Simulation Model

The working model is very similar to the conceptual model shown in Figure 9. Notable changes are: (1) Removal of conceptual variables and links not simulated ("AC Contribution to Urban Heat Island", "Awareness of CSB Benefits," the link between "Ambient Temperatures" and "AC Ownership," and the link between "Median Household Income" and "Demand for Residential CSB." (2) "Ambient Temperatures" is replaced with a series of variables indicating the number of days per year where a given ambient temperature is experienced at 11 p.m. (3) "Housing Demand" is expanded into the full causal relationships shown in Figure 4. (4) "Thermal Preference" is broken down into three parameters in the logistic equation describing the thermal preference curve. (5) The negative relationship between "CSB Fraction of Residential Buildings" and "AC Usage" is replaced with two positive relationships linking "Quantity of Residential CSB" with "AC Usage" and "Quantity of Residential CIB" with "AC Usage;" because the "Quantity of Residential CSB" has a smaller positive effect on "AC Usage" than "Quantity of Residential CIB," the net relationship between "CSB Fraction of Residential Buildings" and "AC Usage" is indeed negative.

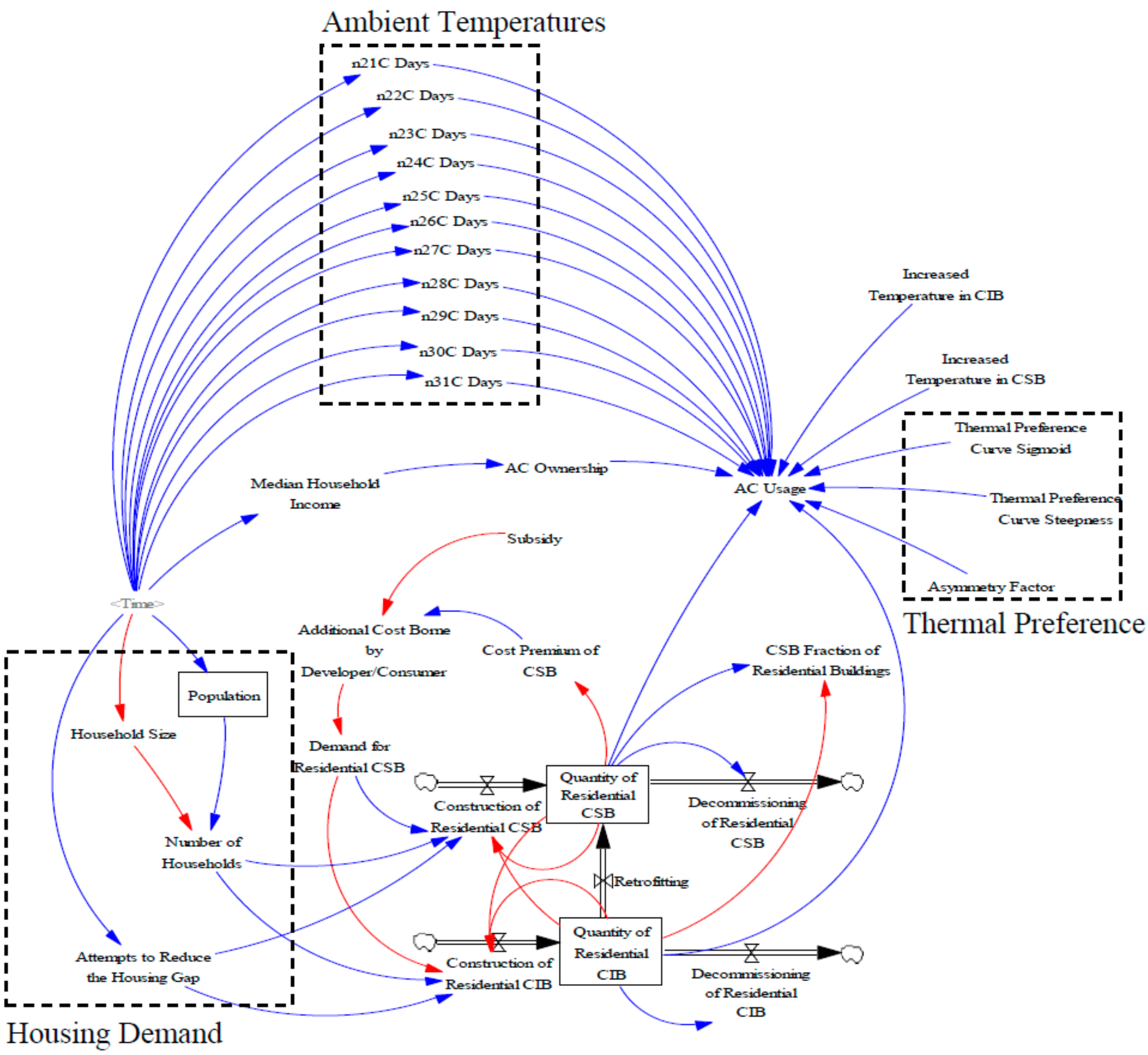

Figure S1: Vensim working model for evaluating subsidy effects on climate-sensitive uptake and night-time air-conditioning use. Blue arrows denote positive causal links while red arrows denote negative causal links. Variables and equations are detailed in Table S1.

Table S1: Model Variables, Equations, and Parameters

Variable	Equation	Variable/ Parameter range	Descriptions/Source
Time	t	t: 0-50	***Time*** steps of 1 year employed in model. The time counter runs from 0-50, representing year 2015 to 2065
Population	$a_1 \times 10^3 \times \text{Time}^2 + a_2 \times \text{Time} + a_3$	a_1: -4.494*10^3 a_2: 5.207*10^5 a_3: 3.12*10^7	2nd-order polynomial fit to projected population data (2015-2040). A graph of projected population and the fitted curve is shown in Figure S13. Source: [57]
Household Size	$b_1 + b_2 \times \text{Time}$	b_1: 4.154 b_2: -3.078*10^-2	Linear fit to Malaysia household size from 1980 to 2010 together with projections for 2020 (5.22 in 1980, 4.92 in 1991, 436 in 2000, 4.31 in 2010, projection to be 4 in 2020). Sources: [57-58]
Number of Households	$\frac{\text{Population}}{\text{Household Size}}$		
Attempts to Reduce the Housing Gap	Fixed: c_1 Reduced/CIB Int: $\frac{c_1}{\left(1 + \frac{\text{Time}}{c_2}\right)^{c_3}}$	c_1: -2,500,000 c_2: 15 c_3: 3	Variable used in scenario analysis of different strategies for shrinking the housing gap. Scenarios: Fixed (baseline) assumes the housing gap stays at the current 2.5 million. Reduced and CIB Int assumes the housing gap is reduced by half over a 15-year period, following a logistic decay curve.

			Source: [37]
Cost Premium of CSB	$d_1 \times \text{Quantity of Residential CSB}^{d_2} + 1$	d_1 and d_2 fitted to progress ratio (0.75-0.9) and initial value (5-10%). Baseline: $d_1 = 59.86$ $d_2 = -0.3219$ High progress ratio: $d_1 = 163.7$ $d_2 = -0.415$ Low progress ratio: $d_1 = 17.94$ $d_2 = -0.152$ Low initial cost premium: $d_1 = 14.96$ $d_2 = -0.3219$ High initial cost premium: $d_1 = 134.7$ $d_2 = -0.3219$	Variable used in sensitivity analysis for progress ratio and initial cause premiums. Power law equation describing experience curve of cost premium for various assumed initial values, progress ratios, and an irreducible cost-premium value of 1%. Sensitivity analysis: Baseline: initial cost premium of 5%, progress ratio of 0.8 High progress ratio: initial cost premium of 5%, progress ratio of 0.75 Low progress ratio: initial cost premium of 5%, progress ratio of 0.9 Low initial cost premium: initial cost premium of 2%, progress ratio of 0.8 High initial cost premium: initial cost premium of 10%, progress ratio of 0.8
Subsidy	f	No subsidy: f = 0	Variable used in all scenarios and sensitivity analysis.

		24% subsidy f = 0.24 75% subsidy f = 0.75 90% subsidy f = 0.9	Fraction of cost premium covered by subsidies. No subsidy: subsidy set to 0 24% subsidy: subsidy set to 24% 75% subsidy: subsidy set to 75% 90% subsidy: subsidy set to 90%
Additional Cost Borne by Developer/Consumer	$(1 - \text{Subsidy}) \times \text{Cost Premium of CSB}$		
Demand for Residential CSB	$\frac{1}{\left(1+\left(\frac{\text{Cost Premium to Developer/Consumer}}{g_1}\right)^{g_2}\right)^{g_3}}$	High: g_1: 64,886 g_2: 0.88 g_3: 5,108 Medium: g_1: 0.329 g_2: 1.77 g_3: 1.00 Low: g_1: 376 g_2: 0.34 g_3: 29.36	Variable used in willingness to pay scenario analysis. Parameter values obtained by fitting four- or five-parameter logistic curves to stated preference data (g_3 set to 1 for four-parameter curve; also, see Figure 2). Values depend on dataset and fit used. Source: [48, 53] Scenarios: High, Medium, Low.
Construction of Residential CSB	$(\text{Number of Households} - \text{Quantity of Residential CIB} - \text{Quantity of Residential CSB} + \text{Attempts to Reduce the Housing Gap}) \times \text{Demand for Residential CSB}$		
Construction of Residential CIB	$(\text{Number of Households} - \text{Quantity of Residential CIB} - \text{Quantity of Residential CSB} + \text{Attempts to Reduce the Housing Gap}) \times (1 - \text{Demand for Residential CSB})$		
Retrofitting	0		

Decommissioning of Residential CSB	0		As CSB stock in Malaysian context consists entirely of new buildings decommissioning is not relevant over the period of the model
Decommissioning of Residential CIB	$h \times \text{Quantity of Residential CIB}$	Baseline: h = -0.02 Long lifespan h = -0.01	Variable used in building lifespan sensitivity analysis Baseline: building lifespan of 50 years Long lifespan: building lifespan of 100 years
Quantity of Residential CSB	$\text{INTEG}(\text{Construction of Residential CSB} + \text{Retrofitting} - \text{Decommissioning of Residential CSB})$ Initial value of 4469.		Initial value based on estimated square footage of completed GBI certified residential new buildings in 2015 (894,000 square meters), assuming average square footage of 200 square meters per housing unit. Source: [35]
Quantity of Residential CIB	$\text{INTEG}(\text{Construction of Residential CIB} - \text{Retrofitting} - \text{Decommissioning of Residential CIB})$ Initial value of 4.9e+006		Initial value based on reported number of residential units in 2015. Source: [37]
CSB Fraction of Residential Buildings	$\frac{\text{Quantity of Residential CSB}}{\text{Quantity of Residential CSB} + \text{Quantity of Residential CIB}}$		
Median Household Income	$i_1 \times \text{Time}^3 + i_2 \times \text{Time}^2 + i_3 \times \text{Time} + i_4$	Baseline: i_1: 1.5410×10^{-1} i_2: 2.1279×10^{1} i_3: 1.0542×10 i_4: 1.8046×10^{4} High income growth: i_1: 3.3881×10^{-1} i_2: 2.5715×10^{1} i_3: 1.2097×10^{3} i_4: 1.8197×10^{4}	Variable used in household income sensitivity analysis. Median household income between 2016 and 2050 was calculated based on projected GDP as described in the text in Section 2.4. A third-order polynomial equation was fitted to the data and extrapolated to 2065. Source: [60, 68] Baseline: GDP growth from PWC, median income grows at 0.8 of GDP growth rate

		Low income growth: i_1: 3.6311*10^{-2} i_2: 1.6969*10^{1} i_3: 9.0605*10^{2} i_4: 1.7893*10^{4} Low GDP growth: i_1: -4.1558*10^{-2} i_2: -7.9502*10^{-1} i_3: 8.4820*10^{2} i_4: 1.8739*10^{4}	High income growth: GDP growth from PWC, median income grows at 0.9 of GDP growth rate Low income growth: GDP growth from PWC, median income grows at 0.7 of GDP growth rate Low GDP growth: GDP growth 50% of PWC estimates, median income grows at 0.8 of GDP growth rate
AC Ownership	$j_1 + \frac{(j_2 - j_1)}{\left(1 + \left(\frac{\text{Median Household Income}}{j_3}\right)^{j_4}\right)}$	j_1: 0.9398 j_2: 0 j_3: 18398 j_4: 1.374	Fraction of households with AC. Four-parameter logistic curve fitted to data. Source: [60-65]
Increased Temperature in CIB	k	k: 4.0	Source: [25]
Increased Temperature in CSB	l	l: 0.5	Source: [25]
nXCdays, where X is 21-31.	m_i	m_i is the annual frequency of i outdoor temperature for a given climate change scenario, obtained from NAHRIM projections.	Variable used in climate change scenario analysis. Temperature frequencies change by scenario and year, and are too complex to represent here. A histogram for selected years is shown in Figure S7. Source: [75] Scenarios:

			Baseline: A1B High ambient temperature increase: A1FI Low ambient temperature increase: B1
AC Usage	$\text{AC Ownership} \times \left(\text{Quantity of Residential CIB} \times \sum_{i} \left(1 - \frac{1}{\left(1 + \left(\frac{21 + \text{ITCIB}}{\text{TPCSig}}\right)^{\text{TPCS}}\right)^{\text{AF}}} \right) \times \text{nXCdays}_{x} + \text{Quantity of Residential CSB} \times \sum_{i} \left(1 - \frac{1}{\left(1 + \left(\frac{21 + \text{ITCSB}}{\text{TPCSig}}\right)^{\text{TPCS}}\right)^{\text{AF}}} \right) \times \text{nXCdays}_{i} \right)$	Baseline: TPCSig = 26.32 TPCS = 298.04 AF = 0.0430 Singapore: TPCSig = 39.09 TPCS = 11.18 AF = 18.04	This variable is used in thermal preference sensitivity analysis. It is in units of "Housing Unit-AC Use Nights/Year," and is derived through (1) multiplying a histogram of temperatures in CSB/CIB buildings at 11 pm by a thermal preference curve (see Figure 7), and (2) incorporating data on AC ownership and CSB/CIB prevalence to obtain AC usage. Note abbreviations: TPCSig –Thermal Preference Curve Sigmoid TPCS – Thermal Preference Curve Steepness AF – Asymmetry Factor ITCIB – Increased Temperature in CIB ITCSB – Increased Temperature in CSB TPCSig, TPCS, and AF values obtained by fitting a five-parameter logistic curve to thermal preference data. Source: [72-73] Baseline: Indonesia thermal preference curve Alternate: Singapore thermal preference curve

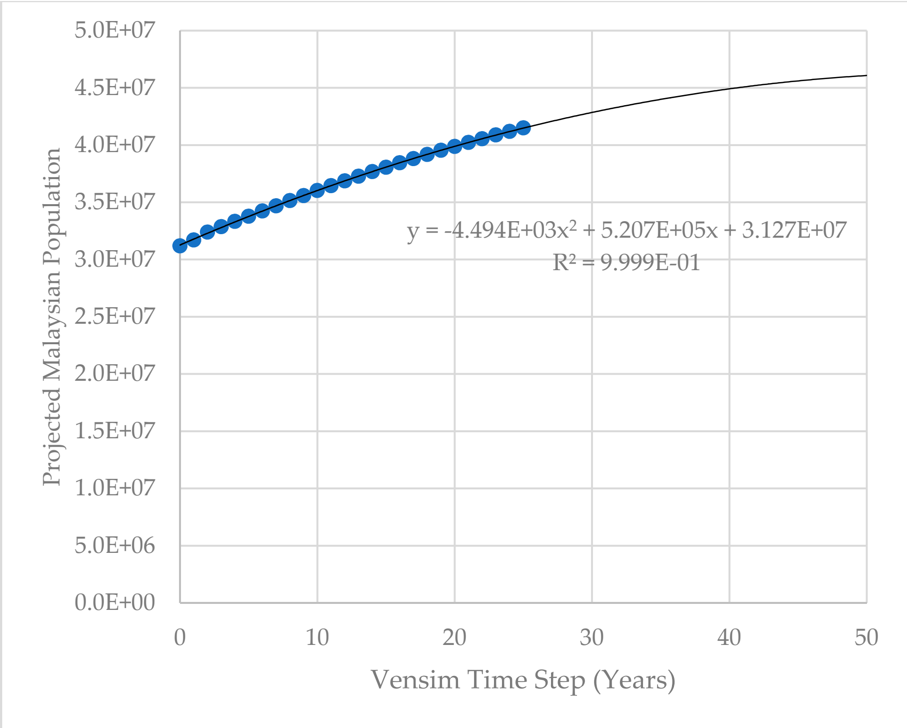

Figure S2: Malaysia projected population. The Vensim time step 0 to 50 correspond to 2015-2065. Datapoints (2015-2040) are estimates from the Department of Statistics Malaysia (2017a).

AC Ownership

AC ownership is closely linked to income. Future increase in median income (Figure S2) will move AC ownership to the right of the curve shown in Figure S3, increasing from 46% in 2015 to 89% in 2065 (Figure S5).

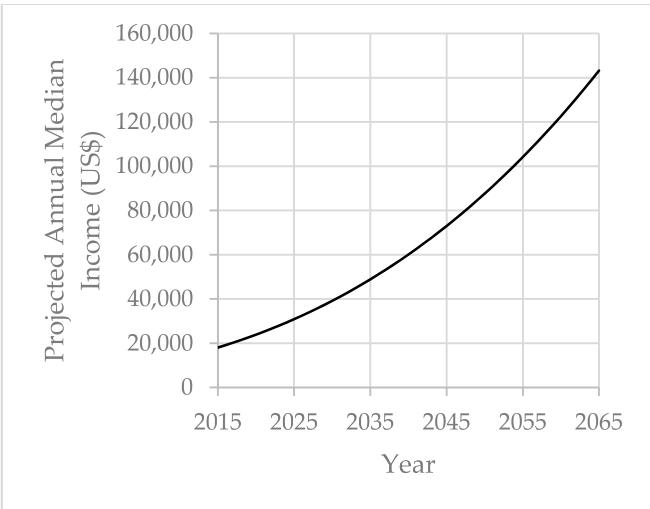

Figure S3: Projected Malaysian median annual household income

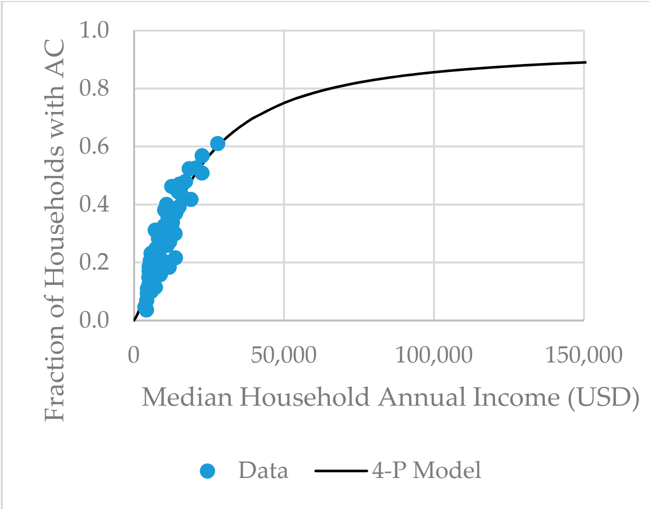

Figure S4: Median household income and AC ownership for the 13 states and Federal Territory in Malaysia, 2002-2014.

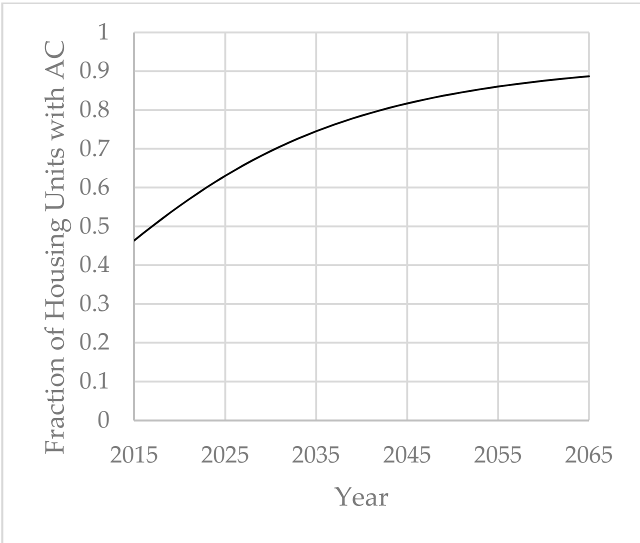

Figure S5: Projected Fraction of Housing Units with AC in Malaysia

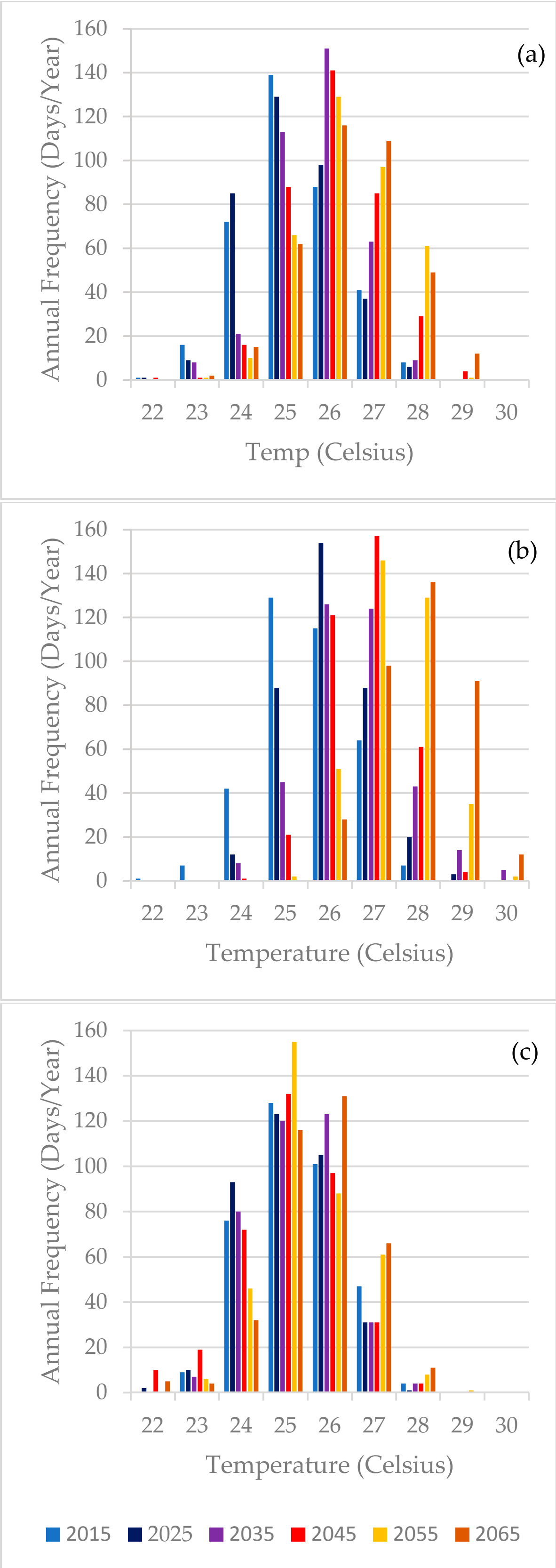

Figure S6: Outdoor temperature distributions at 11 pm under various climate change scenarios: (a) A1B, (b) A1FI, (c) B1.

Sensitivity Analysis

Sensitivity analysis of CSB uptake was carried out for the following: progress ratio, initial cost premium, and building lifespan. Sensitivity analysis of AC usage was carried out for the following: household income growth and thermal preference. Results are shown in Figures S7-S11. CSB uptake and AC usage in 2065 in was compared against the baseline case for all four subsidy conditions, summarised in Table S2.

Among the parameters affecting CSB uptake, initial cost premium had the greatest impact. Under the no-subsidy condition, CSB uptake was 0.233 that of the baseline under the high cost premium case (initial cost premium double the baseline) and 2.73 times that of the baseline under the low cost premium case (initial cost premium 0.4 that of the baseline). However, under the 90% subsidy condition, this changes to 0.884 and 1.06 respectively. This is due to the reinforcing loop in the model, which governs CSB cost premiums, and the shape of the WTP curve. The CSB cost premium decreases most rapidly in the early stages of CSB uptake, but flattens out thereafter, allowing CSB uptake results to converge. Thus, the CSB model is more robust for scenarios with high CSB uptake.

For the parameters affecting AC usage, all cases yielded AC usage within 0.79 of the baseline. Household income effects on AC usage did not vary by subsidy condition as the model assumes that AC ownership (driven by household income) and CSB ownership do not interact. AC usage under the Singapore thermal preference curve appears to converge with the baseline as CSB uptake increases. This is because the two thermal preference curves intersect at 27°C, and indoor temperatures are closer to that intersection point under CSB conditions than under CIB conditions.

Table S2: Summary of sensitivity analysis findings

Sensitivity Analysis	Case	CSB Uptake/AC Usage Relative to Baseline for No Subsidy in 2065	CSB Uptake/AC Usage Relative to Baseline for 24% Subsidy in 2065	CSB Uptake/AC Usage Relative to Baseline for 75% Subsidy in 2065	CSB Uptake/AC Usage Relative to Baseline for 90% Subsidy in 2065
Progress Ratio (CSB Uptake)	High Progress Ratio (0.75)	1.10	1.15	1.09	1.02
	Low Progress Ratio (0.9)	0.337	0.320	0.445	0.761
Initial Cost Premium (CSB Uptake)	High Initial Cost Premium (10%)	0.233	0.263	0.595	0.884
	Low Initial Cost Premium (2%)	2.73	2.29	1.28	1.06
Building Lifespan (CSB Uptake)	Long Building Lifespan (100 years)	0.673	0.684	0.782	0.860
Household Income (AC Usage)	High Income Growth	1.02	1.02	1.02	1.02
	Low Income Growth	1.00	1.00	1.00	1.00
	Low GDP Growth	0.863	0.863	0.863	0.863
Thermal Preference (AC Usage)	Singapore	0.790	0.792	0.822	0.867

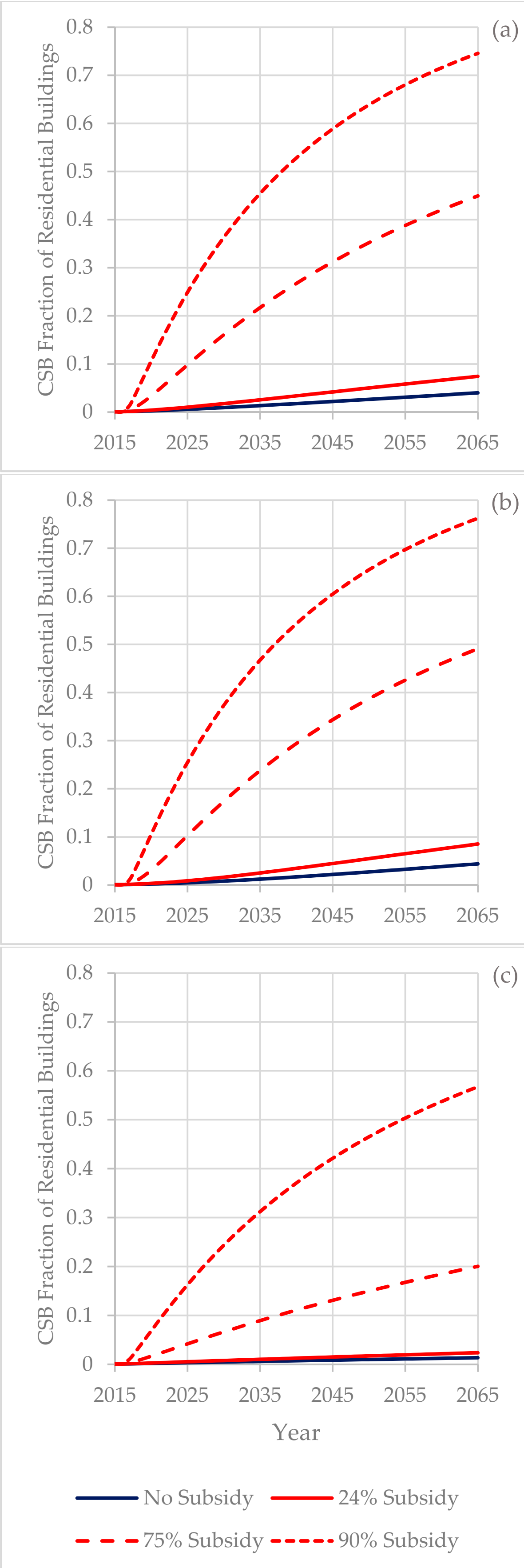

Figure S7: Sensitivity analysis - subsidy effects on CSB fraction of Malaysian residential stock under various progress ratio values: (a) baseline (0.8), (b) 0.75 (high), (c) 0.9 (low).

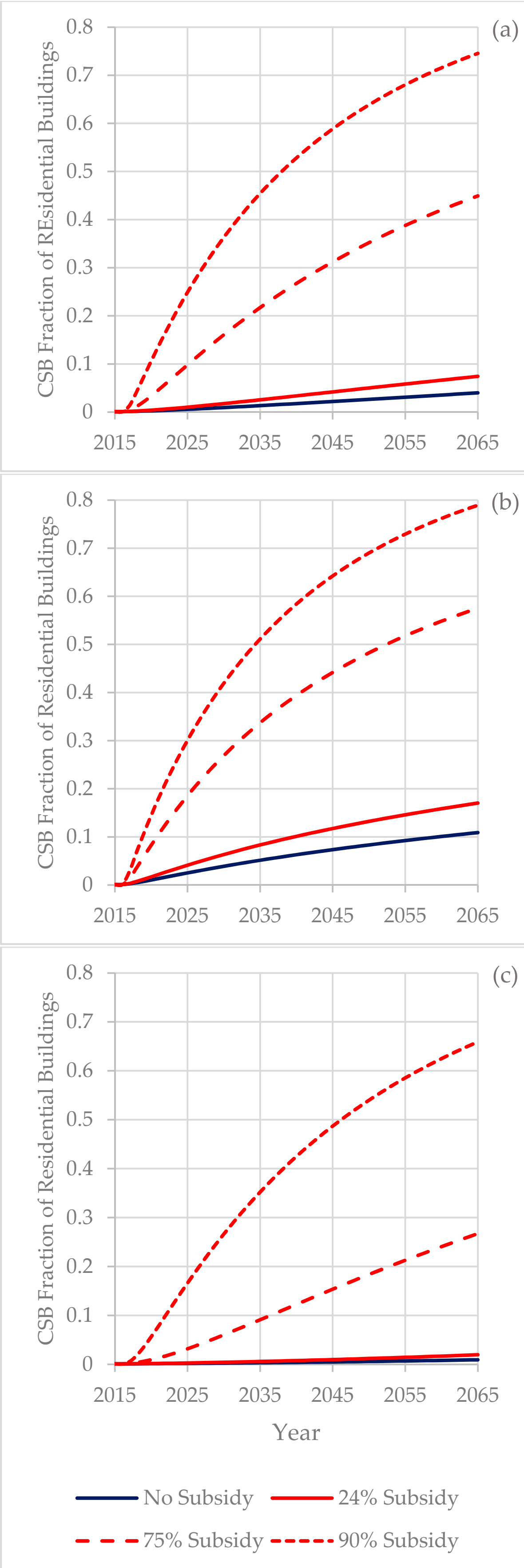

Figure S8: Sensitivity analysis - subsidy effects on CSB fraction of Malaysian residential stock under various initial cost premium values: (a) baseline (5%), (b) 2% (low), (c) 10% (high).

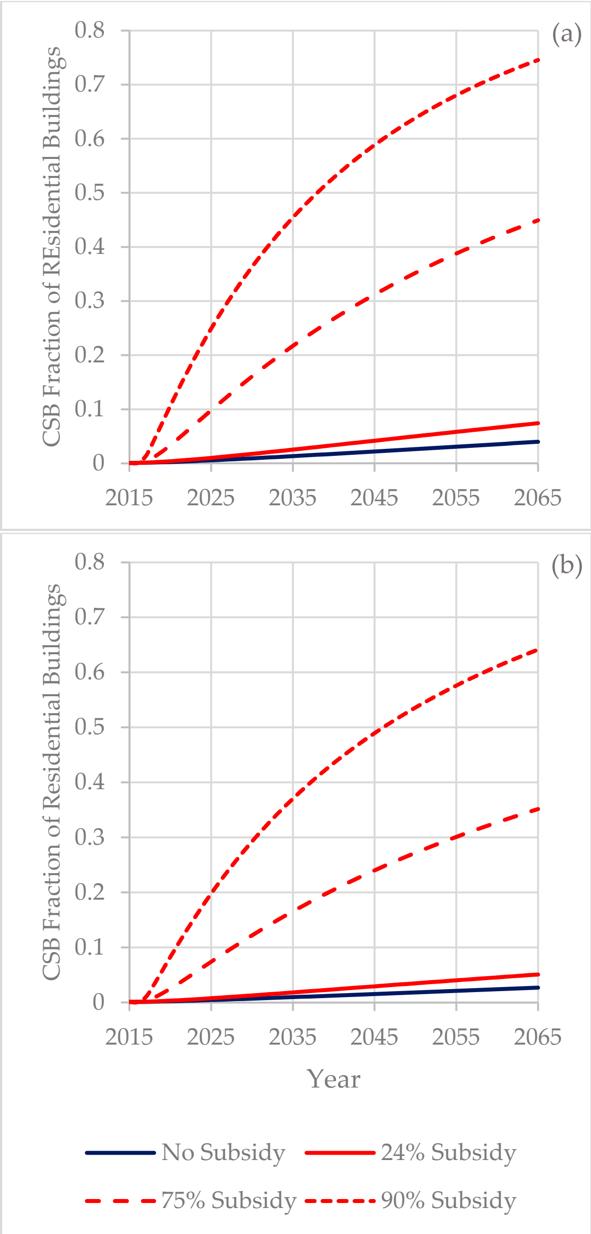

Figure S9: Sensitivity analysis - subsidy effects on CSB fraction of Malaysian residential stock under various building lifespans: (a) baseline (50 years), (b) 100 years.

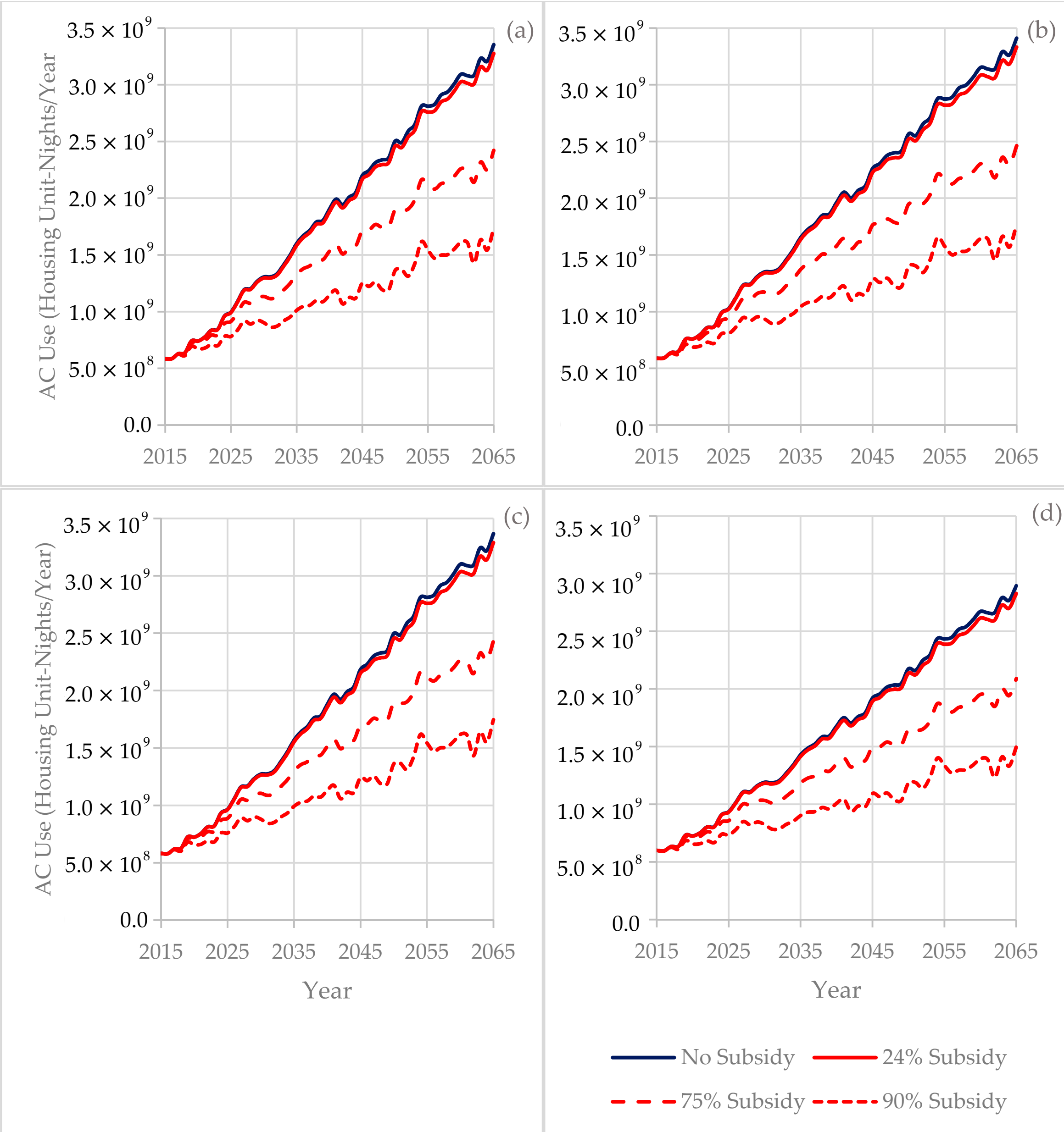

Figure S10: Sensitivity analysis - subsidy effects on Malayisan residential night-time AC usage under various median income scenarios: (a) baseline (income growth at 80% of GDP), (b) income growth at 90% of GDP (high), (c) income growth at 70% of GDP (low), (d) low GDP growth (income growth at 80% of GDP, GDP growth rate at 50% of Pricewater House Coopers projected growth between 2020 and 2050 with subseuqent growth rate of 1%).

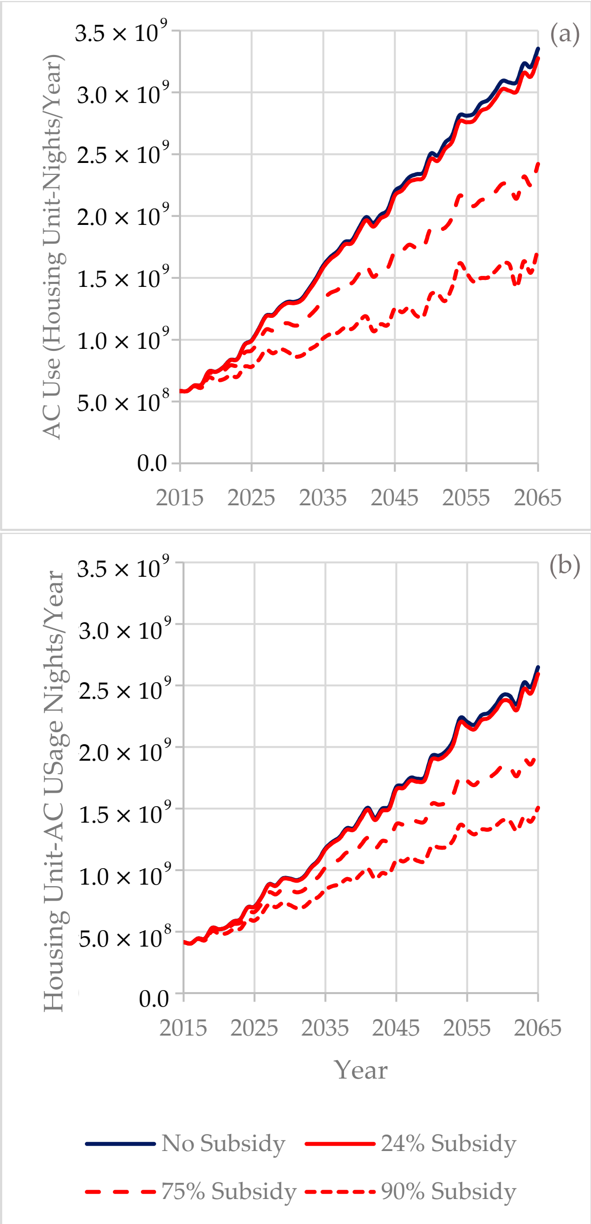

Figure S11: Sensitivity analysis - subsidy effects on Malayisan residential night-time AC usage under various thermal preference curves: (a) baseline (Indonesia thermal preference curve), (b) Singapore thermal preference curve.

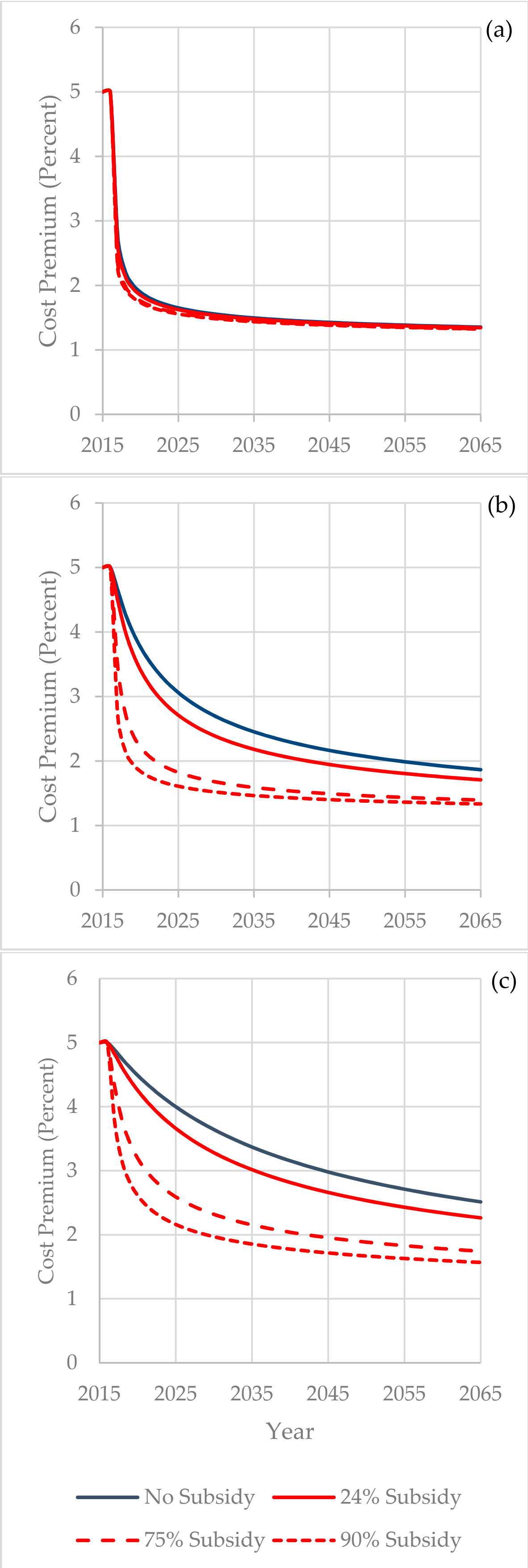

Figure S12: Subsidy effects on cost premium of climate-sensitive buildings for different willingness to pay preferences: (a) High, (b) Medium, (c) Low.

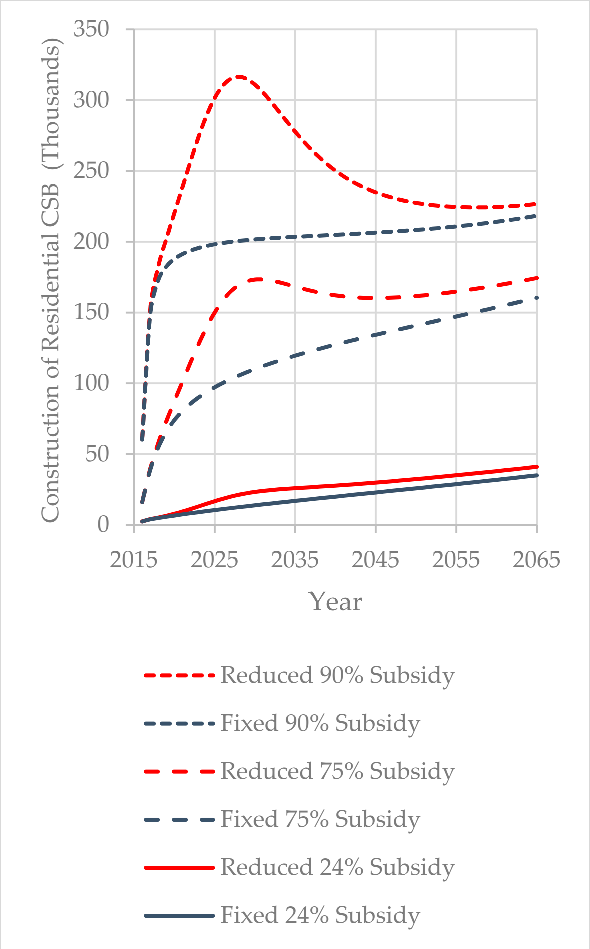

Figure S13: Subsidy effects on Malaysian climate-sensitive building construction (CSB) rates under baseline (Fixed) and shrinking housing gap (Reduced) scenarios. Note that CSB construction rates under the climate-insensitive building intervention (CIB Int) match the Fixed scenario.