Quantifying the Effects of Solar Panel Orientation on the Electrical Grid

by

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Abstract

As the prices of solar panels continue to decline, energy production from solar farms is skyrocketing, leading to a situation where, at certain times, solar farms produce more energy than can be consumed. Today, the only control over this excess electricity generation is curtailment, meaning excess power is wasted. A source of control that is often overlooked is the choice of orientation of fixed (non-tracking) solar panels: panels oriented towards the east, for example, produce more electricity earlier in the day and less later in the day, compared to similar panels oriented south. While this results in an overall reduction in generation, it matches solar generation with electrical grid load better, thus reducing curtailment. We use optimization to study the degree to which non-tracking panel orientation can be used to meet each of four possible grid requirements: load following, peak reduction, reduction in operation cost, and ramp reduction. Assuming complete control over the orientation of all panels, we find that, in the three jurisdictions we studied, i.e., Ontario, British Columbia, and Texas, orientation can be very useful in reducing ramps (reducing them up to 30%) but does not appear to be useful for reducing net load peaks.

Acknowledgements

I would like to thank Professor Keshav and Professor Rosenberg for guiding me through graduate research, as well as Professor Golab for being a reader of this thesis. I would also like to thank every member of ISS4E Lab who assisted me in my graduate studies and research in one way or another.

Dedication

I dedicate this thesis to my beloved wife, Elena Lim, who has been remarkably supportive of my endeavors over the years.

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Chapter 1

Introduction

1.1 Motivation

Solar power is one of the most rapidly growing sources of electricity generation in both developed and developing countries. For example, in the current year (2016), the US is scheduled to add 9.5 GW in installed capacity to utility-scale solar parks alone, over and above any added distributed solar generation capacity. Figure 1.1 illustrates how this magnitude of added solar capacity would exceed any other type of electricity generation growth in the US in 2016. This level of growth is unprecedented, considering that *aggregate* growth over the preceding three years (2013–2015) was 9.4 GW [16]. The US is not the only country developing its solar power capabilities: the government of India expects to reach 20 GW in installed photovoltaic (PV) solar capacity countrywide by March 2017 from the current figure of approximately 5 GW [17]. According to China's National Energy Administration, the country targets to triple its installed PV solar capacity by 2020 by reaching 143 GW level [14].

The main reason for such a rapid growth is the continuing drop in the price of photovoltaic solar modules. Figure 1.2 illustrates that the costs have fallen 150-fold since 1975, while the global installed capacity of solar PV has grown to 100 GW from nearly zero. Solar PV modules have been getting cheaper due to a number of reasons. Over the past years, various regulatory support mechanisms, such as green tariffs and governmental subsidies, were introduced by many jurisdictions in an effort to offset carbon emissions caused by fossil-fueled power plants. Moreover, new financing and ownership schemes were developed to serve the growing distributed residential PV sector by shifting the financial burden of solar panel installation from home-owners to companies with easier access to

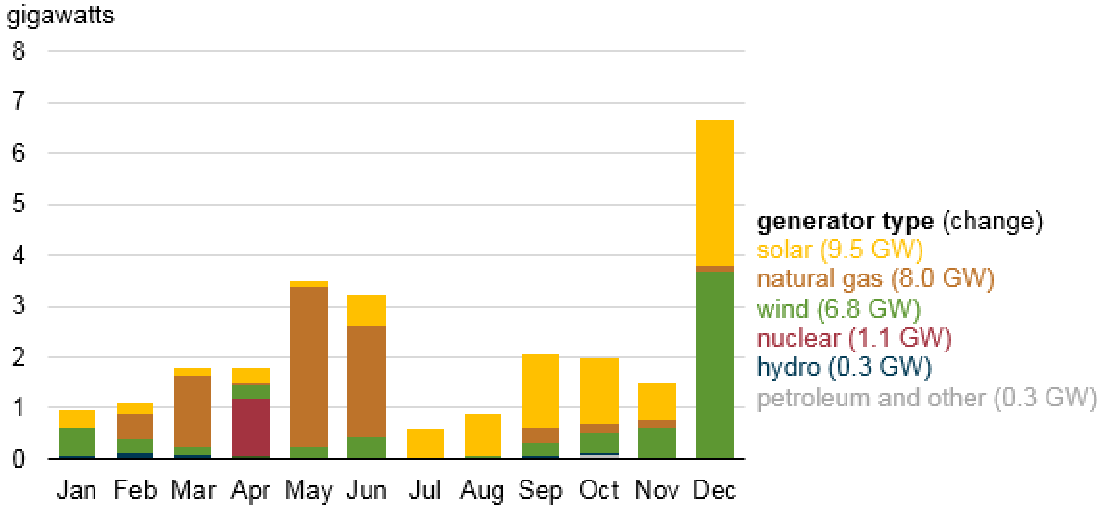

Figure 1.1: Scheduled additions to electricity generation capacity in USA in 2016, EIA [16]

capital. Apart from these factors, technological advances made it possible to manufacture cheaper and more efficient solar modules. Finally, manufacturers in China, who started entering the global solar PV panel market in mid-2000s, used economies of scale to their advantage, thus driving the prices even lower. These factors have been contributing to the growth in the solar PV power generation sector.

As a result, *photovoltaic solar power (PV)* has emerged as the most competitive form of solar electricity generation. Its main competitor, *concentrated solar power (CSP)*, is more expensive in terms of the levelized cost of electricity (LCOE) [1], although it often allows critically important energy storage capabilities. Specifically, in 2015 the LCOE for PV was approximately "US$0.08 per kWh on average according to the International Renewable Energy Agency"[11]. In contrast, the LCOE for CSP was between approximately "US$0.20 and US$0.25 with parabolic trough systems ranging between $0.17 and $0.35 and solar tower plants between $0.17 to $0.29"[11]. In addition, CSP systems have certain climate-related limitations, because they can only produce power from direct solar radiation. These factors led to a much wider adoption of PV over CSP.

In the 2014 technology roadmap report for solar photovoltaic energy, experts from the International Energy Agency (IEA) forecast "PVs share of global electricity reaching 16% by 2050, a significant increase from the 11% goal in the 2010 roadmap. PV generation

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[1] The cost of generating one kilowatt hour of energy, which takes into account both (one-time) capital and (recurring) operational expenses over a 20–25 year equipment lifetime.

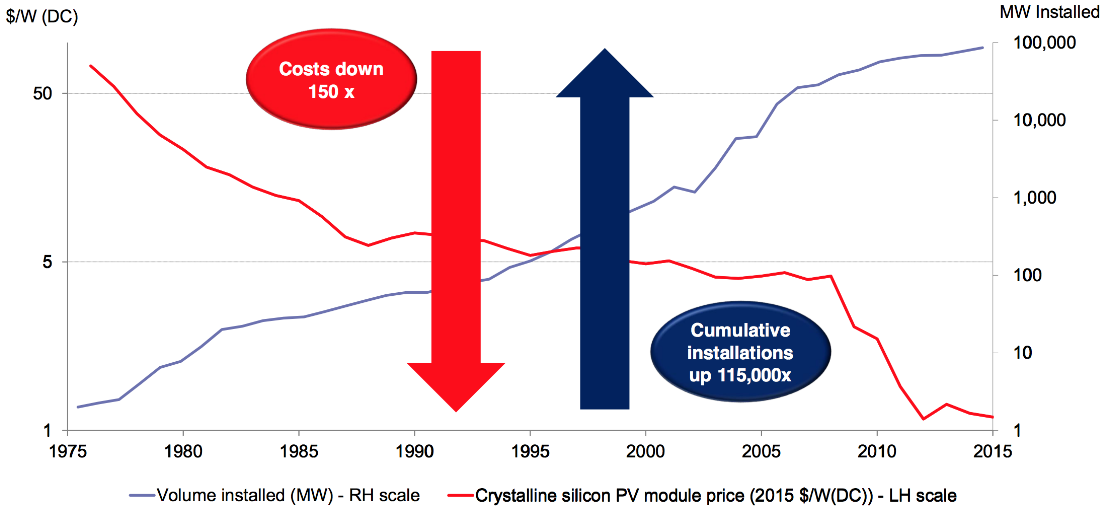
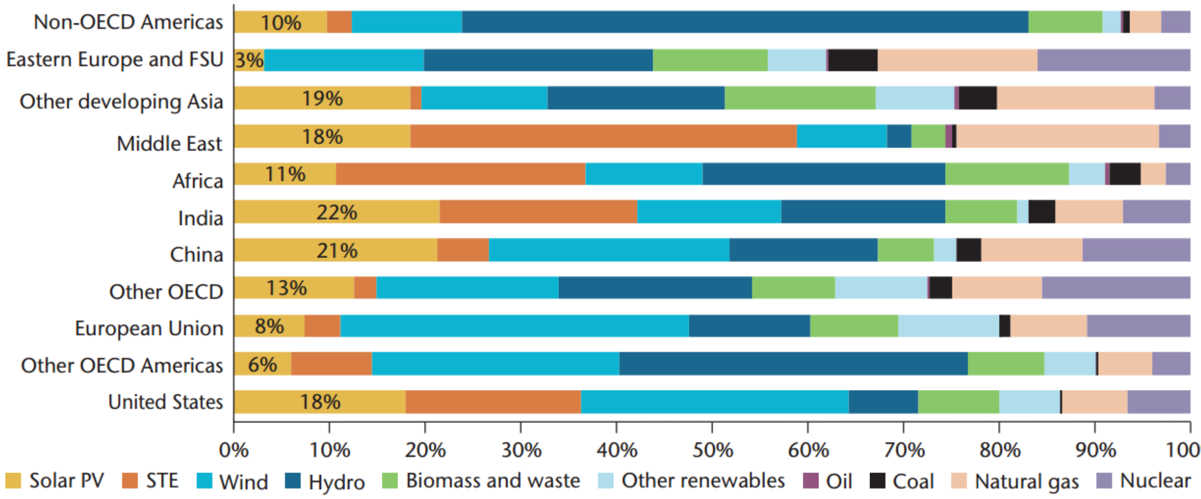


Figure 1.2: PV solar module price vs. volume installed, Bloomberg [18]

would contribute 17% to all clean electricity, and 20% of all renewable electricity. China is expected to continue leading the global market, accounting for about 37% of global capacity by 2050"[27]. Figure 1.3 illustrates that the US, China, India and the rest of Asia are predicted to be the regions with the highest PV shares in their electricity generation mixes by 2050. In some regions, CSP adoption (referred to as *STE* in figure 1.3, which stands for *solar thermal electricity*) may exceed the adoption levels of PV solar. However, this scenario is limited to the Middle East, Africa, and other regions where the climate is hot and dry.

Thus, we are witnessing the global rise of the PV technology, mainly due to its economical attractiveness to investors and the lack of geographical restrictions. In addition, among PV solar panels, fixed panels are significantly more popular than solar trackers, due to lower installation and maintenance costs, which become a concern when deployments are at an industrial scale. As mentioned before, the drawback of the PV solar panels, in comparison to CSP, is that they do not have any inherent energy storage capabilities. PV solar panels produce electricity only during the daytime, but contribute nothing to the electrical grid at night. This cyclical trend results in several problems in the electrical grid, which have become points of concern for the energy community in recent years. These problems are discussed in detail further in this chapter. As solar power becomes more prevalent, the problems are bound to increase, unless appropriate actions are taken to prevent or resolve them.

A number of mitigation actions has been studied in the past [4][24], but most of them



KEY POINT: PV shares vary with the solar resource and electricity load.

Figure 1.3: Generation mix forecast in 2050 by region (in annual energy), IEA [27]

require significant investment in one form or another. For example, mitigation through demand response requires extensive communication infrastructure and mitigation through storage requires expensive energy storage. One of these actions, however, does not require any additional investment, apart from the regular capital and operating expenditures associated with PV solar panels.

Given an electrical grid with high solar penetration, this mitigation action is to optimize individual orientations of solar panels present in the electrical grid for the benefit of the whole system, within which these panels operate. The rationale behind this action lies in the assumption that diversified orientation of panels allows solar generation to follow load patterns more closely, albeit at the cost of a reduction in overall energy generation. The main theme of this thesis is exploring how this planning action, namely centrally controlling individual orientations of a given panel set within a given electrical grid at the time of panel installation, mitigates the problems caused by increased solar generation levels in the electrical grid.

1.2 Definitions

Energy in the electrical grid needs to be studied from two perspectives: *supply* and *demand*. Supply of energy is accomplished through power generation from various sources, most of which are listed in figure 1.3. The majority of electricity is generated by companies called *utilities*, but with the recent rise of PV solar, individual solar panel owners have been engaging in electricity generation at a larger scale than before. Demand for energy (also called *load*) originates from consumers of power from residential, commercial, and industrial sectors of the economy. At any given time the grid supply must be approximately equal to the grid demand. Otherwise, the grid will experience stability problems and may eventually undergo a blackout or suffer extensive damage. The process of maintaining the level of electricity generation equal to consumption is referred to as *matching*. Regional electrical grid operators are in charge of ensuring the seamless matching process.

A key concept in our work is *net load*. In this thesis, net load refers to the fraction of the electrical grid load that must be matched after solar electricity generation has been taken into account. The net load of a grid may be positive, when solar generation is not sufficient to match the grid load, or negative, when solar generation exceeds the grid load. In the first case, the remaining load must be matched by other sources of electricity generation. In the second case, the excess of electricity produced must be either curtailed, stored, or exported from the electrical grid. In the case of *curtailment*, the excess of electricity coming from solar panels is wasted, because the electrical grid cannot use it. If solar generation matches the grid load exactly, then the net load is zero.

Moving away from the generic terms used in the energy industry, we now present a few definitions specific to our work. When discussing solar panels in this thesis we deal with two distinct scenarios: the *base case scenario* and the *flexible orientation scenario*. The base case scenario refers to the status quo of fixed PV panel orientation in the solar industry. Conventional wisdom states that it is always optimal to place panels facing south, when in the northern hemisphere, and north, when in the southern hemisphere. It is also typical to select the fixed panel tilt angle based on the latitude at which solar panels are installed. Such placement maximizes the amount of energy produced over the course of the year, and thus is considered optimal for economical reasons. In contrast, the flexible orientation scenario refers to the planning action explored in this thesis, in which we relax the orientation and tilt restrictions on planned solar panels, thus allowing them to be oriented in a number of different ways at the time of installation. We assume that we have complete control over the orientation of all panels deployed in a specific jurisdiction: while quite unrealistic, this allows us to determine the best possible gains from our approach.

Another important concept in our research is *relative installed PV capacity* of a jurisdiction. We first define a load profile to be the time series of hourly average load readings in a particular jurisdiction over the course of one calendar year, and the generation profile to be the time series of hourly solar energy production readings from a single typical south-facing panel in that same jurisdiction. We then define relative installed PV capacity as the ratio of solar panels installed in the grid divided by the maximum number of panels in the base case scenario that result in zero curtailment, given load and generation profiles in that jurisdiction. In other words, when the relative installed PV capacity equals 100% in the base case scenario, the total number of panels installed is maximized under the constraint that there is absolutely no curtailment in the electrical grid, given hour-by-hour yearly load and generation profiles in that jurisdiction. This relative metric allows us to compare results across jurisdictions that differ in their grid loads and solar generation potentials.

Note that our definition of the relative installed PV capacity differs from the concept of PV share in the generation mix, which is illustrated by figure 1.3. The share of a certain source of energy in the generation mix is sometimes referred to as the *energy penetration* level. Although PV energy penetration does depend on relative installed PV capacity, there is no simple formula to convert between these metrics, because they represent different concepts in the electrical grid. The relative installed PV capacity is based on the number of PV solar panels in the electrical grid. In contrast, the PV energy penetration represents the relative amount of energy generated with PV solar panels annually, while silently ignoring any curtailment. We estimate through simulation that, with a 100% level of relative installed PV capacity, the PV energy penetration in the electrical grid varies from 13% to 15% in select regions in the base case scenario (see section 3.1 for more details). Other sources [24] use the concept of PV *penetration in capacity*, which is defined as the ratio of installed solar PV capacity to the peak load observed in the electrical grid. Conversions between *penetration in capacity* and *penetration in energy* can be performed by applying electrical grid specific factors. For instance, the factor value approximately equals 0.42 for Texas, and 0.40 – for California [24].

PV solar panels cannot produce any energy at night, which means that nocturnal electrical grid load must be met by some other sources of electricity generation. Thermal power plants (i.e., whose prime movers are coal, natural gas, or diesel) currently constitute the largest fraction of the electricity generation market in the world, especially in developing economies. Thermal power plants that are based on fossil-fuels produce carbon emissions that are harmful for the environment and contribute to global climate change. Nevertheless, they are necessary to provide power at night and to meet PV generation shortfalls, such as during cloudy periods.

According to the IAE global generation mix forecast, summarized in figure 1.3, most regions of the world will retain a large proportion of thermal and nuclear electricity generation capacity by 2050. These two types of power plants constitute the backbone of the electrical grid. Nuclear, coal, biomass, and waste power plants typically serve as *base load power plants*, which means they provide a nearly constant output of electricity to match the minimum daily load observed in the electrical grid (hence the name 'base load'). These power plants are generally not very flexible when it comes to changing power production levels, but they are cheaper to operate than more flexible plants described below. Because daily load levels vary dramatically, electrical grids rely on *load following power plants* and *peaking power plants* to match the remaining load. The load following power plants are typically hydro power plants, or select steam power plants, which provide generation to match ordinary daily changes in demand. The peaking power plants are typically based on gas turbines, which can ramp up and down much faster than other types of turbines, thus providing the necessary degree of flexibility for the electrical grid, in case there is a sudden peak in demand. The peaking power plants are more expensive in comparison to the other two types in terms of operational costs. Some hydroelectric power plants may serve as either of the three aforementioned types of power plants, but they are limited by water resources availability, which varies significantly across countries and regions. More details about electrical grid operation can be found in chapter 9 of the book "Electric power systems: a conceptual introduction" by von Meier [29].

In our research, we only consider thermal power plants that serve as load following or peaking power plants in the electrical grid, while attempting to maintain a balance between our optimization objectives and thermal generation levels.

1.3 Benefits of solar PV generation

The benefits of increased solar penetration are difficult to overestimate. The most obvious benefits are the displaced carbon emissions from fossil-fueled power plants as well as the displaced costs of fossil fuels used to produce electricity. In a major electrical grid the latter can account to billions of dollars in savings annually. Another observable benefit is peak reduction in some locales. As mentioned in the previous section, peak energy demand must be met by peaking power plants, and their operation and maintenance are more expensive in comparison to other power plants. It is, therefore, a constant priority for grid operators to decrease the peak load they have to accommodate.

Presence of renewables in the electrical grid is likely to affect load peaks. Figure 1.4, from the MIT report on The Future of Solar Energy [24], illustrates how the Electric Reliability Council of Texas (ERCOT) grid reacts to higher levels of solar energy penetration. More specifically, "as solar penetration grows, the net peak load progressively decreases,

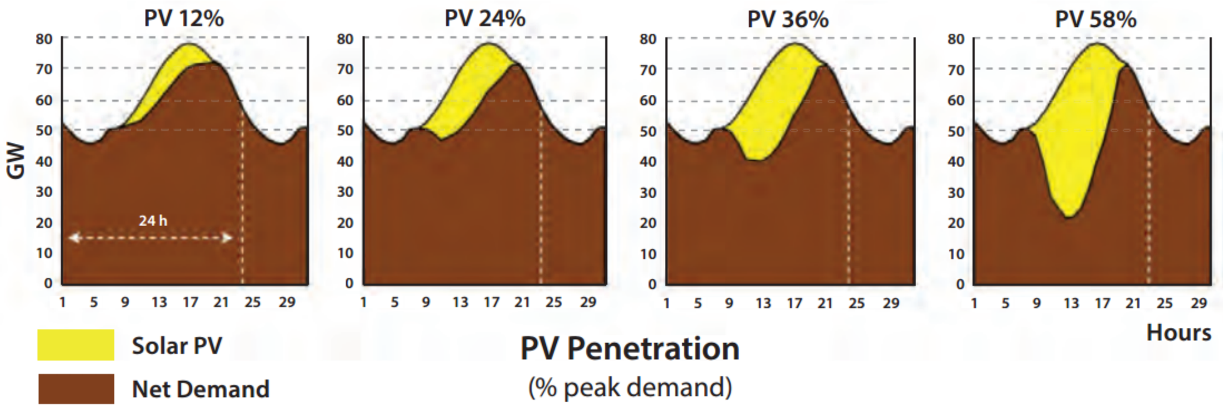


Figure 1.4: ERCOT net load on a typical summer day, MIT [24]. Note that the metric used is penetration in capacity.

narrows, and shifts in time ... At a certain point in the evening, net load stabilizes and is unaffected by any further increase in solar penetration until the next day"[24]. In addition, according to MIT Energy Initiative researchers, "[t]he absolute net peak load, which is usually taken as a good proxy of the additional capacity needed on top of solar PV to supply system demand, can only be reduced when annual peak loads occur during the day. Even if this is the case, the reduction in absolute net peak load is very limited and does not continue to grow at higher levels of solar PV penetration"[24].

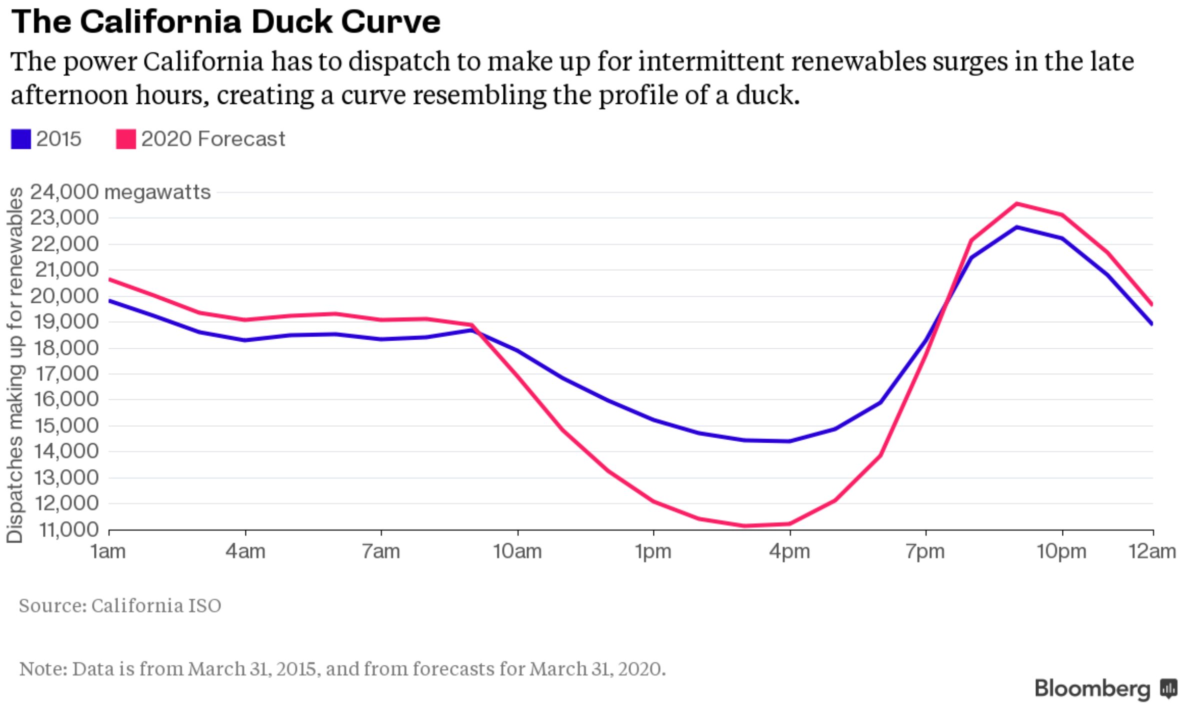
While some of our models deal with the problems arising from increased solar penetration, which are described in the next section, one of our models is designed to explore a possibility of reducing peak net load levels below the figures currently attainable in the industry (section 2.5).

1.4 Problems with solar PV generation

Unlike the conventional sources of electricity, PV solar generation is *variable*, or *non-dispatchable*, meaning it is not available upon request from the electrical grid operator. Solar power can only be generated when the sun is in the sky, and the cloudiness level is low. This daily variation of solar generation contributes to significant variation in the daily net load profile. This phenomenon has been a popular topic in global energy circles in recent years, and it has been referred to as the 'duck curve' [10].

The 'duck curve' derives its name from the shape of the net load curve of an electrical grid with considerable levels of renewables penetration, which resembles the profile of a duck (see figure 1.5). The duck curve has been associated with potential risks affecting the electrical grid stability due to fast ramping of peaking power plants. For example, according to a Bloomberg report, "[t]he California grid's need to call on gas-fired plants to balance shifts in demand and supply shows the potential hazards of tying more renewable generation to power networks"[10].

Keeping these facts in mind, we identified potential problems associated with increased renewable penetration in the subsequent subsections.



The California Duck Curve

The power California has to dispatch to make up for intermittent renewables surges in the late afternoon hours, creating a curve resembling the profile of a duck.

Source: California ISO

Note: Data is from March 31, 2015, and from forecasts for March 31, 2020.

Figure 1.5: California duck curve, Bloomberg [10]

1.4.1 Ramping

An earlier report from 2013 by the California Independent System Operator (CAISO)[7] identified the risk of short and steep ramps as one of the operational challenges associated with the duck curve. The grid would need to gain approximately 13,000 MW in power production in just three hours, which corresponds to the short and steep ramp illustrated by figure 1.5. The 2013 CAISO forecast is confirmed to a degree by a more recent report by the Federal Energy Regulatory Commission in the US, which states that the rapidly increasing solar capacity in California is posing "... a particular challenge in the winter when the sun sets well before the evening peak load. The winter 3-hour ramp requirement climbed to a maximum of 9,131 MW in winter 2014-15, from 6,247 MW in 2011-12 ... This ramp requires other generators to be online and available as needed"[9]. Such dramatic changes in net load profile, caused by the increased renewable energy penetration, have the potential to impact the aforementioned generators in a harmful way.

Specific impacts of increased wind and solar power penetration on conventional fossil-fueled generators within electrical grids have been explored by National Renewable Energy Laboratory (NREL) scientists and other industry experts as part of the Western Wind and Solar Integration Study Phase 2 (WWSIS-2)[26]. One of the concepts that motivated the study is referred to as *cycling*. It is a practice used by conventional utilities to cope with higher levels of renewable penetration in the electrical grid, which, in essence, means that "utilities must ramp down and ramp up or stop and start conventional generators more frequently to provide reliable power for their customers"[6]. In an earlier study [25], Lew et al., stated the following: "[i]ncreased cycling, deeper load following, and rapid ramping may result in wear and tear impacts on fossil-fueled generators that lead to increased capital and maintenance costs, increased equivalent forced outage rates, and degraded performance over time." In addition to monetary considerations, the authors stated that "[h]eat rates and emissions from fossil-fueled generators may be higher during cycling and ramping than during steady-state operation"[25]. The primary goal of WWSIS-2 was to quantify all these costs in monetary terms.

The conclusion of WWSIS-2 was such that "... up to 33% of wind and solar energy penetration increases annual cycling costs by \$35–\$157 million in the West. From the perspective of the average fossil-fueled plant, 33% wind and solar penetration causes cycling costs to increase by \$0.47–\$1.28/MWh, compared to total fuel and variable operations and maintenance (VOM) costs of \$27–\$28/MWh"[26]. On the other hand, the negative impact of cycling was far outweighed by the displaced annual fuel costs in the amount of approximately \$7 billion. On top of the production and operational costs, there were additional plant and transmission construction costs caused by cycling, which were estimated to equal "\$0.14–0.67 per MWh of wind and solar generated compared to fuel cost reductions of \$28–\$29/MWh"[26].

Thus, the costs associated with additional cycling were not estimated to be very high in comparison with the benefits provided by the integration of renewables in the electrical grid. However, the additional cycling costs do put a strain on conventional fossil-fuel power generators, and these costs are measured in millions of dollars annually. Thus, conventional power generation utilities could be interested in minimizing the magnitude of ramping, to reduce wear and tear impacts on their fossil-fueled generators. One of our models (section 2.3) is focused on choosing solar panel orientations to reduce ramping levels in the electrical grid.

1.4.2 Overgeneration

Overgeneration was identified as a risk in the CAISO report mentioned earlier [7]: if 33% of electricity in California is generated from renewables by 2020, the electrical grid faces the risk of overgeneration during times of peak solar generation and low loads, such as on winter Sunday afternoons. But in other places around the world such a risk is not a remote possibility: it is the new reality. In Bavaria, Germany, "overproduction of power [occurs] during daylight hours, as the country's ample solar energy floods onto the grid along with electricity produced by power plants"[5]. Note a recent incident in which the increased presence of renewables in Germany's generation mix drove electricity prices into negative territory on May 8th, 2016 (see figure 1.6). The negative pricing was caused by the inability to utilize the excess electricity and the lack of electrical grid's flexibility required to quickly reduce the output of the conventional power plants. Another example is Chile: solar power penetration is so extensive, the country's spot price of electricity reaches zero on a daily basis (see figure 1.7) The fundamental reasons behind this phenomenon are the increased solar penetration in Chile and the inadequate transmission infrastructure: two disjoint national power networks are unable to utilize local power excesses [13]. Thus, the risk of overgeneration is real and is bound to become ubiquitous with the growing solar penetration worldwide.

If an electrical grid cannot dispose of the excess electricity through trading schemes or large-scale energy storage, power curtailment must be introduced. Curtailment means that some of the energy produced with solar panels present in the electrical grid is wasted, because it cannot be used immediately. The potential for curtailment grows along with the PV solar share in the generation mix, if there are no mechanisms to use the excess energy. One of our models (section 2.4) deals with reducing curtailment in the electrical grid while keeping thermal generation levels in check.

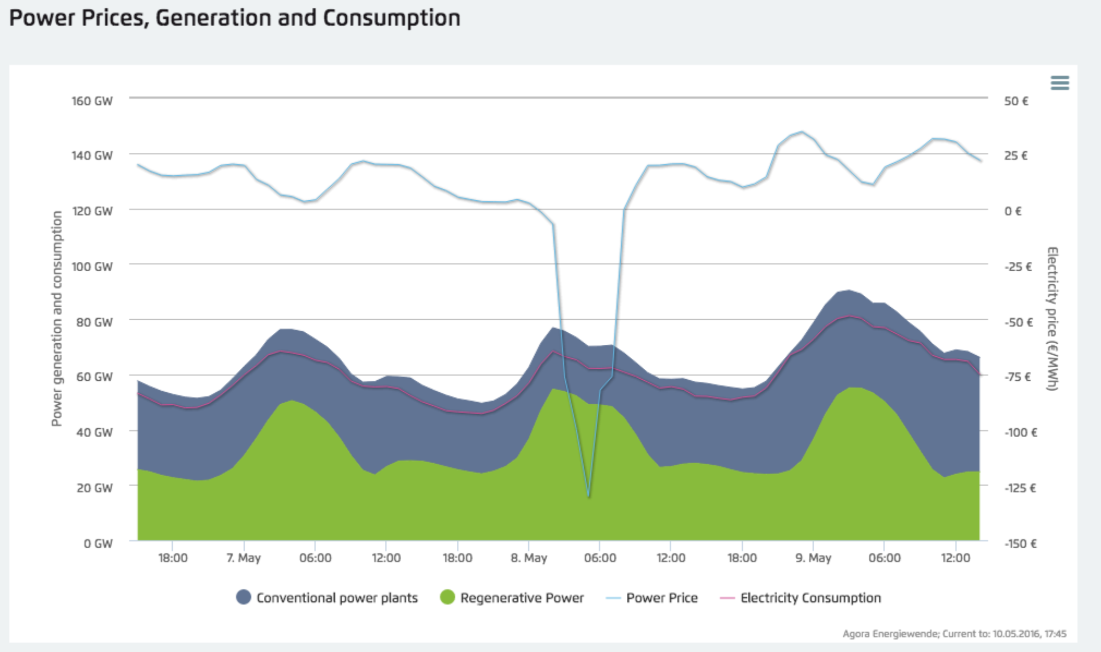

Power Prices, Generation and Consumption

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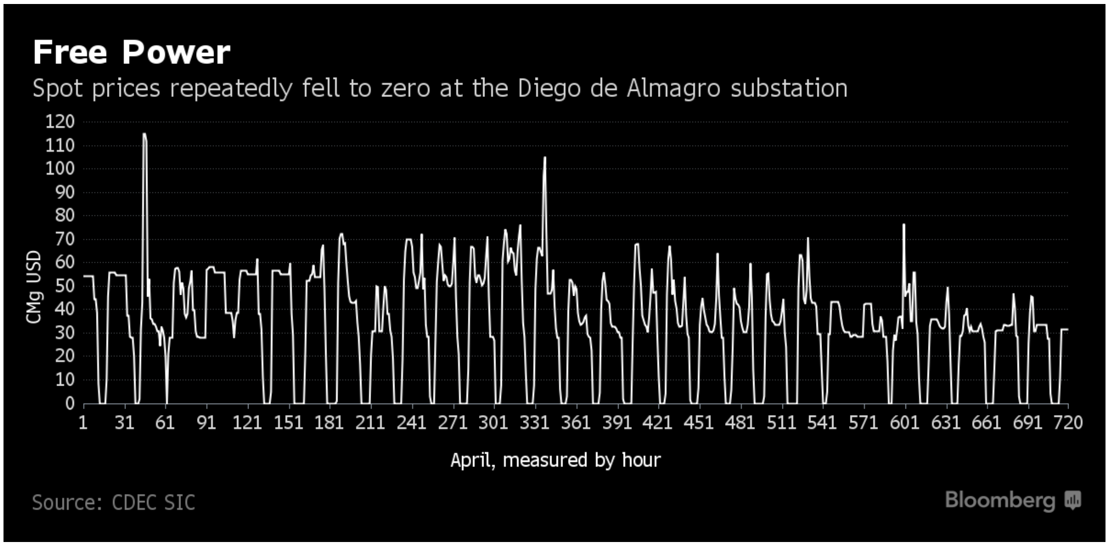
Figure 1.6: Negative electricity prices in Germany, QZ [15]


Free Power

Spot prices repeatedly fell to zero at the Diego de Almagro substation

Source: CDEC SIC

Figure 1.7: Zero electricity prices in Chile, Bloomberg [13]

1.4.3 Economical considerations

Although the price of solar modules keeps dropping, the capital expenditure necessary for panel installation is still significant and motivates the panel owner to extract the maximum amount of revenue from their solar panels. This means that owners will always place their solar panels with an orientation and tilt that guarantee maximum electricity generation over the panel's lifetime, unless there is a policy that provides them with an equal or higher return otherwise. This fact leads us to the topic of electricity tariffs that are used to bill consumers. In case of renewables, renewable electricity tariffs are subsidized by the governments of many countries. In the context of our research, tariffs can include payments to solar generators, payments to thermal generators, and monetized carbon taxes. The last of our models (section 2.6) tries to reduce overall expenditure on electricity bills from the viewpoint of consumers, while ensuring that PV solar power producers are compensated fairly.

1.5 Proposed solutions to the problems arising from solar PV penetration

Numerous ways to address the problems associated with increased penetration of renewables in the generation mix have been proposed on both the supply and demand sides. In 2013, CAISO identified [4] demand response (DR) and energy efficiency (EE) as the potential areas for mitigating some of the problems. These areas encompass methods of various kinds, but they inevitably require infrastructural investment on a grid scale. Specifically, demand response systems require investments in communication infrastructure, while energy efficiency measures require state-of-the-art equipment to be procured and installed.

The MIT Future of Energy report [24] states that cycling effects are less relevant when the generation mix is flexible. Access to hydro resources and energy storage in particular can mitigate most of the problems associated with high solar penetration. However, as mentioned previously, hydro resources are not readily available across the globe. In terms of storage, concentrated solar power (CSP), supercharging water heaters, air-conditioning with thermal storage, and other types of storage are often proposed in this context. Unfortunately, they too require significant investments. Electric vehicles represent a growing potential for mass energy storage, but they currently lack the necessary level of adoption.

Strong interconnections with neighboring electrical grids are also identified as ways to resolve the problems caused by increased solar penetration. Interconnections rely on transmission networks of high throughput, which require heavy investment. Another proposed solution is to retire inflexible coal and nuclear capacity from the generation mix altogether and substitute it with newer and faster generators, such as combined-cycle power plants. These proposals would be expensive to implement as well.

To summarize, all of the solutions proposed thus far require investment in one way or another. This leads us to the question of whether it would be possible to reduce the negative impacts of high solar PV penetration without any additional investments. One proposed method that does not require significant investment is to price electricity based on ramping levels (as opposed to demand levels used in conventional markets) so that less power would be consumed during times of high ramps. If this approach was implemented, it could be useful in mitigating the effects of the duck curve on the electrical grid. However, we leave this approach to future work and focus instead on an alternative solution as described in the next section.

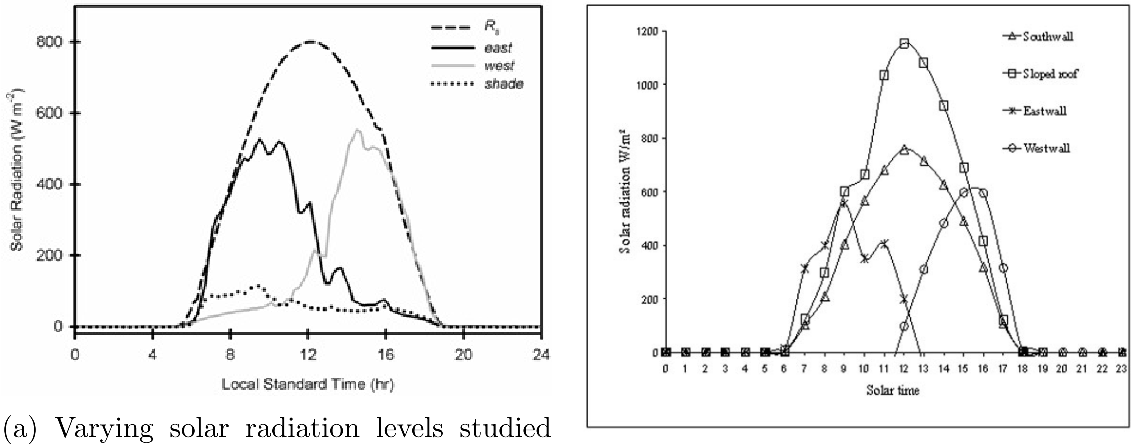
1.6 Our solution

We explore how the impacts of increased solar penetration can be mitigated by quantifying the effects of solar panel orientation on the electrical grid.

As explained in section 1.2, the typical setup for fixed solar panels in the northern hemisphere involves orienting them south with a specific tilt angle determined based on the latitude, at which the panels are installed. This setup maximizes the amount of power generated and the resulting revenue for panel owners over the year. In our research, we relax this rigid setup by allowing a number of various solar panel orientation/tilt combinations in an effort to mitigate the problems faced by electric power producers and electrical grid operators that are outlined in section 1.4.

In contrast to most solutions listed in the previous section, this particular approach was chosen because it does not require any additional investment, apart from the regular capital and operating expenditures associated with PV solar panels. Assuming the same amount of investment during the planning stage, the panels' tilt and orientation can be planned with a high degree of flexibility in mind. This flexibility will alter the solar generation curves and subsequently the net load curves. The altered net load levels may be beneficial for resolving the problems described earlier in this chapter.

The fact that the sun provides different amounts of energy depending on the orientation of the recipient is trivial and was used in various domains of industry and agriculture for many years. Figure 1.8 includes examples from the literature that illustrate how levels of solar radiation vary for east, west and south-facing surfaces.



(a) Varying solar radiation levels studied in the context of grape ripening: radiation graphs for east and west sides of the vine, as well as total radiation and radiation in shade are shown [28]

(b) Varying solar radiation levels studied in the context of lumber drying: radiation graphs for glazed surfaces of a solar dryer are shown [19]

Figure 1.8: Diagrams of solar irradiance curves from various domains

Because solar irradiance curves depend on the movements of Earth around the Sun, they follow a predictable pattern. Specifically, symmetrical sinusoidal curves are commonly used for simulating daily irradiance patterns for different orientations of the recipient [23]. One analytical way to infer orientation-dependent irradiance curves is to use a formula such as the one presented in equation 1.1 [2]. It demonstrates how the sun elevation level (α), the solar panel orientation (θ, also called *azimuth*), and the solar panel tilt angle (β), affect the amount of *direct* solar radiation received by a given panel. The formula requires total direct solar irradiance level on the ground as an input.

$$S_{module} = S_{incident}(cos(\alpha)sin(\beta)cos(\psi - \theta) + sin(\alpha)cos(\beta)) \tag{1.1}$$

But the curves generated using this and other analytical methods do not represent the whole picture. In reality, climate variations significantly affect the magnitude of daily irradiance for each panel orientation: e.g. "... asymmetry of daily insolation patterns can result from variation in atmospheric conditions, for example in locations where afternoon clouds are common"[23]. Based on the equation 1.1 alone it is only possible to estimate very approximate electricity generation levels for PV panels with various orientation/tilt combinations. These estimates are very rough, and do not take into account the fraction of electric power produced from *diffuse* solar radiation, which is quite significant. Fortunately,

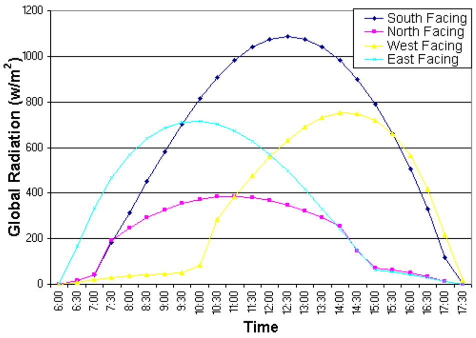
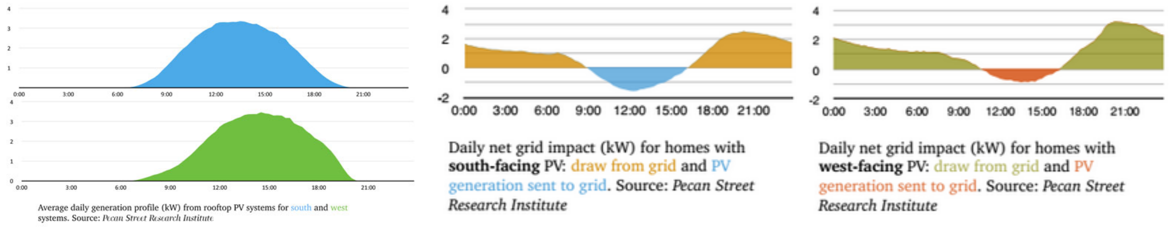


Figure 1.9: Sample daily insolation curves for different orientations [23]

modern software packages are able to generate the necessary irradiance curves, which take into account both direct *and* diffuse solar radiation levels influenced by the peculiarities of climate in a specified geography. For example, figure 1.9 illustrates various solar irradiance curves generated by one such software package: Solar Analyst, an ArcView extension [23].

We are not the first to study the effect solar panel orientation would have on the electrical grid. According to a report on the impact of solar panel orientation on the residential sector in Texas, produced by the Pecan Street Research Institute, "[s]outh-facing panels produced a 54% peak reduction overall, while west-facing solar PV panels produced a 65% peak reduction"[3]. The leftmost image in figure 1.10 illustrates how the solar power generation profile shifts as PV solar panels are oriented westward instead of southward. On the other hand, the other two images in figure 1.10 illustrate how this re-orientation reduces the overall amount of energy produced by PV solar panels, and increases the amount of energy generated via other sources (drawn from the electrical grid). Authors argue their findings "could help inform utility rebate programs for rooftop solar panels and demand response programs". They also speculate that "[i]f more utilities were to move to dynamic pricing models, where power cost more during days of high peak demand, west-facing panels could potentially be more attractive to certain households with high peak loads"[3].

While we also dealt with peak load reduction in our research, the scope of our work was much more diverse, and it was conducted with a significantly larger system scale in mind in comparison to the Pecan Street study. Indeed, we developed four distinct models, all of which had solar panel orientation and tilt flexibility as their principal feature. Each of these models targeted a specific segment of the power market with distinct parameters and requirements. The models have various objectives and feasibility constraints, and are described in detail in chapter 2.



Average daily generation profile (kW) from rooftop PV systems for south and west systems. Source: *Pecan Street Research Institute*

Daily net grid impact (kW) for homes with **south-facing** PV: draw from grid and PV generation sent to grid. Source: *Pecan Street Research Institute*

Daily net grid impact (kW) for homes with **west-facing** PV: draw from grid and PV generation sent to grid. Source: *Pecan Street Research Institute*

Figure 1.10: Impact of solar panels re-orientation, Pecan Street Research Institute [3][8]

1.7 Contributions

We developed four models that exploit the concept of control over tilt and orientation of fixed solar panels at the time of installation to mitigate some of the problems arising from high solar PV penetration. The models address needs of different electric market players. The first model focuses on reducing ramping levels in electrical grids, the second one ensures better load following for solar PV panels, the third concentrates on peak net load reduction, and, finally, the fourth model deals with expenditure reduction for the end consumer of electricity.

Using these models, we conducted simulations in three different regions: Ontario, British Columbia, and Texas. The objective function improvements varied dramatically depending on the model used, but produced similar results across the three regions for each of the models. The ramp reduction model provides a performance improvement of 25–30% under moderate levels of relative installed PV capacity. The gap reduction model provides improvements only with very high levels of solar penetration: a 30% improvement can be achieved when relative installed PV capacity reaches 350% in the electrical grid. The net peak load reduction model does not provide any improvements, because annual peaks in real electrical grids cannot be resolved through solar panel layout diversification for reasons explained further. The expenditure reduction model provides virtually no benefit in a realistic setting, and an improvement of 2–3.5% under extreme conditions that are not encountered in real electrical grids.

Thus, the results of our research comprise a combination of positive and negative results: we achieved noticeable performance improvements with two of our models, although we did not achieve promising improvements with the other two. These results may be beneficial for future energy policy research and power generation capacity planning, as global solar PV penetration increases steadily around the world.

Chapter 2

Models

2.1 Overview

In this work, we consider an electrical grid that supports two forms of electricity generation: solar and generic fossil-fuel[1]. Thus, in all of our models conventional thermal generation is the only available resource to satisfy a positive net load. Moreover, again for simplicity, we do not consider any energy storage or inter-grid trade mechanisms, so if net load is negative, solar power curtailment is the only option to resolve overproduction.

Among the available solar generators, we only consider fixed solar panels, since these are the most robust and commonly used solar systems. We decided to ignore solar trackers and concentrated solar power (CSP) systems due to the factors mentioned in chapter 1. However, in our research, fixed solar panels inherit some benefits of solar trackers in a way that was not studied in depth in this context, namely, control over solar panel orientation and tilt.

Specifically, we allow control over the orientation and tilt of every solar panel in a given jurisdiction at the time of installation. In our models, after a panel is installed it is impossible to change its orientation or tilt for the duration of its lifespan. We do acknowledge the fact that there exist some solar panel systems with adjustable tilt mechanisms, which can yield higher electricity generation gains if operated properly; however we did not take these systems into consideration for the sake of simplicity.

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[1] We focus on the two forms of generation for simplicity. Integration of other forms (wind, nuclear, hydro) into the models may be considered in future work.

Based on these assumptions, we develop four distinct models to address certain needs of electric market regulators and electric power producers. These models are presented in this chapter, and they are accompanied by descriptions of their potential applications. Market regulators and electric power producers have inherently different objectives, and thus some of our models may be suitable for one but not the other. Moreover, some of these models have conflicting objective functions, and we present how they affect each other in section 3.7. It is also important to note that the models are simplistic by design, as the goal is to evaluate each model's upper bound performance, rather than to incorporate every detail of the underlying real-life scenario.

While in the models presented in this thesis the orientation and tilt of all solar panels within an electrical grid are decided upon only once, we also experimented with an incremental (evolutionary) version of this approach, which is more applicable to real life electricity markets. Specifically, we modeled a market, in which newcomers (solar panel owners) join the market in batches. Before each batch arrives, the grid operator or a utility decides upon the batch's panel layout based on the pre-existing solar PV installed capacity, in addition to any other factors under consideration. This incremental approach inevitably leads to results that are worse than those described in this thesis, because having end-to-end control over the whole grid panel layout is always better than incremental batch improvements.

Mathematically, all the models presented in this work are single-agent optimization problems. Numerical computations are formulated in A Mathematical Programming Language (AMPL)[22]. The models are subsequently solved with IBM ILOG CPLEX Optimization Studio (CPLEX)[21] under the default configuration, since they are formulated as *piecewise-linear optimization* problems.

2.2 Notation

This section defines a set of common parameters, variables, and constraints shared by all of the models we developed. We consider calendar year time frame as the basis of all our simulations. Thus, the number of hourly readings for electricity generation and electrical grid load is always $365 \times 24 = 8760$. We also limit the number of tilt/orientation combinations to 29[2]. The chosen tilts are: 15°, 30°, 45°, and 60°. The chosen orientations are: 120°(east), 150°, 180°(south), 210°, 240°, 270°(west). In addition, a combination of 0° tilt and 0° orientation represents a panel that is lying flat on the ground, facing the sky.

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[2] While we assume that all these combinations are feasible, this might not be the case in a real-life setting, e.g., if the panels are being installed on rooftops.

Input parameters

- I – number of hourly electricity generation and electrical grid load readings
- J – number of tilt/orientation combinations
- H_i – aggregate electrical grid load at time i
- $\gamma_{i,j}$ – solar electricity generation level for time i and tilt/orientation combination j
- Q – aggregate number of panels mandated for installation across the electrical grid
- one panel's installed capacity is 200 Wp

Optimization variables

- q_j – quantity of panels with tilt/orientation combination j

Output variables

- G_i – aggregate fossil-fueled electricity generation at time i
- S_i – aggregate solar electricity generation at time i
- C_i – aggregate solar curtailment at time i

Effectively, the only vector variable the solver uses to optimize an objective function is the vector q. Each element of the vector corresponds to the number of panels with a certain tilt/orientation combination. To avoid the computational burden of integer linear programming (ILP), we relax the integer constraints on the vector q to allow non-integer numbers of panels. Taken together, the vector q corresponds to the overall solar panel layout in an electrical grid. Every other output variable listed above is directly dependent on this panel layout.

Constraints

We use the total number of panels Q as a control knob to limit solar penetration:

$$\sum_{j=1}^{J} q_j = Q \tag{2.1}$$

We also experimented with a relaxed version of this equation:

$$\sum_{j=1}^{J} q_j \leq Q \tag{2.2}$$

However, after some more thought, we decided to keep the first version of this constraint. Otherwise, benchmarking of model performance would become problematic. Specifically, equation 2.1 signifies that a grid *must* accept a certain number of panels regardless of whether it would benefit its utility function. This allows us to measure performance improvement between the base case scenario and the flexible orientation scenario given a certain level of relative installed PV capacity.

Aggregate solar electricity generation is a trivial summation of electricity generation levels across all solar panels present in the electrical grid:

$$\forall i : S_i = \sum_{j=1}^{J} \gamma_{i,j} q_j \tag{2.3}$$

The supply following two equations regulate how net load is represented in our models. The curtailment constraint defines the level of power curtailment in the electrical grid:

$$\forall i : G_i + S_i - H_i = C_i \geq 0 \tag{2.4}$$

The supply and demand balance equation restricts thermal generation to levels greater or equal to zero:

$$\forall i : G_i = \max(0, H_i - S_i) \tag{2.5}$$

If net load is positive, it is effectively equivalent to thermal power production level (G_i). If net load is negative, no electricity needs to be produced with fossil fuels, but there is solar power curtailment present in the system (C_i). The max function is piecewise linear, and thus can be processed by CPLEX. Any additional model-specific features are outlined in the subsequent sections.

2.3 Ramp reduction model

Consider a vertically integrated utility, such as BC Hydro or Électricité de France (EDF). Utilities like these may potentially have enough influence to enforce the orientation of solar panels joining the grid during the planning stage, as described at the beginning of this chapter. In this case, it could be in the utility's best interests to dictate the precise orientation/tilt combination of every solar generator entering the market. If the solar generator does not comply, the utility simply declines the generators' connection to the electrical grid.

Mathematically, reducing the magnitude of ramping can be formulated as minimization of the sum of absolute differences between hourly thermal generation levels (G_i). The summation is performed in order to guarantee that the ramping rates remain low throughout the year. These considerations are captured by the objective function:

$$\underset{q_j, S_i, G_i, C_i}{\text{minimize}} \sum_{i=1}^{I} \Big| G_i - G_{i-1} \Big| \tag{2.6}$$

The combination of panel orientation diversification and the aforementioned objective function ensure that the morning and evening ramp effects described in section 1.4.1, as well as any other ramp events occurring during the day, are mitigated. This objective function uses an absolute-value function, which is piecewise linear, hence this model is solvable by CPLEX.

2.4 Gap reduction or load following model

The potential user of the model described in this section is an off-grid microgrid owner, whose microgrid consists of photovoltaic panels and a thermal generator, such as a diesel generator. Thus, the objective function of this model is to minimize the gap between the solar power supply and the grid demand curves, given the total number of panels Q. This is achieved by penalizing the deviation between the net load curve and zero. If the net load is above zero, it has to be matched by thermal generation (G_i). If the net load is below zero, there is curtailment in the system (C_i), which is typically uneconomical, considering the high capital costs associated with installation of solar PV panels. To quantify these losses, we assign different costs to positive and negative net load, the relative trade-off factor connecting the two being ϵ:

$$\underset{q_j, S_i, G_i, C_i}{\text{minimize}} \sum_{i=1}^{I} (\epsilon C_i + G_i) \tag{2.7}$$

Complex arguments can be made to determine the correct value of ϵ, but in this work we simply assume that it is equal to the ratio of the two LCOEs: PV solar and thermal. The rationale behind this is that if 1 kWh of power is curtailed, an amount of money equivalent to solar LCOE of 1 kWh is lost. This assumption is introduced to keep the model linear. Alternative methods for determining the value of ϵ can be developed in future work.

Using LCOE forecasts for new generation resources for 2020 from EIA [12], and assuming a combustion turbine model as a good approximation for a diesel engine, we estimate the value of ϵ to fall in the following range: $\epsilon_l = C_{PV}/C_{CCT} = 0.9$, $\epsilon_h = C_{PV}/C_{ACT} = 1.1$, where CCT stands for conventional combustion turbine, and ACT stands for advanced combustion turbine. In our experiments, an even broader parameter range between 0 and 2.0 is used to see how well the model responds to changes in the LCOEs.

2.5 Peak net load reduction model

Consider an electricity market operator, such as IESO in Ontario. The operator's objective will be significantly different from that of an electricity generator. One of the goals of the market operator is to ensure that peak demand of the electrical grid remains low throughout the year. In this variation of our model the operator acts as the solar panel layout controller.

Peak load (peak demand) refers to a period of time during which its level is significantly higher than usual. Peak load can occur at certain times of the day, which means that by changing solar orientation it may be possible to reduce the net load peak, and lower the degree to which thermal generators should extend their operating capabilities. Peak load also has economical costs associated with it, so lowering the net load peak may be beneficial for electricity consumers.

We attempt to minimize the net peak load level by applying the following objective function, in which P refers to the upper bound by which every thermal generation level throughout the year is limited:

$$\underset{q_j, S_i, G_i, C_i}{\text{minimize}} P \tag{2.8}$$

This is achieved by adding the peak constraint to the model:

$$\forall i : G_i \leq P \tag{2.9}$$

Peak reduction associated with PV solar integration was studied before, and is described in section 1.3. Our flexible orientation model is new in that it could potentially produce better results than those achieved in prior work by allowing proactive control over orientation of the panels during the installation.

2.6 Expenditure reduction model

This model deals with minimizing total expenses that consumers incur for using electricity from the electrical grid. The primary user of such a model could be an electricity market operator, or a governmental body setting power purchase tariffs for solar and thermal power. We introduce a new variable in this model, r_j, which represents the price of solar power imposed for orientation j relative to the thermal power tariff in the electrical grid. The objective function minimizes the overall amount of money spent on electricity:

$$\underset{q_i,G_i,C_i}{\text{minimize}} \sum_{i=1}^{I} \Big(\sum_{j=1}^{J} \gamma_{i,j} r_j q_j + G_i \Big) \tag{2.10}$$

We assume that the price setter determines prices for each solar panel orientation **and** the number of panels that need to be facing those orientations. In other words, the price setter controls solar power producers that wish to enter the market in every regard.

Any correlation in panel orientation within PV clusters can be eliminated by providing an equal amount of money to panel owners regardless of the panel orientation. In this way panel owners will install panels with different orientations as required by the price setter, thus diminishing any correlation effects. To keep the market structure fair, the following constraint is introduced:

$$\forall j : r_j \sum_{i=1}^{I} \gamma_{i,j} = r_0 \sum_{i=1}^{I} \gamma_{i,0} \tag{2.11}$$

where r_0 is the tariff imposed for power produced with panels facing south with an optimal tilt. This equation guarantees that a producer will receive the same annual amount of money from consumers through the market operator regardless of the orientation they have to assume.

Following the same logic as described in section 2.4, we can use the ratio between the LCOEs of PV solar and conventional thermal generators to determine an approximate value of r_0. Based on the same calculations, a typical value of r_0 in 2020 would be fluctuating around 1.0, but in our tariff reduction model implementation we experiment with a range of values between 0 and 2.0, just as we do in the load following model.

Chapter 3

Results

3.1 Data and metrics

Three regions were chosen for our experiments: we start with Ontario, as the default jurisdiction, and use British Columbia and Texas to further validate our findings. The limiting factor for the selection of these jurisdictions was the availability of hourly electrical grid load data. Three organizations have been consistently providing this type of data: the Independent Electricity System Operator (IESO) in Ontario, the British Columbia Hydro and Power Authority (BC Hydro), and the Electric Reliability Council of Texas (ERCOT). The year 2005 was chosen for Ontario and Texas, and 2015 for British Columbia, as typical non-leap years without severe electrical grid distortions due to economic or climate-related factors.

The second component necessary for the experiments was the power output from solar panels with various orientations and tilts. Such data was not readily available, at least not in the the detail required for our models. We attempted to deduce various solar power generation profiles with an analytical approach based on trigonometrical equations, described in section 1.6. This methodology, however, was only successful in providing the amount of power generated from direct solar radiation, and not the diffuse radiation, which was essential for our experiments.

Thus, we had to use specialized software to generate this data. During our research we tested the task on two software packages. The first one is a commercial product called HOMER Energy [1], based on a model developed by the National Renewable Energy Laboratory (NREL). The second one is the System Advisor Model (SAM) developed by

NREL directly [20]. Both software packages were able to produce the necessary power output readings for solar panels oriented in various directions and with various tilts (29 combinations overall). However, SAM was more convenient in terms of usability for our purposes, which is why the results presented in this section are based on its output. The exact locations used to generate this data were Toronto (Ontario), Vancouver (British Columbia), and Austin (Texas). With all the data components available, we were able to proceed with our experiments. The actual grid load data was linearly scaled down by a factor of 10^6 to make the numbers of panels easily manageable. For example, in case of Ontario we took the historical annual peak load of 26 GW for 2005, and scaled it down to 26 kW. The same approach was used for the two other regions.

We study the impact of orientation control as a function of the degree of penetration of solar PV in the grid in the three regions differing by both the electrical grid load profile and solar traces. Thus, it is important to select a solar penetration metric that would be suitable for comparisons among them. The following two metrics have been used in the industry to measure the degree of solar PV penetration in the electrical grid:

- **PV capacity penetration** is a metric, in which the level of solar installed capacity is evaluated against the peak load observed in the electrical grid (e.g., 26 GW in Ontario).
- **PV energy penetration** represents the fraction of energy produced by solar PV in the total generation mix. Note that PV energy penetration values differ in the base case scenario and flexible orientation scenario, as well as in different models. This is because the flexible orientation scenario results in less energy being produced via solar overall.

These metrics have been described in detail in section 1.2, along with our own metric that is more conservative than the other two, namely, **relative installed PV capacity**. As a reminder, the relative installed PV capacity is defined as the ratio of solar panels installed in the grid divided by the maximum number of panels in the base case scenario that result in zero curtailment, given the load and generation profiles in that jurisdiction. We use this metric because it allows us to compare jurisdictions differing by load and solar generation profiles and it is also easy to understand: when the metric is equal to 0% it means there is no solar PV installed capacity in the electrical grid, when the value is 100% it means the electrical grid has reached a threshold after which curtailment begins to occur.

Table 3.1 illustrates numerical differences between the three metrics for a typical scenario. The relative installed PV capacity threshold values (i.e., the number of installed

Table 3.1: Comparison of various penetration metrics in Ontario

number of panels (Q)	50	100	150
absolute installed PV capacity (kW)	10	20	30
relative installed PV capacity	59%	117%	176%
PV capacity penetration	38%	76%	115%
PV energy penetration (base case scenario)	8%	15%	22%
PV energy penetration (flexible orientation scenario in ramp reduction model)	6%	11%	16%

panels that results in zero over-production for every hour of the year) were determined by solving a small optimization problem for each jurisdiction using a scaled-down load profile and a panel peak production of 200W. The threshold values are 38 panels for British Columbia, 85 panels for Ontario, and 151 panels for Texas. This means that when there are at most 85 panels in Ontario, and all of them are facing south with the default tilt, the electrical grid has no curtailment. These threshold values correspond to 100% levels of relative installed PV capacity in each jurisdiction. When converted to PV energy penetration, these values correspond to approximately 13% for Ontario, 14% for British Columbia, and 15% for Texas. All the subsequent sections use relative installed PV capacity as the default metric for installed capacity measurements.

3.2 Results overview

This section presents the results of our experiments with the four models outlined in the previous chapter. To evaluate the performance of our models, we compared the results of each of them to the base case scenario: the status quo, under which most fixed solar systems operate now (facing south with a tilt determined by the latitude of the location). In practical terms, we fix the tilt/orientation vector to contain only one non-zero value q_0 to represent the base case scenario. The optimization component is thus eliminated from the base case scenario altogether, since there is no flexibility of tilt or orientation in the system, and the solutions are deterministic. Ω_0 represents the value of the objective function for the base case scenario.

In the flexible orientation scenario this constraint is relaxed to allow all of the vector q to be used for various tilt/orientation combinations. The objective function value in this case is represented by Ω_1. The relative performance improvement calculated as follows:

$$\frac{\Omega_1 - \Omega_0}{\Omega_0} \tag{3.1}$$

If the value of this metric is negative, it means that the flexible orientation scenario outperforms the base case scenario, because all of the objectives in our research are minimization functions. Under normal circumstances, a properly working model should not give positive values for this metric, since that would mean that giving more flexibility to the model somehow degrades its performance.

Three types of figures are presented in this section: grid load and net load profiles, panel layouts, and relative objective curves. The grid load and net load profiles illustrate the change between base case scenario and flexible orientation scenario net load profiles. The panel layouts illustrate how the layout of panels (vector q) changes in response to the total number of panels mandated (Q). There are 29 rows overall, each corresponding to one tilt/orientation combination, and the X axis represents the relative installed PV capacity. The intensity of the color represents the proportion of all panels allocated to a particular direction: bright copper represents 100%, while black corresponds to 0%. Finally, the relative objective curves illustrate how the performance improvement of various models changes in response to the parameters.

3.3 Impact of orientation flexibility on reducing ramp rates

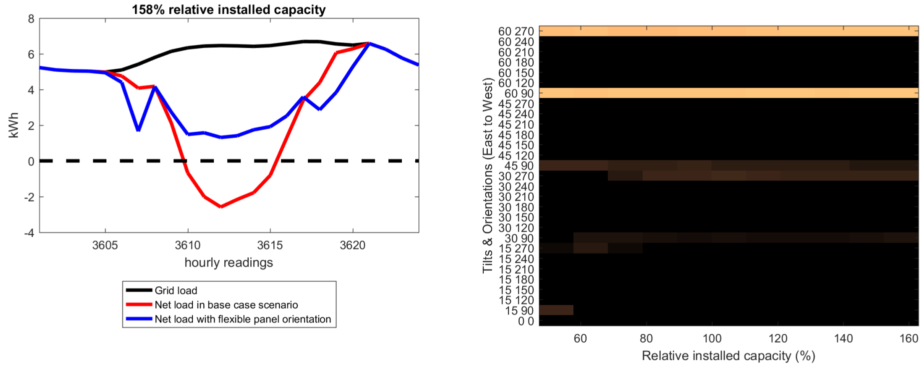
The ramp minimization model is outlined in section 2.3. For Ontario, we consider a range of relative installed PV capacity levels between 60% to 180%. In Texas and British Columbia the upper limit is reduced to 160% because of the computational constraints: higher values of relative installed PV capacity result in very slow computations.

Figure 3.1 illustrates how the ramp minimization objective decreases the variation magnitude of the thermal generation levels. The left hand column shows results for typical days in the year (specifically, at the end of May) for the highest penetration levels in each jurisdiction. The blue line, which corresponds to the net load curve of the flexible orientation scenario, demonstrates no aggressive ramps, such as those observed in the red line, which represents the base case scenario. Panel layouts are presented in the right hand column of the same figure with the X axis corresponding to the relative installed PV capacity. In every case the solver determines that it is optimal to place most panels facing east and west with the highest tilt available (60°) so that solar generation is minimized during the afternoon hours. This helps avoid high levels of thermal generation variation caused by the afternoon sun. Simultaneously, solar generation is maximized in the morning and in the evening. This demonstrates that our model performs as predicted: the objective function is optimized by changing panel orientations accordingly.

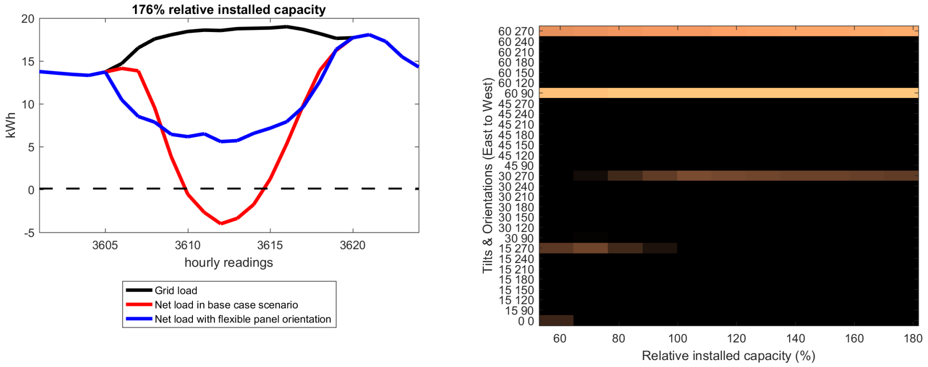
Figure 3.2 illustrates that an improvement of between 25 and 30% in the objective function can be achieved by using this model when relative installed PV capacity exceeds the 100% level. After relative installed PV capacity reaches 120–140%, the objective function relative improvement falls steadily. This decrease in performance improvement is caused by the fact that only positive net load contributes to ramping. Negative net load, represented by curtailment, does not affect the objective function in any way. This means that while both the base case scenario and the flexible orientation scenario perform better in absolute terms, the relative performance gain begins to approach zero as marginal benefits of adding more panels in the flexible orientation scenario diminish.

It is important to note that with such a layout, some re-oriented panels produce less energy overall and thus are being used to a smaller degree than in the base case scenario. Hence, the panel layout is not optimal in terms of PV energy penetration. This is an expected result, because panel utilization is not a factor in the ramp minimization objective function. When the flexible orientation model successfully minimizes the amount of ramping present in the electrical grid, the degree of thermal energy penetration increases, because the remaining load must still be matched by thermal power.

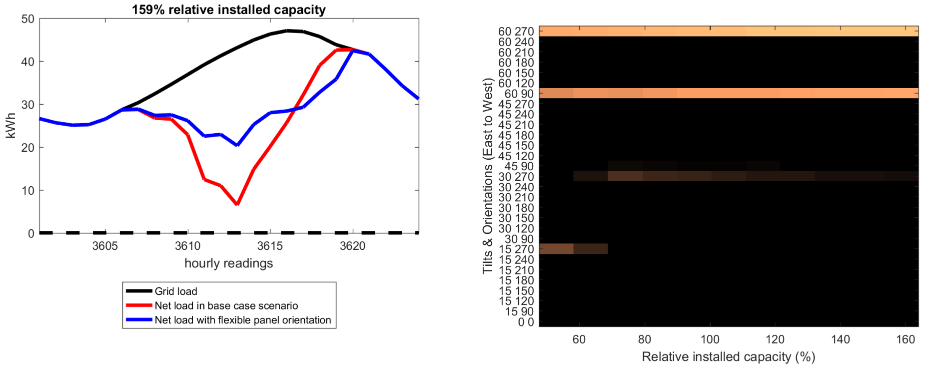
As mentioned in section 1.4.1, the results of WWSIS-2 indicated that cycling costs were not significant in comparison to the savings generated by increased renewable penetration. Considering this finding, it is important to illustrate the increase in overall *thermal* generation in our ramp reduction model. The orange line is added to figure 3.2 to illustrate the increase as a function of relative installed PV capacity. Across the chosen jurisdictions, the thermal energy penetration increase is consistently below 10%, even as relative installed PV capacity exceeds 100%. This 10% increase in thermal energy penetration corresponds to a relative decrease in solar energy penetration of approximately 25–29%. This could be considered reasonable within the context of our research, as it indicates that our approach is not causing nearly as much environmental damage as if the whole solar generation was substituted by thermal generation, which is a positive result overall. We are not evaluating the monetary effects that the re-orientation is causing, but, considering that the objective function improvements exceeds 25% and the increase in thermal energy penetration stays below 10%, the ramp reduction approach could be used in those areas where the cost of ramping is very high, and such a trade-off is acceptable to the decision-making utility.



(a) British Columbia (b) British Columbia

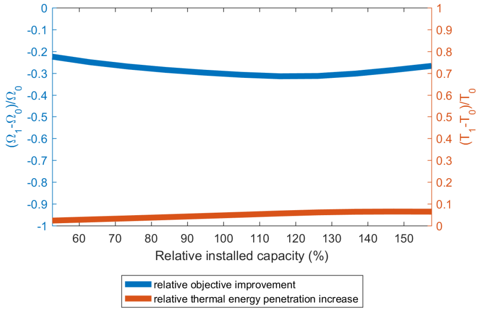


(c) Ontario (d) Ontario

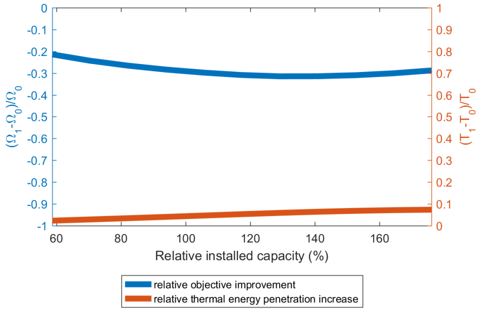


(e) Texas (f) Texas

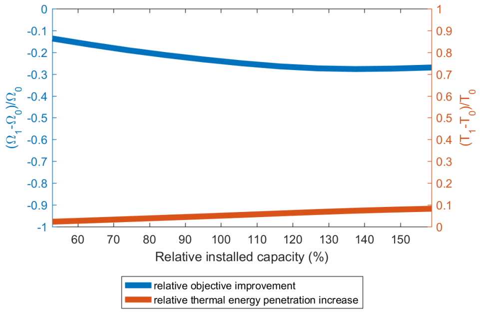
Figure 3.1: Ramp reduction results. The left side illustrates grid load and net load profiles on a typical day in the three jurisdictions. The right side illustrates panel layouts generated for the flexible orientation scenario. The optimal way to reduce ramps is to orient panels east and west with the highest possible tilt available. As a result, morning and evening ramps are significantly reduced, as shown on the left.



(a) British Columbia



(b) Ontario



(c) Texas

Figure 3.2: Ramp reduction results: relative objective curves

3.4 Impact of orientation flexibility on reducing gaps

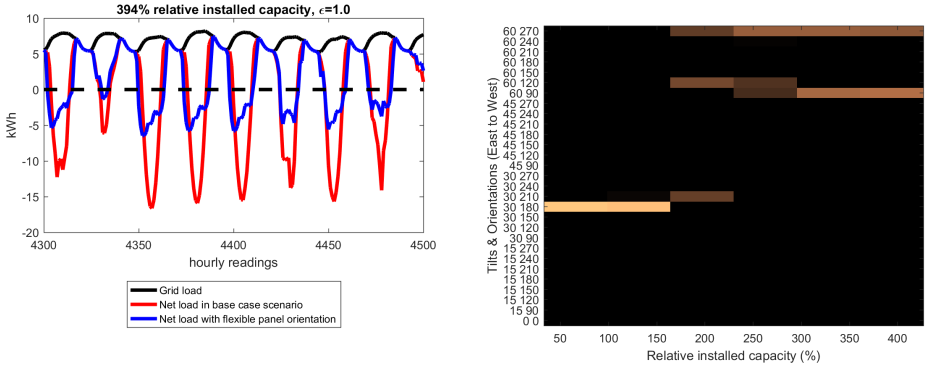
The gap minimization model is outlined in section 2.4. For the three jurisdictions, the relative installed PV capacity varies from 50% to 350%–400%, and the relative trade-off factor ϵ varies from 0 to 2.0 in the 3D graphs in figure 3.4 and 3.5. In the 2D graphs in figure 3.4, we only focus on values of $\epsilon = 0.8, 1.0, 1.2$, which is a reasonable approximation determined in section 2.4. In all figures of this section $\epsilon = 1.0$, unless stated otherwise. Neighboring values of ϵ do not produce drastically different solutions.

The optimal solution is presented in figure 3.3. The grid load and net load profiles are shown only for the maximum levels of relative installed PV capacity for the three regions, to demonstrate the effect of orientation diversification on the largest scale. The flexible orientation scenario solution guarantees that the gap between the net load curve and the reference level of zero is as small as possible.

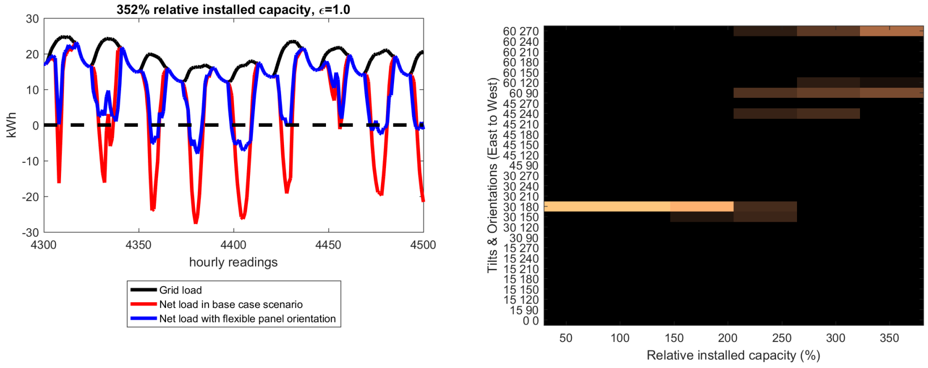
The panel layouts presented in figure 3.3 illustrate that all solar panels are facing south with the optimal tilt of 30° when solar penetration is low. However, as the levels of relative installed PV capacity exceed 150%, the panels are diverted towards east and west with a tilt of 60° in Ontario and British Columbia, and 45° in Texas.

The left hand column of figure 3.4. illustrates the relative objective function surfaces. The surfaces demonstrate how the flexible orientation scenario solution becomes more advantageous to the base case scenario solution as both parameters – the relative installed PV capacity and the value of ϵ – increase. The right hand column of figure 3.4 illustrates the subset of the solutions from the left hand column for the realistic range of values of ϵ between 0.8 and 1.2. In these cases, an improvement of approximately 10–15% can be attained, when relative installed PV capacity exceeds of 300% for the three regions. Considering that this level of relative installed PV capacity is quite high, it may or may not be beneficial for a microgrid owner to employ this technique depending on how much solar capacity he operates.

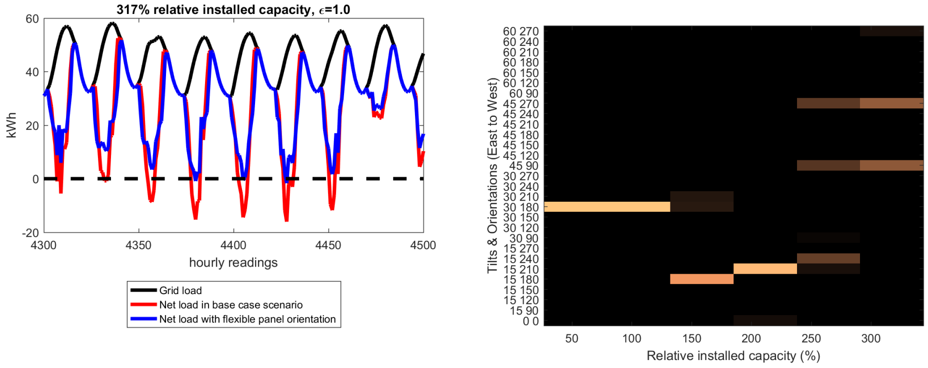
Figure 3.5 is provided for reference, to illustrate the differences between the base case scenario objective function values (red) and the flexible orientation scenario objective function values (blue) for the three regions. Figure 3.4 mentioned earlier is based on these results.



(a) British Columbia (b) British Columbia

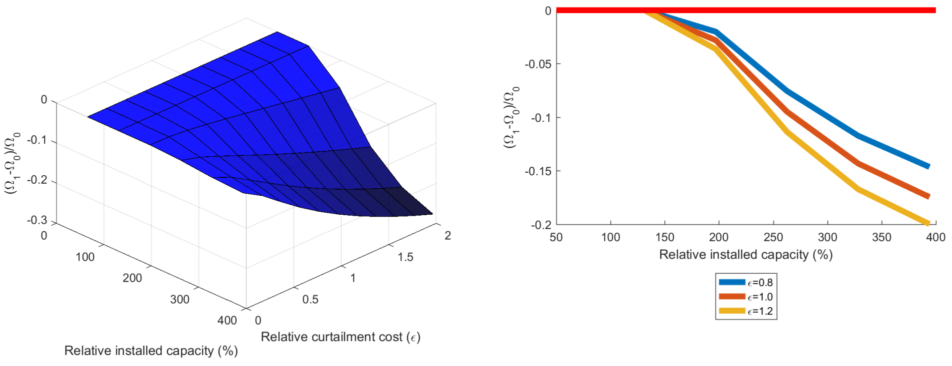


(c) Ontario (d) Ontario



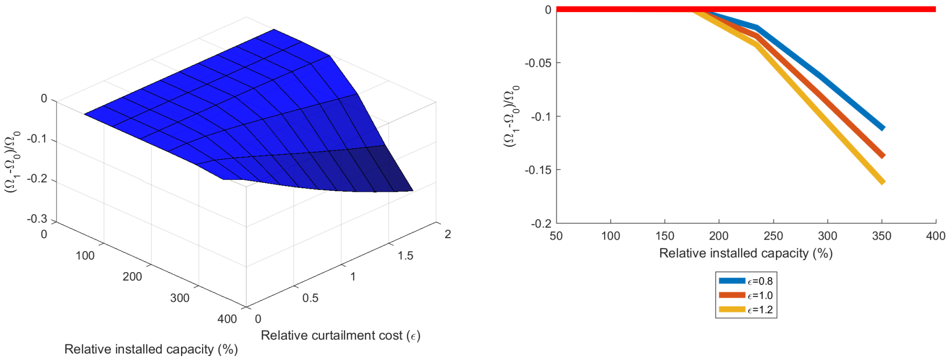
(e) Texas (f) Texas

Figure 3.3: Gap reduction results. Unlike in the previous section, the left side illustrates grid load and net load profiles for a typical week, not a single day, in the three jurisdictions. The right side illustrates panel layouts generated for the flexible orientation scenario. Again, the optimal way to reduce ramps with high levels of relative installed PV capacity is to orient panels east and west, but in this case the tilt varies. Curtailment is significantly reduced, as shown on the left.



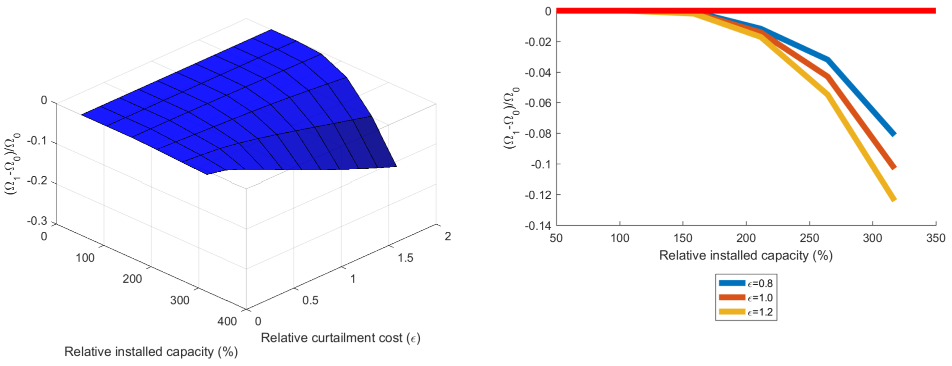
(a) British Columbia

(b) British Columbia



(c) Ontario

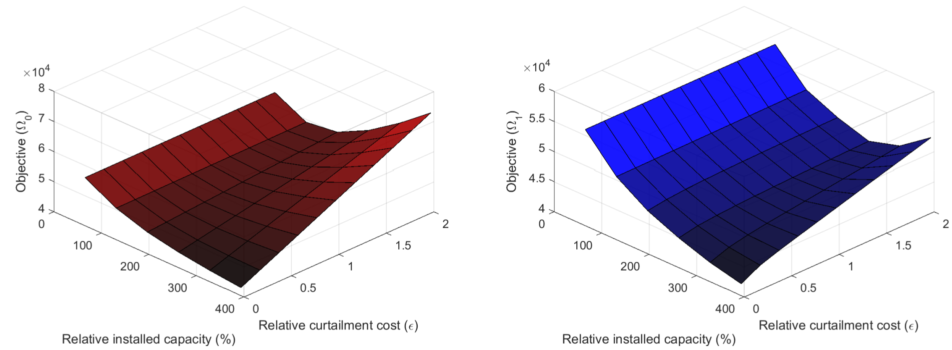
(d) Ontario



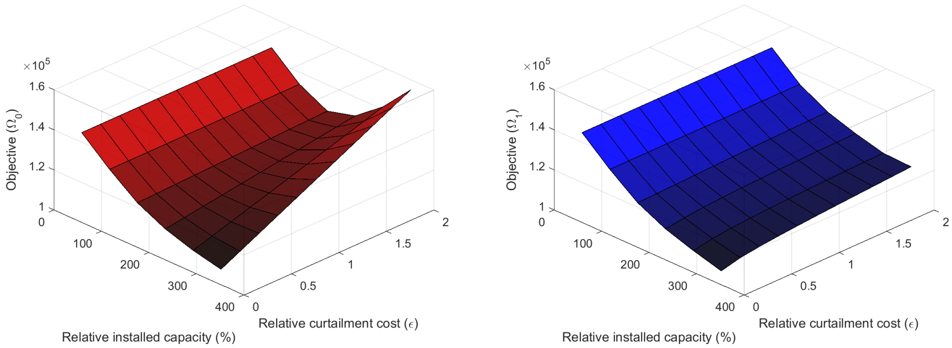
(e) Texas

(f) Texas

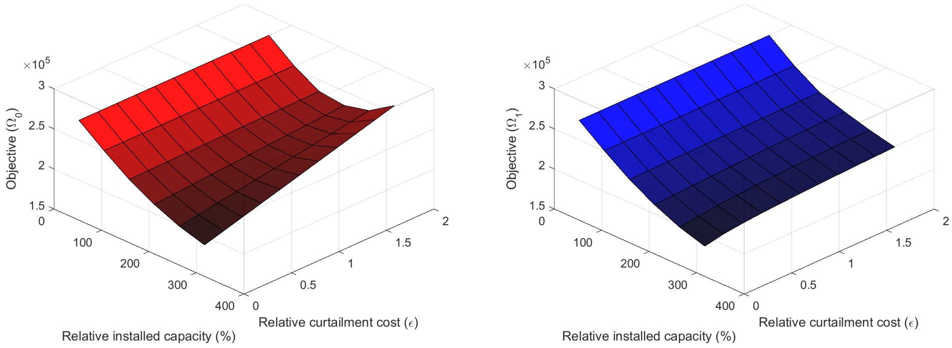
Figure 3.4: Gap reduction results: relative objective curves



(a) British Columbia (b) British Columbia



(c) Ontario (d) Ontario



(e) Texas (f) Texas

Figure 3.5: Gap reduction results: absolute objective curves, base case scenario vs. flexible orientation scenario

3.5 Impact of orientation flexibility on reducing peak net loads

The peak net load reduction model is outlined in section 2.5. To test the validity of this approach, we experimented with *artificial* 24-hour grid load data sets, one of which had a pronounced morning peak, and the other – an equivalent evening peak. The upper row of figure 3.6 illustrates that it was indeed possible to achieve a slight improvement when the simulation only took into account a single typical day of the year. In this test, flexible panel orientation induced a peak net load reduction of 1–3% in comparison to the base case scenario.

However, when the same simulation was repeated for a whole year, as opposed to a single day, the improvement was equal or extremely close to 0% regardless of the level of solar penetration in the electrical grid. In this particular experiment, the reason for such a poor performance was the fact that, during some days in a year, load peaks coincide in time with a period of poor solar irradiance caused by bad weather. In this case, regardless of how one decides to orient their solar PV panels, the amount of solar energy produced will be close to zero: see the lower row of figure 3.6 for the demonstration. Thus, even a single day with a bad weather can render the approach useless.

Similarly, after a number of experiments on *real* electrical grid load data, we concluded that panel orientation diversification is not successful in reducing *actual* annual electrical grid net load peaks as well. The reasons for this are the nature of load peaks:

- load peaks can occur at night,
- load peaks can occur on cloudy days,
- load peaks can persevere for several consecutive hours on a single day.

In all of these cases solar generation is not helpful, regardless of the orientation and tilt of the panels, because solar panels produce nothing or very little power under the circumstances. In short, the peak net load is an external phenomenon, and due to these three reasons we found virtually no reduction in the annual peak net load in the data sets that we studied.

While Pecan Street researchers may argue that placing panels westward could be beneficial for reducing high peak loads in certain individual residential properties in Texas (see section 1.6), the results of our research show that no annual peak net load reduction on a grid scale can be achieved through flexible panel orientation alone. Our grid-scale analysis across Ontario, British Columbia, and Texas shows that these peaks occur under such circumstances that re-orienting panels does not affect them at all.

(a) Morning peak net load reduction, one day simulation. The blue line is slightly below the red line at 10 am, which demonstrates that our approach is working.

(b) Evening peak net load reduction, one day simulation. The blue line is slightly below the red line at 6 pm, which demonstrates that our approach is working.

(c) Morning peak net load reduction, all-year simulation. The morning peak is impossible to reduce because of high cloudiness levels on a particular day. The red and blue lines coincide during the peak on that day.

(d) Evening peak net load reduction, all-year simulation. The evening peak is impossible to reduce because of high cloudiness levels on a particular day. The red and blue lines coincide during the peak on that day.

Figure 3.6: Peak reduction results: grid load and net load profiles

3.6 Impact of orientation flexibility on reducing expenditures

The expenditure reduction model is outlined in section 2.6. The optimal solutions for the three regions are presented in figure 3.7. Here, the panel layouts are not as clearly defined, as in the previous cases. There is also a shift towards east and west orientations at higher penetration levels, but the tilt is at 45°. The panel layout diagrams do not change at all with the varying levels of r_0, meaning that the layouts are independent of this parameter.

We ran this model with the highest relative installed PV capacity levels among all the models, reaching 500–600% for for the three regions, to see if it would result in some tangible improvements. Figure 3.8 illustrates how the value of r_0 affects the relative objective curves: as the relative price of solar drops, the improvements increase. However, even when solar power is absolutely free of charge and levels of penetration are extreme (500–600%), the performance improvement barely reaches 3.5% in Texas and remains at approximately 2% in Ontario and British Columbia.

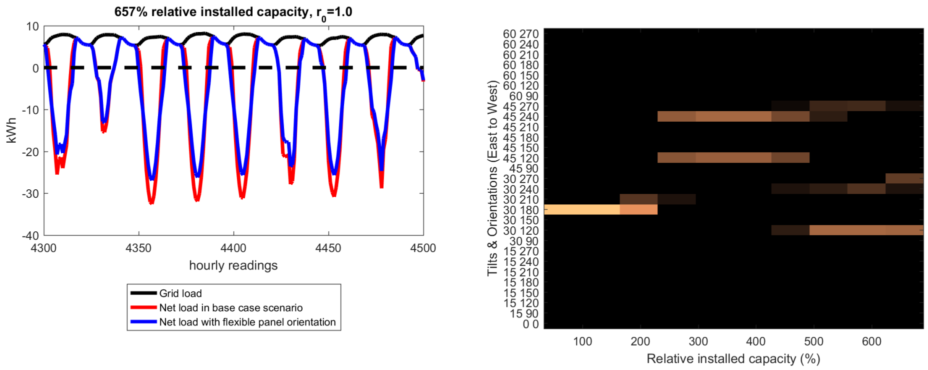
Extreme solar penetration causes extreme levels of curtailment. Given that this model barely provides any benefit even under extreme relative installed PV capacity levels and conditions beyond optimistic (when $r_0 = 0$), and even less so under realistic conditions (when $r_0 = 1.0$), it appears this model is not very viable for real-world applications.

3.7 Impact of ramp reduction on other models

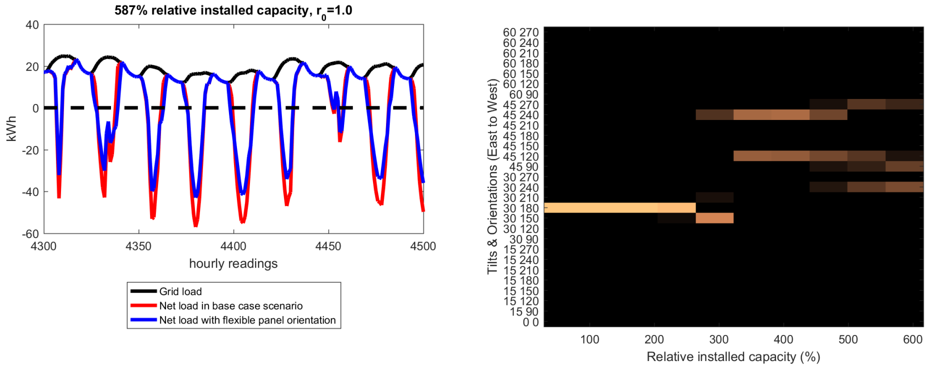
Since the ramp reduction model proved to be the most beneficial in terms of quantifiable performance improvements (see section 3.3), we also evaluated the effects it would have on the other two metrics: gap and expenditure reduction in Ontario.

A 28% reduction in ramp rate is observed with the level of relative installed PV capacity nearing 180% (see figure 3.2 for reference). Assuming the layout generated by the ramp model under that level of relative installed PV capacity, figure 3.9 illustrates a 4–6% drop in performance (i.e., increase in relative objective function value) for both the gap reduction and expenditure reduction metrics, depending on the trade-off factors chosen.

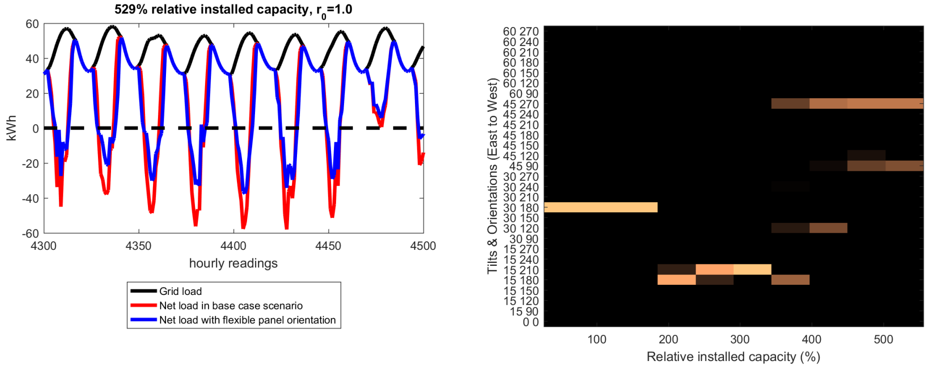
This result indicates that the objective functions of the ramp model and the other models are mutually contradictory, and, subsequently, their values cannot be improved simultaneously.



(a) British Columbia (b) British Columbia

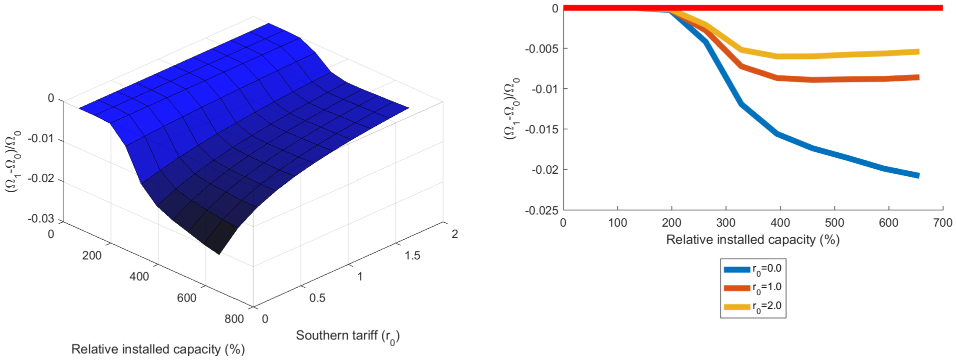


(c) Ontario (d) Ontario

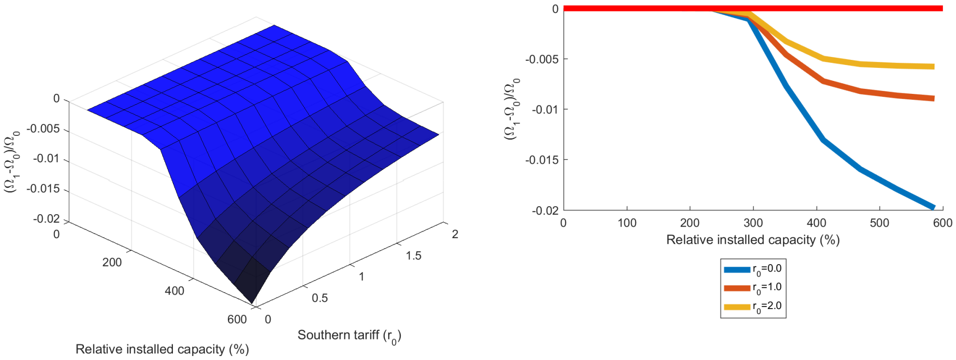


(e) Texas (f) Texas

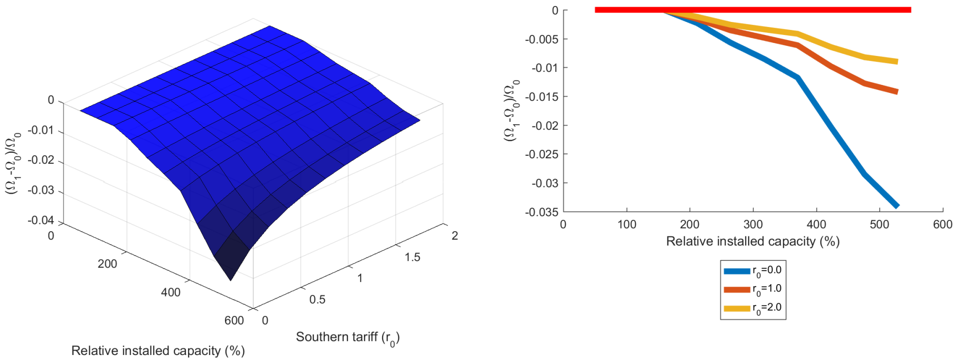
Figure 3.7: Expenditure reduction results. The left side illustrates grid load and net load profiles for a typical week in the three jurisdictions. The right side illustrates panel layouts generated for the flexible orientation scenario. Again, the optimal way to reduce ramps with high levels of relative installed PV capacity is to orient panels east and west, but in this case the preferred tilt is either 30° or 45°. Curtailment is somewhat reduced, as shown on the left.



(a) British Columbia (b) British Columbia

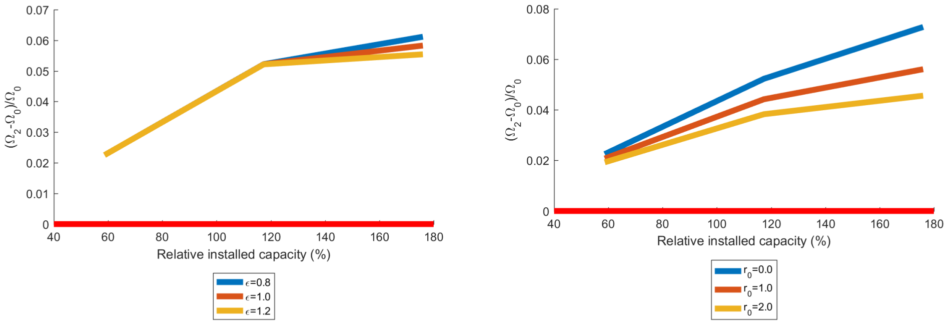


(c) Ontario (d) Ontario



(e) Texas (f) Texas

Figure 3.8: Expenditure reduction results: relative objective curves



(a) Gap increase in Ontario

(b) Expenditure increase in Ontario

Figure 3.9: Ramp reduction effects on other models in Ontario: relative objective curves. The fact that the curves hover above zero level illustrates the adverse effect of the ramp reduction model on the two other models.

Chapter 4

Summary

4.1 Conclusion

Considering the rapidly increasing levels of solar penetration globally, and taking into account the technical challenges associated with this phenomenon, we developed four models that exploit control over tilt and orientation of fixed solar panels at the time of installation to mitigate some of the problems that arise from high solar PV penetration. The models address different needs of electric market regulators and power producers:

- The ramp reduction model (section 2.3) has the objective of reducing the duck curve effect on the electrical grid and could be used by utilities that have the influence to impose their requirements on solar power producers.

- The load following model (section 2.4) was developed to ensure that solar production levels stay as close to the load curve as possible, by penalizing solar power curtailment and thermal power production. This model could be used by a micro-grid owner who operates solar panels in combination with thermal generators.

- The peak net load reduction model (section 2.5) has the objective of reducing the annual peak thermal generation level observed in the grid and could be used by an electricity market operator.

- The expenditure reduction model (section 2.6) was developed to minimize the tariffs that consumers pay for electricity and could be used by a governmental body or an electricity market operator setting purchasing tariffs for solar and thermal power.

We conducted simulations using these models and data from three different regions: Ontario, British Columbia, and Texas. The results demonstrated that not all of our models are equally beneficial for the stakeholders involved in the power market.

The ramp reduction model provides a performance improvement of 25–30%, when relative installed PV capacity levels go beyond 100% and solar power curtailment appears in the system. At the same time, the increase in relative thermal energy penetration stays below 10%, which corresponds to a relative decrease in solar penetration of 25–29%. Thus, this model may be helpful in some jurisdictions where the electrical grid has a very high cost of ramping due to a high proportion of legacy thermal generators or other factors. Overall, this model may be beneficial in reducing the adverse effects of the duck curve, while increasing thermal generation levels by a moderate degree.

The gap reduction model provides improvements only with very high levels of solar penetration. For example, a micro-grid operator in Ontario can benefit from this model only if their relative installed PV capacity exceeds 175%. They would achieve up to 30% improvement when their relative installed PV capacity reaches 350%.

The net peak load reduction model does not provide any improvements to the electrical grid, since annual peaks in real electrical grids cannot be resolved via solar panel layout diversification due to the intermittent nature of solar electricity generation. Net load peaks that cannot be resolved include evening peaks, and peaks on cloudy days. While this result does not provide any obvious benefit for an electricity market operator, it contrasts with the findings previously discovered by other researchers, who claimed to achieve positive peak reduction results while studying solar panel orientation in individual residential properties [3]. Our grid-scale analysis provides a strong negative result in comparison.

The expenditure reduction model provides virtually no benefit in a realistic setting, and an improvement of 2–3.5% under unrealistic circumstances involving extreme levels of relative installed PV capacity. Thus, we assume the model is not practical, considering the adverse monetary effects of excessive solar power curtailment.

As global solar PV penetration increases steadily around the world and network operators and utilities face multiple problems associated with the changing profiles of their electrical grids, the results of our research, comprising a combination of positive and negative results, may be beneficial for future energy policy research and power generation capacity planning conducted by various public and private participants of the electric power market.

4.2 Discussion

Our research has a number of limitations that may be addressed in future work.

The number of panels mandated (Q), is the most important control knob we used in this project. This knob effectively regulates the aggregate installed capacity of solar panels and the subsequent relative installed PV capacity levels within the electrical grid. In some models, we considered levels of relative installed PV capacity that may appear to be unrealistic. Although the ramp reduction model operates well under reasonable levels of relative installed PV capacity, this is not the case for other models. The gap reduction model under the flexible orientation scenario only starts outperforming the base case scenario once the grid commits to moderate levels of curtailment. Otherwise, the flexible orientation scenario is no better than the status quo. For the expenditure reduction model, the performance improvement is negligible even when the relative installed PV capacity level is extreme. It is clear that relative installed PV capacity is a very important factor that must be taken into consideration when reviewing these results. Specifically, when PV penetration is not too high, then orientation is not a significant control mechanism, which is a strong negative result.

In this work we considered Ontario, British Columbia, and Texas. Even though these regions vary by climate and grid load profiles, they still share some characteristics (such as the optimal tilt angle being close to 30°). In future work it could be beneficial to consider other jurisdictions with electrical grid structures differing from the aforementioned regions (e.g. Germany). Different solar generation and power consumption profiles may or may not result in significant performance changes.

In the gap and expenditure reduction models, LCOE values are considered to approximate the relative trade-off factors. A more sophisticated methodology may be devised to improve the accuracy of the experiments.

In the expenditure reduction model, we applied a fairness constraint to ensure that all power producers are compensated equally. This requires operator decision making and oversight in two dimensions: orientation and pricing. Otherwise, the distribution of panel orientations will not be optimal. An alternative idea may be to incentivize panels facing a certain direction by the network operator choosing to provide a higher tariff for those who choose to orient panels at that angle. This idea depends on the market constantly growing, so that there is a possibility of incremental adjustments.

There is always a trade-off between benefits and problems associated with any decision made in the context of high solar penetration. We operated under the assumption that a single party is responsible for all the decision making in the system during the planning stage. As a result, in our research, some market players do not have a high degree of flexibility with regards to capacity planning. This is far from real-world electricity markets, in which various parties involved have conflicting objectives, but may work together to achieve a compromise. Relaxing the single decision maker constraint may be a potential direction for future work: it may prove beneficial to consider the electricity market as a multi-agent model instead of a single-agent model.

As energy storage becomes a more prominent part of electrical grids around the world, it may render the benefits of our models obsolete. Energy storage, however, has high capital costs associated with it. In contrast, our solution does not require additional large-scale investments, which is its main benefit.

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