Early Design Stage Consideration of Building Form and BIPVT Energy Performance

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Abstract

Building form can be an influencing factor on the energy performance of solar net-zero energy buildings. While previous studies have examined the effects of building form on the energy demand of buildings and energy generation through the use of building-integrated photovoltaics (BIPV), fewer exist for the newer building-integrated photovoltaics with thermal heat recovery (BIPVT) system. Therefore this study analyzes the relationship between building form and BIPVT energy performance to provide guidance for commercial and institutional building design at the early design stage. Through TRNSYS simulations, different building plan shapes are analyzed in a heating dominated climate to determine the balance between energy demand and PV electricity generation and thermal heat recovery. Results indicate that configurations of each of the form families studied were able to reach net-zero energy depending on different enclosure parameters, BIPVT tilt angle, and building orientation, offering different pathways to net zero energy for building designers.

Keywords: BIPVT, design support, building form, building typology, net-zero energy building, TRNSYS

1. Introduction

1.1 NZEB, energy performance, tools for building designers

There is growing interest in the building sector for high performance buildings such as net zero energy buildings (NZEBs) as a means to reduce overall energy consumption. One of the common renewable energy technologies integrated into NZEBs is photovoltaic (PV) technology. While PV can be mounted on racking on building facades and roofs – for so-called building-applied PV (BAPV) – the full integration of PV as a component in the building enclosure – for building-integrated PV (BIPV) – offers the potential for better enclosure and architectural integration.

Since, in BIPV, the PV system is now an integral part of the building enclosure, building form will have an influence on the energy-generating performance of the BIPV as well as the overall energy performance of the NZEB. Previous performance studies have examined the effects of building form on the energy demand of buildings and energy generation using BIPV (Hachem, Athienitis et al. 2011; Youssef, Zhai et al. 2016).

Recent research focus has been on an enhancement of BIPV, the building-integrated PV/thermal (BIPVT) system, which includes thermal heat recovery as a means to extract additional benefit from the sun's energy at the building enclosure. Typically, when generating electricity, in a BIPV design, the heat at the panel backface is evacuated to the outside to cool down the PV panel and to prevent heat damage to proximate building materials. In the case of a BIPVT system, this heat is recovered for building use. Delisle and Kummert (2016) have examined building form and BIPVT in the context of cost-benefits for residential buildings. Athienitis et al (2018) have produced a BIPVT case study for commercial/institutional buildings, but the BIPVT application was limited to vertical facades. Therefore, this study analyzes the relationship between building form and roof-mounted BIPVT performance to provide guidance for commercial/institutional building design at the early design stage when major design decisions are yet to be made.

More specifically, the objective of this study is to determine the benefit of the thermal heat recovery in addition to the PV electric generation potential in a BIPVT system depending on building form, whilst maintaining an annual net-zero energy balance between energy demand and energy generation.

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2. Methodology

2.1. Building typology

The building type proposed in this study is 2 storey commercial/institutional, with a floor plate of 1 500 m^2, for a total useable floor area of 3 000 m^2. The floor plan is for an open-plan office space with a depth of 15 m to maximize the potential for daylighting that can be used in the space. Other locations will have different maximum building depths for daylighting depending on climate (Guglielmetti, Pless et al. 2010, Yip, Chen et al. 2015). The roof is pitched symmetrically about the longitudinal axis of each building wing to function as the BIPVT surface. Roof surfaces that are oriented between 90° and 270° azimuth are clad with BIPVT. While this makes for unequal total surface areas of BIPVT between building configurations, it represents realistic tradeoffs inherent in design choices. Using the bar plan shape (RE) as a reference point, several plan shapes were used to generate the 2-storey building configurations of equal floor area. These are simplified representations of common building plan types in the urban environment. The L- and U-shapes are further defined by a plan rotation angle from 15° to 75° to denote the rotation of a wing of the building vis-à-vis the other wings. (See Figure 1). The study uses weather conditions for the heating-dominated climate of Montreal, Canada (ASHRAE zone 6A).

All the building configurations tested use the same occupancy density, set point temperatures, and operating schedules.

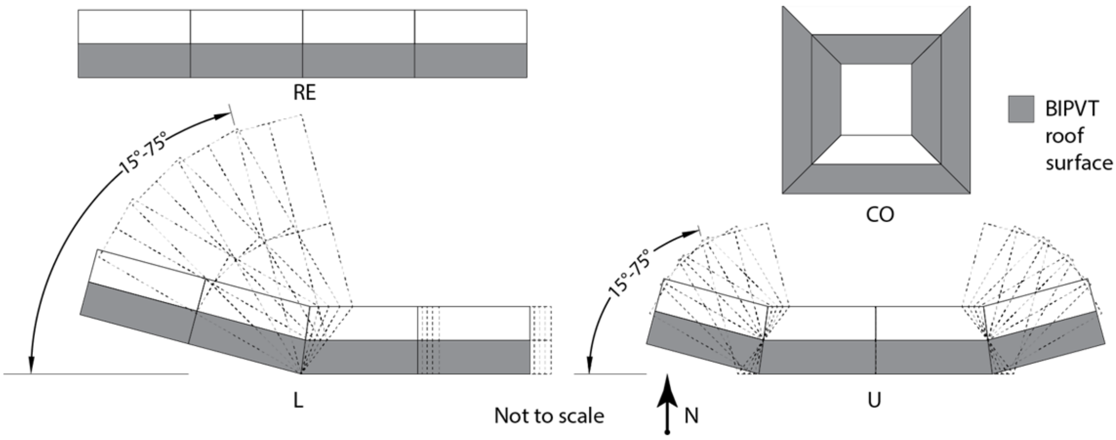


Figure 1: Plan shape families; grey shading indicates BIPVT surfaces; and the L- and U-shape plan rotation angles

2.2. Roof surface shape efficiency

The BIPVT surface area calculations do not account for potentially unusable, residual area due to possible mismatches between overall roof surface dimensions and total PV module dimensions since actual PV module sizes and layout are usually not yet known at early design stage. However, all triangular surface areas are excluded from usable BIPVT surface area. (See Figure 2). This represents the inherent inefficiency for roofs depending on the angle of intersection of the adjoining roofs.

Aside from ensuring daylighting penetration through the entire floor plate, the other reason to limit the depth of the building is to limit the height of the roof due to its pitch. For medium-sized commercial/institutional buildings, the roof is the principal surface for PV application. In a BIPV or BIPVT rooftop application, the PV tilt angle *is* the roof tilt angle; and the PV plane *is* the roof plane. For northern climates (latitudes), a balance must be achieved between providing a large surface area at a useful tilt angle for PV electricity generation and minimizing interior ceiling volume and space that must be conditioned and assigned a productive function or use.

This is a constraint that does not exist for BAPV rooftop applications. The deeper building is at best beneficial (at worst indifferent) for BAPV because the tilt angle and tiling of the BAPV is independent of roof slope or orientation due to the racking systems.

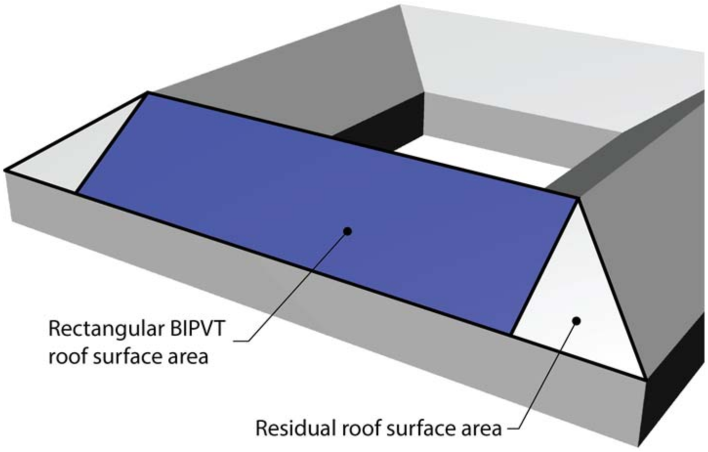


Figure 2: Detail of roof volume showing BIPVT surface (in blue) and residual area (in light grey)

2.3. TRNSYS model

TRNSYS 18 is used to simulate the building energy performance as well as the BIPVT electricity generation and thermal heat recovery. The three-dimensional building form derived from the plan shapes is used in the TRNSYS Type56 along with semantic variables such as thermal insulation quantities, window characteristics, building occupancy, setpoints, and schedules. Since this study is concerned with conditions for the early stage of a building design, ideal heating and cooling loads are calculated at hourly time steps based on a simplified heat pump with a heating coefficient of performance of 2.5, and a cooling coefficient of performance of 3.0. The minimum insulation values represent the minimum required under the National Energy Code of Canada for Buildings (Canadian Commission on Building and Fire Codes and Construction 2015) for Montreal. (See Table 1 for a summary of the main variables and values used in the simulations).

Table 1: Model inputs

Parameter	Value(s)
Location	Montreal, Canada
Azimuth	135° – 225°
Floor plate / storeys	1 500 m^2 / 2
Total floor area	3 000 m^2
Roof pitch	25° – 45°
PV nominal efficiency	0.16
BIPVT channel height	0.025 m
Total roof surface area	827 – 1591 m^2
Total BIPVT surface area	827 – 1233 m^2

Parameter	Value(s)
Wall insulation	1.0 – 1.5 (h/kJ)*m^2K
Roof insulation	1.5 – 2.0 (h/kJ)*m^2K
Window (see Table 2)	WinID 300, 500
WWR(S, E, W, N)	0.1 – 0.9
Heating Setpoint	21°C, 15°C night setback
Cooling Setpoint	26°C
Heating COP	2.5
Cooling COP	3.0
Schedule (occupancy)	M-F: 07h-20h; Sa-Su: 09h-18h

The BIPVT system is represented by TRNSYS Type568; uses a simple PV efficiency of 16%, and is connected to Type56 to access the Type56 roof inside surface temperature. Type568 uses this as the collector back surface temperature to calculate the lower air channel surface temperature. Type56 in turn uses this as the roof outside temperature to calculate the roof inside surface temperature. This process repeats until convergence is reached.

2.4. Windows

The sizes of fenestration are described by a window to wall ratio (WWR) variable. A separate WWR is calculated for each vertical building surface orientation. Two triple-glazed window types are used: one with a relatively high solar heat gain coefficient (SHGC) and daylight transmittance and the other with a lower SHGC and daylight transmittance. (See Table 2). Both window types are selected from the Window v7.4.6.0 database incorporated in TRNSYS 18.

Table 2: Window properties

Parameter	Window 1	Window 2
Description	High SHGC, high Tvis-daylight	Low SHGC, low Tvis-daylight
Description	Triple-glazed, argon-filled, low-e	Triple-glazed, argon-filled, low-e
WinID	300	500
U-value	0.61 W/(m^{2}K)	0.73 W/(m^{2}K)
g-value	0.5	0.3
Tsol	0.425	0.256
Tvis-daylight	0.72	0.54

Solar heat gain is managed through the use of an internal sunshade that is activated when incident solar radiation is above 140 W/m^2, blocking 70% of the solar radiation, and is deactivated when incident solar radiation is below 120 W/m^2.

2.5. Parametric model

Each building configuration is generated from a parametric model using a Python script which draws from the plan-shape families described in section 2.1 along with values for other parameters within the ranges listed in Table 1. The Python script then calls the TRNSYS executable to run the simulation of building energy demand, and BIPV/T electricity generation and thermal heat recovery. The simulation results are collected and stored using modeFRONTIER.

2.6. Evaluation criteria (NZEB)

The current study uses only one locale and uses site energy calculations to compare the relative performance of the different building configurations. The convention used in this study is that energy demand is a positive number; renewable energy generated is a negative number.

At each time step, the heating demand is first reduced by whatever amount of BIPVT heat that is recovered; the surplus BIPVT heat is exhausted to the exterior. Then, the net energy demand is calculated by summing the remaining heating demand along with the cooling demand, plug-loads, electrical lighting, and the BIPVT-generated electricity. The net energy demand is integrated over the whole year to obtain the annual net energy performance of the building. If this annual quantity is negative, the building will have achieved net zero energy (NZE) for the year.

3. Results and discussion

The results show that many of the building configurations from each family of plan shapes are able to reach NZE for Montreal. Figure 3 maps the net annual energy balance versus plan shape, BIPVT slope, and azimuth. These results are broken down further by plan shape in Figures 4 to 7. The dominating factor is the BIPVT roof tilt angle. Without exception, the best NZE performing configuration for each of the plan shapes is for a BIPVT roof tilt angle of 45°, which corresponds well to the angle of the site latitude (45.5°) and the general rule-ofthumb optimal tilt angle for annual solar radiation being equal to the site latitude (Duffie and Beckman 2013). Across all plan shapes, NZE was attained for roof tilt angles of 35° to 45°. Each of the different variants of each family of plan shapes (shapes 0 to 11) was able to reach NZE.

Since orientation refers to the nominal direction of the building plan on a site, the plan shapes with wing rotations result in BIPVT surface areas with different orientations. This ensures that the building can capture solar radiation at different times of day even though it may not be optimal. For example, the courtyard shape reaches NZE in a diamond configuration at azimuth 225°. Since this is a study for the early design stage, this particular configuration can be refined to adjust the quantity and placement of the BIPVT surfaces as the design progresses.

With the exception of the BIPVT tilt angle, each of the other input variables was able to reach NZE in configurations using all values from the entire input value range. As mentioned before, for the BIPVT tilt angle, NZE was reached only when the tilt angle was between 35° and 45°. Therefore, aside from the BIPVT tilt angle, choosing input values for reasons other than for net annual energy demand reduction, such as choosing a plan shape for architectural space planning reasons, will not compromise the NZEB goal.

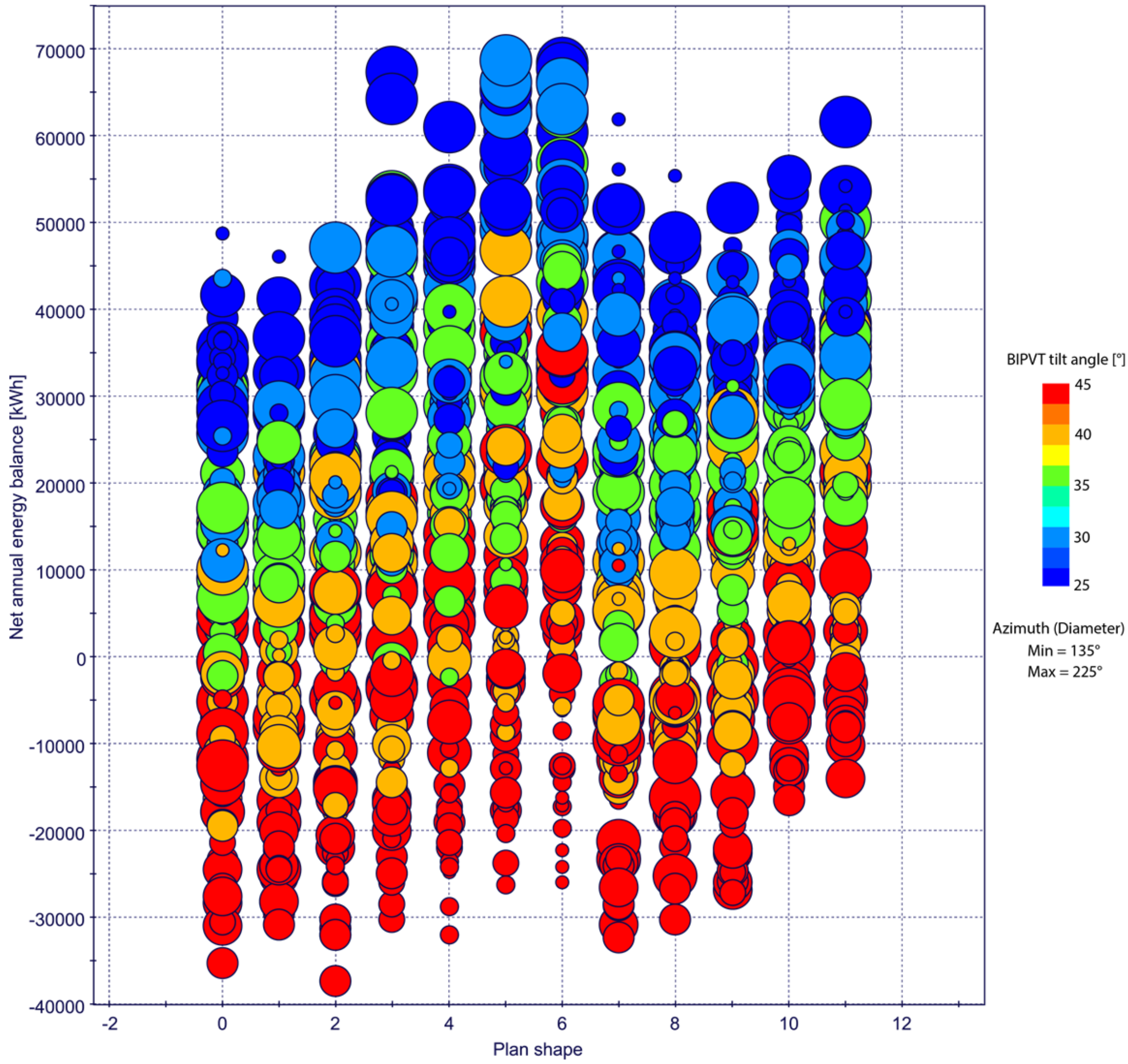


Figure 3: 4D plot of net energy balance versus plan shape, NZEB, BIPVT tilt angle, and azimuth (negative net annual energy means NZE reached)

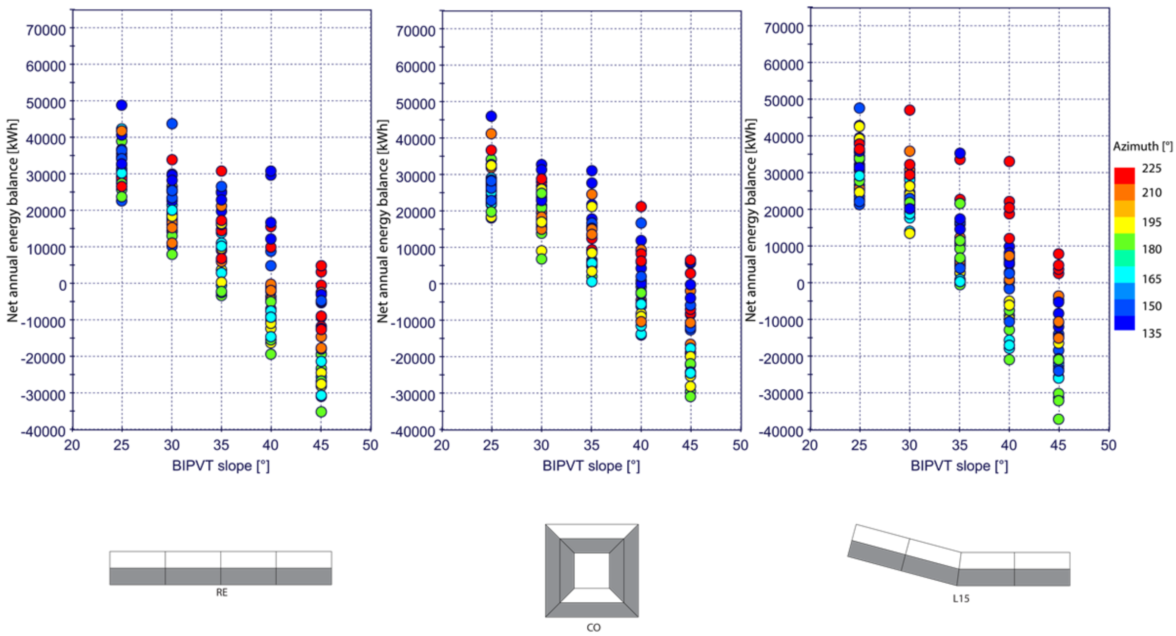


Figure 4. Plan shapes 0, 1, 2; net annual energy balance versus BIPVT slope and azimuth (negative net annual energy means NZE reached)

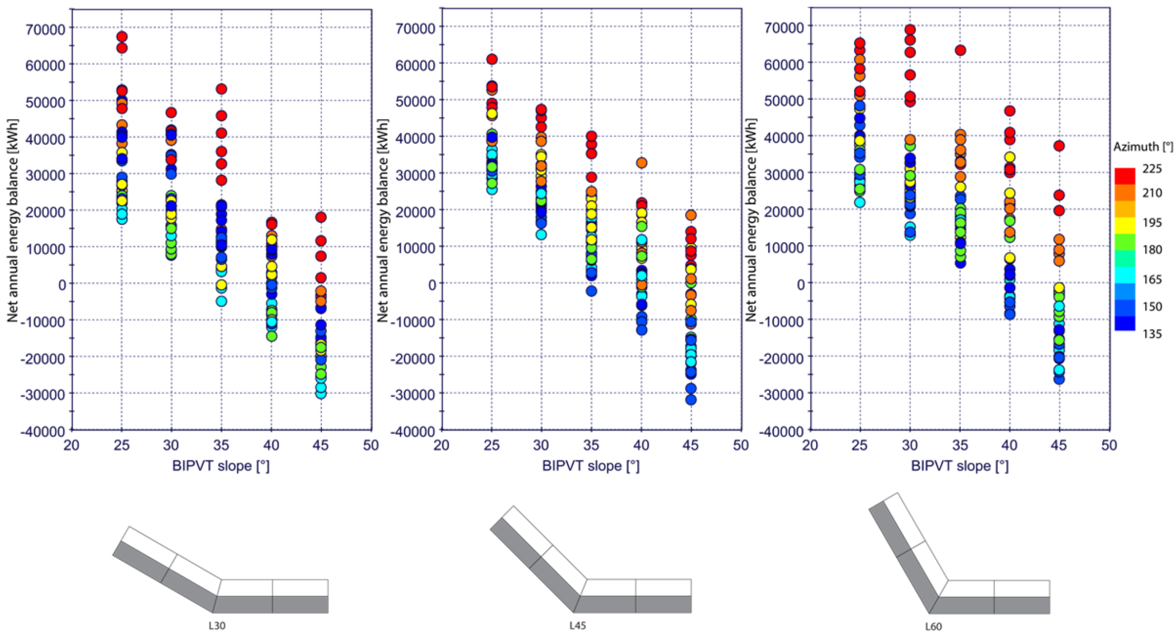


Figure 5: Plan shapes 3, 4, 5; net annual energy balance versus BIPVT slope and azimuth (negative net annual energy means NZE reached)

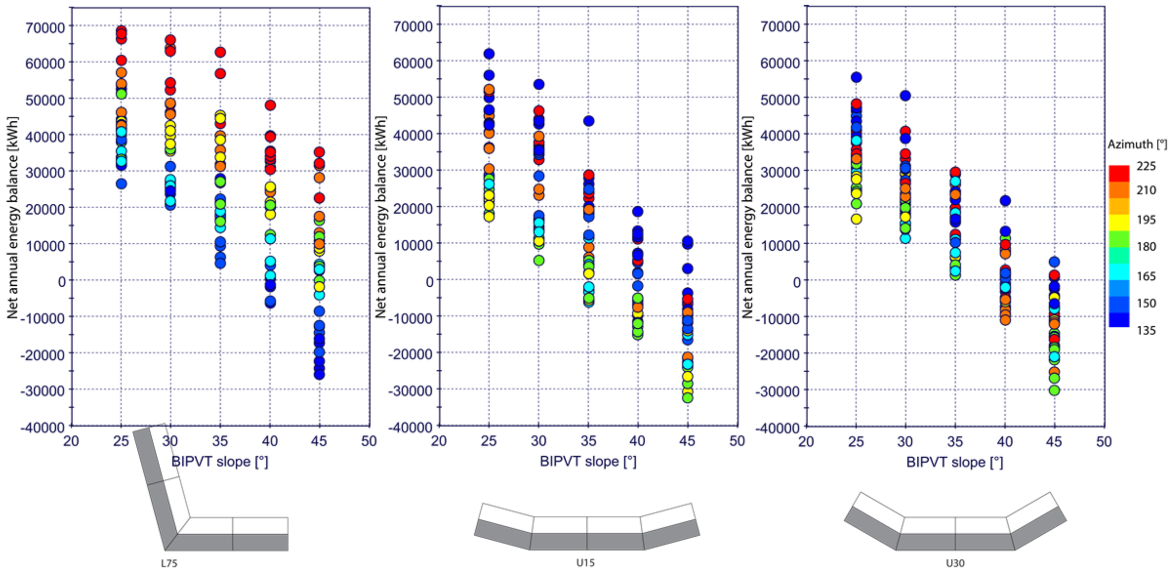


Figure 6: Plan shapes 6, 7, 8; net annual energy balance versus BIPVT slope and azimuth (negative net annual energy means NZE reached)

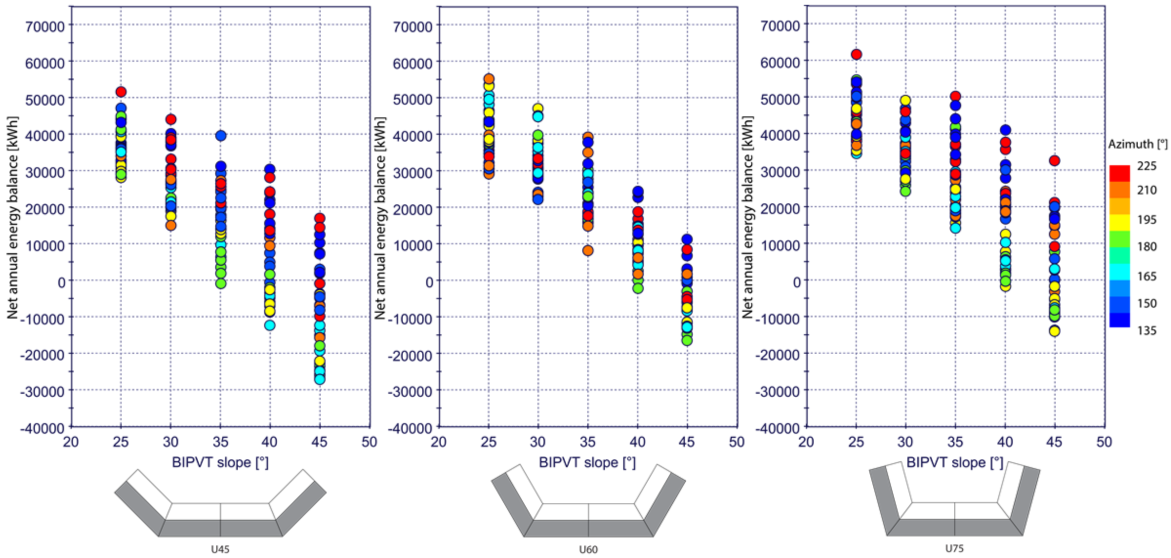
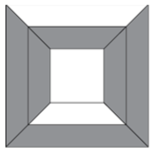
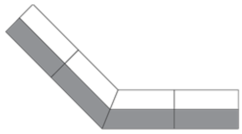
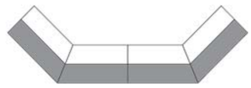


Figure 7: Plan shapes 9, 10, 11; net annual energy balance versus BIPVT slope and azimuth (negative net annual energy means NZE reached)

From Table 3, the CO, L, and U shape configurations with the best NZE performance compared to the RE reference shape share the same south orientation (azimuth = 180°) and root tilt angle (45°) but have notably lower cooling demands due to the combination of using the lower SHGC window, different WWRs, and smaller South-facing surface area.

Of particular note is the CO shape which manages to have an EUI that is only 0.35% greater than that of the reference RE shape. Its electricity and heat recovery is 2.70% and 2.67%, respectively, less than the reference RE shape but is achieved using more BIPVT surface area than the other configurations. On the other hand, its building footprint is more compact than any of the other plan shapes studied. This highlights the conflicting demands inherent in the building design process. In exchange for more BIPVT surface area at less optimal East/West orientation to achieve NZE, the CO shape provides a better internal plan for space use and circulation patterns and a semi-protected outdoor courtyard.

Table 3: Best net annual energy performance per plan shape family; Qh=annual heating demand; Qc=annual cooling demand; PV=annual electricity generation; T=annual thermal heat recovery

RE (Reference) shape				CO shape				L shape				U shape			
															
Annual totals (MWh); negative indicates energy generated or recovered															
Qh	Qc	PV	T	Qh	Qc	PV	T	Qh	Qc	PV	T	Qh	Qc	PV	T
125	54	-222	-371	139	40	-216	-361	150	35	-221	-369	147	45	-221	-369
Relative performance with respect to RE (reference) shape (%)															
Qh	Qc	PV	T	Qh	Qc	PV	T	Qh	Qc	PV	T	Qh	Qc	PV	T
-	-	-	-	10.75	-25.97	-2.70	-2.67	19.74	-35.04	-0.26	-0.34	17.58	-16.50	-0.44	-0.48
Energy use intensity without renewables (kWh/(m^2*y))															
71.01				71.26				72.22				72.96			
Net annual energy balance (kWh); negative indicates energy surplus															
-35 249				-30 851				-37 318				-32 353			
Total PVT surface area (m^2)															
1061				1233				1061				1061			
Roof tilt angle (°)															
45				45				45				45			
Azimuth (°)															
180				180				180				180			
Insulation – Wall | roof ((h/kJ)*m^{2}K)															
1.10		1.90		1.40		1.80		1.40		1.50		1.10		2.00	
WWR (E, N, S, W) (%)															
60	20	20	20	10	30	40	20	60	10	10	40	10	60	30	30
Window ID															
300				500				500				500			

4. Conclusions

The results show that each of the plan shapes studied is able to reach net zero energy using different combinations of input parameters and with the requirement of a BIPVT roof tilt angle of 35° to 45°.

Orientation is a misleading indicator of performance when using L, CO, and U shapes because they are not adversely affected as rectangular shapes to orientations oblique to the sun.

The CO courtyard plan shape is particularly interesting because its best NZE configuration performs almost as well as the reference RE rectangular shape while offering a compact footprint that has benefits to architectural space planning and urban planning.

Altogether, this shows that through different plan shapes and the other input parameters, there are different pathways to net zero energy that can satisfy architectural and engineering design requirements at the same time. Thus, these results can provide valuable insight into creating design guidelines and a methodology at the earliest stages of the building design process when there is the greatest opportunity to influence the energy profile, solar energy utilization, and form of a building.

5. Acknowledgements

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