Sensitivity analysis of building form and BIPVT energy performance for net-zero energy early-design stage consideration

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Abstract. This study examines the influence of building form – comprised of plan shape and roof slope – on the net annual energy performance of solar net-zero energy (NZE) buildings. The renewable energy system used is the building-integrated photovoltaics with thermal heat recovery (BIPVT). BIPVT is a relatively new enhancement of the building-integrated photovoltaics (BIPV) system which others have studied for the effects of building form on building energy demand and energy generation. Previous sensitivity analyses of building form have typically not considered BIPV or BIPVT. When they have, it has been limited to simple, prismatic forms; it is unclear how more complex or compound building forms impact building energy demand and BIPVT generation. Therefore this study analyzes the relationship between building form and BIPVT performance to provide guidance for medium-sized NZE commercial and institutional building design at the early design stage. The main input parameters are the building form: compound or complex plan shapes, and BIPVT roof slope. Also included are: building orientation, window to wall ratio (WWR), and U-value. These parameters are evaluated in a heating dominated climate to determine the parameters sensitive to the net energy demand – the balance between annual energy loads including heating/cooling energy demand and PV electricity generation and useful thermal heat recovery. A customized BIPVT model is used in TRNSYS simulations. A variance-based ANOVA global sensitivity analysis method is used for both main and interaction effects. Results show that each of the form variations studied is able to reach NZE using different combinations of input values. The most sensitive input parameters for the NZE output target are the BIPVT roof tilt angle, the azimuth, WWR (South), plan shape, and WWR (North). Each one is quantified. This information may provide building designers guidance at the early design stage.

1. Introduction
In order to assist the building sector in reducing overall energy consumption of buildings, guidance should be provided to designers in how to best integrate renewable energy technologies (RET) into design processes and future buildings. This design guidance will have the greatest impact during the early stages of the design process when little information exists to support designers in making decisions that will have significant impacts on the energy profiles of the eventual finalized building designs.

One common solar RET is the photovoltaic (PV) cell which has evolved into systems such as building-integrated PV (BIPV) where the electricity-generating components are integrated into the
building enclosure proper – offering the potential of greater systems and architectural integration in the enclosure and the reduction of the quantity of construction materials. Previous studies have examined how aspects of building form have an influence on the energy demand and the PV electricity-generating capabilities of BIPV systems [1].

The most recent evolution of the BIPV system is the building-integrated PV with thermal heat recovery system (BIPVT) which, in addition to electricity generation, captures the otherwise exhausted heat from the back of the PV surface and redirects it into the building for low-grade heating applications such as air heating. Research has progressed at the level of the system design [2] but not many studies exist in the application of BIPVT at the level of whole building design. [3] have studied BIPVT as applied to the façade of a building where the PV tilt-angle was directly constrained by the vertical walls of the building.

Previous research in sensitivity analysis (SA) for building energy performance has looked at different forms of SA from local to global methods. The global methods are preferred because they examine the entire model input space [4]. Among the global SA methods, some provide qualitative analyses like the Morris method [5, 6] while others also provide quantitative ranking using methods such as standardized rank regression coefficient (SRRC) [7] or analysis of variance (ANOVA) [8].

In particular, the ANOVA method offers two typical SA measures. The main effects calculate the first order contribution of each input on the output variation. This is useful for prioritizing or ranking input parameters. The other measure is the total sensitivity which also takes into account the higher order effects such as the interactions among different inputs and their effects on output variations. This second measure is useful when the SA objective is to screen for important design parameters or conversely to eliminate input parameters that have no practical impact on the output variations [4]. However, among the disadvantages of the global methods are increased sampling requirements leading to increased computation time.

[3] have implemented SA in a simulation tool and used it for the case study of the building energy demand and RET energy generation for an office building. However, that studied looked at BIPVT on vertical facades. [6] parametrized building form among the different variables not including RETs, but only performed qualitative SA.

Due to the possible interactions between building form and RETs, it may not be accurate to separate passive design strategies (energy reduction) from the energy generation strategies in a whole building energy analysis. Furthermore, it is common in the design process to work with sub-optimal parameters due to fixed project constraints like building site conditions or jurisdictional ordinances that are beyond the control of the building designer. For these reasons, this paper proposes the integrated approach to examine both passive and RET strategies together.

2. Methodology

In this paper, building form is studied through the components of plan shapes and roof slopes. Four building plan shape families are used as representatives of common urban building types. The plans are constrained to a maximum depth to permit daylighting throughout the entire floor plate. This maximum depth has been demonstrated in other studies [9]. The maximum depth used for the Montreal, Canada climate (ASHRAE climate zone 6A, 45.5°N, 73.58°W) is 15 m. The rectangular shape is the reference plan shape. Different wings of this shape are rotated in plan to form the O-, L-, and U-shaped plan families. See figure 1 which depicts the plan shapes in their base orientation of due south (azimuth 180°).

The architectural program is open plan commercial/institutional of medium size, which represents a total usable floor surface area of between approximately 900 m² to 5 000 m². In this study, each building has two floors, with 1 500 m² of floor surface area each for a total of 3 000 m². For this building size type, the BIPVT surface is the roof. Therefore, the roof slope comprising the BIPVT tilt angle is varied as a component of the building form. The nominal efficiency of the PV is 16%.

Minimum thermal resistance values for insulation and windows are determined based on the requirements in the National Energy Code of Canada for Buildings, 2015 [10]. The maximum
insulation values are determined based on a case study of a Passivhaus building for the same climate. Since this is a study for new construction at the early design stage, inputs are considered equally likely across their ranges. The window types are taken from the LBNL Window v7.4.6.0 database. There are separate window to wall ratios (WWR) for each building surface orientation. In total, 10 different input parameters were studied with their value ranges listed in Table 1.

Table 1. List of parameters and input ranges.

| Input parameter      | Range          |
|----------------------|----------------|
| Plan shape           | 0 – 11         |
| BIPVT tilt angle (°) | 25 – 45        |
| Azimuth (°)          | 135 – 225      |
| Window ID            | 300, 500       |
| Roof insulation ((h/kJ)*m²K) | 1.5 – 4.5   |
| Wall insulation ((h/kJ)*m²K) | 1.0 – 2.5   |
| WWR east             | 0.1 – 0.9      |
| WWR north            | 0.1 – 0.9      |
| WWR south            | 0.1 – 0.9      |
| WWR west             | 0.1 – 0.9      |

The Sobol sampling method is used within modeFRONTIER to generate the parameter input values for all candidate designs. Then a Python script is used to generate the 3d building designs and other input files required for the TRNSYS 18 simulation engine. Python calls TRNSYS to run the building energy, electricity generation, and thermal heat recovery simulations. Output data is collected and managed by modeFRONTIER for the sensitivity analysis.

The output variable, or evaluation criteria, used is the net annual energy demand which is obtained by offsetting the heating, cooling, plug load, and electric lighting demands with the generated electricity and recovered heat at each hourly time step. Site energy calculations are used for all quantities since only one climate/location is considered. Negative values will indicate an energy generation surplus and the successful attainment of net zero energy for that design candidate.

The SA implementation used is the smoothing spline ANOVA (SS-ANOVA) of modeFRONTIER [11]. Since the purpose of this study is to identify at the early design stage all the input variables that have significant impact – or conversely, have no significant impact – on the output, the total sensitivity contribution of the primary effect of each input and the second-order effects of the interactions between each input is used as a more complete measure of the overall effect of each input on the output variation.
3. Results and discussion

The total sensitivity magnitude of the input variables as well as the most significant input variable interactions is shown in table 2. A graphical representation of all the normalized inputs and interactions is shown in figure 2. The analysis shows that the BIPVT tilt angle is the most sensitive component of building form, with a contribution index of 0.686. This is much more significant than the other building form component studied, the plan shape, whose contribution index is 0.052.

| Input parameter                      | Contribution index |
|--------------------------------------|---------------------|
| BIPVT tilt angle                     | 0.686               |
| Azimuth                              | 0.055               |
| WWR South                            | 0.052               |
| Plan shape                           | 0.052               |
| WWR North                            | 0.049               |
| Window type * Azimuth                 | 0.044               |
| Plan shape * Azimuth                  | 0.042               |
| Window type                           | 0.025               |
| Plan shape * Window type              | 0.016               |
| Window type * WWR North               | 0.011               |
| Window type * WWR South               | 0.011               |
| BIPVT tilt angle * Window type        | 0.008               |
| WWR East                             | 0.004               |
| WWR West                             | 0.003               |
| Roof insulation                       | 0.002               |
| Plan shape * WWR South                | 0.001               |
| Roof insulation * Window type         | 0.001               |
| Window type * WWR West                | 0.001               |
| Wall insulation                       | 0.0008              |

The BIPVT tilt angle is also, by far, the most significant input parameter, accounting for almost 70% of the total variation on the NZE output target. The least sensitive primary inputs are the WWR for the East and West orientations, and roof and wall insulation variables, with the wall insulation one order of magnitude less significant than the roof insulation. As mentioned in the methodology section, such insensitive input parameters can be excluded from consideration at an early design stage to simplify the design process.

One interesting result is that there is a series of input parameters clustered between 0.044 – 0.055 in the contribution index, more than one order of magnitude less significant than the BIPVT tilt angle. The azimuth angle and plan shape appear in this range, three and two times, respectively, as either primary or part of second order inputs.

The fact that the azimuth and plan shape are relatively less influential may be explained by the use of compound plan shapes in the study. Aside from the reference rectangular case, each family of plan shapes is composed of wings that are not limited to one unique orientation. Therefore, even if the nominal building orientation is sub-optimal, for example with an azimuth of 225°, the different wings of the L-, O-, and U-shapes will be at other azimuth angles and may mitigate this adverse effect on both the energy demand and energy generation potential of the building.
Figure 2. Normalized total sensitivity index.

Figure 3 shows one such case, where the O-shaped plan with a 225° nominal azimuth angle and BIPVT tilt angle of 45° is able to reach NZE with an annual net energy surplus of 22,646 kWh – even though two of the BIPVT roof surfaces are oriented away from the equator. Since all building configurations are generated automatically by Python script, a second round of refinement will identify that there are indeed two BIPVT surfaces that are not contributing to the electricity generation and eliminate them in case this candidate is selected by the design team for further design development.

Figure 3. O-shaped plan with 225° nominal azimuth angle.

In the end, each of the plan shapes is able to reach NZE with different combinations of values of the input parameters. Furthermore, NZE was achieved with the entire range of input values for all parameters except for BIPVT tilt angle for which a minimum of 25° was needed.

In terms of design flexibility, the dominating influence of the BIPVT tilt angle allows for more diverse plan shape options at the early building design stages knowing that the sensitivity of plan shape on NZE is relatively minor compared to BIPVT tilt angle. This may permit freer architectural
design exploration of plan shape beyond the simple square or rectangular plan shapes that are generally encountered at early design stage.

Finally, the results show that the window type is relatively insensitive for the NZE target. The window types used from the LBNL Window database (ID 300 and 500) are high performance triple-glazed units with U-values of 0.58 W/(m²*K) and 0.70 W/(m²*K), respectively, based on the minimum energy code requirements and appropriate for the Montreal climate. For a milder heating dominated climate – or a cooling dominated climate – windows with a higher U-value may be sufficient for energy code purposes and would increase the range of the input design space in the sensitivity analysis. Thus, further study of the input parameters’ ranges is required when expanding the study to other climates and locations.

4. Conclusion and implications

Building form – consisting of a series of plan shapes based on L-, O-, and U-shapes, and roof tilt angles – is examined for medium-sized, 2 storey commercial/institutional buildings in terms of net annual energy demand and BIPVT roof electricity generation and thermal energy recovery. Along with plan shape, and roof tilt angle, eight other input parameters were varied. The BIPVT tilt angle is identified as the most significant building form component and overall input parameter using an ANOVA sensitivity analysis of primary and second order effects. Among the other significant input parameters, in order of importance, are the azimuth, the south window to wall ratio, the plan shape, the north window to wall ratio, the interaction between the window type and the azimuth and the interaction between the plan shape and the azimuth.

The most important conclusions for building designers are that BIPVT tilt angle is the critical input achieving NZE. The study shows that below a tilt angle of 25°, NZE is not possible for the Montreal climate. Also, when using compound plan shapes, the plan shape and orientation have much less impact on the NZE variation than tilt angle. This permits design flexibility with a greater range of architectural plan diversity with different pathways to NZE, thus offering a way to satisfy architectural and engineering requirements at the same time.

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