The impact of roof morphology on solar potential: making Toronto suburbs solar ready

Javeriya Hasan¹, Miljana Horvat¹, Charles Riddell¹, Rita Wang¹

¹Ryerson University, Toronto (Canada)

Javeriya.hasan@ryerson.ca

Abstract. Rapid urbanization, the increasing effects of climate change, the need to reduce fossil fuels’ dependency as well as to improve cities’ resiliency are accelerating the shift towards renewable energy. Additionally, unnecessary complex roof morphologies that are often pushed by suburban divisions’ developers to make houses look more “opulent” and appealing to homebuyers, also impede the smooth integration of active solar technologies. To address this, and to respond to increasing homebuyers’ interest in renewable energy, this study looks to demonstrate how relatively minor design changes could affect the potential for solar generation and create ‘solar ready’ homes without compromising on the aesthetic of the roof morphologies in styles expected by homebuyers. It looked at six different roof morphological forms ranging from small to large houses, a common suburban house archetype in Canada. The roof configurations were remodelled to remove ‘fake dormers’, minimise ridges and valleys, etc. This process helped maximize the south, south-east, south-west, east and west facing surfaces. The results show that these changes could have a significant impact on the magnitude of solar power generation. The power output from a remodelled neighborhood at an optimized orientation exceeded the community’s electricity demand by 24%.

1. Introduction
The Canada Government target of reducing Greenhouse gas (GHG) emissions below 2005 levels in 2030 puts a spotlight on the need to synergize renewable power generation and urban built form. Due to a rapid growth in population in the recent years, there has been a significant rise in housing development in the Greater Toronto Area (GTA). Between 2018 and 2019 alone, some suburban neighborhoods experienced a growth rate between 5.1% and 13.3% [1]. The culmination of the Covid-19 pandemic has resulted in most people working from their homes, which has increased household electricity demand in Ontario [2]. To mitigate any adverse after-effects of energy supply-chain disruption, it is necessitated that future neighborhood developments are designed in accordance with sustainability principles and should focus on onsite power generation. Additionally, the opportunity to bring the energy source as close to users as possible has resulted in an expansion of technologies such as BIPVs, BIST and hybrid technologies, which can be easily incorporated into the urban / suburban fabric and within buildings.

2. Background
The design and building of low-rise residential suburban developments in North America are still under the domain of developers who are often driven by tested-and-true approach and that usually follows semi- “traditional” look of single-family houses. The concern in regards this approach is that roof morphologies are unnecessarily complex and are often pushed by suburban divisions’ developers to
make those houses look more “opulent” and thus appealing to homebuyers (see Figure 1). This impedes the smooth integration of active solar technologies, and in some cases, affects the efficacy of the power generation performance, if at all they are implemented. Still, for many owners, the integration of renewables into the “traditional” North American houses feels like an additional cost with long returns and is often met with resistance.

![Figure 1: Examples of unnecessarily complex roofs in typical North American homes [3, 4]](image)

To address this problem, this study looks to demonstrate how relatively minor design changes could affect the potential for solar generation and create ‘solar ready’ homes without compromising on the aesthetic of the roof morphologies in styles expected by homebuyers. According to the National Renewable Energy Laboratory (NREL), a ‘solar ready’ building is defined as being designed and built, “to enable installation of solar photovoltaic and heating systems sometime after the building is constructed” [5]. A solar ready building allows the incorporation of PVs at later date without having to change the roof structure, open walls for conduits and electrical cables, create a location for electric components, as well as storage tanks components [6].

The earlier study by the same authors looked at roof geometries of a “typical” new suburban development in Toronto, Canada, applicable anywhere in North America. It includes 85 single-family homes of various sizes (2 to 5 bedrooms); smaller houses are situated on narrow lots, they are closer together, while bigger houses also have additional space around them. The study simulated solar potential on various roof surfaces in original, and variations of modified geometries: simplifying roof surfaces, removing unnecessary additions, such as “fake” dormers, mirroring the plans, etc., to achieve surfaces better suitable for integration of active solar systems. The original attempt provided promising results but also acknowledged major shortcomings: limitations of the simulation tool at the time, looking only at the total annual solar potential output rather than considering daily or seasonal variations and aligning them with variations in consumption, etc. [7]. Revisiting this case by using more powerful, and versatile tools, better suitable for larger scale (i.e., neighborhood scale) simulation would provide not only more accurate results but also present the case for augmented benefits of pooling the generation from individual to neighborhood scale and shared resources. The study objectives entail the following:

- Examining a typical North American suburban development; determining the increase in solar potential in individual house examples when minor roof design modifications are introduced, while keeping the original architectural language.
- Then, by looking into the solar potential of the whole neighbourhood, investigating whether this approach can better offset their collective electricity consumption.
- Finally, finding the most favourable neighbourhood orientation through the optimisation of the total solar potential of the surfaces.

### 3. Methodology and Results

The process of investigation was three-pronged focusing on the roof design (i.e., roof tectonics) of houses and the neighborhood design, followed by a solar analysis and finally, the computation of solar power generation potential of the residential community. These roof configurations were named as A to K (see Figure 2), and six different scenarios of orientation i.e., the north, south, east, west, north-west and south-west direction were examined to assess the variation of solar potential of different surfaces. Interior configuration of spaces within houses was not addressed at this time.
The potential of solar power generation from the roofs essentially depended upon specific surfaces i.e., the south, south-east and south-west surfaces. The existing roof typologies were then examined to explore configurations of dormers, ridges, valleys, and high slopes, which would create overshadowing and reduce usable area for PV implementation. The next step included simplification of roof surfaces, changing roof slopes to better suit the optimal PV positions for this latitude, removing of unnecessary fake dormers, mirroring plans to expose larger roof surfaces to favourable orientation, while keeping the overall architectural expression favoured by prospective homebuyers. Figure 3 shows Models A and D, as they represent the typical size of smaller and larger house models in the study. The next step involved estimation of the actual maximum PV coverage on the redesigned roof surfaces, using typical commercially available residential PV panels dimensions of 1.65m (length) x 0.99m (width) with an 18% efficiency at standard operating temperature.

$$\text{Total power generated (kWh)} = \text{Solar radiation intensity (kWh/m}^2\text{) x PV coverage (m}^2\text{) x Efficiency (\%)}$$
3.2. The results of the house roof models

Table 1: Seasonal solar power generation for Model A as an example

| Season | Original | Remodelled | Increase from original to remodelled house |
|--------|----------|------------|------------------------------------------|
|        | N S E W N S E W N S E W |                                      |
| Spring | 1769 903 1195 1200 2108 1671 1211 1285 |                          | 19% 85% 1% 7% |
| Summer | 3902 3928 5659 5365 5950 4186 6532 6025 |                          | 52% 7% 15% 12% |
| Autumn | 1955 1096 1201 1300 2402 2035 1220 1354 |                          | 23% 86% 2% 4% |
| Winter | 968 773 984 1144 1396 946 996 1175       |                          | 44% 22% 1% 3% |

Table 2: The annual solar potential (kWh) for the original and remodelled Model A and D roofs

| Model A | North | South | East | West | South-East | North-West |
|---------|-------|-------|------|------|------------|------------|
| Original | 8,594 | 6700  | 9,039| 9,009| 5,753      | 6,988      |
| Remodelled | 11,856| 8,838 | 9,959| 9,839| 6,255      | 8,071      |
| Change   | +38%  | +32%  | +10% | +9%  | +9%        | +15%       |

| Model D | North | South | East | West | South-East | North-West |
|---------|-------|-------|------|------|------------|------------|
| Original | 9030  | 10,322| 9,331| 8,084| 7,526      | 6,875      |
| Remodelled | 11,889| 11,958| 12,521| 13,629| 13,173     | 10,943     |
| Change   | +32%  | +16%  | +34% | +69% | +75%       | +59%       |

An analysis indicating the seasonal and annual variation of solar potential was undertaken for all the models, which is seen to vary across the north, south, east, west, north-west, and south-east orientations (see Tables 1 and 2). The highest contribution of power generation potential is when the house models are east orientated (i.e., the entrance faces east, while the largest roof surface faces south), where the annual solar radiation intensity incident is on average about 1000-1400 kWh/m². This indicates that just by slightly reconfiguring and simplifying the roof morphologies, the increase in electricity production can reach up to 38% production of solar power during specific months. Remodelling roof surfaces result in a higher magnitude of solar radiation intensity, longer durations of solar exposure and larger surface area to accommodate more PV panels on the roof. Slight changes in orientation also bring forth higher gains, particularly for houses aligned along the east-west axis. For model A, the greatest change in the output due to remodelling the roof typology is at the north orientation and this change is 38%, especially
during the spring and autumn period. On the other hand, reconfiguring larger roof models like D resulted in an increase in the power generation potential along the north, southeast, northwest, east, and west direction, which is primarily due to large surfaces facing almost every direction.

### 3.3. The results of modelling the neighborhood

The original neighbourhood design included internal streets orientated about 24° east from north. Most of the houses in the neighborhood were either orientated towards the north-west or south-east directions with the south, south-east and south-west faces as being the solar generating surfaces. Models that were originally oriented towards the north-west were mirrored along the south-east direction, such that larger surfaces were exposed to the south-west direction. Changing the roof configurations from original to remodelled typologies resulted in an overall 16% increase in the annual solar power generation. Given that the average annual electricity consumption of a house in Ontario is 9500 kWh, in the idealistic context, the solar power generation from the original configurations could meet up to 94% of this consumption [7]. On the other hand, the annual power generation for the neighborhood with the remodelled roof configurations met all the community’s electricity demand and produced about 9% surplus electricity (see Figure 4 and Table 3). Reorienting the neighborhood such that almost all the houses were aligned along the east-west axis raised the power generation capacity of the neighborhood by 32%, whereby there was 24% of surplus electricity produced (see Table 4).

![Figure 4: Renderings showing the solar radiation intensity for the remodelled neighbourhood at the original orientation (right) and rotated to the new orientation (left)](image)

| Configuration | New orientation | Original orientation |
|---------------|-----------------|----------------------|
| Annual power generation potential | 998,211 kWh | 882,366 kWh |
| Percentage change in annual power generation | +13% | +16% |
| Percentage of electricity that could be offset | 124% | 109% |

### 4. Discussion

It is important to emphasize that the simulated outputs of this exercise are rather optimistic, especially as the electricity losses due to balancing of system, inverters, delivery, overshadowing by trees,
mechanical or plumbing attachments on roofs, and/or the snow and dust coverage are not considered. Similarly, the neighbourhood houses in this study are inclined along relatively favourable orientations in the first place, whereas actual house orientations in GTA suburbs greatly vary, as they may be constrained by the existing streets and site configuration. Finally, the considerable contributors to the overall total neighbourhood output are number of larger houses, which not only feature greater roof areas suitable for more PVs but are also situated on larger lots with more space around them that prevents overshadowing from the adjacent houses. The average annual power generated from these models ranged around 12,000 kWh, which is about 25% greater than the average household electricity demand in Ontario. This provides an important context to the benefits of harvesting and sharing solar energy at the neighbourhood level, where houses that are more well-endowed in generating solar power can pool the excess electricity produced to other households in the community. A consequence of this interdependence is the equitable distribution of energy and is an important step towards establishing a system of district energy sharing. Furthermore, advanced approaches to energy management would also open possibilities in incorporating district energy storage technologies which would bring additional benefits in electricity availability and cost sharing [8]. Unfortunately, this concept is still quite novel in North America, where the legal aspects of individual ownership still impede introduction of more efficient approaches in energy harvesting and management, such as district sharing. It is our hope that examples such as this would demonstrate benefits to developers, law and policy makers, and contribute to changing the mindsets of stakeholders for the benefit of all.

5. Conclusion
This study is important in the context of Canada’s 2030 emissions target. There is a growing traction towards energy efficiency in the residential sectors, and design considerations at the conceptual stage need to address the issue of technological integration on suburban houses. It is important to re-examine typical North American housing typologies, as their peculiar style and shape, impede efforts towards attaining energy resilience at the house and neighborhood level. Each house surface can be viewed as a potential resource, particularly in terms of the generation of electricity. As this study showed, roof configurations need to be designed in accordance with solar readiness principles, focusing on simplification of surfaces and the optimization of roof surface orientations. Design adjustments can help generate sufficient solar power to meet household electricity demand. If all the houses in a community pool together the renewable resources, this is significant step towards achieving net-zero/net-positive status. Contemporary residential development needs to be re-viewed from the lens of energy self-sufficiency and resilience, as this is especially important in the current Covid-19 pandemic.

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