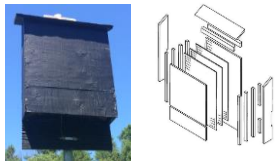
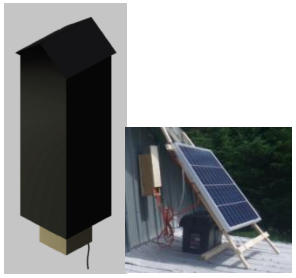
Supplementary Information. Using thermodynamics to improve bat houses in cold climates. Amélie Fontaine, Anouk Simard, Bryan Dubois, Julien Dutel, Kyle H. Elliott.

Table S1. Description of bat house models tested in Quebec, Canada, from 2016 to 2019. Model names referred to their shape and number of passive heating (PH) zones (1, 2 or 3 reflexives faces). New models were designed in collaboration with Julien Dutel, engineer from Transition Énergétique Quebec, and Bryan Dubois, architect from Ncube Architecture.

Model (number of chambers)		Image(s)	Dimensions and materials	Description	Years tested
Traditional					
1	Classic (4)		78x43x11 cm wood	Rectangular shape. Commonly used in North America. Developed by Bat Conservation International. Cheap and easy to build.	2016-2019
2	European (1)		44x29x9 cm woodcement	Rectangular shape. Chillon bat box from wildcare. Woodcement commonly used in Europe. This material has similar properties than wood, but more durable and heavier.	2016-2019
Rocket					
3	Insulated rocket (1)		120x34x34 cm wood and 2.5 cm thick styrofoam insulation	The rocket model has an elongated shaped that allow a vertical gradient of temperature. One big eccentric chamber.	2016-2019
4	Insulated heated rocket (1)		120x34x34 cm wood, 2.5 cm thick styrofoam insulation, heated mat, and a solar kit (undulator, timer, converter, battery, and solar panel)	The rocket model has an elongated shaped that allow a vertical gradient of temperature. One big and eccentric chamber. Developed by Genivar in 2011 and adapted to solar energy by Quebec MFFP in 2016. Considering the capacity limit of the battery, a timer was set to turn on the heated mat for 30 minutes three times per night: 12:00AM, 2:00AM, and 4:00AM.	2016-2019

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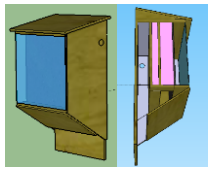
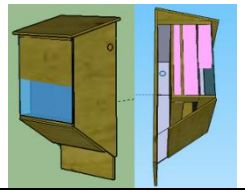
Newly designed model					
5	Biclimate.0 PH1 (2)		60x30x20 cm wood, 2.5 cm thick styrofoam insulation, permabase cement board, and plexiglass	One "cold" chamber at the back. In the middle, the insulated "hot" chamber stands against a frontal passive heating zone that conducts the heat inside. The passive heating zone is made of plexiglass, an empty space (air) and a conductive material (permabase cement board).	2016-2019
6	Biclimate PH1 (2)		81x43x23 cm wood, 2.5 cm thick styrofoam insulation, permabase cement board, and plexiglass	Same as the Biclimate model but bigger dimensions and a reduction of the passive heating zone by two thirds. at Transition Énergétique Quebec.	201-2019
7	Rocket PH2 2017 (1)		120x34x34 cm wood, 2.5 cm thick styrofoam insulation, plexiglass, and permabase cement board	Same as the insulated rocket model, with the addition of two passive heating zones of 25cmx25cm at the bottom facing east and west.	2017-2019
8	Classic PH2 (3)		65x58x20 cm wood, 2.5 cm thick styrofoam insulation, clapboards, corrugated PVC panel, and permabase cement board,	Same shape as the classic model but insulated at front and the back and covered with clapboards. Reduction of the entrance to one inch wide. Two passive heating zones on each side, facing east and west, made of corrugated plexiglass to increase the contact surface, an empty space (air) and a conductive material (permabase cement board). Designed for pole.	2018-2019

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9	Classic PH1 (3)		65x53x24 cm wood, 2.5 cm thick styrofoam insulation, plexiglass, and permabase cement board	Same as the Classic PH2 2018 but with only one passive heating zone at the front facing east. Designed for building.	2018-2019
10	Ncube.0 PH1 (3)		77x52x24 cm wood, 2.5 cm thick styrofoam insulation, plexiglass, and clay brick	Similar shape as the classic PH1 model, but fully insulated. Use of a reduced chicane entrance (2.5 x 10.2 cm). One passive heating zone at the front facing east, overlapping with the entrance preferably facing east. The passive heating zone is made of a high-core corrugated plexiglass, an empty space (air) and a conductive material (clay brick) slowly diffuse the heat inside the three chambers. Convection principle due to an opening at the top of zone. Removable insulated roof. Designed for building.	2018-2019
11	Ncube.0 PH3 2018 (4)		92x41x24 cm wood, 2.5 cm thick styrofoam insulation, plexiglass, and clay brick, light cement panel	Same as the Ncube PH1 2018, but with three passive heating zones facing east, south, and west overlapping with the entrance and the chambers. Conduction principle due to the fixation of the brick on a light cement panel. Designed for pole.	2018-2019
12	Ncube PH1 (4)		92x41x24 cm wood, 5 cm thick styrofoam insulation, plexiglass, and clay brick, light cement panel	Improved version Ncube PH1 2018 and Ncube PH3 2018 with thicker insulation (10.2 vs. 5 cm). A cool zone, called the veranda at the bottom of the entrance had been added made of 3 wood wall and a fence where bats could safely go if overheating in the main chambers. One passive heating zone at the front facing east overlapping with the main chambers only. Heating zone using conduction principle.	2019

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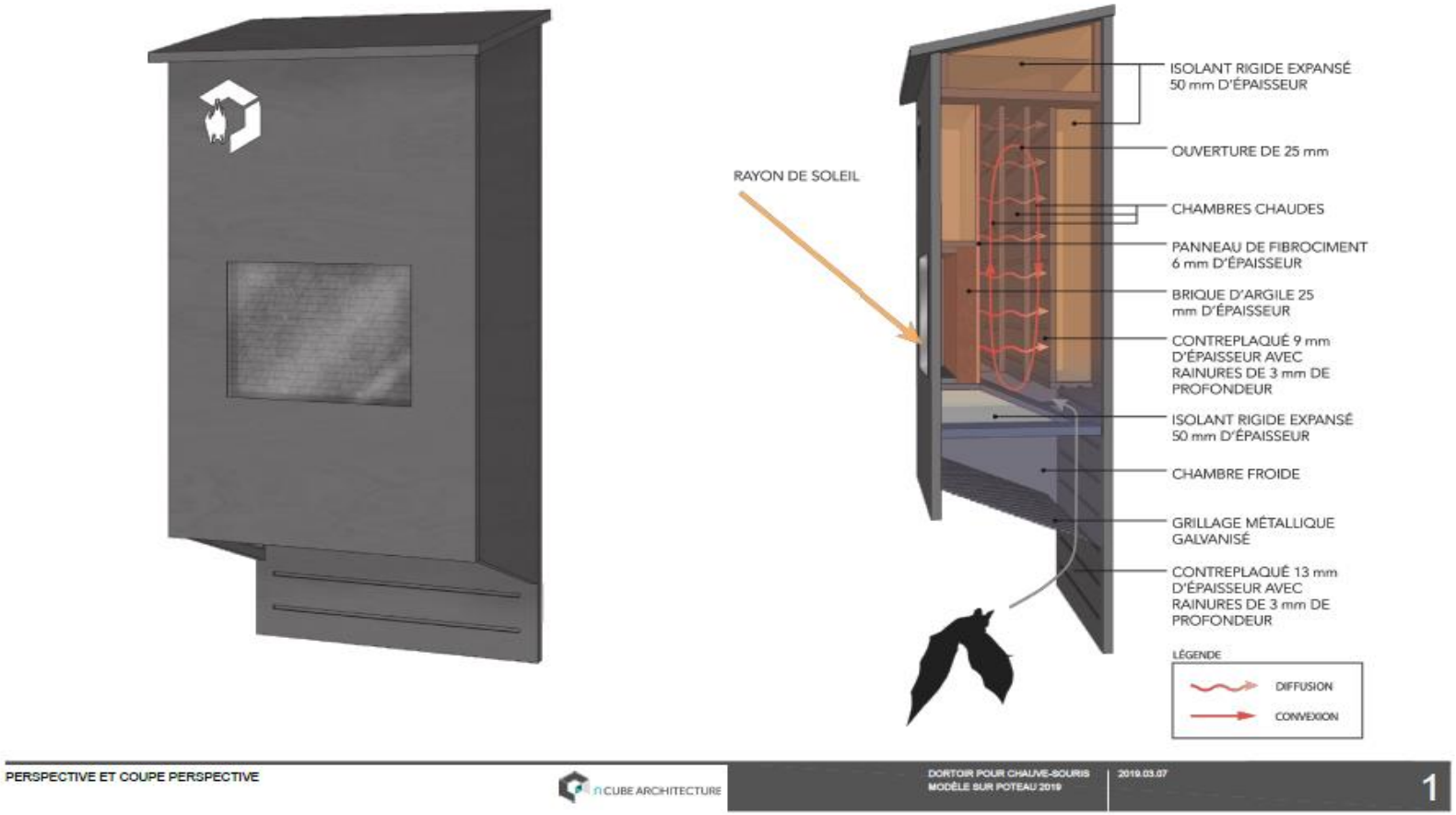

Figure S1. Schematic view of the Ncube PH1 2019. The improved Ncube PH1 2020 plan is available in French and English on Batwatch.ca.

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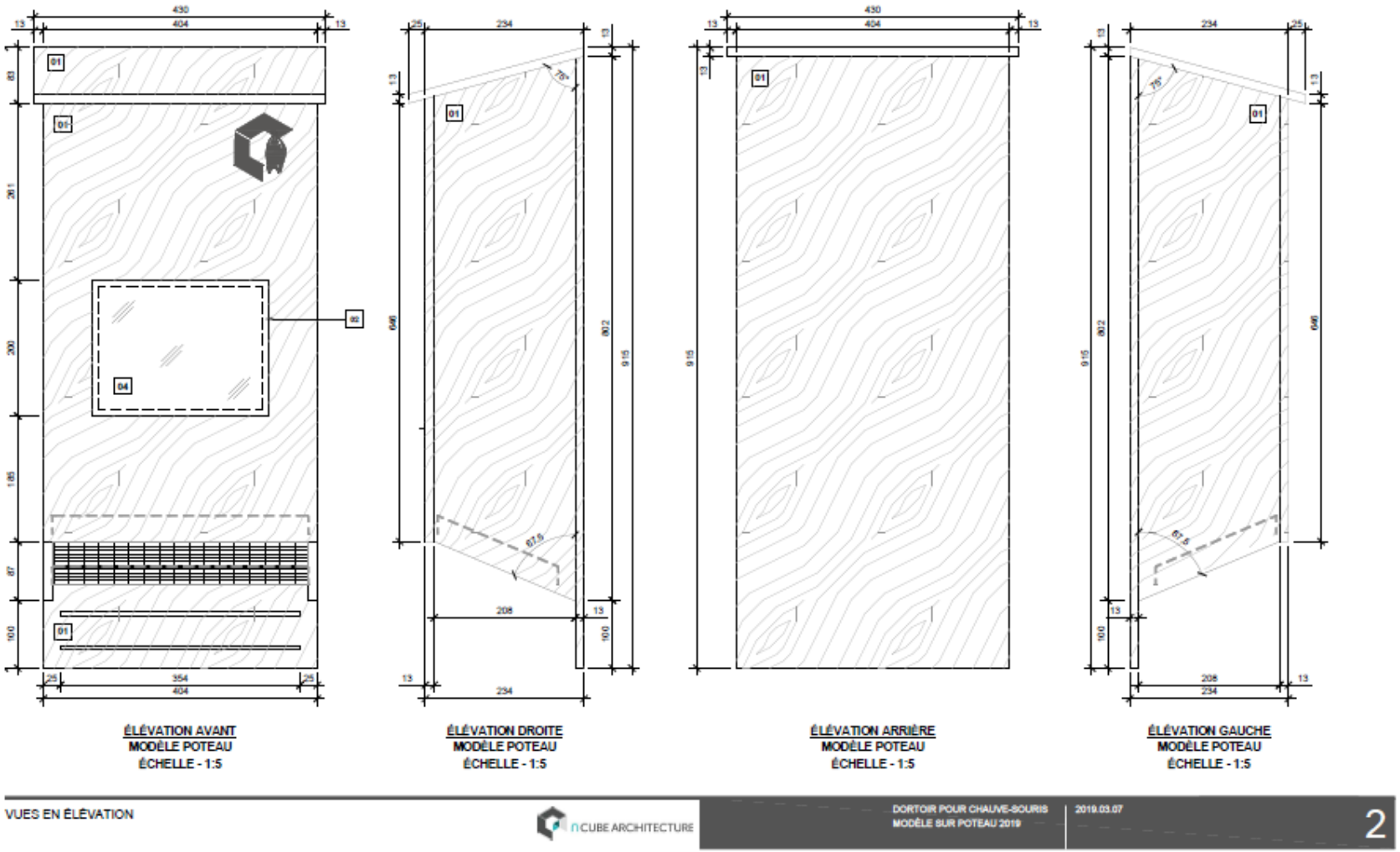

10

11 **Figure S2.** Design plan of the Ncube PH1 2019. Elevation view.

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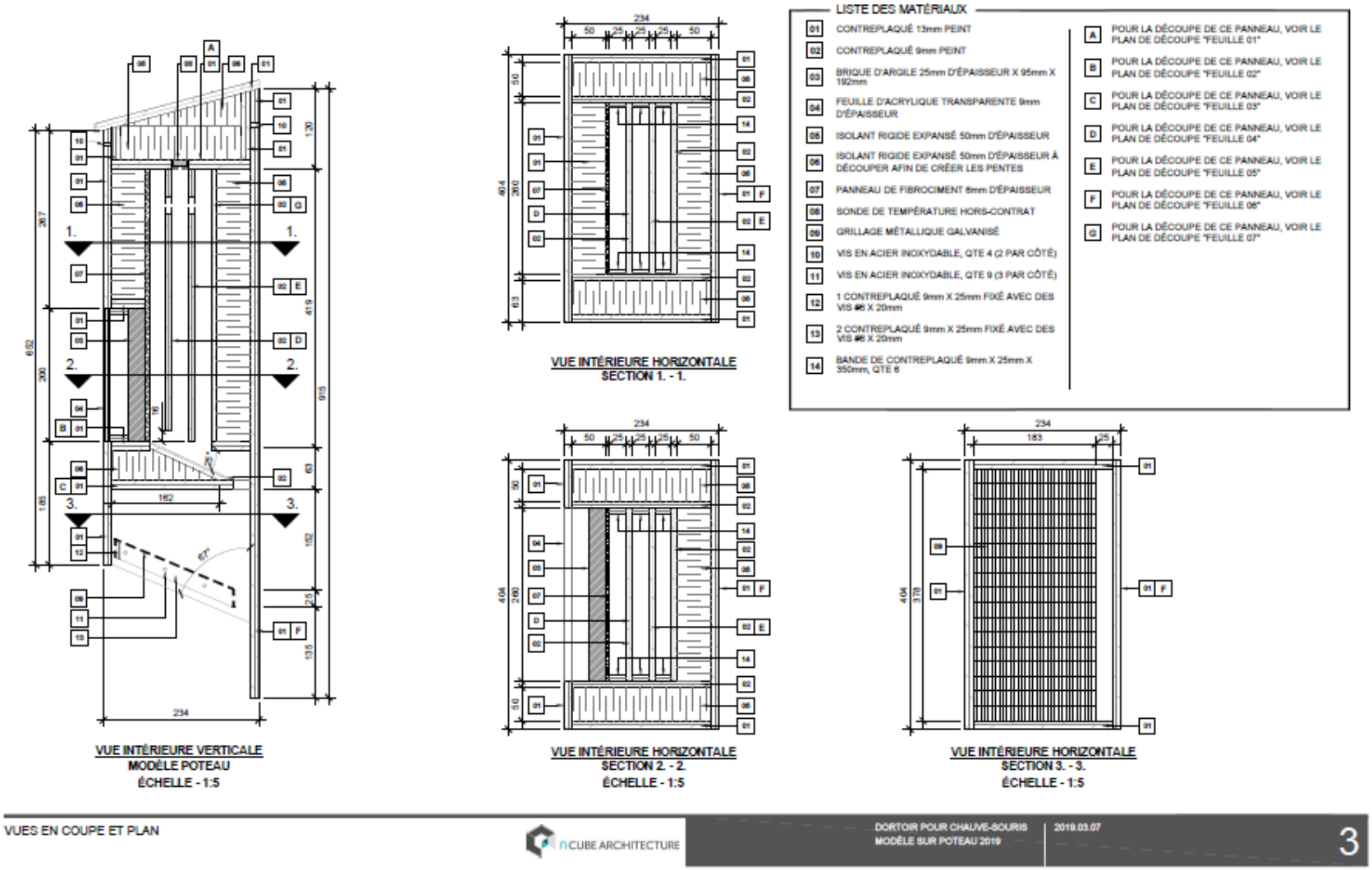

Figure S3. Design plan of the Ncube PH1 2019. Cutting plane view.

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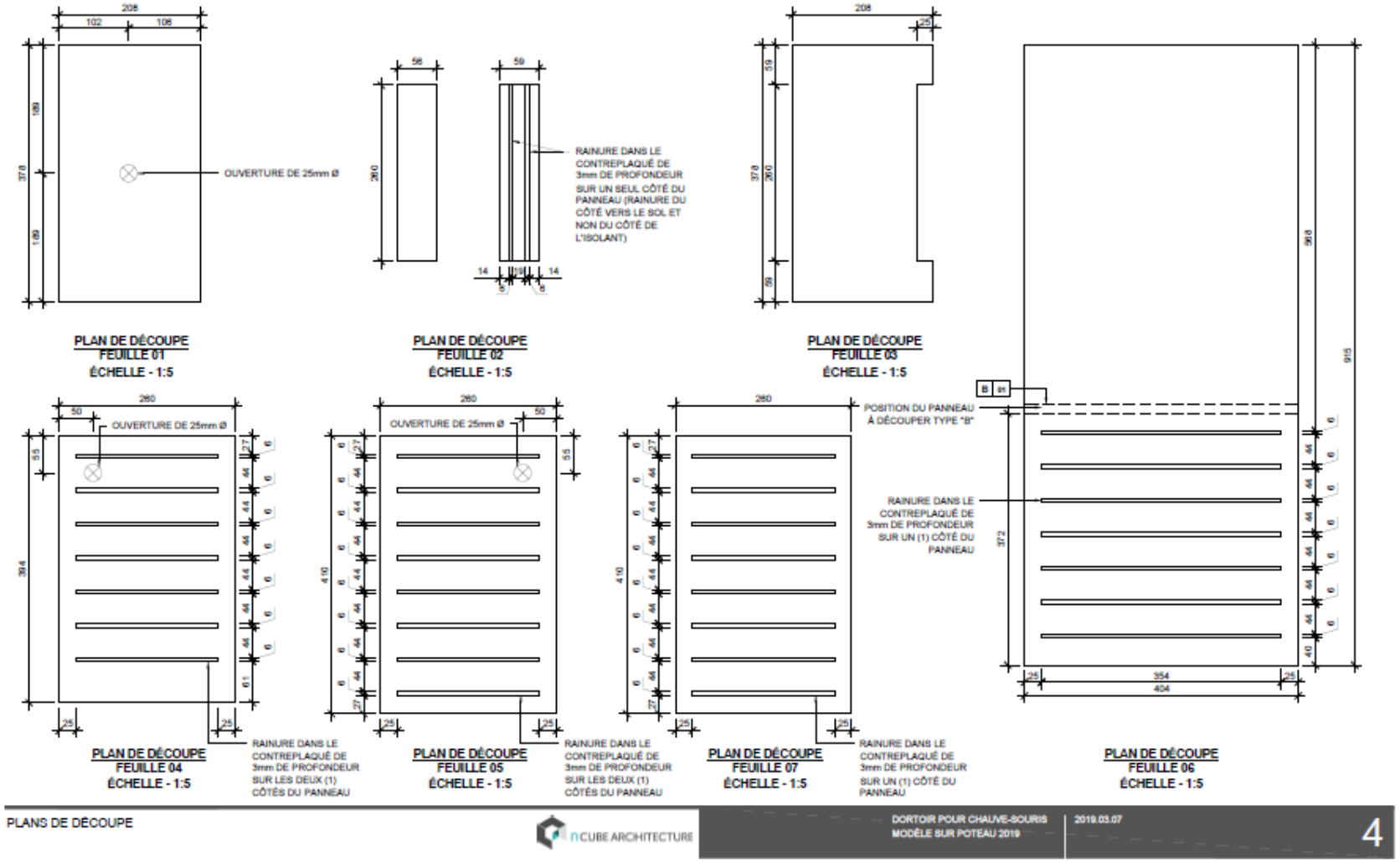

14

15 **Figure S4.** Design plan of the Ncube PH1 2019. Cutting plane view (2).

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Table S2. Site GPS position, location, climate, meteorological station type, and distance of the meteorological station from bat houses.

Sites	GPS location	Regional location	Köppen climate type	Type	Distance
Warm1	45.50393, -75.81336	Montreal	Humid continental	Davis vantage vue In situ	< 100 m.
Warm2	45.41109, -73.94468	Outaouais	Humid continental	Environment Canada station (Ste Anne de Bellevue)	< 1000 m.
Warm2	46.71640, -71.54246	Outaouais	Humid continental	Environment Canada station (Ste Anne de Bellevue)	< 1000 m.
Intermediate2	46.59438, -72.11343	Quebec	Humid continental	Davis vantage vue In situ	< 100 m.
Intermediate1	46.61753, -71.84768	Centre-du-Quebec	Humid continental	Davis vantage vue In situ	< 100 m.
Cold1	47.32049, -71.14918	Quebec	Subarctic	Environment Canada station (Forêt Montmorency)	< 500 m.
Intermediate2	51.68861, -75.82278	Quebec	Humid continental	Davis vantage vue In situ	< 100 m.

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Table S3. GAMM model description for the orientation, mounting and model experiments.

Treatments	Response variable (Y)	Explanatory variable (x)	Fixed factor	Random factor
Orientation	T_{int}	Orientation	Time (as smoothed term and a categorical interaction with Orientation), T_{ext} (with a categorical interaction with Orientation), Date, Structure	Location (with a random intercept), individual bat house Id (with a random intercept)
Mounting	T_{int}	Structure	Time (as smoothed term and a categorical interaction with Structure), T_{ext} (with a categorical interaction with Structure), Date, Orientation	Location (with a random intercept), individual bat house Id (with a random intercept)
Model	T_{int}	Model	Time (as smoothed term and a categorical interaction with Model), T_{ext} (with a categorical interaction with Model), Week, Structure	Location (with a random intercept), individual bat house Id (with a random intercept)

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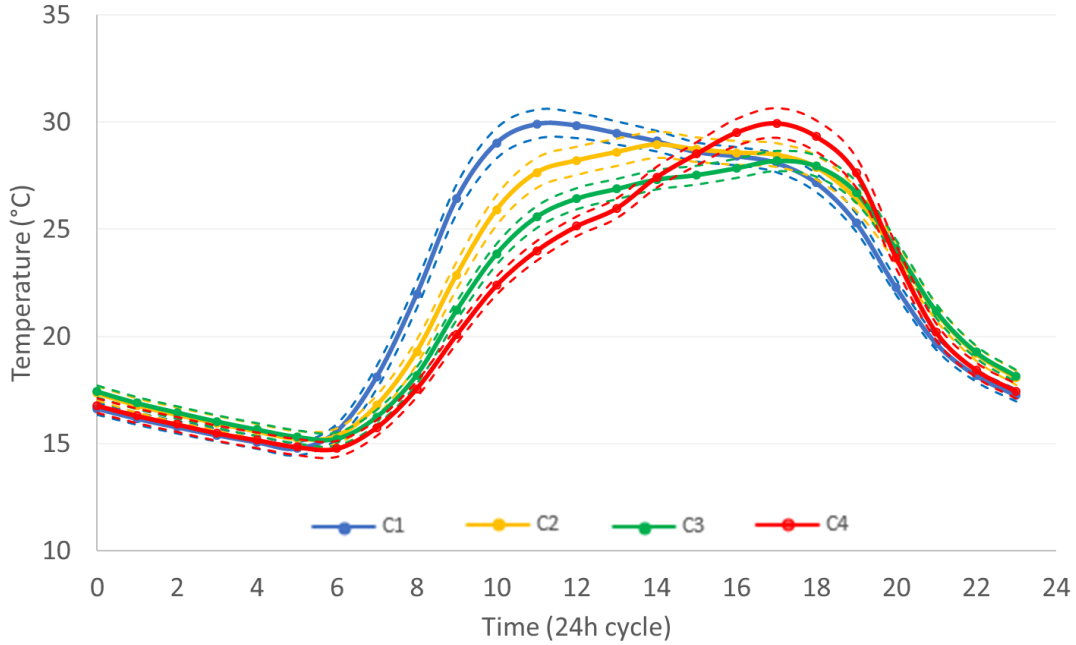

Figure S5. Daily mean temperature (°C) of a classic 4-chambers bat house in the four chambers from mid-May to Mid-September 2017 on pole at intermediate and warm sites (n=2) Québec, Canada.

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Table S4. Parameter estimates, standard error (SE), *t* value, and the probability of observing any value equal or larger than *t* from generalized additive mixed model accounting for time, date, external temperature, orientation, site, and individuals bat house id for T_{int} mounting tests.

	Estimate	**SE**	***t* value**	**Pr(>|*t*|)**
Intercept	18.110	2.039	8.882	< 2e-16 ***
Heated building	3.176	0.360	8.815	< 2e-16 ***
Non heated building	3.556	0.360	9.871	< 2e-16 ***
Pole	3.570	0.360	9.911	< 2e-16 ***

Table S5. Adjusted p-values of the mounting comparisons from generalized additive mixed model accounting for time, date, external temperature, orientation, site, and individuals bat house id. Asterisks (*) represent significative T_{int} differences between structure during the day and night. P-values have been adjusted for multiple comparisons using the R function wald_gam.

Model comparison	**Heated building**		**Non-heated building**		**Pole**	
	Day	**Night**	**Day**	**Night**	**Day**	**Night**
Heated building			0.326	0.740	0.050*	0.009**
Non-heated building	0.326	0.740			0.326	0.023*
Pole	0.050*	0.009**	0.326	0.023*		

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Table S6. Parameter estimates, standard error (SE), *t* value, and the probability of observing any value equal or larger than *t* from generalized additive mixed model accounting for time, date, external temperature, structure, site, and individual bat house id for T_{int} orientation tests.

	Estimate	**SE**	***t* value**	**Pr(>|*t*|)**
Intercept	-2.041e-05	3.840e-04	-0.053	0.958
External	-3.618	0.597	-6.057	1.4e-09 ***
South	-1.178	0.598	-1.972	0.049 *
South-East	0.214	0.299	0.716	0.474
West	-0.145	0.597	-0.243	0.808
Non heated building	0.401	0.597	0.671	0.502
Pole	0.141	0.598	0.235	0.814
Year	0.011	4.454e-04	24.253	< 2e-16 ***
External:Non heated building	-0.298	0.810	-0.368	0.713
South:Non heated building	0.448	0.845	0.530	0.596
West:Non heated building	-0.509	0.845	-0.603	0.547
External:Pole	-0.037	0.81	-0.046	0.963
South:Pole	0.670	0.845	0.792	0.428
South-East:Pole	0.214	0.299	0.716	0.474

Table S7. Adjusted p-values of the orientation comparisons from generalized additive mixed model accounting for time, date, external temperature, structure, site, and individual bat house id. Asterisks (*) represent significative T_{int} differences between orientations during the day and night. P-values have been adjusted for multiple comparisons using the R function wald_gam.

Orientation comparison	**Heated building**		**Non-heated building**		**Pole**	
	Day	**Night**	**Day**	**Night**	**Day**	**Night**
East-South	0.046 *	0.274	0.023*	0.876	0.023 *	0.642
East-West	0.033*	0.007 **	0.014*	0.417		
South-West	0.310	0.106	0.787	0.334		
East-SouthEast					0.232	0.977
South-SouthEast					0.283	0.624

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Table S8. Parameter estimates, standard error (SE), *t* value, and the probability of observing any value equal or larger than *t* from generalized additive mixed model accounting for time, week, year, structure, external temperature, site, and individual bat house id for T_{int} model tests.

	Estimate	**SE**	***t* value**	**Pr(>|*t*|)**
Intercept	612.775	275.523	2.224	0.026 *
Batclimate 2017 hot chamber	2.098	0.605	3.467	5.28 e-04 ***
Batclimate 2017 cold chamber	0.080	1.906	0.042	0.967
Batclimate 2016 cold chamber	1.110	0.740	1.500	0.134
Batclimate 2016 hot chamber	2.994	0.739	4.053	5.06e-05 ***
Classic	1.080	0.508	2.110	0.035 *
Classic PH1 2018	2.152	0.734	2.933	0.003 **
Classic PH2 2018	3.042	0.674	4.514	6.38e-06 ***
European	0.246	0.613	0.401	0.688
External	-2.662	0.497	-5.355	8.60e-08 ***
Ncube PH1 2018	2.742	0.707	3.879	1.28 e-04 ***
Ncube PH3 2018	3.995	0.703	5.686	1.31e-08 ***
Ncube PH1 2019 veranda	-0.270	0.747	-0.362	0.718
Ncube PH1 2019 main chamber	3.968	0.746	5.320	1.05e-07 ***
Heated Insulated Rocket	4.540	1.012	4.485	7.32e-06 ***
Insulated Rocket	-0.293	0.695	-0.421	0.673
Rocket PH2 2018	1.693	0.597	2.834	0.005 **
August 2	-0.485	0.064	-7.613	2.75e-14 ***
July 1	0.195	0.065	3.026	0.002 **
July 2	0.166	0.064	2.586	0.010 **
June 1	-0.171	0.076	-2.260	0.024 *
June 2	0.0149	0.067	0.223	0.823
May 2	-0.798	0.089	-8.925	< 2e-16 ***
September 1	-0.808	0.073	-11.069	< 2e-16 ***
Pole	-0.325	0.236	-1.375	0.169
Year	-0.293	0.137	-2.148	0.032 *

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Table S9. Adjusted p-values of the bat house model comparisons from the generalized additive mixed model accounting for time, week, year, structure, external temperature, site, and individual bat house id. Asterisks (*) represent significative T_{int} differences between models during the day and night. P-values have been adjusted for multiple comparisons using the R function wald_gam.

Model comparison	Classic		European		Bilimate 2017 hot chamber		Biclimate 2017 cold chamber		Classic PH1 2018		Classic PH2 2018		Ncube PH1 2018	
	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night
Classic			0,68	0,522	0.006 **	0,909	0,288	0,328	0,403	0.039 *	0,808	0.013 *	0,959	0.013 *
European	0,68	0,522			0.009 **	0,659	0,592	0,782	0,649	0.022 *	0,614	0.010 *	0,732	0.008 **
European V2	0,303	0.077 .	0,243	0,153	0,872	0.093 .	0,144	0,191	0,178	0.008 **	0,406	0.005 **	0,363	0.005 **
Biclimate 2016 hot chamber	2.93e-05 ***	0,642	4.54e-05 ***	0,972	0.061 .	0,741	9.28e-06 ***	0,792	1.13e-04 ***	0.048 *	0.002 **	0.028 *	0.001 **	0.025 *
Biclimate 2016 cold chamber	0,444	0,698	0,331	0,917	0,278	0,792	0,168	0,74	0,224	0.055 .	0,649	0.033 *	0,566	0.029 *
Biclimate 2a 2017 hot chamber	0.006 **	0,909	0.009 **	0,659			0.001 **	0,463	0.009 **	0.057 .	0.074 .	0.027 *	0.056 .	0.024 *
Biclimate 2a 2017 cold chamber	0,288	0,328	0,592	0,782	0.001 **	0,463			0,993	0.012 *	0,324	0.004 **	0,42	0.004 **
Classic PH1 2018	0,403	0.039 *	0,649	0.022 *	0.009 **	0.057 .	0,993	0.012 *			0,383	0,856	0,467	0,807
Classic PH2 2018	0,808	0.013 *	0,614	0.010 *	0.074 .	0.027 *	0,324	0.004 **	0,383	0,856			0,882	0,946
Ncube PH1 2018	0,959	0.013 *	0,732	0.008 **	0.056 .	0.024 *	0,42	0.004 **	0,467	0,807	0,363	0.005 **		
Ncube PH3 2018	0,432	6.95e-04 ***	0,338	8.07e-04 ***	0,211	0.002 **	0,15	2.51e-04 ***	0,198	0,339	0,582	0.001 **	0,554	0,457
Ncube 2019 main chamber	0.022 *	0.018 *	0.021 *	0.011 *	0,869	0.030 *	0.006 **	0.005 **	0.013 *	0,82	0,809	0.005 **	0.063 .	0,992
Ncube 2019 lower chamber	0,251	0,344	0,466	0,701	0.004 **	0,449	0,771	0,88	0,799	0.019 *	0,133	0,259	0,321	0.007 **
Heated Rocket	0,951	4.79e-04 ***	0,877	2.97e-04 ***	0,147	8.09e-04 ***	0,628	1.63e-04 ***	0,645	0.056 .	0,388	2.11e-04 ***	0,932	0.079 .
Non Heated Rocket	0.006 **	0.086 .	0.034 *	0.045 *	1.27e-05 ***	0,111	0,102	0.027 *	0,161	0,742	0.023 *	0.014 *	0.030 *	0,558
Rocket PH2 2017	0,1	0.063 .	0,324	0.043 *	2.14e-04 ***	0.097 .	0,631	0.017 *	0,705	0,587	0.089 .	0.012 *	0,224	0,397
External	1.07e-13 ***	1.83e-04 ***	4.70e-07 ***	0.036 *	2.16e-16 ***	0.009 **	1.24e-05 ***	0.080 .	7.19e-04 ***	2.09e-05 ***	6.90e-04 ***	0,56	7.68e-06 ***	1.69e-06 ***

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Model comparison (Continued)	Ncube PH3 2018		Ncube 2019 main chamber		Ncube 2019 lower chamber		Heated Rocket		Non Heated Rocket		Rocket PH2 2017		External	
	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night
Classic	0,432	6.95e-04 ***	0.022 *	0.018 *	0,251	0,344	0,951	4.79e-04 ***	0.006 **	0.086 .	0,1	0.063 .	1.07e-13 ***	1.83e-04 ***
European	0,338	8.07e-04 ***	0.021 *	0.011 *	0,466	0,701	0,877	2.97e-04 ***	0.034 *	0.045 *	0,324	0.043 *	4.70e-07 ***	0.036 *
European V2	0,582	0.001 **	0,809	0.005 **	0,133	0,259	0,388	2.11e-04 ***	0.023 *	0.014 *	0.089 .	0.012 *	6.90e-04 ***	0,56
Biclimate 2016 hot chamber	0.008 **	0.004 **	0,146	0.028 *	5.91e-05 ***	0,714	0.008 **	7.68e-04 ***	3.05e-08 ***	0.087 .	2.22e-06 ***	0.098 .	< 2e-16 ***	0.093 .
Biclimate 2016 cold chamber	0,957	0.004 **	0,285	0.032 *	0,154	0,669	0,588	9.04e-04 ***	0.008 **	0.099 .	0.086 .	0,112	2.36e-06 ***	0.079 .
Biclimate 2a 2017 hot chamber	0,211	0.002 **	0,869	0.030 *	0.004 **	0,449	0,147	8.09e-04 ***	1.27e-05 ***	0,111	2.14e-04 ***	0.097 .	2.16e-16 ***	0.009 **
Biclimate 2a 2017 cold chamber	0,15	2.51e-04 ***	0.006 **	0.005 **	0,771	0,88	0,628	1.63e-04 ***	0,102	0.027 *	0,631	0.017 *	1.24e-05 ***	0.080 .
Classic PH1 2018	0,198	0,339	0.013 *	0,82	0,799	0.019 *	0,645	0.056 .	0,161	0,742	0,705	0,587	7.19e-04 ***	2.09e-05 ***
Classic PH2 2018	0,641	0,396	0.086 .	0,956	0,257	0.008 **	0,845	0.070 .	0.020 *	0,604	0,145	0,415	1.23e-06 ***	1.30e-06 ***
Ncube PH1 2018	0,554	0,457	0.063 .	0,992	0,321	0.007 **	0,932	0.079 .	0.030 *	0,558	0,224	0,397	7.68e-06 ***	1.69e-06 ***
Ncube PH3 2018			0,207	0,467	0,122	7.79e-04 ***	0,603	0,224	0.007 **	0,197	0.056 .	0.089 .	2.23e-07 ***	1.61e-08 ***
Ncube 2019 main chamber	0,207	0,467			0.005 **	0.009 **	0,145	0.084 .	9.40e-05 ***	0,572	0.002 **	0,421	9.44e-11 ***	4.86e-06 ***
Ncube 2019 lower chamber	0,122	7.79e-04 ***	0.005 **	0.009 **			0,516	2.67e-04 ***	0,254	0.037 *	0,924	0.034 *	0.003 **	0,225
Heated Rocket	0,603	0,224	0,145	0.084 .	0,516	2.67e-04 ***			0,122	0.031 *	0,44	0.017 *	0.004 **	8.62e-07 ***
Non Heated Rocket	0.007 **	0,197	9.40e-05 ***	0,572	0,254	0.037 *	0,122	0.031 *			0,228	0,853	0.091 .	7.27e-05 ***
Rocket PH2 2017	0.056 .	0.089 .	0.002 **	0,421	0,924	0.034 *	0,44	0.017 *	0,228	0,853			1.35e-04 ***	3.66e-06 ***
External	2.23e-07 ***	1.61e-08 ***	9.44e-11 ***	4.86e-06 ***	0.003 **	0,225	0.004 **	8.62e-07 ***	0.091 .	7.27e-05 ***	1.35e-04 ***	3.66e-06 ***		

75

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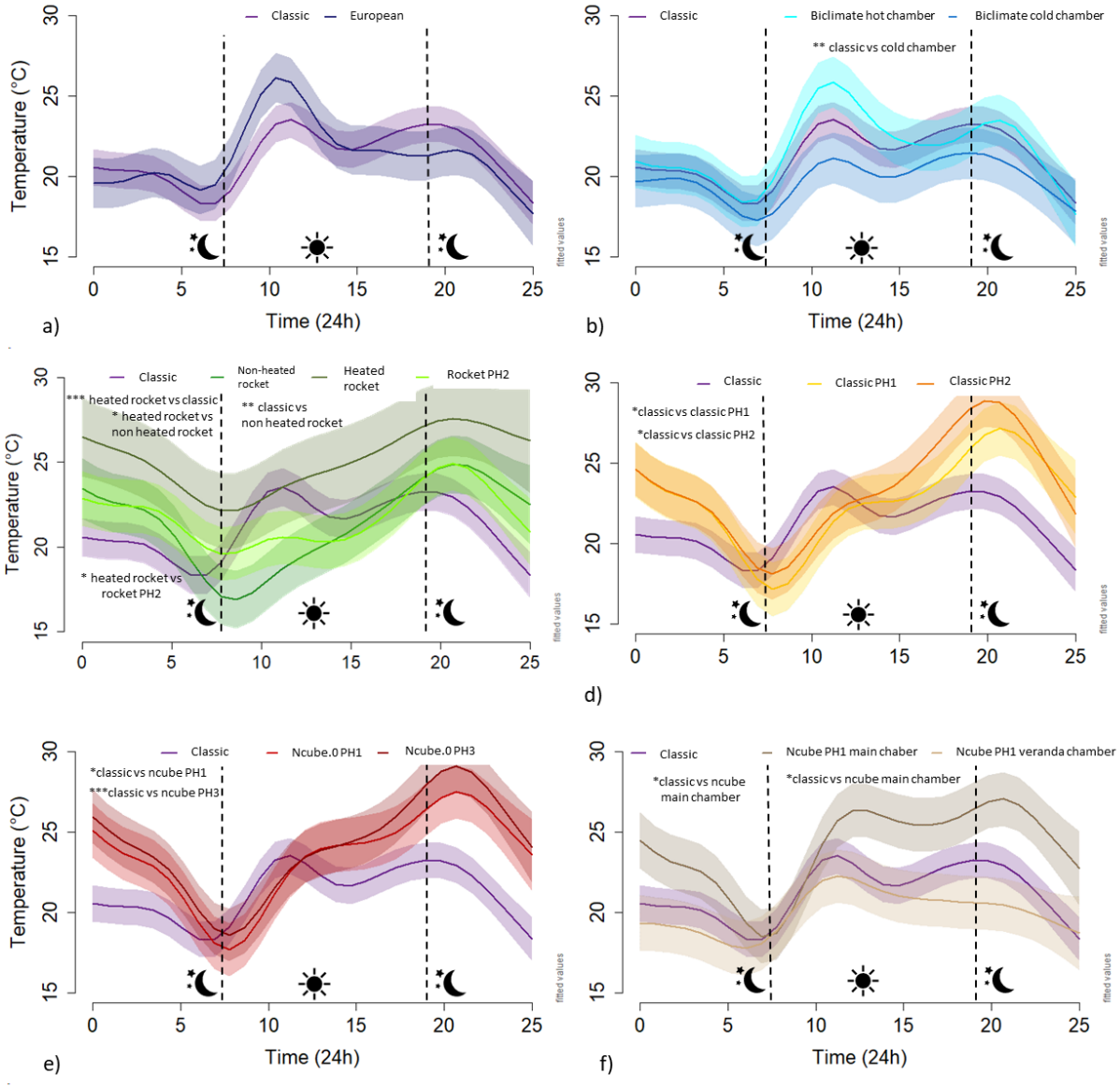

Figure S6. Estimated hourly patterns for different bat house designs compared with the Classic models. The estimated values are based on a generalized additive mixed model accounting for time, week, year, structure, external temperature, site, and individual bat house id. Values of fixed factors have been set to: week = first half of July, year = 2019, structure = building, external temperature = 18°C. a) European, b) Biclimate 2017 cold and hot chambers, c) Heated Rocket and Rocket PH2 2017, d) Classic PH1 2018 and PH2 2018, e) Ncube PH1 2018 and PH3 2018, and f) Ncube PH1 2019 main and lower chambers. The asterisks (*) represent significant differences between models during the day and night.

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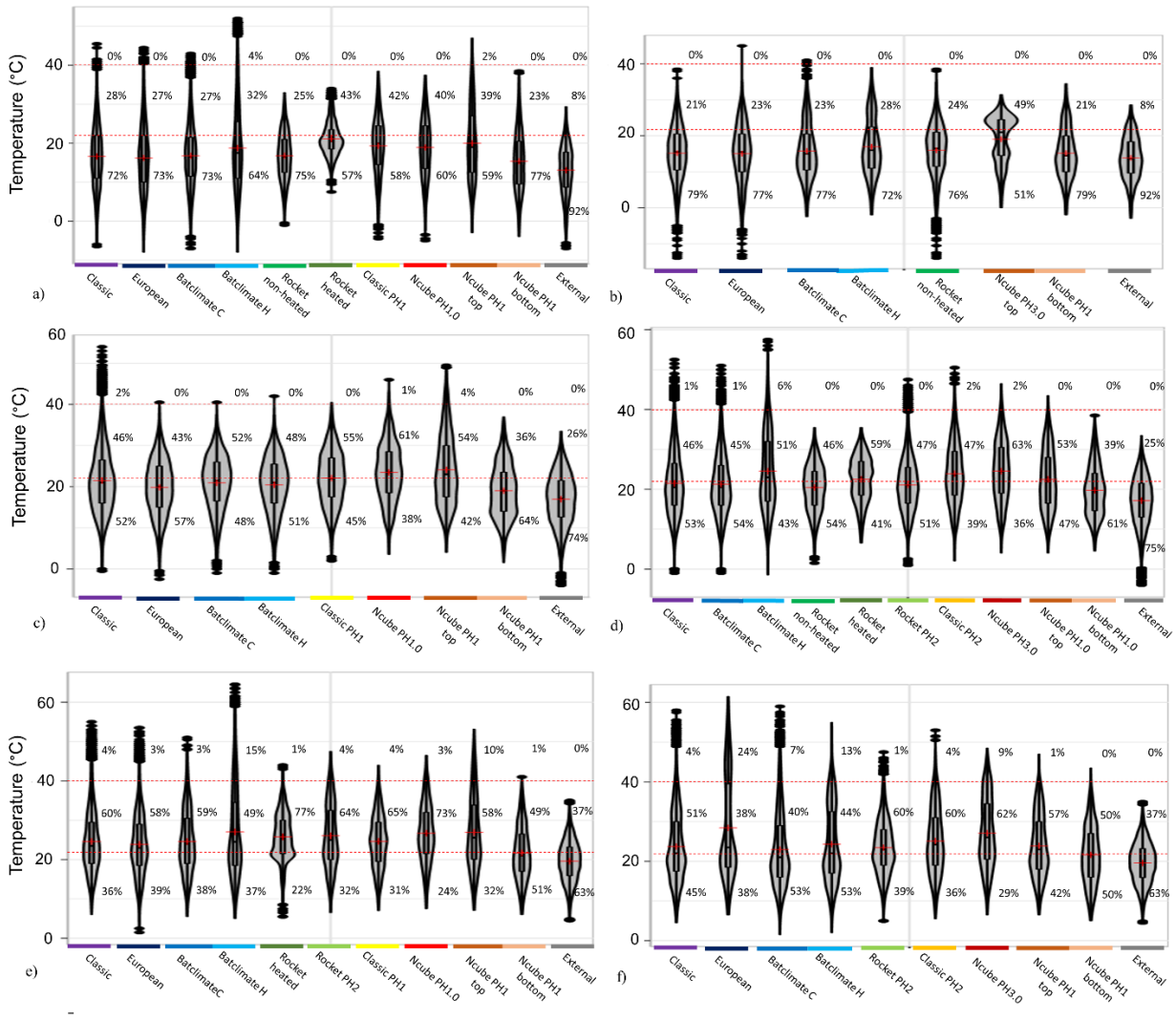

Figure S7. Variation of internal temperatures for all models from mid-May to mid-September 2017-2019 per climate and mounting type in Quebec, Canada: a) cold site on building, b) cold site on pole, c) intermediate site on building, d) intermediate site on pole, e) warm site on building, f) warm site on pole. The violins represent the temperature range of each model with the minimal and maximal temperature represented by the bottom and the top of the violin respectively. The width of the violin represents the distribution of the data. The black horizontal bar represents the median and the red cross the mean value. The red dotted line represents the extended optimal temperature range of 22-40 °C. The percentages below, in between, and over the extended optimal temperature range are represented beside each violin.

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