Accepted by PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt. Res. Appl. 2015; DOI: 10.1002/pip.2651

BROADER PERSPECTIVES

Impact of electricity tariffs on optimal orientation of photovoltaic modules

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This is the pre-peer reviewed version of the following article: Prog. Photovolt: Res. Appl. (2015) Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.2651, which has been published in final form at http://onlinelibrary.wiley.com/doi/10.1002/pip.2651/abstract.

ABSTRACT

Maximum revenue (or cost saving) from non-tracking photovoltaic (PV) modules used for distributed generation can be achieved by a module orientation that depends on how the electricity tariff varies with time of day and time of year. Many jurisdictions have real-time market prices of electricity for large customers, time-dependent tariffs, or tariffs that depend on peak demand. This paper quantifies the impact of such tariffs on the optimal orientation of non-tracking PV modules using example tariffs from California, Nevada and Ontario, and concludes that modules should be oriented to the west of south by 28°, 46° and 54° respectively. In order to focus on the impact of tariff, the results are based on simulations of a constant-efficiency PV system operating under year-round clear-sky conditions. A generalized relationship between optimal azimuth and the on- to off-peak ratio of time-dependent tariffs is also presented. The paper quantifies the sensitivity of the dollar value of the power generated to non-optimal orientation of the modules. Compared to conventional south facing modules tilted at an angle just under the latitude, the paper demonstrates that optimal orientation adds 4-19% to the revenue/cost savings, potentially affecting the economic viability of a PV installation. The peak demand components of the Ontario tariff have a much more substantial effect on the optimization and resultant revenues (cost savings) than variations in the real-time market price of electricity.

KEYWORDS
photovoltaics; tilt; azimuth; revenue; optimization; tariff.

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1. INTRODUCTION

In order to maximize the annual electric energy generated by non-tracking photovoltaic (PV) modules, the modules should be oriented south in the Northern Hemisphere and north in the Southern Hemisphere. Also, assuming clear sky conditions, the optimal tilt is approximately equal to the latitude [1-3].

Many local factors influence the optimal orientation for individual locations, including cloudiness, temperature, shading, dust, rain (which washes away the dust), snow and bird droppings [4]. General cloudiness increases the proportion of diffuse irradiance resulting in an optimal tilt angle less than latitude. A US study [5] shows that, when cloudiness is taken into account, the optimal tilt is reduced by up to 10°, particularly in the northern United States. An analytical approach [6] finds that the optimal tilt in cloudy US locations is reduced by 12° to 16°. Two European studies [7-8] find that the optimum tilt must be reduced by 10° to 20° between southern and northern Europe due to the same effect.

In off-grid implementations, obtaining a uniform power output throughout the day or year may be of more importance than maximizing the total energy generated [9].

The aim of this paper is to maximize *financial benefit*. To achieve this, one must account for the dollar value of the energy depending on the time of day and year. Ref [10] shows that grid-scale PV systems selling to the wholesale market with higher prices on summer afternoons in the USA result in optimal orientations west of south for an increase of 1-5% in revenue. A similar optimization for Ontario wholesale market prices gave an azimuthal adjustment of 1° to 4° west of south [11]. The present paper addresses PV used for distributed generation, and quantifies the impact of three types of tariffs on the optimal tilt and azimuth of fixed solar modules. These three scenarios are 1) feed in tariffs (FIT) 2) time of use (ToU), and 3) large commercial customers. For these scenarios, we find the dollar value to be increased by 4-19% compared to a due south orientation.

1.1 Feed in tariffs

Many PV installations sell their power at a FIT available in their local jurisdiction, and the majority of FIT contracts are at a fixed price per kWh for 10-20 years. This results in an optimal orientation that is the same for both maximum revenue and maximum energy. By contrast, other FITs depend on the time of day and time of year, such as in Sacramento, California [12].

1.2 Time-of-Use tariffs

Many jurisdictions have been reducing their FITs, [13], resulting in the importance of non-FIT opportunities. For these, the economic viability of PV power generated at customer sites is determined by offsetting the cost of purchasing power, such as load displacement, and possibly by selling power back to the grid (i.e. net-metering). In this case, optimal orientation of PV modules is determined by the time varying cost of electricity. Many jurisdictions have ToU tariffs designed to incentivise a reduction in demand at peak times. Thus, orienting PV modules to maximize power production during high tariff periods results simultaneously in a financial benefit to the customer and a reduced peak demand for the grid.

Ref. [14] projects that 14% of US consumers will have ToU tariffs by 2020. The early work in [15] showed the dependence of electricity cost on tilt of PV modules at six European locations, but restricted consideration of ToU tariffs to how they match the building load profile. An analysis of 2005 ToU pricing in Ontario found the optimal azimuth to be 5° east of south [11]. Ref. [16] investigates a residential subdivision in Nevada with roof integrated photovoltaics, and found houses facing 40° west of south (tilt 22.5° dictated be the architectural design) derived the most dollar savings from the ToU tariff and contributed significantly to peak load reductions. In Section 3.2 we investigate the Nevada tariff for commercial customers to determine both the optimal tilt and azimuth where both can be selected, such as modules mounted using racking on the ground or on a nearly flat surface.

1.3 Tariffs for large commercial customers

Electricity tariffs for large customers can incorporate peak-dependent components, including:

a) The real-time cost of electric energy on the wholesale market ($/kWh of consumption);
b) A charge dependent on the customer's peak demand each month.
   - This is designed to represent the cost borne by the grid for the capacity of the transmission and distribution networks used to deliver the power to the customer ($/kW of peak customer demand);
c) A charge dependent on the customer's demand at times when the total grid demand is at its peak.
   - This is designed to represent the capital costs borne by the grid operator for the peak capacity of the generation, transmission and distribution equipment ($/kW of customer demand at grid peak times).

Since the electric power industry is capital intensive, the costs of supplying power at peak times, represented by b) and c) above, are very significant. Even though items b) and c) are based on the customers' consumption during very specific hours of the year, they can contribute over 50% of the electricity bill. The hours during which peak demand occurs therefore play an important role in determining the optimal orientation of PV modules designed to offset demand. Section 3.3 of this paper analyses this situation based on tariffs for Ottawa, Ontario.

2. MODEL OF REVENUE FROM PV MODULES

Two proven approaches to estimating the amount of solar energy reaching PV modules are (a) from Global Horizontal Irradiance (GHI) data and (b) from a clear sky model. The GHI data, by its empirical nature, takes into account cloudiness and atmospheric pollution, and must be used when assessing a project's viability at a specific location. We choose a clear-sky model because it allows for direct analysis and avoids the possible influence of site-specific atmospheric effects, enabling us to focus our research on a single factor: the impact of tariff on optimal orientation.

The simulation is based on the model provided by [17], which estimates Watts of solar irradiance per square meter of PV collector, as detailed in Appendix A. Combining this with the time-dependent tariff values gives a surface of revenue in terms of tilt and azimuth from which we can find a maximum revenue. The surface also indicates how sensitive revenue is to non-optimal tilts and azimuths, which are important considerations for constrained system installations.

3. OPTIMUM PV MODULE ORIENTATION

3.1 Time-dependent feed in tariff

In this section we investigate the impact of a time-dependent FIT on the optimal orientation by taking the example of the FIT contract [12], in Sacramento, CA, (latitude 38.56° north), given in Table 1. It is designed to alleviate stress on the grid at peak times, particularly the June-September “super peak” period from 14:00 to 20:00 when air conditioning usage is at its maximum. At those times, the FIT is more than twice the average, and the sun’s azimuth is west of south, significantly affecting the optimal orientation for PV modules.

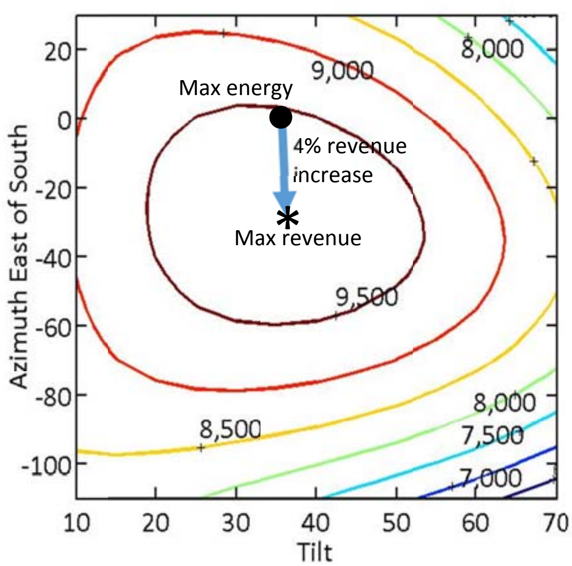

Figure 1. Variation of annual revenue ($) with tilt and azimuth from a clear sky simulation using the FIT in Sacramento, CA. The optimum energy maxima point is donated by ●, while the optimum revenue point is denoted by *.

The results of simulating the revenue from non-tracking PV systems at various tilts with azimuths from 10° east of south to 110° west of south are given in Figure 1 for a nominal 50 kW system. The optimal orientation for revenue is 36° tilt and azimuth 28° west of south while the optimal orientation for energy maximization is at a 35° tilt and 0° azimuth. The difference, shown by the arrow in Figure 1, is a marginal revenue increase of 4%. 95% of the maximum revenue can be obtained for azimuths between 7° east of south and 63° west of south.

Table 1. FIT for a 20 year contract, Sacramento, CA ($/kWh).

2014	Super Peak	On Peak	Off Peak
	14:00-20:00	6:00-14:00; 20:00-22:00	Other times
Oct.-Feb.	0.0929	0.0777	0.0662
Mar.-May	0.0693	0.0670	0.0575
June-Sept.	0.2275	0.0784	0.0712

3.2 Time-of-use tariff

If a FIT is not available or is oversubscribed, a customer may choose to install PV modules to offset power purchased from the grid instead. In this case, the tariff used to purchase power determines the optimal panel orientation. Increasingly, jurisdictions have ToU tariffs [14]. We chose the small business tariff for Las Vegas, NV [18], since it illustrates the effect of large ratios between the peak rate and the other rates as shown in Table 2.

Table 2. Small business ToU tariff ($/kWh) for Las Vegas, NV.

Summer Peak	13:00-19:00 June-Sept	0.30031
Summer Off-Peak	19:00-01:00 June-Sept	0.06144
Regular	Other times	0.04887

The results of simulating the revenue from a nominal 50 kW system with different tilts and azimuths are shown in Figure 2. The optimum orientation is a tilt of 34°, just under the latitude of Las Vegas (36°), and an azimuth of 46° west of south. The azimuth is further west than in Sacramento, reflecting the higher peak tariff in Las Vegas due to the more pronounced air conditioning peak for that case.

The arrow in Figure 2 indicates a 9% increase in financial benefit for this optimal PV module orientation compared to a conventional installation facing due south with a tilt of 35°. This potentially has a significant impact on the Return on Investment (RoI) and the economic viability of the system. At the optimal tilt, 95% of the maximum revenue can be obtained by an azimuth between 11° and 79° west of south.

3.3 Tariff that reflects peak demand

Large commercial and industrial customers are sometimes subject to tariffs that take peak demand into account in a more explicit way. Appendix B contains an analysis based on a tariff structure which applies to large customers in Ottawa, ON with a peak demand over 3MW.

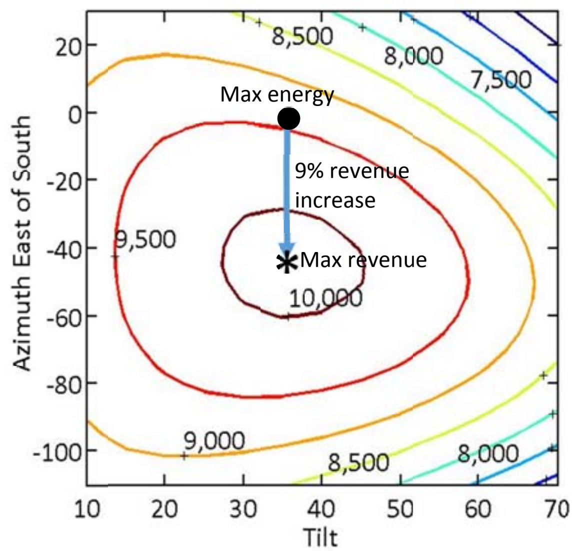

Figure 2. Variation of annual financial benefit ($) with tilt and azimuth from a clear sky simulation using a ToU tariff in Las Vegas, NV. The optimum energy maxima point is donated by ●, while the optimum revenue point is denoted by *.

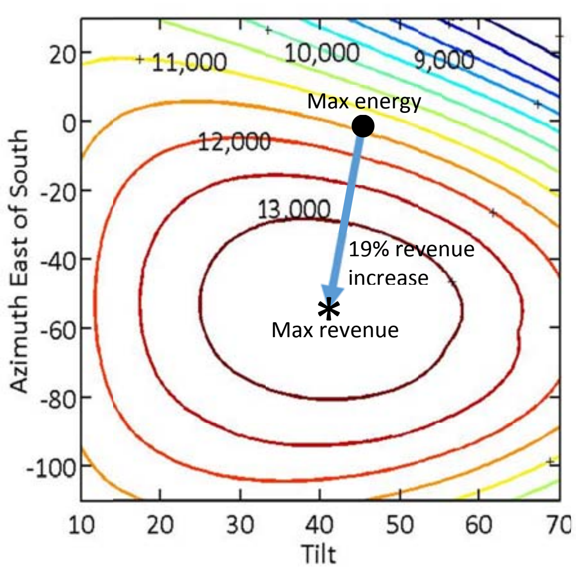

Figure 3. Variation of annual financial benefit ($) with tilt and azimuth from a clear sky simulation using a peak-dependent tariff, Ottawa, ON. The optimum energy maxima point is donated by ●, while the optimum revenue point is denoted by *.

Figure 3 shows the results of simulating a nominal 50 kW PV system for a hypothetical commercial customer in Ottawa, ON (latitude 45°). The split of charges among wholesale price/customer peak/grid peaks is in the ratio 22%/23%/55%. The high percentage associated with grid peaks is typical of large customers in Ontario. The optimal orientation is an azimuth of 54° west of south with a tilt of 41°, just below the Ottawa latitude. This gives 19% more revenue than a 45° tilt pointing due south, substantially increasing the RoI from such an installation. At the optimal tilt, 95% of the maximum revenue can be obtained by an azimuth between 24° and 84° west of south.

4. DISCUSSION

4.1 Comparison with other studies

Table 3. Summary of the impact of tariff on optimal orientation of PV modules and revenue increase compared to south facing modules tilted just less than latitude.

	Sacramento, CA	Las Vegas, NV	Ottawa, ON
Type of Tariff	Time-dependent FIT	Time-of-use tariff	Peak-depend-ent tariff
Latitude	38°	36°	45°
Optimal tilt	36°	34°	41°
Optimal azimuth west of south	28°	46°	54°
Revenue increase	4%	9%	19%

Table 3 summarises the optimal orientation results of Section 3 and indicates a substantial change in azimuth compared to a conventional installation, but little change in tilt. Authors who have studied the effect of cloudiness [5-8] without considering tariff, have found that it affects tilt without a significant impact on azimuth. In order to investigate the effect of both tariff and cloudiness, empirical estimates of cloudiness from [21] were incorporated into the optimization for the peak dependent tariff in Ottawa, ON. The results were an optimal azimuth of 55° west and tilt of 40°, within one degree of the values in

Table 3. This shows that in Ottawa, the peak dependent tariff has a far greater impact than cloudiness on optimal PV module orientation. The same study showed a 15.5% increase in revenue compared to a south facing orientation.

The optimal orientation when selling power at the time varying wholesale price studied in [10] had an azimuth -2° to 30° west of south, giving a 1% to 5% increase in revenue, over a range of US markets. For comparison with [10], we ran our simulation for Ottawa, ON, using only the wholesale price of electricity and excluded the peak-dependent charges described in Appendix B. The result is a 1% (3%) dollar benefit with a 5° (6°) azimuth west of south and 40° (34°) tilt for clear sky conditions (cloudiness from [21]). These azimuths and dollar benefits are comparable with those in [10]; however, they are much lower than the results in Table 3 which suggests that the peak-dependent components of the tariff play a much more important role in determining the optimal orientation and increase in revenue than does the real-time wholesale price.

In summary, the peak-dependent components of the tariff for Ottawa, ON play a major role in the increased dollar value that can be obtained from an optimal orientation, and are more important than cloudiness or variations in the wholesale electricity price.

4.2 On- to off-peak ratios with time-dependent tariffs

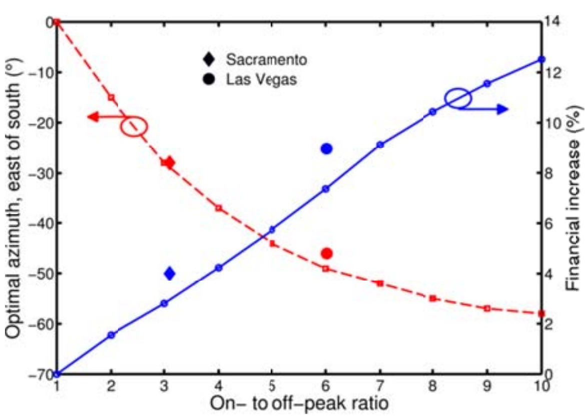

Figure 4. Impact of on-peak (13:00-20:00 June-Sept.) to off-peak ratio on optimal azimuth and financial percentage increase compared to a south facing orientation with tilt = latitude = 35°. Results for the two calculated examples in this paper (Sacramento and Las Vegas) are also shown.

Clearly, a major determinant of the optimal orientation is the on- to off-peak ratio. Figure 4 shows simulations for a hypothetical location with latitude 35° over a range of on- to off-peak ratios during summer afternoons (13:00-20:00 June-Sept.) compared to a uniform $0.06/kWh tariff at other times. The financial benefit of optimal orientations continues to increase with on- to off-peak ratio, although the optimal azimuth itself tends towards an asymptote of around 60° west of south. The results for the Sacramento and Las Vegas tariffs are superimposed, although they deviate from the trends due to slight differences in latitude and the fact that their off-peak tariffs are not completely uniform.

4.3 Customer demand profile with peak-dependent tariffs

The benefits described in Section 3.3 for the peak-dependent tariff in Ottawa, ON assumed the customer's peak was reduced by exactly the PV generation amount, which applies only if the power generated does not itself shift the position of the peaks. An example of peak shifting is given in Appendix C.

As tariffs evolve and as customers seek to offset a larger proportion of their demand from PV, the possibilities of peak shifting and net-negative power consumption need to be taken into account in conjunction with the individual demand profile of each customer.

4.4 Future trends

Most FITs are not time-dependent and, as the cost of solar power approaches grid parity [20, 21], and becomes economical without government incentives, [22-24], regulators are gradually reducing FITs. Within a few years, residential and small business PV installations may therefore need to rely on offsetting the costs of regular tariffs, which are increasingly time-dependent [14]. A major difference between FITs and ToU tariffs is that there is no long term contract associated with ToU tariffs. As customers adapt their demand to ToU tariffs the distribution companies may reduce the ratio between on- and off-peak charges so that the optimal orientation of PV modules is altered.

This point also affects large customers subject to grid-peak-dependent tariffs. In Ontario, the average hourly demand over the grid's peak days is shown in Figure 5 for 2010 and 2013. The peak has flattened during this period due to large customers seeking to offset the grid peak charge itself, commercial buildings being pre-cooled in the early morning, and also due to ToU pricing and recently implemented demand response programs. Future years could see more grid peaks at mid-day and less in the late afternoon. An optimization for Ottawa with a 50/50 probability of grid peaks at 12:00 and 17:00 eastern standard time (EST) resulted in an optimal azimuth 30° west of south and a tilt of 35°.

The results of the current paper are also important in jurisdictions *without* time-dependent tariffs today, since [14] indicates their increasing introduction in the future. The optimal orientation of solar modules today depends on tariffs anticipated tomorrow, emphasising the importance of utilities announcing tariff plans in advance. An alternative would be to design a PV racking system that allows the azimuth to be changed on occasion.

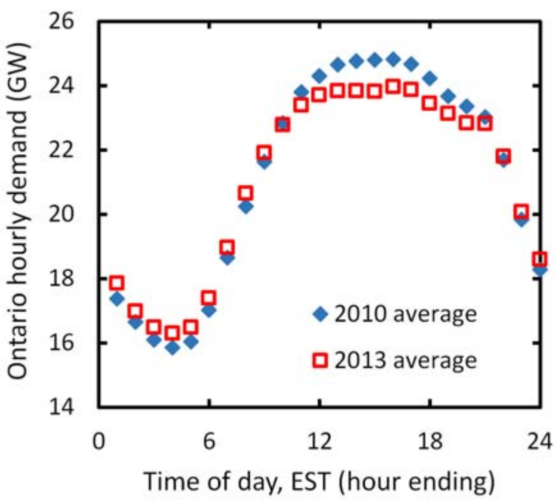

Figure 5. Ontario diurnal demand averaged over the 5 days for which grid peak charges were calculated.

5. CONCLUSION

This paper quantifies the extent to which time of day/year pricing affects the optimal orientation of non-tracking PV modules for time-dependent FITs, ToU tariffs and peak dependent tariffs. It also gives the percentage increase in revenue compared to a south facing orientation tilted just less than the latitude, and is based on tariffs in Sacramento, CA, Las Vegas, NV and Ottawa, ON. In order to focus on the impact of tariff, the analysis is based on simulations of a constant-efficiency PV system operating under year-round clear-sky conditions. The results show that these tariffs significantly affect the optimal azimuth, shifting it west by 28° to 54°, with little effect on tilt. Compared to a south facing orientation with tilt just less than latitude the dollar value of the power generated is increased by 4% to 19%. The peak-dependent components of the Ontario tariff contribute substantially more to these results than the wholesale electricity price variability, while cloudiness is found to be a minor factor.

For time-dependent tariffs, as the ratio between the charges at times of grid peak (13:00-20:00 June-Sept.) and those at non-peak times increases, the optimal azimuth tends towards an asymptote around 60° west of south and the percentage increase in revenue increases approximately linearly (assuming a latitude of 35° which is typical for such a tariff in North America). In other tariffs, some customers are charged an amount dependent on their own peak usage, which may occur at a different time of day than the grid peak, so that the possibility of PV generation shifting the time of the customer peak needs to be taken into account on a customer by customer basis.

From the viewpoint of a PV system owner, the increase in revenue from an optimal orientation can have a proportionately larger impact on the return on investment, since the costs are unchanged. Only the FIT includes a contract with a term comparable with PV module lifetimes. In jurisdictions with time- or peak-dependent tariffs, installers and owners need to plan for future changes by (i) using an increased (decreased) azimuth if there is a reason to anticipate higher (lower) tariffs on late summer afternoons in the future, or (ii) designing an initial installation for which the cost of re-orienting the PV modules at a later date is acceptable. In jurisdictions without time- or peak-dependent tariffs today, installers and owners need to use a non-south facing orientation in order to plan for future introduction of such tariffs.

From the viewpoint of a government regulator, tariffs of this type provide a clear incentive to generate solar power at times when the grid is experiencing high demand, and thus aid in deferring grid maintenance and upgrade costs. Regulators may wish to consider long term plans in which certain tariffs are announced for future years, if they wish to incentivize investments that reduce demand at grid peak times.

ACKNOWLEDGEMENTS

The authors acknowledge the support by the Ontario Research Foundation – Research Excellence Grant, the Natural Sciences and Engineering Research Council of Canada and the Canada Research Chair program. They are also grateful to Pierre de Gagné and Faizal Sudoollah of Utilities and Campus Sustainability at the University of Ottawa and to Raed Abdullah of Hydro Ottawa Limited for many valuable discussions.

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Appendix A: Model of Revenue from PV Modules

The irradiance model, [17], takes into account the following:

- the orientation of the earth relative to the sun at different times of year;
- the apparent extraterrestrial flux at different times of the year;
- an empirically fitted relation between air mass ratio and beam radiation;
- the tilt and azimuth of the PV module;
- the angle between the module and the beam radiation;
- the way in which diffuse irradiance varies with time of year;
- reflected irradiance, due to reflection of both beam and diffuse irradiance by the surface in front of the collector.

The complete model is described in [17, pp. 388-418] and the equations are listed in [17, pp. 423-4]. The resulting figure for solar irradiance I_{mh}, in W/m^2 is:

$$I_{mh}(\varphi,\tau) = B_{mh}(\varphi,\tau) + D_{mh}(\varphi,\tau) + R_{mh}(\varphi,\tau)$$

where:

B, D, R are the beam, diffuse and reflected irradiance respectively
m, h are the month and hour respectively
φ, τ are the azimuth and tilt of the PV module, using the convention established by [17] that azimuth is positive to the east of south.

Irradiance is converted into Watts of electric power yield, *P*, using an efficiency factor for the PV module itself and an efficiency factor for the balance of the system including cabling and inverters. The model assumes a constant photovoltaic conversion efficiency of 15% for modules and overall system conversion efficiency of 80% for balance of the system. Thus:

$$P_{mh}(\varphi,\tau) = 0.80 * 0.15 * I_{mh}(\varphi,\tau)$$

The model takes into account the cosine dependence of power generated on the angle of incidence between the module and the irradiance, but does not include secondary variations in PV module efficiency due to factors such as irradiance magnitude, temperature and the reflectance losses at high angles of incidence, which all depend on location and/or technology.

The electrical power yield at each hour of each day throughout a year is then mapped to the tariff applicable at that particular time to calculate the revenue (cost saving) at each hour of the year. The net yearly revenue (cost saving), *R*, as a function of tilt and azimuth is found by summing the hourly revenue over an entire year for a range of tilt and azimuth angles for the PV modules:

$$R_{\varphi,\tau} = \sum_{m,h} P_{mh}(\varphi,\tau) V_{mh}$$

where V_{mh} is the value in dollars of one kilowatt hour (kWh) of electric power at hour *h* of month *m*.

Appendix B: Tariff for Ottawa, ON, Reflecting Peak Demand

Customers large enough to be subject to this type of tariff typically have campuses with multiple buildings. The tariff for large customer (> 3 MW) in Ottawa, ON, includes three components:

a) The wholesale price of power, Hourly Ontario Electricity Price, HOEP [19], is determined by the balance between supply and demand on the wholesale market. Large customers are subject to regulatory charges and a debt retirement charge, also based on total consumption, which average 50% on top of the HOEP. We use the average HOEP for each hour and each month of the year, which has an average of 0.03 $/kWh at most PV-generation times and a range of 0.06-0.07 $/kWh on summer afternoons.
b) The customer's peak demand each month is assessed during the hour when demand was greatest. The hour in general varies from month to month. We take the situation of a hypothetical customer whose peak demand is in the hour ending 10:00 EST from November to March and 14:00 EST from April to October. The charge represents the costs associated with the transmission and distribution networks amounting to a total of $7.62/kW per month.
c) The grid peak tariffs are assessed using the top ranked 5 hours of demand throughout the whole year, announced retroactively. These peak hours for the 4 years of operation of this tariff are given in Table B1, from which it can be seen that they typically occur late in summer afternoons, at times when the sun is significantly west of south. The charge during the following year is based on the percentage that the customer's peak demand contributed to overall system demand during the five peak hours. The charge represents costs associated with peak grid operation, maintenance, upgrades and the difference between power purchase contracts and HOEP, and amounted to $270.30/kW per year or $22.53/kW per month in 2013.

Items a) and c) apply throughout Ontario, and item b) includes a component specific to Ottawa.

Table B1. Grid peak hours for Ontario 2010-13.

2010		2011		2012		2013	
Date	Hour-ending, EST	Date	Hour-ending, EST	Date	Hour-ending, EST	Date	Hour-ending, EST
July 6	16:00	July 18	16:00	June 20	16:00	July 15	17:00
July 7	16:00	July 19	17:00	July 04	17:00	July 16	17:00
July 8	15:00	July 20	17:00	July 06	16:00	July 17	17:00
Aug 31	16:00	July 21	16:00	July 17	16:00	July 18	17:00
Sept 1	16:00	July 22	12:00	July 23	14:00	July 19	14:00

Appendix C: Customer Demand Profile with peak-dependent tariffs

The power generated at a single customer site is unlikely to affect the time of the peak demand for the entire Province on Ontario. However, for many customers, the diurnal load profile is broader than the diurnal PV generation profile so that the net profile may have a new time at which the peak occurs. The magnitude of the net decrease in peak is dependent on the demand profile of the customer, the PV generation profile and the ratio between PV generation and customer demand. In Figure C1 we analyse a hypothetical customer having a broad demand profile (with peak of 97 kW at 14:00) combined with the July PV generation profile for the nominal 50 kW system in Section 3.3, which was optimized including late afternoon grid peaks. The net demand after consuming the generated power has a peak of 67 kW at 10:00. The peak has been reduced by only 30 kW, although the PV generation at the time of the gross peak (14:00) was 38 kW. This situation is caused by the tariff structure emphasising late afternoon grid peaks, more than the customer's peaks in early afternoon, and due to the high ratio of PV generation to load of 51%.

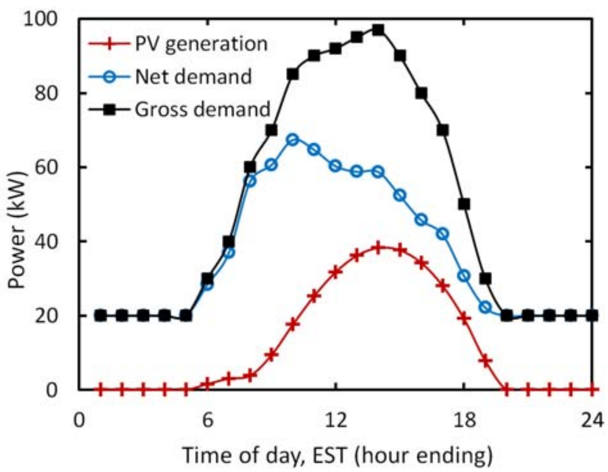

Figure C1. Example of the shifting peak in the diurnal net demand profile as a result of the difference between gross demand and the PV generation implemented as per the optimized system in Section 3.3 for July.

This effect occurs for customers subject to tariffs that have an explicit charge for the peak customer demand. By contrast, time-dependent tariffs such as those analysed for Sacramento and Las Vegas assign a value to solar whenever it is generated, independent of shifts in peak demand.

Another situation in which the customer demand profile is important in assessing the value of solar offsetting is when solar generation is higher than customer demand. Time-of-use tariffs are being introduced more widely [14], but may or may not allow power to be fed into the grid and credited in this case.