Full Paper

Energy Use and Carbon Emission of Low-medium-income Houses in Northern Thailand

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Abstract: Thailand is located in the tropical region of Southeast Asia. Traditional Thai house design has evolved under prevalent climate conditions and the dwellings are comfortable. Urbanization, shrinking family size, proliferation and ready availability of steel, cement, and concrete as construction materials, change in life style, and increasing penetration of air-conditioning all are factors that have influenced design and choice of materials for the present housing construction and household energy consumption. This will lead to higher energy intensity and higher carbon emission. This paper reports resultant baseline data on house design and construction, and interior thermal and visual environmental conditions of low-middle-income households obtained through physical measurements of selected houses in the northern region of Thailand. Interviews were also conducted with senior female members of the households on general socio-economic information and uses of electrical appliances. Data on house construction obtained enable quantification of embedded energy and carbon of the houses. Information of residential electricity consumption from the distribution utility and other information from the National Statistical Office enables formation of a model of typical household of a middle income family of the northern region, of typical electricity consumption and operational carbon emission.

Keywords: Household surveys, low-income housing, traditional houses, carbon dioxide emission.

INTRODUCTION

This paper reports first results from a multi-partner research project entitled 'Energy and Low Income Tropical Housing' funded under the Energy Programme of the UK Research Council. Partners in this project include Warwick University and Cambridge University in the United Kingdom and organizations in China, Tanzania, and Uganda. The main objective of the project is to identify where and how to improve houses of low-middle-income earners so that the houses are energy efficient and less carbon is emitted due to using them. The main concerns of the project on energy efficiency are energy efficient cooling (if air-conditioning is employed), thermal comfort (if air-conditioning is not employed, and lighting energy use. The project does not intend to directly address the use of household appliances. It is intended that the eventual outcome of the project will lead to reduction of energy use and carbon emission in low-medium-income households. The results reported here pertain to an attempt to obtain baseline data on household construction and thermal and visual conditions in the houses through field investigation and interviews. The next step in the project is to define a set of qualitative and quantitative criteria for energy efficient and environmentally benign house design. The results from the survey will be used to set a reference baseline design.

Thailand is located in the tropical region of Southeast Asia. The climate is hot and humid, although the northern part of the country is further away from the sea than the rest and thus is slightly less humid. Nevertheless, the use of cooling for thermal comfort is becoming common. With electrification reaching practically 100% of households, air-conditioning now penetrates 24% of residential households nationally and 44% of those in the Greater Bangkok area (Bangkok and five adjacent provinces) [1]. The use of air-conditioning is highly energy intensive and are growing annually at over 7% nationally and 4% in Greater Bangkok. The same source reports that electric fans, fluorescent lamps, television sets, refrigerators, electric rice cookers penetrates over 90% of households nationally, while electric iron, electric kettle, DVD player, and washing machine penetrate over 60%. The prevalence of these common household appliances will eventually reach saturation. Kidhen et al. [2] identify 4 categories of end-uses in households that require electricity: lighting, entertainment, amenity, and cooking. Amenity that includes air-conditioning is responsible for about 55% of total electricity consumption and other categories for about 15% each in 2011. The average household electricity consumption is 1,641 kWh per year in 2011. The 2015 Power Development Plan, an official plan used for planning addition of electric generation plants to meet forecasted load in 2036 [3], expects the electric load of residential households to grow from 41.07 TWh in 2015 to 65.37 TWh in 2036. These figures imply that energy use in Thai households would still grow significantly. Many factors could be identified as causes for this phenomenon. These include the facts that use of common household appliances has not reached saturation and that there is significant proportion of families still living under poverty line that will rise above it and use energy more intensively. Also, there is a continuing increase in the number of families due mainly to the reduction of family size. Moreover, the load forecast is likely to under estimate the growth in electricity consumption due to air-conditioning as the load forecast on which the Power Development Plan is based does not yet specifically account for such growth.

The amount of carbon dioxide emission due to electricity consumption by residential households could become more substantial in 2036. Some studies of emission of carbon dioxide during construction or during production of construction materials used in houses have been conducted, although the studies have been undertaken on specific residential and other buildings [4, 5].

Adelaja et al. [6], reasoned that increasing demand for electricity in universities, especially in the University of Lagos, Nigeria, led to electricity outages at peak times. This motivated the authors to conduct an energy audit in the university. The authors found that electricity contributed 97.48% of total energy consumed in four categories of buildings, academic, administration and services, residential, and commercial, and eleven categories of end-uses. Air-conditioning, refrigeration, and electric lighting were found to offer the highest opportunities for energy efficiency improvement. Yao et al. [7], reported that from 2001 to 2008, Chinese rural residential energy consumption was in transition from traditional sources to commercial and new renewable sources with increasing overall consumption and carbon emission due to rising income of rural population. The share of traditional biomass energy dropped from 81.5% in 2001 to 70.9% in 2008, commercial energy increased from 17.1% to 25.1%, and biogas and solar energy increased to 19.8%. The authors recommended to change the energy mix of electricity generation and to promote energy conservation in order to reduce carbon emission. Zheng et al. [8] conducted a survey of 1450 households in 26 provinces of China. The survey methodology was developed from that of the Residential Energy Consumption Survey of the Energy Information Administration of the US Department of Energy. The survey includes six categories of information: demography and socioeconomic condition, dwelling configuration, end-use pattern and appliances, space heating and cooling, transportation, and energy usage and cost. It was found that an average household consumes 1,426 kg of coal equivalent per year, which was equal to 44% of that in the USA. Space heating took the highest share of end-use energy consumption (56%), followed by cooking (23%), water heating (14%), home appliances (7%), and cooling (2%). While urban households rely on commercial energy, rural households still rely heavily on firewood (59% of total). Praseeda et al. [9] examine 16 buildings located in 5 climate zones of India to compare embedded and operational energy of each building. The building structures mainly comprise walls, roofs and floors, doors and windows, and foundation. The authors report that the share of embedded energy and of operational energy in life cycle energy of 50 years depend on the types of materials used in construction and the extent of space conditioning adopted. Buildings with high content of reinforced concrete frame and walls have the highest embodied energy. The authors report that from the 16 buildings studied, there is no clear correlation between building mass and embodied or operational energy. Comparing operational energy of Indian residential buildings with those reported in literature imply that those from India are lower. Villareal and Moreira [10] report that per capita electricity consumption in Brazil in 2011 was 2,940 kWh. Share of residential consumption in 2013 was 26% of the total and grew at 4.9% per year between 2003 and 2013. The authors undertake linear regression analysis on quantitative data of electricity consumption, household size, household income, and electric tariff for the residential sector provided by Instituto de Pesquisa Economica Aplicada to obtain elasticity values of electricity consumption with respect to family size, income, and tariff of 1.53, 0.188, and -0.233 respectively. The authors conclude that tariff is an effective measure to curtail demand for electricity.

This paper first presents a summary on demography and socio-economic condition of the northern region obtained from reports. It then describes the methodology used in the field investigation. Discussion of results from the field investigation and conclusion are then presented.

A SUMMARY ON DEMOGRAPHY AND SOCIO-ECONOMIC CONDITION OF THE NORTHERN REGION

As a part of the preparation for field data acquisition, reports on demography and socio-economic condition of the northern region were examined. The followings form background information for comparison with that from field investigation.

Population

The results of the population and housing census conducted by the National Statistical Office (NSO) in 2010 show that the Thai population has reached 65.98 million. The comparative data from 1990, 2000, and 2010 also show that the national population growth and family size have steadily declined to 0.8% and 3.1 persons, while the number of households has grown to 20.52 million as shown in Table 1 [11, 12]. The size of the aged population, those over 60 years, has also increased significantly. There is also a marked increase in the number of single-member families. Urbanization has reached 44.2% nationally. Similar trends are observed for the northern region of Thailand except for population growth which is observed to be lower than the national average. This is due largely to migration of people in the region to Greater Bangkok for better job opportunities. The migration also results in smaller family size. There is also less urbanization in the northern region.

Table 1. Population, size, and number of households from national censuses.

Description	1990		2000		2010	
Demography	**National**	**North**	**National**	**North**	**National**	**North**
Population (million)	54.55	10.58	60.92	11.43	65.98	11.66
Population in urban area (%)	29.4	20.7	31.1	20.6	44.2	34.6
Population growth (%)	1.96	1.54	1.10	0.77	0.80	0.19
Aged population (%)	7.4	8.4	9.5	11.2	12.9	15.3
Household						
Number of households (million)	12.37	2.63	15.94	3.20	20.52	3.77
Members per household	4.4	4.0	3.8	3.5	3.1	3.0
Share of single-member family (%)	5.1	4.9	9.4	8.9	18.4	18.1

Income and Poverty

The census mentioned above [13], reveals that annual average household income reached about 300,000 THB or about USD 10,000 in 2010 and the share of income from agricultural activities was 14.5% nationally and 21.6% for the Northern Region, as shown in Table 2. The figures for the Greater Bangkok are also shown for comparison.

Table 2. Monthly income per household in 2013.

Geographical area	Total (THB)	Wage and Salary (%)	Small Business (%)	Agriculture (%)	Others (%)
Whole Kingdom	25,194	40.8	18.5	14.5	26.2
Greater Bangkok	43,058	58.5	21.2	0.3	20.0
North	19,267	28.7	19.7	21.6	30.0

The World Bank defines poverty line as the income level below the level necessary to meet basic needs. This level is not absolute. From a publication of the World Bank, the poverty head count ratio at USD 2 per day (PPP) as percentage of Thai population is 3.5% in 2010, but is *none* at USD 1.25 per day in 2013 [14].

The National Economic and Social Development Board (NESDB) of Thailand, defines the Thai poverty line on the assumption that food accounts for 60% of overall consumption of people at the line. At the poverty line, 60% of its value is the amount required to satisfy the basic need for food per person per month [15]. Table 3 shows the poverty lines and poverty ratios at the national and regional levels from 2007 to 2011 [16]. The northern region has higher poverty ratio, at 16% in 2011. The Thai poverty line is higher than USD 2 a day and most rural people under or at the poverty line have their own houses.

Table 3. Poverty line and poverty ratio at national and regional level from 2007 to 2011.

Poverty line	2007		2008		2009		2010		2011	
	THB	Ratio, %	THB	Ratio, %	THB	Ratio, %	THB	Ratio, %	THB	Ratio, %
National	2,031	20.94	2,170	20.49	2,220	19.08	2,305	16.91	2,422	13.15
Bangkok	2,565	3.55	2,677	2.26	2,722	2.89	2,778	2.43	2,910	1.83
North	1,792	26.53	1,925	28.68	1,974	24.79	2,055	22.85	2,160	16.04

Note: The figures of poverty lines are derived from the income of a person per month; the ratios are the ratios of the number of persons living under the poverty line to the total number of people.

Housing

The traditional Thai house known as 'Ruen Thai Derm' is a wooden house on a platform raised up on posts by a floor height and capped with a gabled tapering roof. The house is well ventilated by open windows and doors and is well shaded by extended roof. Such houses are commonly situated near rivers, water ways, or close to ponds [17, 18]. Scarcity of hard wood and the changes in environment due to construction of roads and other factors influence tremendously the features of and materials used in modern houses.

From the 2010 national census, the Bureau of Statistical Forecasting reported that 77% of families in the whole kingdom and 90% of families in the northern region lived in detached houses as shown in Table 4. The same census also recorded that almost all dwellings were constructed with concrete block and cement only (54%), wood only (23%), and a combination of concrete block and cement and wood (22%).

Table 4. Types of dwellings, percent.

Type of dwellings	National	Bangkok	North
Detached house	77.3	45.7	90.2
Twin/town house	7.3	25.3	1.5
Shop house/row house	12.9	25.6	6.3
Flat/condominium	1.8	2.8	1.3
Others[*]	0.7	0.6	0.7

[*]Includes raft, room in office, dormitory, prison, and welfare homes.

METHODOLOGY OF FIELD DATA ACQUISITION AND INTERVIEWS

In order to gain detailed baseline data on configurations and constructions of houses of target group, it was decided to conduct field investigation that involves measurements of parameters related to thermal and visual environmental conditions and interviews of ten detached houses selected by a local village head in Chiangmai Province of the region.

The field data acquisition and interviews aims to obtain information on the items shown in Table 5.

Table 5. Data to be acquired from the investigation of sample houses.

Item	Details
House history, configuration and materials	Configurations, dimensions and material used on roofs, glazing and walls.
Indoor thermal and lighting condition	Visual and thermal sensation at the time of interview when illuminance, air temperature, relative humidity, wind speed, radiant temperature (from globe thermometer), and CO_2 were simultaneously measured.
General information	Income, education, age, family size, etc.
Appliance uses	Appliances and duration of use for lighting, cooking, entertainment and, amenity.
Trends in appliance use	Occupants' views on trend in acquisition and replacement of appliances and switching of fuels used, e.g. for cooking

The activities took place in September 2014. Lighting and data pertaining to thermal environment were measured by sensors and recorded on a data logger. The measuring instruments, except the illuminance meter, were housed on a stand placed near the interviewee(s) in order to obtain data on thermal environmental conditions at positions close to the interviewees. Photographs were also taken on both the interior and exterior of the house. In all cases, photographs were taken in the living quarter where the interview took place. In some cases, photographs were taken in all quarters of a house. The occupants were interviewed based on a prepared questionnaire. The interviewers carried with them prepared information on the electric power rating of types and makes of appliances and inspected each appliance during the interview.

Each data acquisition team comprised two groups. One group conducted the interview while the other group inspected and photographed appliances used in different quarters and took note of the dimensions and materials used for the roof, walls, windows, and floors.

RESULTS AND DISCUSSION

Data on socio-economic conditions from the field data acquisition are generally consistent with those from the census report published by the Bureau of Statistical Forecasting of the National Statistical Office. Measurement and observation data obtained include house configurations and constructions, indoor thermal and lighting conditions.

Socio-economic and Demographic Data

The number of members in a family in the investigated households varies from one to six as shown in Table 6. It is noted that there are two distinct groups, where the family sizes in the first group are only up to two persons, and the family sizes in the second group are at least five. In the former group, the family members are either an elderly single person or two elderly persons, whose working age offspring are employed in the cities. The second group comprises extended families where elderly grandfathers and/or grandmothers live with the families. The occupation of these families in the second group is farming. These insights can be used to partially explain the statistics in Table 1. Availability of jobs in the cities is drawing away working age families from homes and the number of farmers is still shrinking. The average family size found is 3.3. This figure is comparable to the figure of 3.0 for the northern region in Table 1.

Table 6. The number of households in each family size.

Family size, persons	Percentage (%)
1	20
2	40
5	10
6	30

Table 7 shows the number of persons in each age range of the households. The number of persons at age below 15 equals that of the elderly people (over 60 years old), and each constitutes 15% of the total. The same proportion of elderly residents and the phenomenon of population aging are also observed regionally and nationally [19]. Moreover, an increasing percentage of old age people live alone, as can be observed in Table 7 and noted in [20, 21]. The references also note that education and employment opportunities draw children and working age people away and leave elderly parents at homes.

Table 7. Age distribution of the residents.

Age, year	Percentage (%)
Less than 15	15.2
16-30	12.1
31-45	27.2
45-60	30.3
More than 60	15.2

In terms of family income, 90% of the families earn less than THB 15,000 per month as shown in Table 8. Examining the figures in Table 2 and Table 3, the families fall into the category

of low to medium income earners. Table 9 shows that 55% of household members are unemployed (retired persons and students), only 26% are privately employed near where they live and 6.4% are farmers with low income.

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Table 8. Distribution of family incomes.

Family Income	Percentage (%)
Less than 5000	40
5001-15000	50
15000-30000	0
More than 30000	10

Table 9. Occupation of members in the families.

Occupation	Percentage (%)
Unemployed (retired)	25.8
Farmers	6.4
Students	29.0
Government employees	6.5
Small commercial services	6.5
Employees (private)	25.8

House Configuration and Construction

As is common for houses in rural areas, the selected houses are all single detached houses. The older houses (more than 20 years), two out of ten, are constructed of wood and retain general features of original Thai houses with well-shaded windows from extended roof. However, the original platform or floor of these houses has been lowered almost to the ground level while the original walls and pitched roof are retained. Corrugated fiber cement tiles are used as roofing material (available since more than 40 years ago). Figure 1 shows a photograph of one such house where it has a single story. It was discovered from the interview that as the owners aged, it was difficult for them to climb up the steep traditional stairs used in the old houses. Besides, the families were becoming smaller, so there was no need to retain two floors.

Figure 1. A one-storied house constructed from wood.

All houses surveyed have only one floor. Two of the remaining houses are constructed of concrete block and cement and wood and are more than ten years old. The parts of the walls under windows are constructed of concrete block and cement, and the upper parts comprise wood salvaged from original wooden walls (Figure 2 a)). The wall is laid up layers by layers of concrete block, bonded by cement mortar and plastered on both sides with cement mortar to form a smooth surface. The remaining houses are less than ten years old and are all constructed of concrete block and cement (Figure 2 b)). Hard wood suitable for housing construction are now scarce. The sample houses in the survey show clear trend that concrete block and cement was the choice in the recent past. Such houses are sturdy and promote a sense of security. To some owners, such construction represents a modern trend.

a) b)

Figure 2. A one-storied house of concrete block and cement and wood and a) and a house of concrete block and cement (b).

The ratio of the number of houses constructed with concrete block and cement only, wood only, and concrete block and cement and wood from the survey is 3:1:1, while the ratio reported by the Bureau of Statistical Forecasting from the 2010 census in is 2:1:1.

Floor Shape and Area

A common feature of all the houses is that the layout or the shape of the floor is rectangular. Among the older houses the interior comprises a single space without interior wall. The owners used a part of the interior space as living quarter. At night, mattresses are laid on the floor at another location and mosquito nets are strung above the mattresses. The kitchen and toilet are located in opposite directions in an extended area at the back of the house.

The floor area of the houses varies from 32 to 90 m^2. The average floor area is 72 m^2 and the average area per person is 34.4 m^2.

Thermal Environment and Thermal Comfort Assessment

Field studies of thermal comfort have been undertaken in Thailand in cities and urban areas. The first result of such studies was reported by Busch [22], where office workers in government buildings and bank branches were subjects. The author reported that the mean thermal sensation vote of subjects in the air-conditioned spaces was four degree Celsius lower than that for subjects in

un-conditioned spaces. All studies were conducted in public spaces. One study was conducted by Khedari et al. [23] where the authors used 183 male and 105 female university students as subjects in naturally ventilated spaces. Fans were used to enhance air flow at speeds of up to a few meters per second around the bodies of subjects. At air speed of 0.2 m/s, the mean thermal sensation vote was 27.2 °C (dry-bulb temperature). When the air speed was increased to 0.5 m/s, the mean thermal sensation vote was 28.3 °C.

For the houses visited, major features of traditional houses such as extended roofs that shade solar radiation well and open windows and doors that allow air to flow through, well, were present in the houses. In addition, most houses had a ceiling under roofs that helps reduce thermal radiation from the roofs into the spaces below. During the period of visit, the interior air temperature and radiant temperature did not differ to significant extent from the exterior ambient temperature. This condition prevailed in most houses and made it sufficiently amenable for residents to live in the houses. September month is in the late rainy season, and the air would be humid and hot as the sun is near the zenith at noon. Table 10 shows the results of the measurements of interior environmental parameters. The range of air temperature recorded during the time of visit (daytime only) is typical for the time of the year. The non-zero air speed implies that fans were turned on and the houses were well ventilated. The relatively low level of carbon dioxide recorded implies that the spaces were sufficiently naturally ventilated.

Table 10. Values of thermal environmental parameters.

Range	Air temperature, °C	Relative humidity, %	Radiant temperature, °C	Air speed, m/s	Carbon dioxide, ppm
Maximum	34.1	70.3	34.5	0.8	537
Minimum	30.6	58.9	31.1	0.2	460
Mean	32.4	65.1	32.6	0.6	494

For thermal comfort assessment, the ASHRAE 7-point scale was used. The interviewee(s) would be told to equate the +3 point to the condition that he/she would feel when he/she was seated at the same position during daytime in the month of April (warmest in Thailand), and the -3 point to the December (coolest month). Figure 3 shows plots of the thermal sensation values (TSV) obtained against operative temperatures, T_o. As is expected, most respondents reported 'warm and too warm' sensations even when electric fans were on. For this group of respondents, the neutral temperature was obtained as 29.2°C. This is a projected value and is outside the range of air temperatures measured, but is not unexpected. Memon et al. [24] also arrive at a similar projected mean thermal sensation value of 29.3°C from a study in a tropical location in Pakistan. Similar mean thermal sensation values are reported by Khedari, Yamtraipat [23] and Busch [22] for subjects in naturally ventilate spaces. A few respondents even reported being satisfied with the thermal environment as can be surmised in Figure 3. Note that the respondents here were residing in their private quarters, not in public spaces.
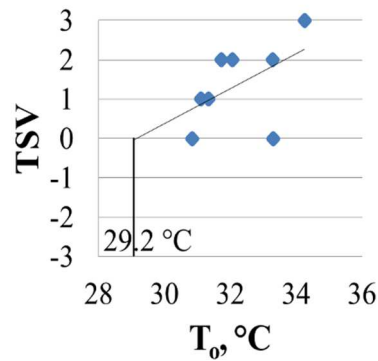
Figure 3. A plot of thermal sensation values against operative temperatures.

Lighting Condition

Daylight illuminance at the work plane level in the living quarters and bedroom was measured by an illuminance meter. Table 11 shows the resulting values. Most values are as expected but deemed to be on the slightly low side. Wooden walls were not painted and the color of the surfaces appeared dull brown and has low reflectance for light. Spaces enclosed by such walls would tend to be less illuminated. No measurement was recorded in three houses. The values corresponding to those of house no. 7 and 8 appear to be too low. One occupant in house no.7 was ill and so windows were intentionally closed to reduce light. The occupant in house no.8 did not reside in the house and windows were closed.

Table 11 Values of illuminance at work plane level, lux.

Space	House number										Average
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	
Living quarter	-	225	200	740	-	-	42	70	250	424	278
Bedroom	-	-	-	-	-	-	-	-	-	265	165

Electrical Appliances and Electricity Consumption

Table 12 shows average number of each type of 18 appliances per household of the year 2004 and 2015. The figures in three leftmost columns of numerical values are obtained from reports of Bureau of Social Statistics, [1, 25]. Such list of 18 appliances for the whole country is available from the Bureau from 2000 to 2015. For the northern region, such list is available for up to 2004 only. Results from the field survey in 2014 are shown in the fourth numerical column in Table 12. The figures for most items in the lists from the bureau show certain degrees of saturation, except for personal computer, air-conditioner, electric heater for shower, microwave oven, and electric oven. These five items clearly are not yet near saturation.

Table 12. Average number of electric appliances per household.

End-use Category	Appliance	Year				
		2004		2015	2014 Filed data acquisition	
		Whole country	Northern region	Whole country	Appliance	% share of electricity
Lighting	Long fluorescent lamp	5.32	5.28	5.43	6.1	9.9
	Compact fluorescent lamp	0.23	0.16	1.23	0.8	
	Incandescent lamp	0.28	0.31	0.32	0.1	
Entertainment	Television set	1.12	1.10	1.36	1.3	8.8
	VDO/VCD/DVD/Blu-ray player	0.66	0.56	0.51	0.4	
	Radio	0.70	0.71	0.51	0.0	
	Personal computer	0.13	0.11	0.29	0.2	
Amenity	Electric fan	2.09	1.95	2.57	2.5	65.6
	Refrigerator	0.80	0.83	0.99	0.9	
	Electric iron	0.77	0.72	0.83	0.4	
	Washing machine	0.36	0.42	0.66	0.3	
	Air conditioner	0.17	0.10	0.38	0.3	
	Water heater for shower	0.10	0.14	0.19	0.5	
Cooking	Electric rice cooker	0.83	0.81	0.99	0.7	15.6
	Electric kettle	0.57	0.51	0.72	0.60	
	Microwave oven	0.10	0.07	0.23	0.30	
	Electric oven	0.12	0.13	0.15	0.10	

The figures in the table good correspondence with those from the Bureau. Average electricity consumption per household per month was obtained as 191.7 kWh. Electricity consumption from the use of each appliance was calculated by multiplying the average time of use, obtained from the respondents, with the power rating of the appliance. The figures of electricity consumption obtained are grouped into the corresponding category and expressed as percentage of the total. These appear in numerical column five of Table 12. The percentage figures roughly correspond with those reported by Kidhen etal [2], but the percentage of the amenity category here is larger.

Figure 4 shows plots of electricity consumption per month against floor area of household, family size, and family income. All three plots exhibit certain degree of correlation between electricity consumption and each of the three parameters, but its correlation with family income is clearest. The top electricity consumers are also the households that have air-conditioning and electric hot water heating. The results are similar to those in [7], where it is reported that the income of rural farmers is the main factor that influences the consumption of commercial energy.
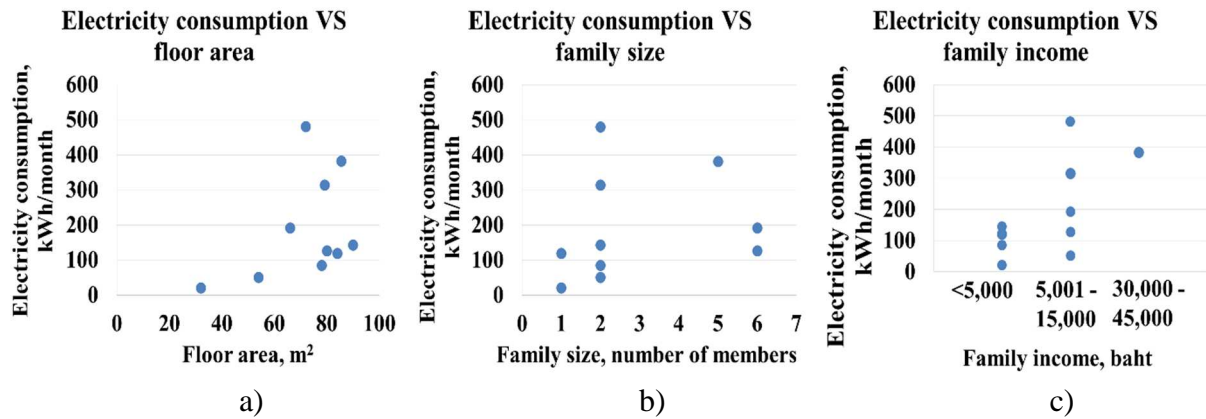
Figure 4. Plots of electricity consumption against floor area (a), family size (b) and family income (c).

Carbon Dioxide Emission

This paper considers carbon dioxide emission from a house in two parts. One part is the indirect carbon dioxide emission due to the production of the amount of electricity consumed by the household. This part is also called operational carbon dioxide. The other part is the carbon dioxide emitted during production of materials used to construct the house, called embodied carbon dioxide.

The average monthly electricity consumption obtained from the houses investigated may not represents that from an average house in the northern region. From the report of electricity consumption that appears in the website of NSO [26], electricity consumption by residential households in the northern region in 2014 was 4,942.4 GWh and the total number of households is given as 3.77M [27], thus electricity consumption of an average household in the northern region in 2014 was 1,310.9 kWh. This figure is smaller than that obtained from the houses investigated.

The houses investigated comprise some houses that are constructed from wood, some that are constructed from a combination of concrete block and cement and wood, and some that are constructed from a combination of concrete block and cement. However, it is clear that the trend in the near future is the preference for concrete blocks and cement for walls. Materials for construction are readily available, the time required for construction is short, and the finished wall is durable, sturdy, and economical. In the following sections, a house model is used that is envisaged as a representative detached house of the northern region. Calculation will be made on carbon dioxide emission from construction materials used and operational carbon dioxide emission from the consumption of electricity of the model house.

Figure 5 shows a perspective rendering of the model house. There is an external space under the roof in front of the house. This space is used to welcome casual guests or for casual relaxing activities in the early morning or early evening.
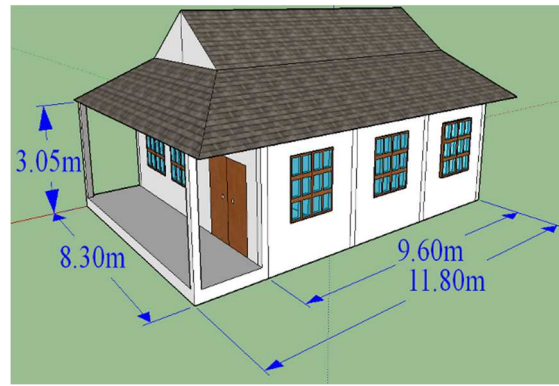
Figure 5. Perspective view of the house model.

The house has a rectangular shape and its dimensions are: length 9, width 8.3 (area 75 m²), and height of 3 m. The house has two bedrooms. The kitchen, cloth washing area, and restroom (toilet and bathroom) are located on a separate but adjoined space at the back of the house. The supporting columns are steel-reinforced concrete. The walls are constructed from concrete blocks that are bonded by cement and plastered with cement mortar. The pitched roof comprises corrugated fiber cement tiles laid on metallic support. The ceiling comprises fiber cement panels. The windows comprise flat 5 mm glass with wooden frame. The doors are made of wood. The floor is constructed with reinforced concrete. Such simple houses are common among low-middle-income households where local contractors are employed to build them. For a small house of this size, the Building Control Act does not have a requirement that qualified architect and engineer be employed to design it.

Table 13 shows quantities of building materials used, emission factors used in these calculations with references, and calculated carbon dioxide emissions from each type of material used and total embodied carbon dioxide.

Table 13. Quantity and type of construction material, emission factor and CO_2 emission.

Item	Quantity, kg	Emission factors, kg CO_2/kg material	Reference	Emission, kg CO_2
Sand	7,914	0.081		641
Concrete slab, column and beam	35,314	0.107		3,779
Cement	6,806	0.74	University of Bath, 2011 [28]	5,037
Concrete block	14,826	0.078		1,156
Steel	795.80	1.46		1,162
Roof tiles	2,104	0.78		1,641
Fiber cement panels	768	1.09		837
Lime	747	0.78		583
Glass	195	0.59		115
Total				14,950

Note: University of Bath is the university bearing this name in the United Kingdom.

The top major contributors to the emission are concrete, cement, and steel. Here, wood is not counted, although in some situation it could be considered to contribute negatively.

Alternative materials *used for walls* include bricks and light weight concrete. Traditional bricks used for construction of walls in Thailand are formed from mud into a rectangular shape of length of 8 by width of 4 inches and one inch thick. The dry formed mud is then fired using a combination of rice husk and wood into bricks. Walls made of such bricks are still constructed in rural areas. The drawback on the use of such bricks for a wall is that it takes longer to lay such bricks layer-by-layer to from a wall. Concrete blocks of larger size have been introduced to replace such bricks. Blocks of light weight concrete of even large sizes have been introduced to replace concrete blocks, but its penetration in rural areas is still limited.

Table 13 summarizes embodied carbon emission from the reference house model. The electricity consumption of an average house in the northern region in 2014 is 1310.9 kWh/Y. The life of such house is assumed to be 50 years and this is a commonly assumed value [29]. In order to calculate operational carbon dioxide emission, the value of emission factor of power generation is required. In Thailand, the present Power Development Plan announced in 2015 (PDP15) [30] includes 20% of renewable energy and two 1,000 MW nuclear power plants at the advanced stage of the plan. The values of emission factors in the plan are shown in Figure 6 a) with a least-square-fitted linear trend. The average annual electricity consumption per household in the northern region is assumed to increase in the same trend as that of electricity demand of the whole residential sector (business-as-usual case) projected to 2036 in PDP2015, as shown in blue line in Figure 6 b). The red lines in both figures extend the same trends further to 2066.
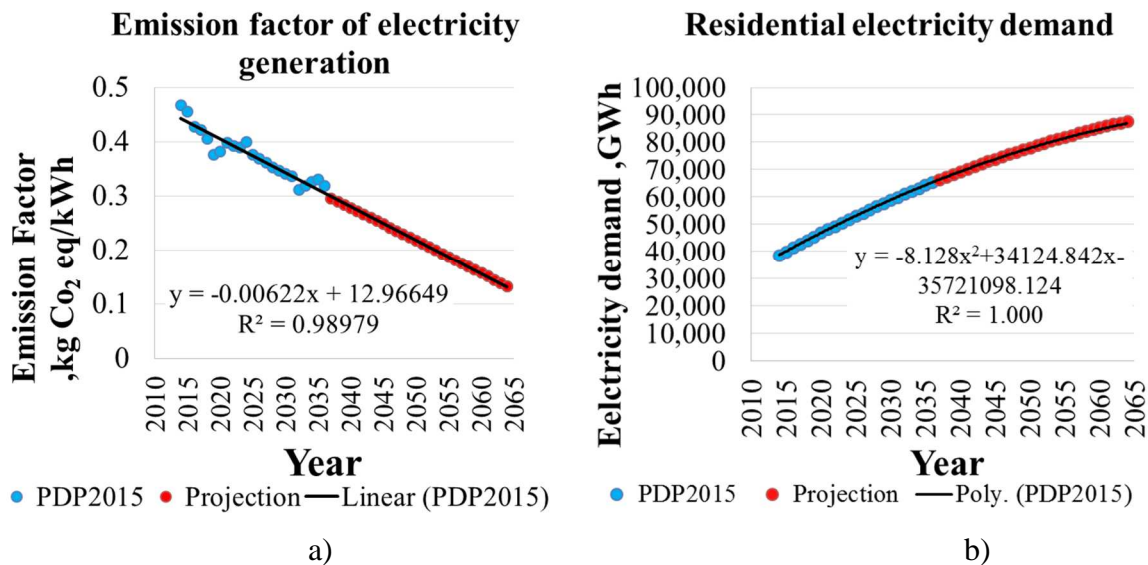

Figure 6. A plot of emission factor a) and residential electricity demand b) over the period of the PDP15 and their trends to 2066.

Using the planned values for up to 2036 and using the project values from the trend line to 50 years, total operational carbon dioxide emission for a 50-year life of the reference house is calculated at 30,714 kg.

Table 14 shows total embodied carbon dioxide emission of the reference house in Figure 5 and four alternatives. The alternatives are identical to the reference except that the walls of each are constructed from alternative materials listed on row number two in the table. Even though different materials used for walls result in significant difference in embodied carbon dioxide, operational carbon dioxide emission is much larger. The total emission is dominated by the operational carbon emission.

Table 14. Embodied carbon dioxide of the house models constructed from various wall materials.

Type of carbon emission	Main material of walls				
	Concrete block and cement	Wood, concrete block and cement	Wood	Light weight concrete	Brick
Embodied carbon dioxide, kg CO_2	14,950	9,622	6,781	15,285	13,575
Embodied and operational carbon dioxide, kg CO_2	45,664	40,336	37,495	45,999	44,289

The resulting extent of energy use and carbon emission obtained above will be used as the reference values for the Northern Region in the project.

CONCLUSION AND POLICY IMPLICATIONS

The socio-economic conditions of the interviewed households match those from the national census, so that a model house with detailed features and construction could be formed to represent contemporary (and immediate future) houses of low income earners of the northern region. From the results on electricity consumption and construction materials identified, carbon dioxide emission from construction materials used ('embodied carbon dioxide') and emission from occupants' daily home activities that consume electricity have been quantified. The investigation on thermal comfort illustrates that rural houses are reasonably comfortable with natural ventilation, at least during the duration of the field investigation. Present house design and features also allow natural daylight into the interior during daytime without the need for electric lighting.

Thailand has adopted an energy conservation plan since 2011 [3]. The plan for residential buildings dwells mainly on voluntary programs for energy efficient appliances, especially air-conditioners and hot water heaters. There is no specific program on the house design and construction since no suitable information was available during the plan development. Implementing building energy standards and codes are effective means to foster energy efficient buildings [31, 32]. Adopting and enforcing a mandatory code on residential buildings is unlikely to be accepted in Thailand soon. Introducing and promoting a voluntary rating scheme for design of residential houses is plausible. Granadeiro et al. [33] consider that the most significant component that affects energy performance of a building is the building envelope. The energy and environmental rating scheme for house design will therefore addresses the building envelope. This will include development of an energy performance indicator for thermally efficient and cost effective walls and roof. The scheme will include a requirement of the design that enhances sufficient natural flow of air for ventilation and thermal comfort and entry of daylight for lighting. The rating scheme will utilize information from this study to form baseline design and include guidelines to achieve more efficient and more environmental benign cost-effective design.

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