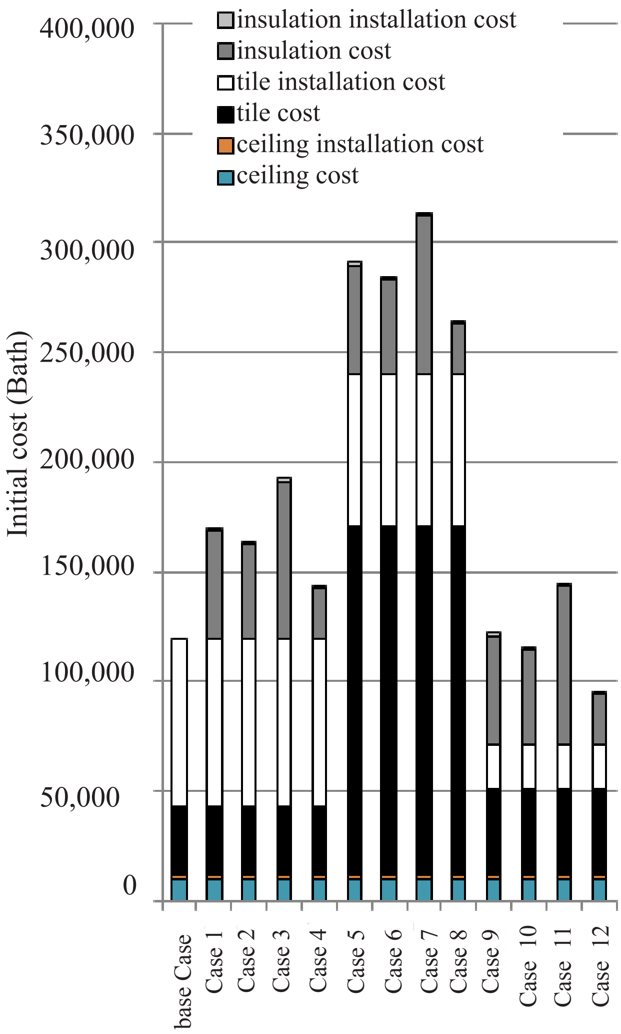

Figure 7 Initial costs of different roof systems

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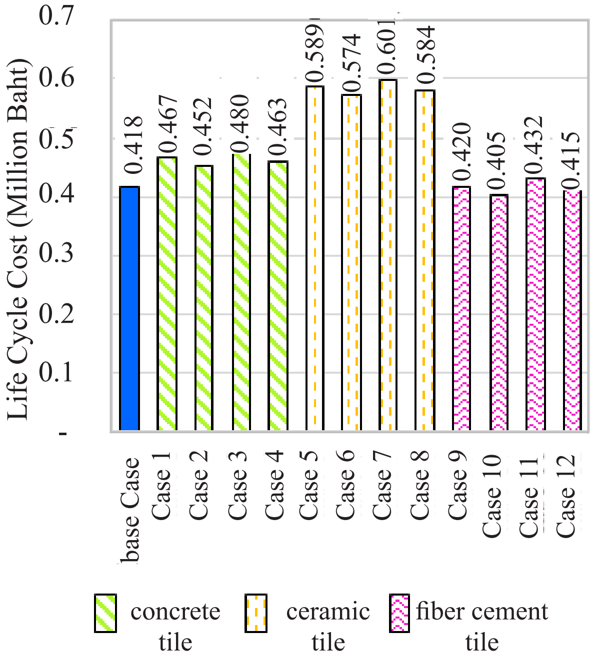

Figure 8 Life cycle cost of different roof systems.

Conclusion

The study clearly shows that considering only initial cost or energy saving separately could not provide the most cost effective option. To choose roof tiles and roof insulation initial cost, operating life time and thermal performance should be considered simultaneously.

For typical modern Thai houses as used in this study, fiber cement tiles with polystyrene insulation show the lowest LCC among all cases.

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