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Rooftop PV Impacts on Fossil Fuel Electricity Generation and CO2 Emissions in the Pacific Northwest

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Rooftop PV Impacts on Fossil Fuel Electricity Generation and CO2 Emissions in the Pacific Northwest

by

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Abstract

This thesis estimates the impacts of rooftop photovoltaic (PV) capacity on electricity generation and CO2 emissions in America's Pacific Northwest. The region's demand for electricity is increasing at the same time that it is attempting to reduce its greenhouse gas emissions. The electricity generated by rooftop PV capacity is expected to displace electricity from fossil fueled electricity generators and reduce CO2 emissions, but when and how much? And how can this region maximize and focus the impacts of additional rooftop PV capacity on CO2 emissions? To answer these questions, an hourly urban rooftop PV generation profile for 2009 was created from estimates of regional rooftop PV capacity and solar resource data. That profile was compared with the region's hourly fossil fuel generation profile for 2009 to determine how much urban rooftop PV generation reduced annual fossil fuel electricity generation and CO2 emissions. Those reductions were then projected for a range of additional multiples of rooftop PV capacity. The conclusions indicate that additional rooftop PV capacity in the region primarily displaces electricity from natural gas generators, and shows that the timing of rooftop PV generation corresponds with the use of fossil fuel generators. Each additional Wp/ capita of rooftop PV capacity reduces CO2 emissions by 9,600 to 7,300 tons/ year. The final discussion proposes some methods to maximize and focus rooftop PV impacts on CO2 emissions, and also suggests some questions for further research.

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Glossary and Units

Ancillary Services: Activities that keep the grid balanced, reliable, and efficient

CC Generators (CC): Combined-cycle natural gas powered electricity generators

Coal Generators (Coal): Coal powered electricity generators

The Grid: The physical electricity system; the network of electricity generation, storage, transmission, and distribution

Fossil Fuel Generation: Electricity from coal and natural gas powered electricity generator; MWh

Peak-Watts: A measure of the quantity of PV capacity and the maximum expected power from PV capacity in full, clear sunlight; Wp

The Region: One hundred and twenty-nine counties in America's Pacific Northwest

Rooftop PV Capacity: Grid-connected photovoltaic electricity generators, located on residential, commercial and industrial rooftops; Wp

Rooftop PV Density: An area's rooftop PV capacity divided by its population; Wp/ capita

Rooftop PV Generation: Electricity output from rooftop PV capacity; MWh

Rooftop PV Impacts: Reduced demand for centralized electricity generation; MWh

SC Generators: Simple-cycle natural gas powered electricity generators

Transmission and Distribution Savings: Electricity conservation from rooftop PV generation; MWh

Watt-Hours: A measure of electricity; Wh

Section 1: Background

Chapters 1 – 3 review the electricity system in the Pacific Northwest and provide context for understanding the impacts of additional rooftop PV capacity. Beginning with a definition of the region, Chapter 1 reviews the growth and change of uses and sources of electricity and their CO2 emissions, and then describes the growth and distribution of regional rooftop PV capacity. Chapter 2 reviews the literature of studies on regional PV impacts, and Chapter 3 explains why rooftop PV capacity is most likely to displace fossil fuel generation. At the end, you understand the relationship between rooftop PV generation and fossil fuel generation.

Chapter 1. The Electricity Scenario in the Pacific Northwest

In the Pacific Northwest, rooftop PV capacity is a rapidly growing source of electricity. Rooftop PV capacity generates electricity from sunlight and reduces the demand for electricity from fossil fuel sources. Although each rooftop PV system is small relative to the electric gird, on a regional scale they are adding up to potentially substantial impacts on regional electricity generation and CO2 emissions, however, the prevalence, distribution, and impacts of rooftop PV capacity in the region are not well known.

Defining the Pacific Northwest Region

The region for this thesis is America's Pacific Northwest. The region includes 129 counties, including all counties in Washington, Oregon, and Idaho, and nine counties in western Montana (Fig.1.1).

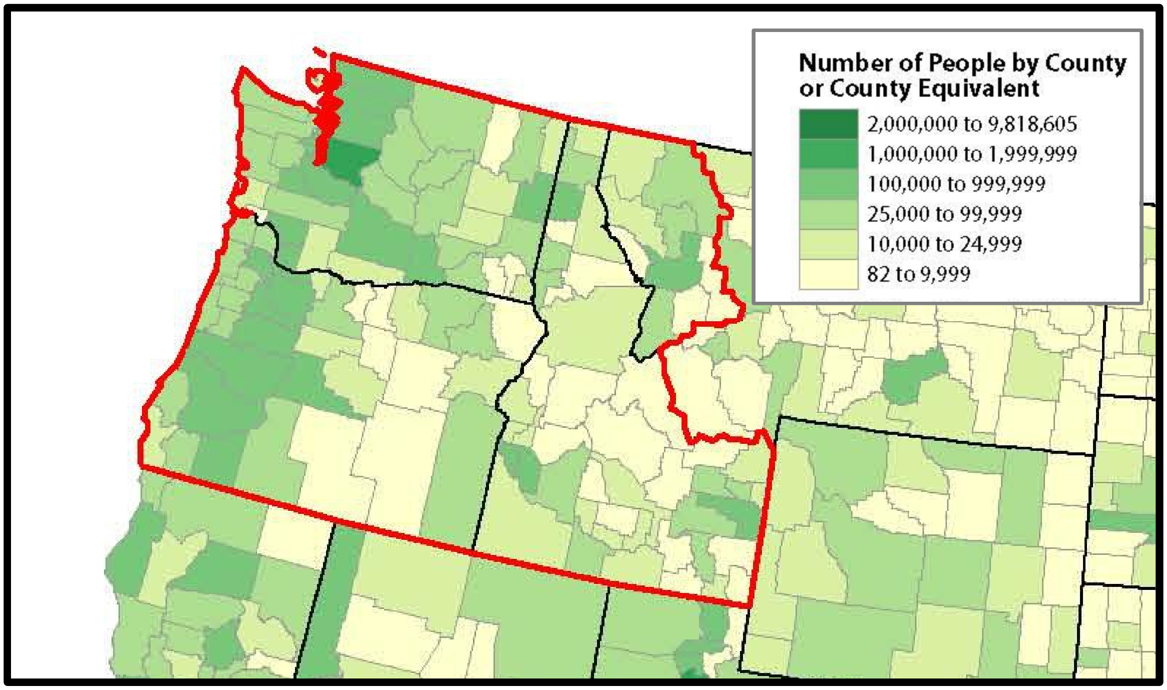
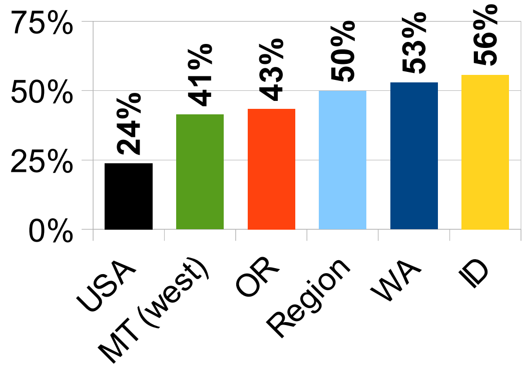


Fig. 1.1 – The Pacific Northwest Region (U.S. Census, 2010)

Growth and Change in the Pacific Northwest

The Pacific Northwest is a growing region of the United States (Fig. 1.2). Since 1900, the population of this region has increased from around 1.5 million residents in 1900, to over 12 million in 2010 (U.S. Census, 1996 & 2011). From 1990 to 2010, the region's population grew over twice as fast as the population of the USA.

Fig. 1.2 - Regional Rates of Growth (1990 -- 2010)



The Pacific Northwest in 2009

This thesis focuses on the year 2009. Table 1.1 shows that over 50% of the region's residents lived in Washington, and about 16% lived in Idaho and western Montana (US Census, 2009).

Table 1.1 - Pacific Northwest Population 2009

State	Population	% of Regional Population
Washington	6,664,195	54%
Oregon	3,825,657	31%
Idaho	1,545,801	13%
Montana (west)	310,897	3%
Regional Population	**12,346,550**	100%

Regional Electricity Systems

Generally, it is difficult to definitively measure regional energy relationships.[1] This region, however, is defined by a tightly inter-connected and somewhat insular electricity grid. It corresponds closely to the Bonneville

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[1] Alvarado & Griffin (2007) explain that, “tracking electricity generation from source to use is complicated by both actual market operations and data availability. While the system is dispatched on a least cost, transmission-constrained basis, buyers and sellers engage in multi-year, seasonal, daily and hourly sales and exchanges. Energy may be sold multiple times and may be a financial settlement rather than an actual dispatch. Tracking of generation currently doesn’t account well for gross exports across state lines or trading.” (p. 3)

Power Administration (BPA) transmission and balancing area (BPA, n.d.) and the planning area for the Northwest Power and Conservation Council (NPCC, 2013a). Montana's state-level energy data are not included in the region because most of Montana's energy resources are located in eastern Montana and transmitted eastward. However, the Colstrip coal power generator (PPL Montana, n.d.) is included in the region because it is mostly owned by utilities in the region and most of its electricity is transmitted directly into the region along the Montana Intertie. The Jim Bridger (WY) and North Valmy (NV) coal plants could be included for the same reasons, but for the purposes of this study Colstrip is sufficient as a representative "extra-regional" generator. Otherwise, except for some relatively small electricity exchanges with California and Canada, transmission constraints limit inter-regional exchanges of electricity and changes of electricity use within the region primarily affect the sources of electricity within the region.

Over the past century this region has repeatedly changed the ways that it generates and uses electricity. The patterns of electricity in 2009 are a mix of traditional and new uses.

Regional Electricity Consumption: Growth and Change

Traditional Uses of Electricity

Around 1900 electricity was new and uncommon. During the 20th century, however, the region experienced a dramatic shift towards it. Initially, electricity was almost exclusively used for lighting, but quite rapidly it became used for a wide variety of activities. Schafer (1918) describes how:

> the abundance of water powers in these states has also suggested a very general and widespread use of electric energy for the doing of all kinds of work... Beginnings have already been made toward equipping homes with electric heating appliances which can be done where power is cheap at rates which are economical as compared with heating by means of wood or coal. There are chimney-less farmhouses in certain sections, all cooking as well as heating being done with electricity. On some farms too electric power is employed to drive household and barn machinery to pump water etc. (p. 280)

Electric motors first supplemented, but then soon replaced the mechanical water-wheels of industry, and as electric lighting flickered into existence, the population became familiar with the benefits of electric utility services. Residents have become increasingly familiar with electricity and over the past century it has become an integral part of their civilization.

New Uses of Electricity

Because of the growing population and its new uses for electricity, the region's total use of electricity is expected to continue to grow (NPCC, 2012b; Pacific Northwest Utilities Conference Committee, 2013). NPCC (2010a) identifies the growth of home electronics, elder-care facilities, commercial data centers, and air conditioning as the most significant new uses of electricity. In addition to increasing the total annual demand for electricity, changes of activity patterns are changing the timing of electricity use in the region. For example, NPCC (2010a) explains:

> residential air conditioning has grown rapidly in the region. The market penetration of air conditioning by Northwest homeowners was relatively low, about 10-20 percent, during the 1980s and 1990s. Air conditioning use has been increasing significantly in recent years. This shift in demand can be attributed to warmer summer temperatures, reduced prices of air conditioning units, and the number of new people moving into the region who are accustomed to using air-conditioning in their previous homes. (B-15)

This rapid growth of air conditioning in the Pacific Northwest has serious implications for the power system. NPCC (2010a) explains that, “the Northwest has always been a winter-peaking power system. However, due to growing summer load, mostly because of the increased use of air conditioning, the difference between winter- and summer-peak load is expected to shrink over time” (p. 3-1). Along with a general increase of use of electricity, the growth of air conditioning requires special consideration because it coincides with the season when the region's hydro-power resources are low.

Regional Electricity Generation: Growth & Change

Traditional Sources of Electricity

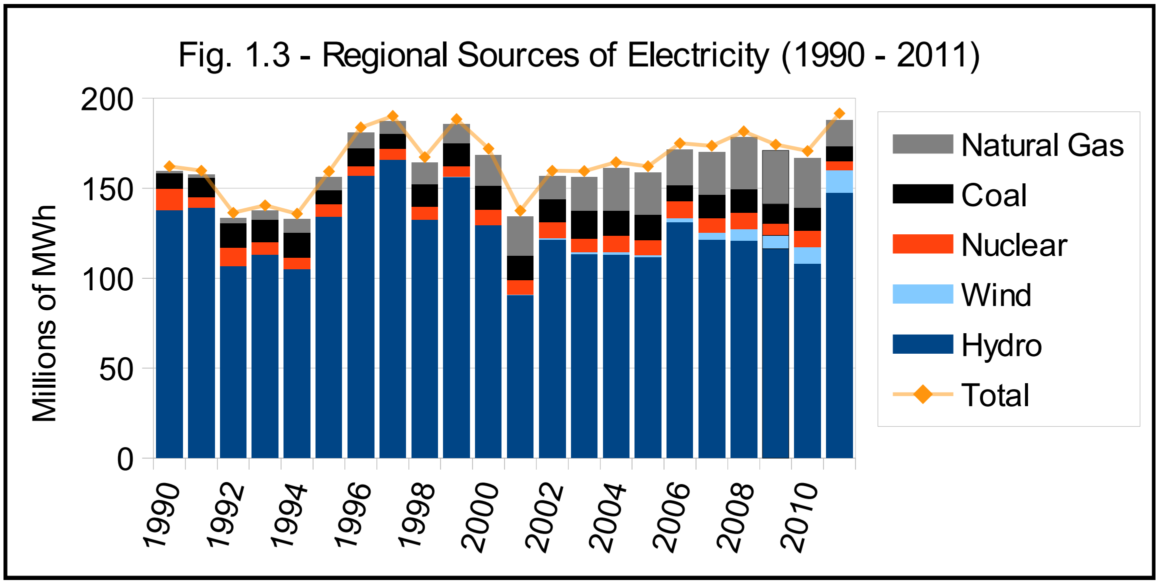
Growth and change of electricity usage has been accompanied by the growth and change of electricity generation. During the early 20th century, electricity generation was located in urban areas close to locations of use. As the residents of the Pacific Northwest realized the usefulness of electricity, they began building massive dams and long transmission lines to transform their steep terrain and powerful rivers into reservoirs of electric power (Hammarlund, 2002). Over the past fifty years, their local networks of energy transmission and distribution have interconnected with global networks of fossil fuels and the region has shifted away from clean and local sources of electricity and towards fossil fuel sources (State of Washington, 2004).

New Sources of Electricity

Prior to the 1960's, almost all of the electricity generated in the region was generated by local hydro-power. Since then, very little hydro-power has been developed, and although hydro-electric dams are still the region's primary source of electricity, the last stages of major dam construction during the 1960's exhausted most of the region's economically viable opportunities for more (NPCC, 2010a, p. 6-19).

Shifts towards Thermal Electricity Generation

The five sources shown in Fig. 1.3 generated about 98% of the electricity generated in the region since 1990 (EIA, 2012)[1].



Through the 1960's and 1970's the demand for electricity appeared to be rising continuously and regional energy planners such as the BPA and public and private utility companies anticipated that demand for electricity would continue rising into the future (Blumm, 1983). Planners, power companies, and politicians recommended and invested public and private resources into a new phase of electricity generation that is often called the 'hydro-thermal phase' whereby rising electricity loads were met by generation from several large nuclear and coal powered generators. Although these new sources improved the electricity system's reliability, financial problems raised prices and their waste products have degraded the environment. The coal generators developed at that time

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[1] State level data for Montana are not included because most of Montana's energy resources are located in eastern Montana and transported and transmitted to Midwestern states to the east. Adding Colstrip data to Fig. 1.5 would approximately double the share of coal generation.

were the beginning of major regional fossil fuel generation and rising CO2 emissions.

The Growth of Natural Gas Generation

In the late 1980's rising populations and new uses for electricity increased the demand for electricity generation at the same time that new legislation opened new markets for non-utility independent power producers. The technology of stationary natural gas fired electricity generators had recently become practical and economical (Environmental Protection Agency [EPA], 2008), and although the Pacific Northwest was among the last regions of America to utilize natural gas (Washington State, 2001 & 2004), by 2009 natural gas was the region's second largest source of electricity (Fig. 1.3). NPCC (2010a) explains that:

> in the Northwest, gas-fired capacity increased from 1,550 megawatts, representing about 3 percent of regional capacity, to over 9,000 megawatts in 2009, representing 16 percent of regional capacity. This development has been motivated by the introduction of reliable, low emission, high efficiency combined-cycle gas turbine power plants, and generally attractive natural gas prices (despite several relatively short term peaks). (p. D-23)

Natural gas generation has become a very important part of the regional power system, and it is expected to be the majority of new electricity generation sources in the region (NPCC, 2010a, pp. 6-31 – 6-36, & Chapter 10).

Regional Fossil Fuel Generation

Fig 1.4 shows five years of monthly regional fossil fuel generation (EIA, 2013). These five years around 2009 show a clear seasonal pattern of less fossil fuel generation around springtime, and more fossil fuel generation from mid-summer into late-winter months.

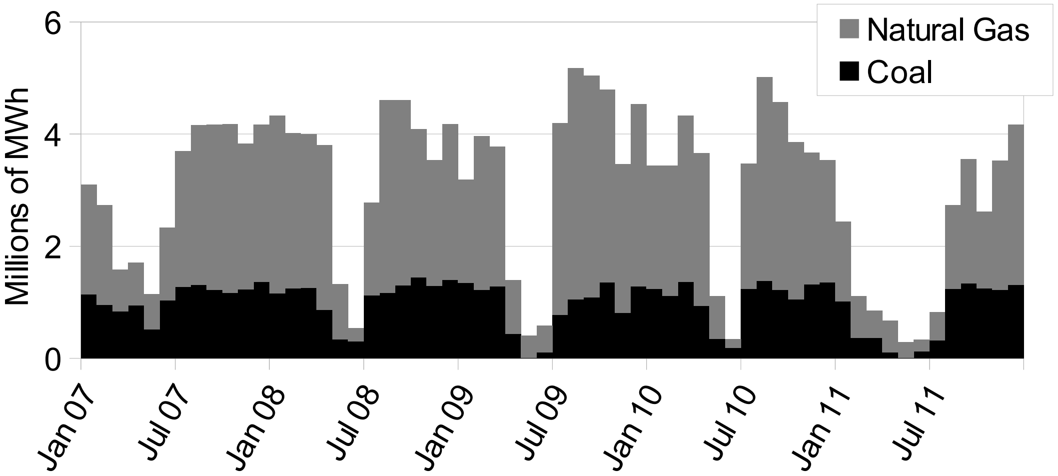


Fig. 1.4 - Fossil Fuel Generation Monthly (2007 - 2011)

Although the annual *electricity* demand peaks occur during winter months, because those electricity demand peaks coincide with heavy rainfall and snow melt, much of that annual peak demand for electricity is met by hydro-power. As summer progresses, however, hydro-power declines and more fossil fuel resources are used to meet demand. Fig 1.5 shows the average monthly fossil fuel generation for those five years (ibid.), and shows that August and September have been the peak-season for fossil fuel generation.

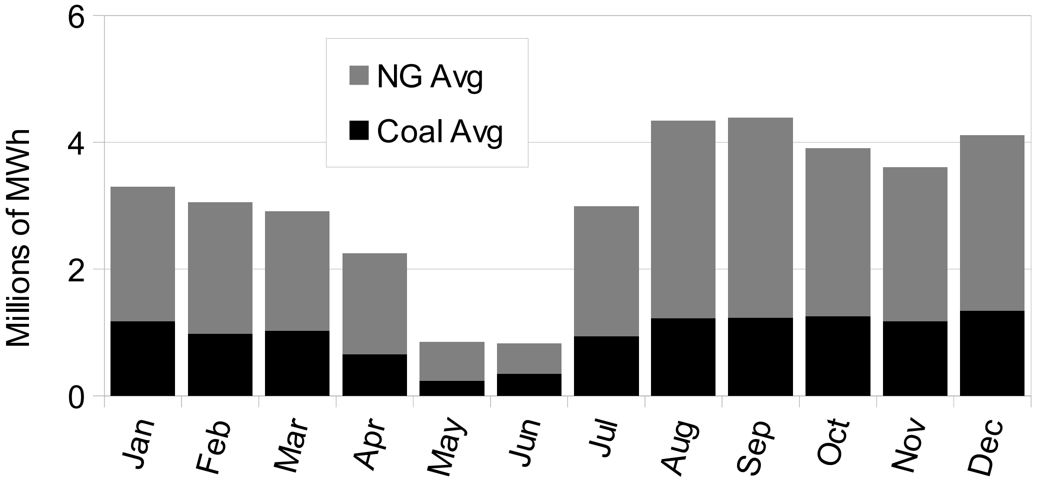
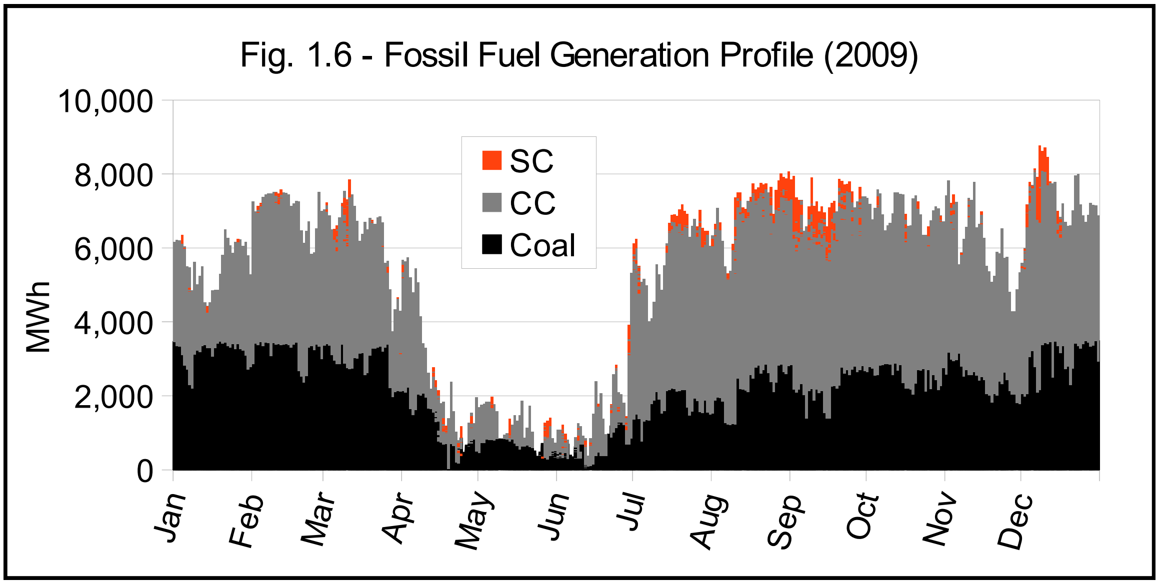


Fig. 1.5 - Average Fossil Fuel Generation Monthly (2007 - 2011)

Fossil Fuel Generation 2009

To analyze the details of regional fossil fuel generation an hourly fossil fuel generation profile for 2009 was created with data from the Environmental Protection Agency's Continuous Emissions Monitoring System (EPA, 2009 – 2010).



This data for the region includes 37 fossil fuel turbines located at 20 facilities (Appendix A), listed as three types of fossil fuel generation: coal steam turbines (ST), natural gas combined-cycle turbines (CC), and natural gas simple-cycle turbines (SC). Fig. 1.7 shows this fossil fuel generation data by month (cf. Fig.1.5).[1] SC generation relatively small and invisible.

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[1] These totals are slightly different from EIA (2013), because the EIA data include numerous smaller generators that are not included in CEMS, and because the Colstrip data raises the CEMS coal generation by about 50% above EIA estimates for OR, WA, & ID. Both data sets show the same pattern of peak fossil fuel season from August – December, and seasonal lows from April – June.

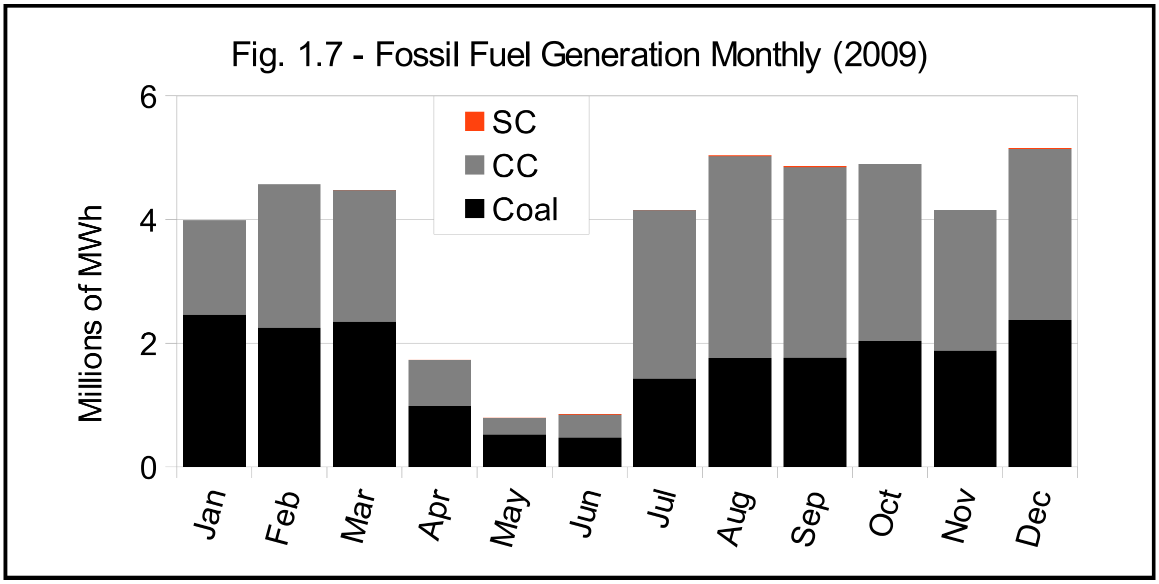


Table 1.2 and Fig. 1.8 show the EPA (2009—2010) totals by state by type.

Table 1.2 – EPA CEMS: Fossil Fuel Generation (2009) MWh

State/Type	SC	CC	Coal	Total
WA	89,501	9,204,926	7,886,785	17,181,212
OR	45,665	13,917,761	3,365,683	17,329,109
ID	46,039	1,210,441	0	1,256,480
MT*	0	0	9,012,377	9,012,377
Total by Type	**181,205**	**24,333,128**	**20,264,845**	**44,779,178**
Share of Total	0.40%	54.34%	45.26%	100%
Hours/ Year	17.04%	94.93%	99.99%	99.99%

Coal operated all but one hour in 2009. Some CC generators ran for most of the year, and others operated intermittently. SC generators operated the least, and although they generated only about 0.4% of the region's fossil fuel electricity, they provide unique and valuable contributions to the grid. SC generators are the most flexible generators and they are used to balance short-term, hourly variations within the region's electricity grid. Therefore, SC generation indicates hours with rapidly changing demand (load following),

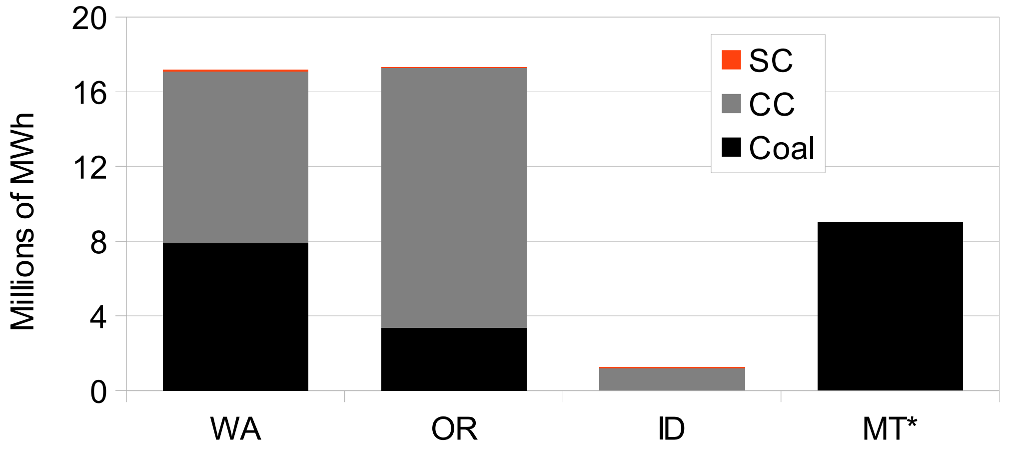
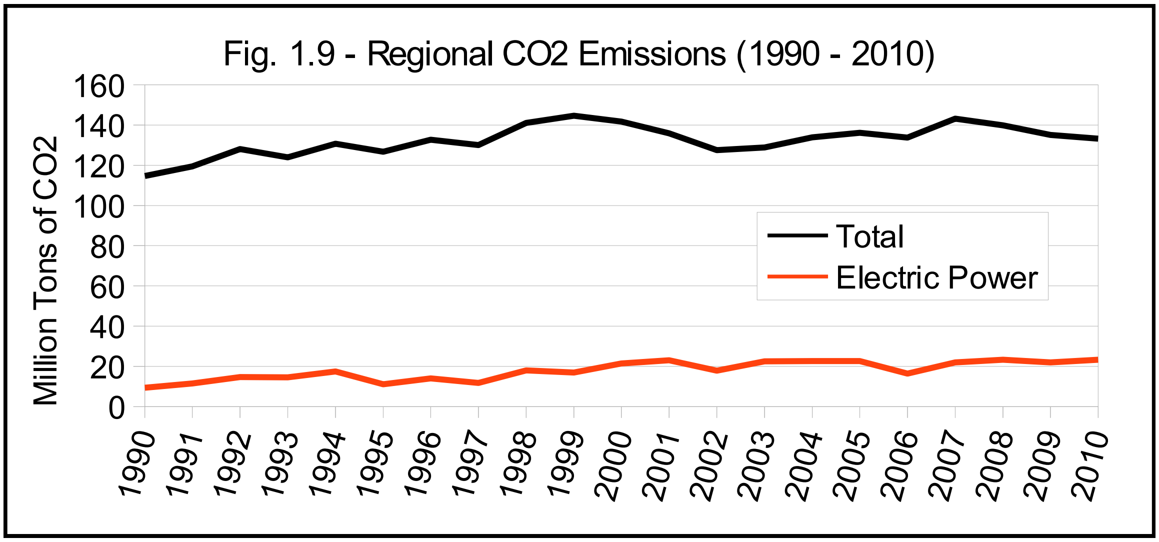


Fig. 1.8 - Fossil Fuel Generation by State byType (2009)

or hours with high-demand for reactive power (voltage regulation). SC generators also provide electricity for peak demand hours, when electricity is needed most. Most SC generation occurred during summertime, and most SC generation was during hours when both coal and combined-cycle generation were operating at high levels. Because SC generation is the most expensive source of electricity, it also indicates when electricity is most valuable. Overall, because the demand for SC generation often indicates when other resources are insufficient (see Section 3 below), the hours with SC generation are generally indicative of high prices and high stress on the grid.

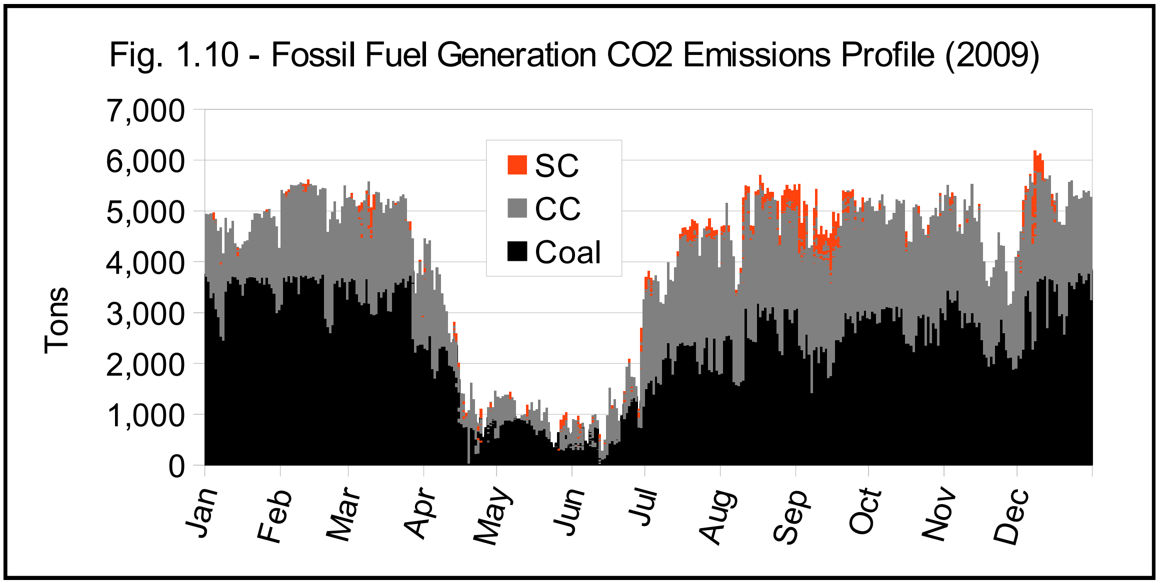
Regional CO2 Emissions

These fossil fuel generators are a large and growing source of regional CO2 emissions. Fig. 1.9 (EPA, 2013) shows that over the past 15 years the region (excluding Colstrip) has produced about 135 million tons of CO2 per year. In 1990 regional fossil fuel electricity generators released about 9 million tons of CO2, and since 2000 their emissions have risen to around 22 million tons per year[1]. Since 1990 the share of CO2 emissions from fossil fuel generators has risen from 8% to 17% of total CO2 emissions.



Fossil Fuel Generation CO2 Emissions Profile 2009

Fig. 1.10 focuses on the hourly CO2 emissions for 2009 (EPA, 2009 – 2010) for the generators listed in Appendix A (including Colstrip).



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[1] Annual data for Colstrip is not readily available. Including Colstrip would add between 7 – 11 million tons of CO2 per year to the total CO2 emissions and the CO2 emissions from electric power.

As expected, the seasonal pattern of CO2 emissions follows fossil fuel generation (cf. Fig. 1.6), except that coal generation produces noticeably more CO2 emissions than natural gas generation (more CO2/ MWh). Table 1.3 shows the 2009 annual totals of these CO2 emissions by state and by type. The in 2009 these regional fossil fuel generators released approximately 33.4 million tons of CO2.[1]

Table 1.3 – EPA CEMS:
Fossil Fuel Generation CO2 Emissions (2009) Tons

State/Type	SC	CC	Coal	Total
WA	56,533	3,925,568	9,377,767	**13,359,867**
OR	25,104	6,449,891	3,304,645	**9,779,640**
ID	27,739	496,079	0	**523,818**
MT*	0	0	9,716,992	**9,716,992**
Total by Type	**109,376**	**10,871,538**	**22,399,403**	**33,380,317**
Avg. CO2 Rate (tons/ MWh)	0.67	0.48	1.11	
Share of Total	0.33%	32.57%	67.10%	**100%**
Hours/ Year	17.07%	95.10%	100%	**100%**

The average CO2 emission rate for coal is highest, and the CO2 emission rate for CC generation is the lowest.

Looking Ahead

Electricity Options for the Future

The Oregon Department of Energy (2011, p. 7) predicts that, "growing demand [for energy] will increase in the role of energy conservation and efficiency and require the

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[1] Additional greenhouse gasses come from the extraction and transportation of natural gas. For example, although natural gas combustion releases less smokestack CO2 emissions than coal generation, the extraction and transportation of natural gas releases fugitive methane emissions (EPA, 2013). Methane is a more potent greenhouse gas than CO2. Modern fracking methods for extracting natural gas may release greater methane than traditional extraction methods (Howarth, Santoro, & Ingraffea, 2011). Consequently, the CO2 emissions calculated below are conservative of total GHG emissions from natural gas use.

siting of new energy resources." While efficiency and conservation are the preferred and lowest cost options for meeting the growth of electricity demand, they will probably not meet forecast load growth (NPCC, 2013b). New electricity sources will be developed, and the majority of new electricity generators are tending towards wind power and natural gas generators. Wind is a clean source of power, but it requires large transmission connections to remote areas, which are costly and usually contentious. Furthermore, wind power impacts on birds (Cappiello, 2013) and impacts on scenery are a persistent argument against additional wind power capacity. And although natural gas generation produces fewer emissions than coal generation, it is not benign, and it exposes the region to supply disruptions and price-spikes. Additional natural gas generation will also require extended and expanded transmission capacity. In light of those issues, rooftop PV capacity is gaining credibility as a clean, renewable alternative.

Regional Rooftop PV Capacity

Two useful measures of PV capacity are the capacity per capita (Wp/ capita) and the total capacity (kWp). Capacity per capita is useful for comparing different areas and regions, and total capacity is useful for estimating overall impacts.

The Growth of Rooftop PV Capacity

From the 1960's until around 2005, rooftop PV capacity generated only a very small part of the electricity in the region.[1] Yet as shown in Fig. 1.11, rooftop PV capacity is a growing source of electricity in the region (Sherwood, 2009; Sherwood, 2010; Sherwood, 2011; Sherwood, 2012).

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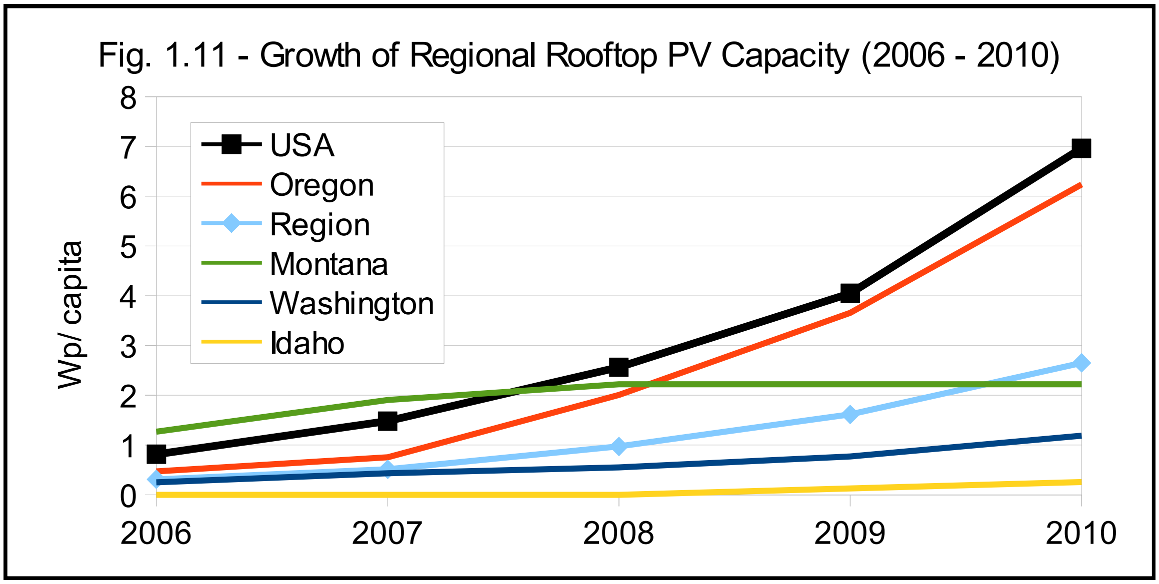
[1] For example, the Energy Trust of Oregon (2003) estimated that in 2002 Oregon had about 107 kWp of rooftop PV capacity. Yet, as shown in Fig. 1.10, by 2006 Oregon had around 1,800 kWp of rooftop PV capacity.



Although rooftop PV generation remains much less than any of the five major sources, regional energy planners are beginning to notice its growth and to consider its impacts on other sources of electricity (NPCC, 2013).

Rooftop PV Capacity in the Pacific Northwest 2009

In the Pacific Northwest, most of the grid-connected PV capacity is rooftop PV capacity.[1] In 2009 the region had about 1.62 Wp/ capita (Table 1.4). Figures 1.12 & 1.13 show the regional distribution of grid-connected rooftop PV capacity for 2009 (Sherwood, 2010). Oregon has over two-thirds of the regions total capacity, probably mostly because it has the largest financial incentives for commercial and residential installations[2]. Washington has some substantial incentive, but Idaho and Montana provide smaller financial incentives, and they have the least capacity,.

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[1] The one major exception for 2009 is the Wild Horse Wind and Solar Facility, with 500 kWp of PV capacity (Puget Sound Energy, 2013).

[2] Residents of the United States are eligible to receive federal rooftop PV tax credits. The state of Oregon provides additional tax credits to qualified Oregon residents, and within Oregon, customer's of PGE, Pacific Power, and Idaho Power are eligible for additional rebates.

**Table 1.4 -
Rooftop PV Capacity (2009)**

Area	MWp	Wp/ capita	%
Washington	5.2	0.78	26%
Oregon	14.0	3.66	70%
Idaho	0.2	0.13	1%
Montana	0.7	2.25	3%
Region	**20.1**	**1.62**	**100%**
USA	1,250	4.07	

Fig. 1.12 -
Rooftop PV Capacity MWp (2009)

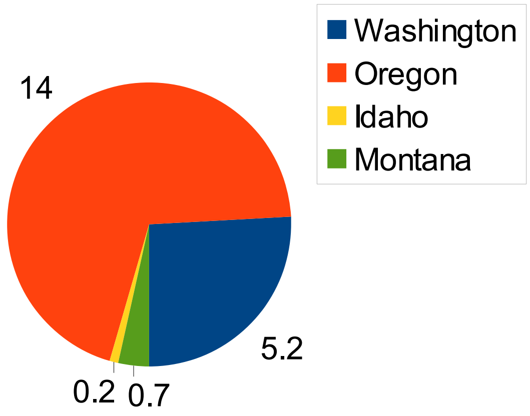
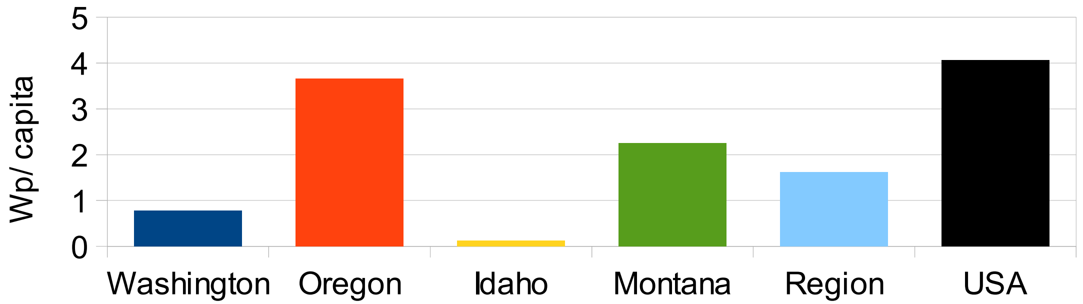


Fig. 1.13 - Rooftop PV Capacity Density (2009)



Rooftop PV Capacity Impacts on CO2 Emissions

Rooftop PV capacity reduces the quantity of electricity demanded from other sources of electricity, and most people who support rooftop PV capacity rightly believe that it displaces fossil fuel generation and CO2 emissions, however, the details of its regional impacts are not clearly known. This thesis provides some answers.

Chapter 2. Literature Review

Research into the regional impacts of rooftop PV capacity has grown over the past fifty years, and it has been consistently motivated by the connection between fossil fuel electricity generation, pollutant emissions, and global climate change. While people have always understood that rooftop PV capacity generates clean electricity, high prices have limited its development and until recently it remained an expensive, eccentric, and regionally insignificant source of electricity. Because of the relatively high cost of electricity from rooftop PV capacity, some early research sought to measure other benefits as justification for subsidies (Bezdek & Kannan, 1982). For example, rooftop PV capacity might mitigate energy supply disruptions (Brady, 1984), and it has the potential to produce peak-demand reductions for utilities (Hass, 1994; Leng & Martin, 1994). Early studies often compared the output from a single rooftop PV system with a utility's electric loads and estimated the benefits of rooftop PV as a marginal, intermittent, and distributed must-take generator.

During the 1990's the prices for rooftop PV capacity began to decline at the same time that individuals and governments began to take more responsibility for reducing their contributions to CO2 emissions (Flavin & Lennsen, 1992). Although prices were still a barrier to the widespread use of rooftop PV capacity, the idea of regional impacts became more realistic. A number of studies were developed to identify and measure the large-scale pollution mitigation benefits of rooftop PV capacity. For example in 1992 the EPA began a nationwide study of the potential for PV systems to displace fossil fuel generation (Spiegel, Kern, & Greenberg, 1998; Spiegel, Greenberg, Kern, & House, 2000). Because many of these systems were the first rooftop PV systems located in their respective utility territories, this research identified several barriers to additional rooftop PV capacity and set precedents for future research. They assume that because rooftop PV is a demand-side generator, it does not affect the dispatch order of other generators, and assume that rooftop PV generation usually displaces load-following, marginal generators. Inverter failure was identified as one of the major obstacles to the effectiveness of rooftop PV capacity. Their research, like much that followed, concluded that each region's marginal sources of electricity are the most significant determinant of rooftop PV impacts (more significant than the region's solar resource). As satellite imaging improved, studies of solar resources shifted from using measured data to using modeled data (Spiegel, Leadbetter, & Chamu, 2005). Although modeled data misses some important factors of rooftop PV performance (e.g. technical failures, snow cover, and dust), it enables a broad geographic scope and eliminates the problem of measurement failures that plagued early research.

Since the turn of the century, the development of PV capacity has been accelerating (Tyagi, Rahim, Rahim, & Selvaraj, 2013), and research into regional impacts rooftop PV has expanded along with it. This has compelled even more complex and thoughtful research into the impacts of large quantities of additional rooftop PV capacity.

Since 2005, substantial research has been directed towards understanding and improving large quantities of additional PV capacity. Connors, Martin, Adams, Kern, & Asiamah-Adjei (2005) conducted a detailed study of the impacts of rooftop PV capacity across the U.S. Another benchmark series of studies of additional rooftop PV capacity was conducted by Denholm & Margolis (2007a & 2007b) to evaluate the potentials and limitations of additional PV capacity in Texas' power grid. They predictably find that during summertime, rooftop PV generation corresponds well with the generation from established fossil fuel sources, and they also find that during springtime, especially on weekends, high-levels of PV generation may have negative impacts on baseload coal generators. They conclude that regions with more flexible resources (hydropower and natural gas generators) are more capable of utilizing PV generation. In a similar studies, Myers, Klein, Reindl (2010) make an assessment of Wisconsin's potential for additional PV capacity, and Jo, Loomis, & Aldeman (2013) evaluate the optimal level of utility-scale PV capacity for Illinois, with regard to achieving its RPS goals and its solar carveout.

Planners and policy makers concerned with climate change must continue to identify local issues and establish policies that maximize and focus rooftop PV impacts on CO2 emissions. Although several national studies have included the Pacific Northwest in their analysis, there have not been many detailed studies of this region in particular (Dragoon & Schumaker, 2010). Although several utilities in the region have estimated the cost-effectiveness of adding PV capacity into their generation profile, they haven't analyzed the regional impacts.

Because the Pacific Northwest has such cloudy winters, and because of the large share of generation from hydro-power, people sometimes assume that rooftop PV is not worthwhile. However, neither of these are strong reasons against additional rooftop PV capacity. Research about rooftop PV impacts on emissions usually find that a region's annual solar radiation is less important for determining rooftop PV impacts on emissions than a region's marginal sources of electricity. Consequently, the Pacific Northwest is similar to other region's with marginal natural gas generation. Furthermore, the region's flexible hydro-power generation increases its ability to integrate additional PV capacity without disrupting other baseload generators.

Chapter 3. Primary and Marginal Electricity Generation

This section explains why rooftop PV capacity mostly impacts fossil fuel electricity generation, especially natural gas generation. Although it is impossible to precisely and definitively model and predict how new sources impact existing sources, and although some research finds counter-intuitive results[1], by observing historical patterns of primary and marginal generation, it is possible to develop some general conclusions about the impacts of additional rooftop PV capacity on the grid.

The Supply Curve: Primary and Marginal Sources of Electricity

Fig 3.1 shows five years of monthly generation data for the region (EIA, 2013). These major sources of electricity are organized into a supply-curve of 'primary' and 'marginal' sources, according to their variable costs and flexibility.

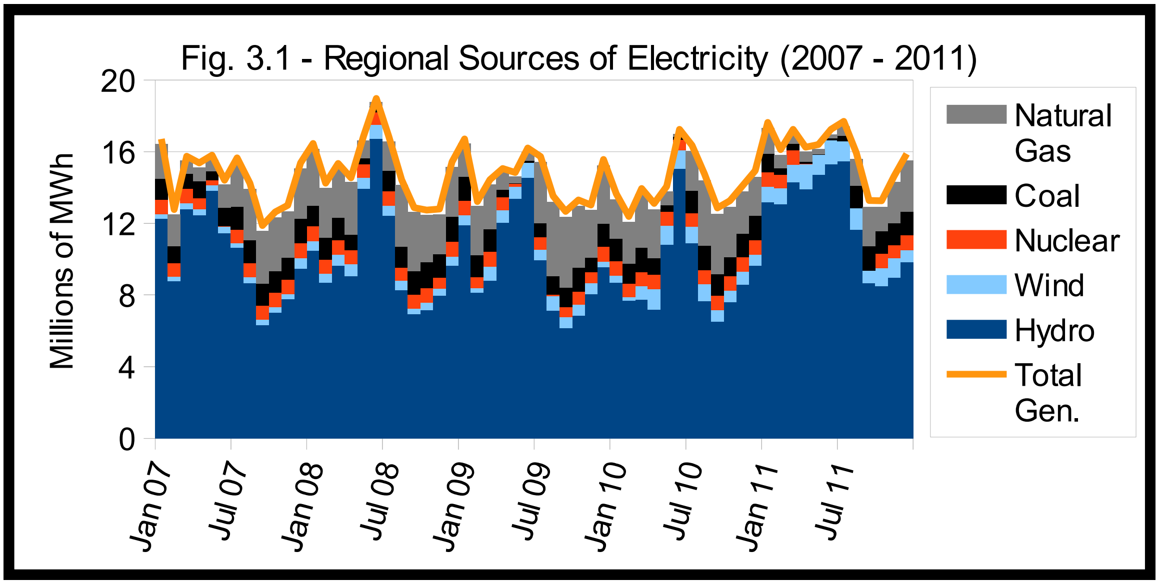


Fig. 3.1 - Regional Sources of Electricity (2007 - 2011)

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[1] For example, a model developed by Blumsack & Xu (2011) found that interactions between transmission congestion and large-scale wind power development in the Pacific Northwest would actually increase coal powered generation. They (ibid.) also concluded that small-scale and widely distributed PV capacity produces outcomes that are very similar to the outcomes from general reductions of the use of electricity.

NPCC (2008) explains that:

> generating resources are typically brought online in the order of their operating costs. In other words, resources with low operating costs are used before resources with higher costs. In general, hydroelectric, nuclear and wind generating units will be brought on-line before coal-fired or natural gas-fired generating units. (p. 3)

Primary sources have lower variable costs, and when they are available, they are usually used instead of marginal sources. When primary sources are insufficient, then marginal sources generate electricity to meet demand.

Determining the marginal sources of electricity is essential for predicting the impacts of additional rooftop PV capacity. PV impacts on emissions are mostly determined by each regions mix of marginal generation sources (Connors et al., 2005). They (ibid., p. 8-1) explain, “broadly speaking, the units that are affected by PV generation are those units that are following short-term variations in regional electricity demand.” Throughout the western US and the Pacific Northwest, those units are usually hydropower and natural gas generators (Mills & Wiser, 2012).

Primary Sources of Electricity

Although regional sources of electricity have become much more diverse, hydropower is still the region's largest source of electricity (average of 66% of total generation for 2007 – 2010). Hydropower has low variable costs, but it is limited by a seasonal cycle of abundance and scarcity. Except for maintenance and environmental considerations it is used whenever it is available, and within reservoir and spill limits, it is a flexible source that can be quickly adjusted to meet short-term variations of load. Hydropower's flexibility means that rooftop PV generation could displace it, however, if hydropower is well managed, then any displacement will eventually displace higher-cost resources at later times (Connors et al., 2005, p. 3-9).

Wind power is also classified as a primary source because of its low variable costs. Like hydropower, wind power is almost always used whenever it is available. Unlike hydropower, however, wind power does not have any capacity to 'reserve' power for later times and so its electricity must be used as it is generated. Consequently, wind power relies on the flexibility of hydropower for load-balancing, and they cooperate to generate clean, local power. Yet, because a large fraction of hydropower reservoirs are used to balance wind power, there is less flexibility remaining to balance other daily and hourly variations of electricity on the grid. Unfortunately, however, wind power has an inverse relationship with extreme temperatures, so it is less reliable when demand is high (NPCC, 2010a, p. 12-3). Occasionally, abundant hydropower and wind power coincide with low demand and create oversupply conditions that force the grid operators to curtail wind power (EIA, 2011; BPA, 2011).

Nuclear-power is another primary source of electricity. Because of its thermal inertia nuclear-power operates most efficiently when operating continuously. And although nuclear is less flexible than hydropower, it is available at almost anytime. The region's only nuclear reactor. It rarely adjusts output to meet hourly variations of load. When this plant does reduce output, it usually completely stops producing electricity for days, weeks, or months. Nuclear power is rarely impacted by variations of demand (Baek & Hadley, 2011), and in this thesis it is classified as a primary source and assumed to be unaffected by variations of demand caused by rooftop PV generation (cf. Connors et al., 2005, p. 3-11).

Over the five years from 2007 – 2011, these three primary sources generated 77% of the electricity generated in the region (EIA, 2013).

Marginal Sources of Electricity

When primary resources are insufficient to meet the region's demand for electricity, marginal sources of electricity are used. In the Pacific Northwest, these marginal sources are usually fossil fuel electricity generators. Between 2007 – 2011 coal and natural gas generated about 21% of the electricity generated in the region (EIA, 2013). Most of this electricity is generated by the coal and natural gas generators listed in Appendix A.

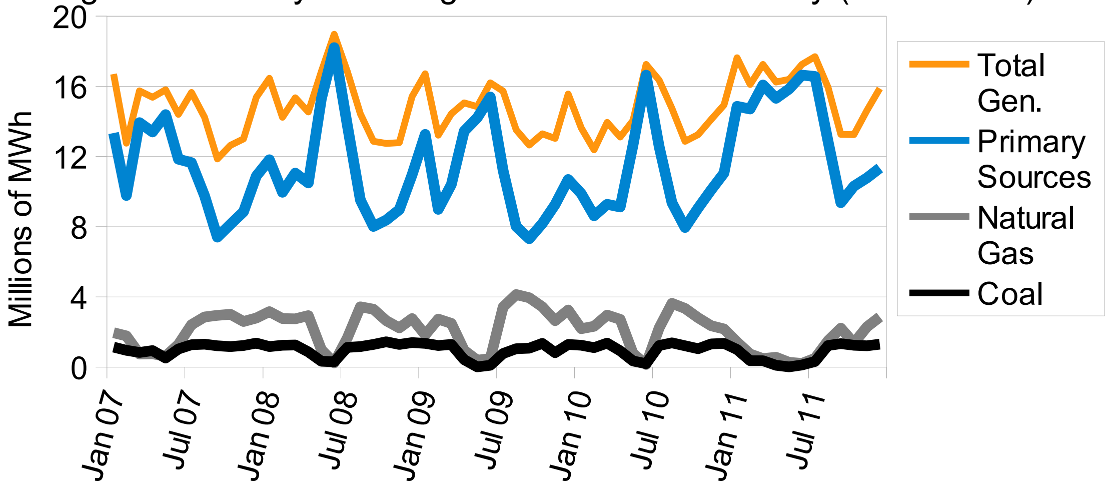
Coal power is somewhat like a primary resource because it runs fairly continuously throughout the year (Table 1.2). Long runs of steady output are most efficient and produce less emissions per kWh of output (Eyer & Corey, 2010). However, coal generation also declines when primary sources are sufficient, and during those conditions coal could be impacted by rooftop PV generation.

Natural gas turbines are another a marginal source of electricity. Natural gas turbines are distributed throughout the region and operate throughout the year. Although they are often the most costly to operate, they are also especially valuable because they have low thermal inertia and so their output may be adjusted relatively easily to meet changes of demand for electricity. Natural gas generation can adjust according to daily and hourly variations of load (IEA, 2010a). Because of their higher variable-costs and high flexibility, natural gas turbines are almost always the marginal generators of electricity (EIA, 2011; NPCC, 2010a, p. D-2).

The Gap

The region's pattern of generation[1] can be understood by observing “The Gap” between primary sources of electricity and total generation.[2] Fig 3.2 shows that when The Gap between primary sources and total generation is small, then there is less fossil fuel generation (EIA, 2013).

Fig. 3.2 - Primary and Marginal Sources of Electricity (2007 - 2011)



For example, BPA (2010, p. 1) says, “in early June [2006], Snake River streamflows nearly tripled and Columbia River streamflows nearly doubled... during this time, most Northwest thermal generation shut down or reduced to minimum operating levels.” The Gap is calculated by subtracting the primary resources (hydro-, wind-, and nuclear-power) from total generation. The Gap between primary sources and total demand is filled by fossil fuel generation sources, therefore, either reductions of load or increases of primary generation reduce The Gap and thereby reduce fossil fuel

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[1] This could be called the regional electricity generation supply curve.

[2] Total generation is approximately equal to the total demand for electricity.

generation. This relationship between The Gap and fossil fuel generation can be analyzed further by a scatter-plot of monthly generation.

Fig. 3.3 shows that when The Gap is smaller, fossil fuel generation also smaller (EIA, 2013).

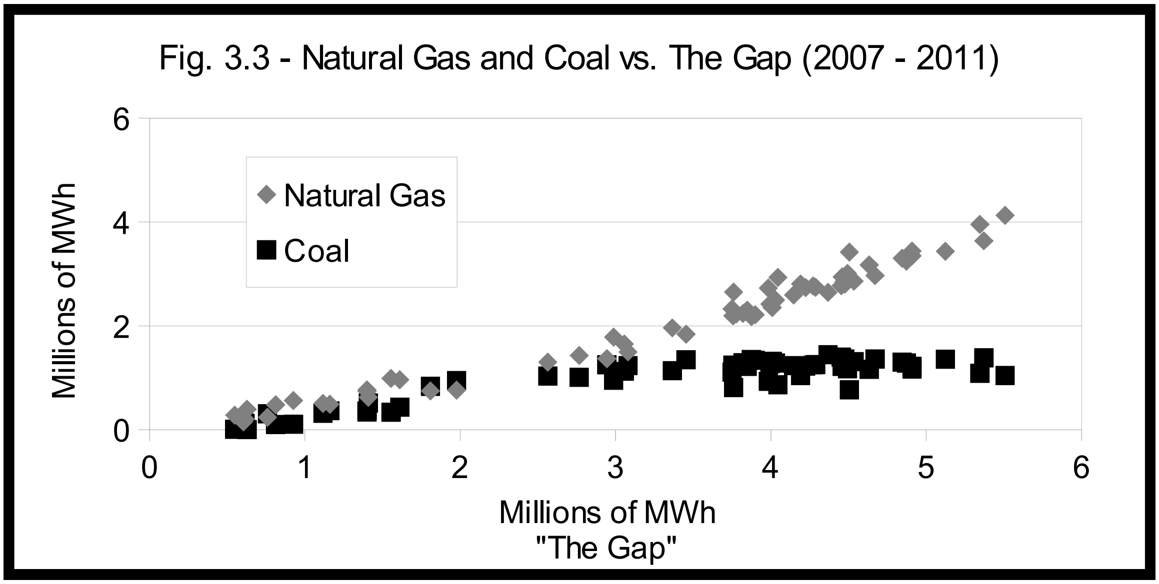


Fig. 3.3 - Natural Gas and Coal vs. The Gap (2007 - 2011)

Conversely, when The Gap is larger, fossil fuel generation is also larger. When the Gap exceeds 3,000,000 MWh, coal generation is near its maximum output and natural gas generation is used for additional generation. This indicates that reducing The Gap reduces fossil fuel generation.

Rooftop PV Capacity Impacts on Existing Sources of Electricity

Rooftop PV capacity works like both generation and conservation. On the one hand, rooftop PV capacity is like a primary generation source because it adds low variable cost electricity to the electricity system. On the other hand, rooftop PV capacity works like demand reductions because it is located close to final demand and because system operators cannot adjust rooftop PV generation. As Denholm & Margolis (2006, p.

1) explain, “deploying solar PV effectively reduces the amount of “conventional” generation required from traditional generation plants.” And Connors et al. (2005, p. 8-1) explain how, “the use of PV systems lowers the electricity demand seen by a regional grid.” From either perspective, rooftop PV generation reduces The Gap and therefore it usually reduces marginal fossil fuel generation. Furthermore, because of the higher costs and greater flexibility of SC natural gas generators, they are more likely to be affected by the hourly variations caused by rooftop PV capacity.

When regional natural gas generation is low, rooftop PV capacity also reduces coal-powered generation. However, if the region continues to add natural gas generators to meet additional demands for generating capacity, it becomes even more true that rooftop PV capacity will usually impact natural gas generation and reduce emissions from natural gas generators.

Section 2: Rooftop PV Profiles

Chapters 4 – 7 develops the hourly rooftop PV impacts profile.

Chapter 4 develops the rooftop PV capacity profile, which estimates the distribution of rooftop PV around the region. It concludes that most of the rooftop PV capacity is located around Portland and Seattle.

Chapter 5 develops an hourly regional rooftop PV generation profile by applying each urban area's solar resource to its rooftop PV capacity profile. The rooftop PV generation profile is an hourly estimate of electricity generated by the region's rooftop PV capacity in 2009.

Chapter 6 add transmission and distribution savings to the rooftop PV generation, to create the rooftop PV impacts profile, which shows when and how much rooftop PV capacity impacts marginal generators of electricity.

Chapter 7 reviews the quantities of solar panels in other regions and suggests a reasonable range of additional rooftop capacity for the region.

Chapter 4. Rooftop PV Capacity Profile

Urban areas include the majority of the region's population, and they use the majority of the region's electricity. Areas with larger populations and more buildings also have a greater potential for additional rooftop PV capacity. The regional rooftop PV capacity profile is created by multiplying each county's population by each state's rooftop PV density (Table 1.4). Table 4.1 shows the populations of the 25 most populous counties in the region (U.S. Census, 2009). Together, these urban counties have a total population of 9,348,051 which is 75.7% of the total regional population (cf. Table 1.1). Table 4.1 also associates each of these 25 counties with one of 14 urban areas, according to their populations and proximity.

Urban Counties' Rooftop PV Capacity

Each county's rooftop PV capacity is calculated by multiplying its population by its state's Wp/ capita. For example, the rooftop PV capacity estimate for King county is:

King county population (1,916,441) x

Washington State's Rooftop PV Density (0.78 Wp/ capita)

= 1,495 kWp

This method assumes that rooftop PV is distributed evenly across these states according to population. In reality, rural and urban areas may have different levels of rooftop PV capacity, but no studies of this topic were found.

Table 4.1 – Regional Urban Counties & Urban Areas							
Urban County		State	State Wp/ Capita	2009 County Population	Share of Total Regional Population	kWp	Urban Area
King	🟪	WA	0.78	1,916,441	15.5%	1,495	Seattle
Pierce		WA	0.78	796,836	6.5%	622	Seattle
Multnomah		OR	3.66	726,855	5.9%	2,660	Portland
Snohomish		WA	0.78	694,571	5.6%	542	Seattle
Washington		OR	3.66	537,318	4.4%	1,966	Portland
Spokane	🟫	WA	0.78	468,684	3.8%	366	Spokane
Clark		WA	0.78	432,002	3.5%	337	Portland
Clackamas		OR	3.66	386,143	3.1%	1,413	Portland
Ada		ID	0.13	384,656	3.1%	50	Boise
Lane		OR	3.66	351,109	2.8%	1,285	Eugene
Marion	🟥	OR	3.66	317,981	2.6%	1,164	Salem
Thurston		WA	0.78	250,979	2.0%	196	Olympia
Kitsap		WA	0.78	240,862	2.0%	188	Seattle
Yakima		WA	0.78	239,054	1.9%	187	Yakima
Jackson		OR	3.66	201,286	1.6%	737	Medford
Whatcom	🟧	WA	0.78	200,434	1.6%	156	Bellingham
Canyon		ID	0.13	186,615	1.5%	24	Boise
Benton		WA	0.78	168,294	1.4%	131	Yakima
Deschutes		OR	3.66	158,629	1.3%	581	Bend
Kootenai		ID	0.13	139,390	1.1%	18	Spokane
Skagit	🟨	WA	0.78	119,534	1.0%	93	Bellingham
Linn		OR	3.66	116,584	0.9%	427	Salem
Missoula		MT	2.25	108,623	0.9%	245	Missoula
Douglas		OR	3.66	103,205	0.8%	378	Medford
Cowlitz		WA	0.78	101,966	0.8%	80	Portland
TOTALS				9,348,051	75.7%	15,339	

Fig. 4.1 illustrates these twenty-five most populous counties by color. The five most populous counties are located around Seattle and Portland, and 15 of these urban counties are located along the I-5 corridor. Seventeen of these 25 urban counties and 80% of the region's urban population are located west of the Cascades.

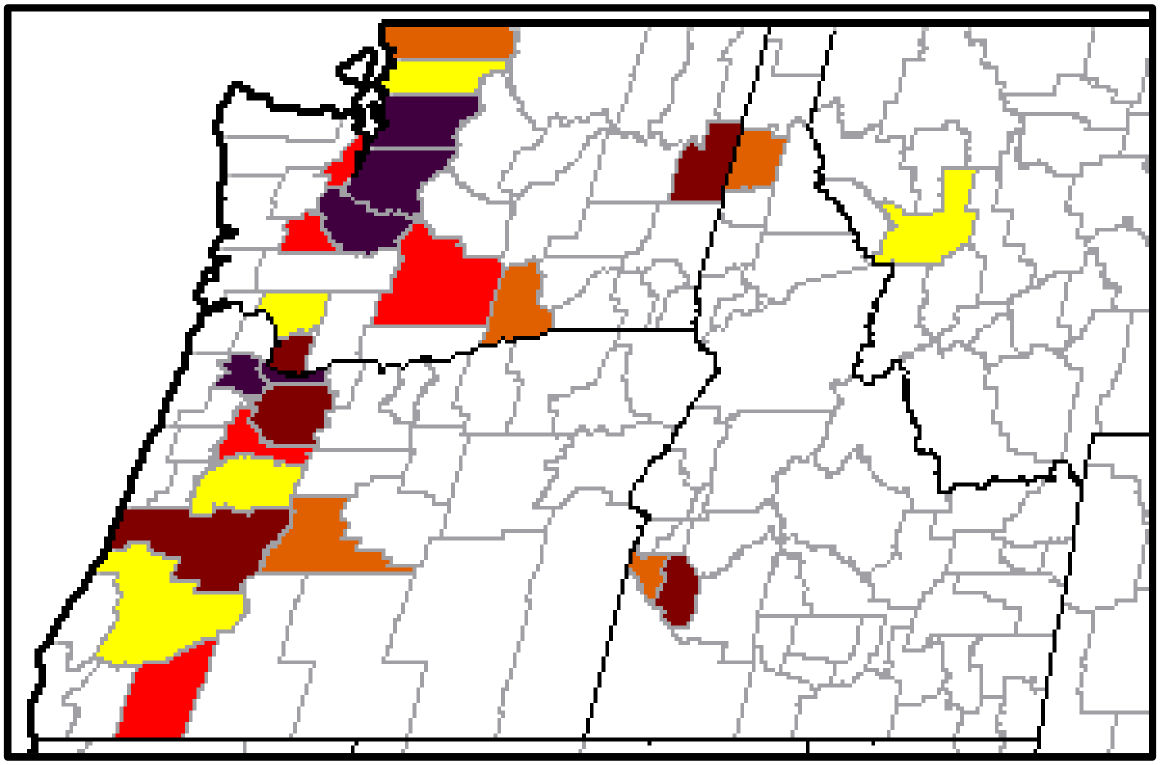


Fig. 4.1 – Regional Urban Counties by Population (2009)

Table 4.2 consolidates these 25 urban counties into 12 major urban areas, to facilitate assigning them solar resource locations from the National Solar Radiation Database [NSRDB]. It shows estimates of the total rooftop PV capacity for each urban area and includes about 75% of the state's estimated rooftop PV capacity (cf. Table 1.4). It would be possible to extend this model to rural areas, however, areas with lower population densities require a greater number of solar resource locations. By focusing on urban areas, a smaller number of solar resource locations can be to create estimates for a majority of the population. Table 4.2 also shows the data quality class for each NSRDB location (1 = best); (Wilcox 2012, p. 7).

Table 4.2 - Rooftop PV Capacity Profile (2009)

Urban Area	Urban Area Population	kWp	NSRDB Location & Data Quality Indicator
Portland	2,184,284	6,456	Portland International AP #726980, 3
Seattle	3,648,710	2,847	Seattle-Tacoma Intl AP #727930, 1
Salem	434,565	1,590	Salem McNary Field #726940, 1
Eugene	351,109	1,285	Eugene Mahlon Sweet AP #726930, 1
Medford	304,491	1,114	Medford Rogue Valley Intl AP #725970, 1
Bend	158,629	581	Redmond Roberts Field #726835, 2
Spokane	608,074	384	Spokane International AP #727850, 1
Yakima	407,348	318	Yakima Air Terminal #727810, 1
Bellingham	319,968	250	Bellingham Intl AP #727976, 2
Missoula	108,623	245	Missoula International AP #727730, 1
Olympia	250,979	196	Olympia Airport #727920, 1
Boise	571,271	74	Boise Air Terminal #726810, 1
Totals	**9,348,051**	**15,339**	

Fig. 4.2 shows the region's urban rooftop PV capacity profile. About 60% of the region's rooftop PV capacity is located around Portland and Seattle and about 10% is located east of the Cascades.

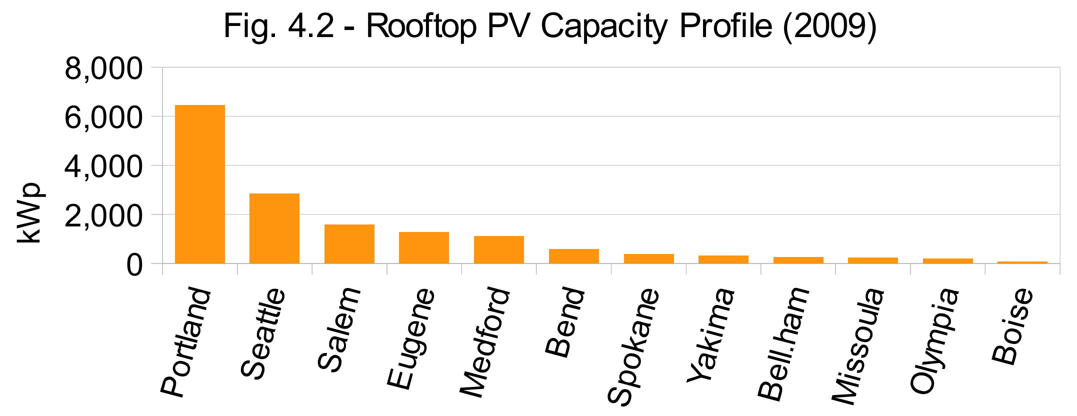


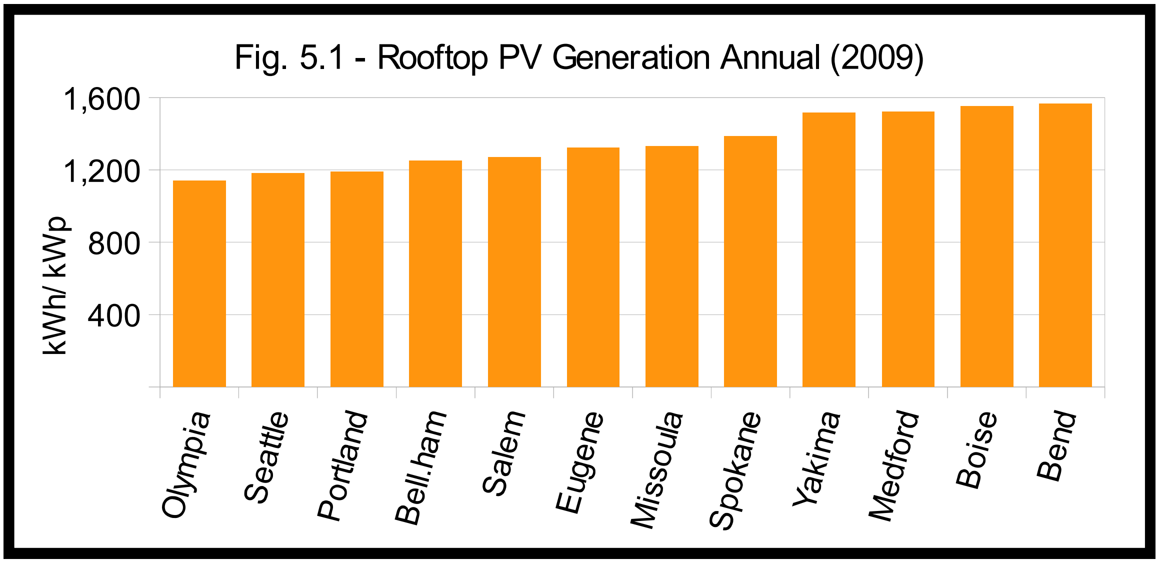
Fig. 4.2 - Rooftop PV Capacity Profile (2009)

5. Rooftop PV Generation Profile

This section develops a regional rooftop PV generation profile for 2009. Rooftop PV generation is the electricity output from rooftop PV capacity. Solar resource data for each NSRDB location was applied to each urban area's rooftop PV capacity to create a rooftop PV generation profile for each urban area (Appendix B). These were then combined into a single, regional, hourly rooftop PV generation profile.

Annual PV Generation for the Urban Areas

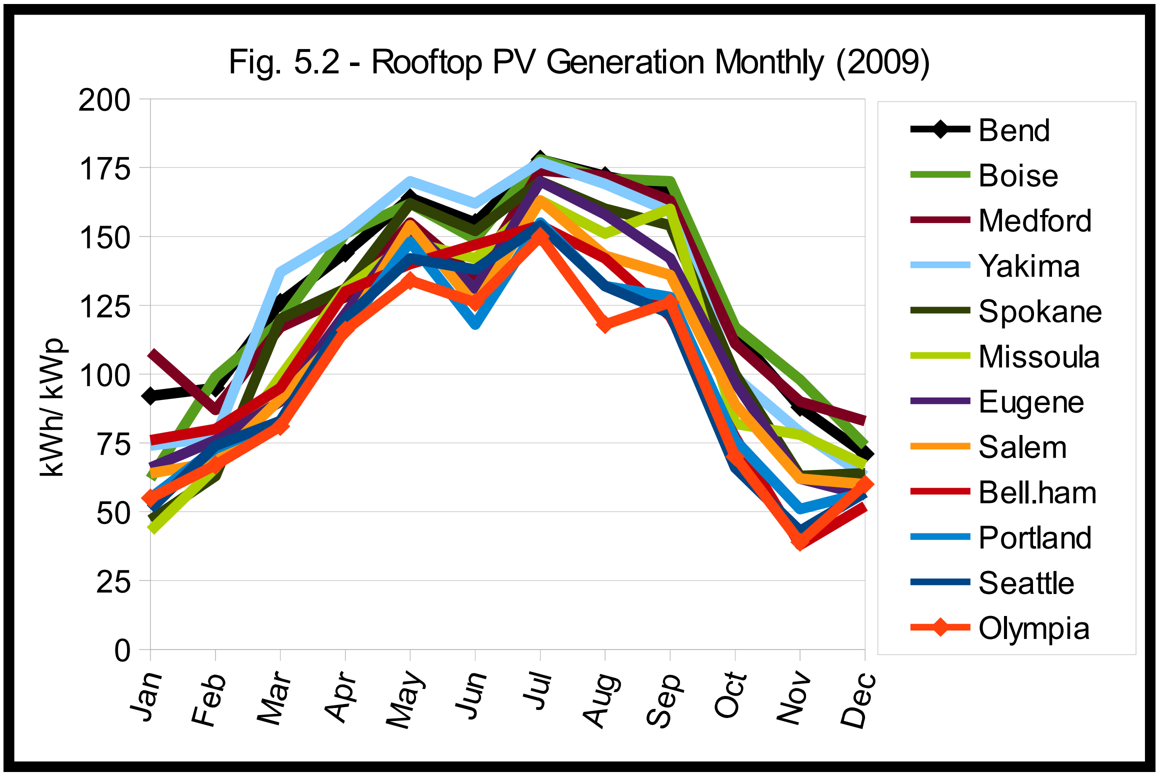
The region's urban areas have different solar resources, so their rooftop PV capacities generated different quantities of electricity. Figure 5.1 illustrates the annual rooftop PV generation (kWh/ kWp) for each urban area.



Rooftop PV capacity in cities on the region's eastern high plateau (Spokane, Yakima, or Bend) generated more electricity than capacity located around Puget Sound and in the Willamette Valley (Olympia, Portland, Bellingham). In 2009, rooftop PV capacity in Bend generated about 37% more electricity than the equivalent capacity in Olympia.

Monthly PV Generation

Fig 5.2 shows the monthly rooftop PV generation for each urban area.



June was especially cloudy in 2009.

All cities show the same seasonal pattern of cloudier winters with less generation, and sunnier summers with more generation. PV capacity is more productive during summertime because the daylight is longer, the skies are clearer, and the altitude of the sun is higher, so most fixed-axis collectors receive more direct irradiation. Cities to the east are sunnier during most months, yet especially so during winter months.

Regional Hourly Rooftop PV Generation Profile

The hourly rooftop PV generation profile for each urban area for 2009 was created by multiplying each area's hourly rooftop PV generation by each area's rooftop

PV capacity (Appendix B). Those hourly rooftop PV generation profiles were then added together into a single hourly rooftop PV generation profile (Fig 5.3).

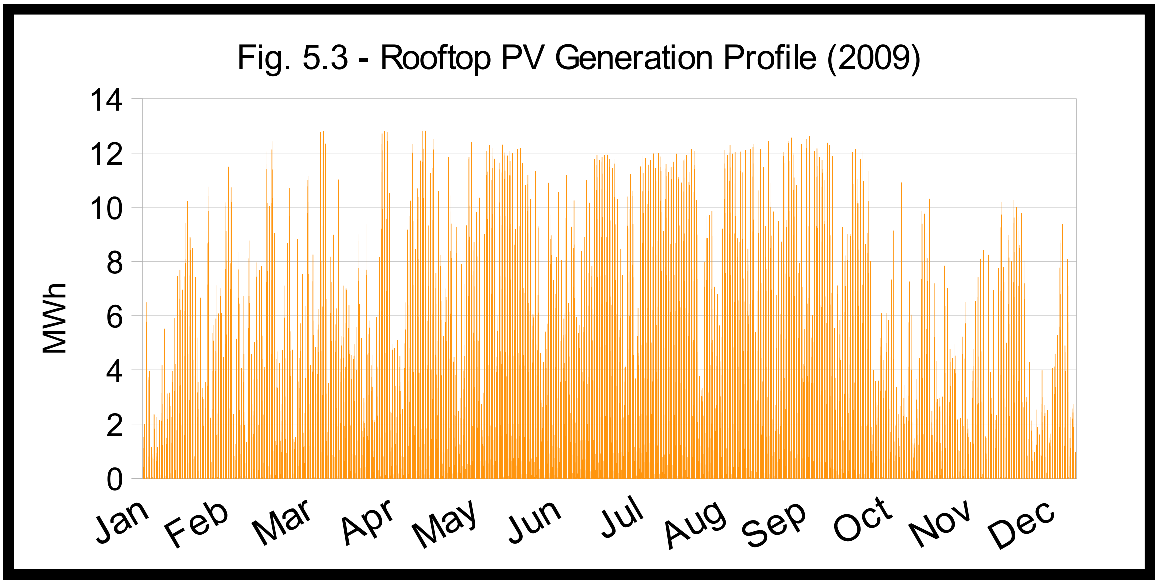


Fig. 5.3 - Rooftop PV Generation Profile (2009)

This profile approximates the timing and the intensity of the region's rooftop PV generation in 2009. Because Oregon has about 70% of the region's rooftop PV capacity, this regional rooftop PV generation profile is dominated by Oregon's urban rooftop PV generation profiles. Seattle's large quantity of rooftop PV capacity also has a strong influence on the regional generation profile. And although urban areas east of the Cascades have the best solar resources, they also typically have the least rooftop PV capacity (cf. Fig. 4.2) and therefore they have the least generation.

6. Transmission and Distribution Savings

In addition to their generation of electricity, distributed rooftop PV generation also reduces the demand for the transmission and distribution [T & D] of electricity from centralized sources. Centralized electricity generators like hydropower, wind power, coal, nuclear, and natural gas generators are usually located away from urban areas and their electricity must be transmitted long distances and then distributed to consumers. Transmitting and distributing electricity consumes electricity, so distributed rooftop PV generation produces T & D savings. Denholm and Margolis (2008, p. 1) explain, "by deploying photovoltaics on building rooftops... the system is deployed at the point of use, which minimizes transmission and distribution requirements and losses."

Rooftop PV generation reduces the demand for electricity much like other forms of demand reduction. On a regional scale, the impacts of rooftop PV capacity are very similar to other demand reductions such as insulation, appliance efficiency, demand-response, and conservation. Conclusions from other studies of demand reductions may be judiciously applied to rooftop PV generation. One significant difference between other demand reductions and PV generation is the timing of rooftop PV generation. Just like other methods of conserving electricity, distributed generation can also relieve demands for additional T & D capacity (NPCC, 2010a, p. E-11), and it may also provide some ancillary services (as discussed in the conclusions below).

Other Estimates of T&D Energy Savings

A number of studies show that T & D savings vary in place and time, and show that they are positively correlated with distance, outdoor temperatures and high-demand for electricity. Grover (2007, p. 3) explains that because of T&D losses, "fossil fuel plants must generate 7 percent more electricity than PV systems to provide end-users with an equivalent amount of electricity." For the U.S. as a whole, IREC (2012, p. 3) estimates a general range of T & D losses between 5 – 11%, depending seasons and overall demand. Wong (2011) provides a detailed exposition of California's T & D losses and estimates average statewide T & D losses between 5.4 – 6.9% for the years 2002 – 2008. She discuss how actual T & D losses vary according to individual utilities, geographic differences, temperature differences, transmission constraints, and local peak-demand coincidences. For the Pacific Northwest, NPCC (2010a, p. E-3) estimates that, "overall conservation avoids line losses that range between 9 percent and 10 percent depending on the load shape of each measure's savings." Based upon their estimates, this thesis uses a T & D consumption estimate of 9%.

Regional T&D Savings Factor

Wong (2011) explains a simple method to estimate the T & D savings factor for rooftop PV generation. Table 6.1 shows the T&D savings factors for T&D losses between 6 – 12%. For a the T&D consumption estimate of 9%, each MWh of rooftop PV generation corresponds to a T&D Savings Factor of about 1.10.

Table 6.1 – T&D Savings

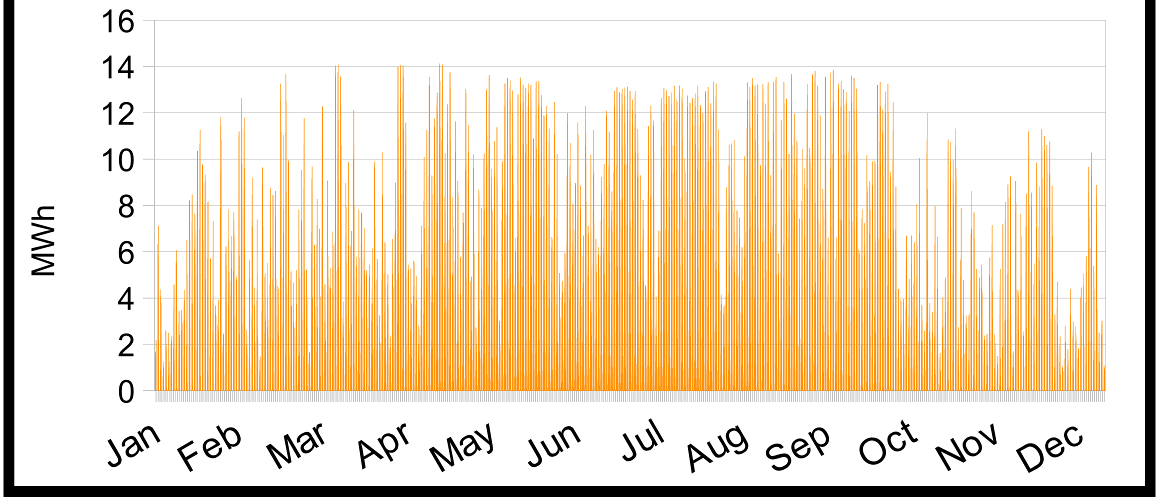
T&D Consumption Estimate	T&D Savings Factor
6%	1.06
7%	1.08
8%	1.09
9%	**1.10**
10%	1.11
11%	1.12
12%	1.14

$$\mathbf{1\ MWh / (1 – 0.9)\ =\ 1.10\ MWh}$$

The Rooftop PV Impacts Profile

The rooftop PV impacts profile is an estimate of when and how much rooftop PV generation impacts other sources of electricity (Fig. 6.1). It follows the same pattern as the rooftop PV generation profile, but by adding T & D savings, it more accurately estimates the impacts of rooftop PV capacity on the grid.

Fig. 6.1 - Rooftop PV Impacts Profile (2009)



7. Estimates of Additional Rooftop PV Capacity

This section develops a realistic range of additional rooftop PV capacity, based upon the capacity found in other regions and projections of additional rooftop PV capacity for the U.S.

Other Estimates of Rooftop PV Capacity

Capacity in Japan and Europe

Japan and Europe are leaders of PV capacity, and their accomplishments are examples of what is technically possible. In 2009, the International Energy Agency (IEA, 2010b) estimated that Japan had about 20.7 Wp/ capita, Germany had 119.6 Wp/ capita, and Spain had 76.1 Wp/ capita. For 2012, the European Photovoltaic Industry Association (EPIA, 2013) estimated that Germany had 398 Wp/ capita, Italy had 273 Wp/ capita, and Belgium 241 Wp/ capita.

Projected Potential Capacity in the U.S.

Denholm & Margolis (2008) estimate that America's maximum potential total rooftop supply is, “348 GW for residential rooftops and 313 for commercial – or a total of about 661 GW for the buildings sector” (with 2010 USA population, that's about 2,141 Wp/ capita). That 630 times America's capacity in 2009.

Grover (2007) evaluates the Solar America Initiative and describes the national goals of 10,000 MWp (32 Wp/ capita) by 2015, and 100,000 MWp (3,239 Wp/ capita) by 2030. That's an increase of 9.4 to 94 times America's rooftop PV capacity in 2009.

Paidipati, Frantzis, Sawyer, & Kurrasch (2008) developed several scenarios for the growth of residential and commercial rooftop PV capacity for every state in America.

For Washington, Oregon, and Idaho they estimate maximum technical potentials of about 19,000 MWp (1,600 Wp/ capita). However, their most optimistic realistic projection is the "Focused Policy Scenario with Solar America Initiative prices." With that scenario, they estimate that by 2015 these three states could total about 1,400 MWp (120 Wp/ capita). That would be an increase of about 86 times over the region's capacity in 2009.

A Range of Additional Regional Rooftop PV Capacity

The discussion above suggests a realistic range of additional regional rooftop PV capacity between 0 and 200 Wp/ capita. Based on data from the Interstate Renewable Energy Council (IREC, 2008 – 2012) it is possible to extrapolate the growth of regional rooftop PV capacity (Fig. 1.11). Over those years, the average annual rooftop PV capacity growth for the region is about 70%. At that rate, the region would exceed 200 Wp/ capita around 2018. Therefore, the impacts of an additional 1.62 – 16.2 Wp/ capita are a good estimate for projections over the next few years, and larger multiples show what might occur several years from now. This thesis considers additional rooftop PV capacity up to 162 Wp/ capita, which corresponds to the development of 100 times the estimated capacity in 2009.

The predictions of the impacts of additional capacity is probably reliable for predicting the next several years of impacts from additional rooftop PV capacity. On the one hand, larger expansions and longer time-frames increase the uncertainty of these predictions, yet on the other hand, these predictions will be more accurate if the regional power system remains similar as it was in 2009.

Section 3: Rooftop PV Impacts

Chapters 8 – 10 estimate the impacts of rooftop PV capacity on fossil fuel generation and provide conclusions and discussion of the results.

Chapters 8 compares the hourly rooftop PV impacts (Fig. 6.1) with the hourly fossil fuel generation profile (Fig. 1.6) to estimate when and how much rooftop PV capacity reduces regional fossil fuel electricity generation. It also shows when rooftop PV impacts are most likely to exceed regional fossil fuel generation and produce a solar surplus.

Chapter 9 uses the hourly fossil fuel generation reductions from chapter 8 to estimate rooftop PV impacts on CO2 emissions from fossil fuel generators.

Chapter 10 presents some conclusions and discussion about how to maximize and focus the impacts of rooftop PV generation on CO2 emissions.

8. Rooftop PV Impacts on Fossil Fuel Generation

To calculate rooftop PV impacts on fossil fuel generation, the hourly rooftop PV impacts are subtracted one-for-one from fossil fuel generation (Denholm & Margolis, 2006), according to the suggested order of dispatch. Rooftop PV impacts are first subtracted from hourly SC generation. If the hourly load reductions exceed that hour's SC generation, then the remainder is subtracted from that hour's CC generation. Any remainder after that is subtracted from that hour's coal generation, and anything else is the 'solar surplus.' Table 8.1 shows the annual totals of rooftop PV impacts and fossil fuel generation for additional rooftop PV capacity.

The "Base" column shows the fossil fuel generation data without any additional rooftop PV impacts. It shows what fossil fuel generation was in 2009, and it implicitly includes the impacts of the rooftop PV capacity in place in 2009. Column "1" estimates regional rooftop PV impacts and fossil fuel generation for an additional 1.62 Wp/ capita, distributed according to Table 1.4. Columns "10" – "100" calculate multiples of additional rooftop PV capacity, corresponding to a range of an additional 16.2 – 162 Wp/ capita, also distributed according to Table 1.4.[1]

Rows for "PV Impacts" show the corresponding multiples of rooftop PV impacts, and rows for "Generation w/ PV" show the generation from each type of fossil fuel minus the reductions from rooftop PV impacts. Rows for "% Reduction by Type" show reductions of electricity generation for each fossil fuel type from its baseline of 2009. For instance, an additional 16.2 MWp of rooftop PV capacity reduces CC generation by

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[1] These multiples suppose that the region's distribution of rooftop PV capacity remains relatively constant as it expands. This rate of growth assumes that the state's with slower growth will grow faster, and that states with more rapid growth will slow down. An improvement to this model could project the growth of rooftop PV capacity at rates specific to each state.

about 0.1%. Rows for “% of Total Reduction” show how much each fossil fuel type is reduced relative to total fossil fuel generation reductions. For instance, with an additional 16.2 MWp, about 61% of rooftop PV impacts would be reductions of CC generation.

Table 8.1 – Rooftop PV Impacts on Fossil Fuel Generation

Multiple	Base	1	10	20	30	40	50	60	70	80	90	100
Additional Wp/ capita	**0**	**1.62**	**16.2**	**32.4**	**48.6**	**64.8**	**81.0**	**97.2**	**113**	**130**	**146**	**162**
Additional MWp	0	20	201	402	603	804	1,005	1,206	1,407	1,608	1,809	2,010
Rooftop PV Impacts	**(1000's of MWh)**											
PV Generation	0	19.4	194	388	581	775	969	1,163	1,357	1,550	1,744	1,938
T&D Savings	0	1.9	19	38	57	77	96	115	134	153	172	192
PV Impacts	**0**	**21.3**	**213**	**426**	**639**	**852**	**1,065**	**1,278**	**1,491**	**1,704**	**1,917**	**2,130**
F. Fuel Reductions	**(1000's of MWh)**											
SC	0	6.5	57	87	102	109	114	117	119	121	122	124
CC	0	13.8	146	316	496	679	860	1,038	1,214	1,387	1,558	1,726
Coal	0	1.0	10	23	41	62	86	114	142	172	200	227
Solar Surplus	0	0.0	0	0	0.3	2	4	9	15	24	36	52
F. Fuel Gen. w/ PV	**(1000's of MWh)**											
SC	181	175	124	94	80	72	67	64	62	60	59	58
CC	24,333	24,319	24,187	24,017	23,837	23,654	23,473	23,295	23,119	22,946	22,775	22,607
Coal	20,265	20,264	20,255	20,241	20,224	20,203	20,178	20,151	20,122	20,093	20,065	20,037
Total Fossil Fuels	44,779	44,758	44,566	44,353	44,141	43,929	43,719	43,510	43,303	43,100	42,899	42,702
Solar Surplus	0	0	0	0	0	2	4	9	15	24	36	52
% Reduction by Type	**(change from 0 Wp/ capita)**											
SC	0.0%	-3.6%	-31%	-48%	-56%	-60%	-63%	-65%	-66%	-67%	-68%	-68%
CC	0.0%	-0.1%	-0.6%	-1.3%	-2.0%	-2.8%	-3.5%	-4.3%	-5.0%	-5.7%	-6.4%	-7.1%
Coal	0.0%	0.0%	0.0%	-0.1%	-0.2%	-0.3%	-0.4%	-0.6%	-0.7%	-0.8%	-1.0%	-1.1%
% of Total Reduction	**(each column totals 100%)**											
SC		31%	27%	20%	16%	13%	11%	9%	8%	7%	6%	6%
CC		65%	69%	74%	78%	80%	81%	81%	81%	81%	81%	81%
Coal		5%	5%	5%	6%	7%	8%	9%	10%	10%	10%	11%
Solar Surplus		0.0%	0.0%	0.0%	0.1%	0.2%	0.4%	0.7%	1.0%	1.4%	1.9%	2.5%

Additional Rooftop PV Capacity

Fig. 8.1 illustrates Table 8.1 rows for "Generation w/ PV".

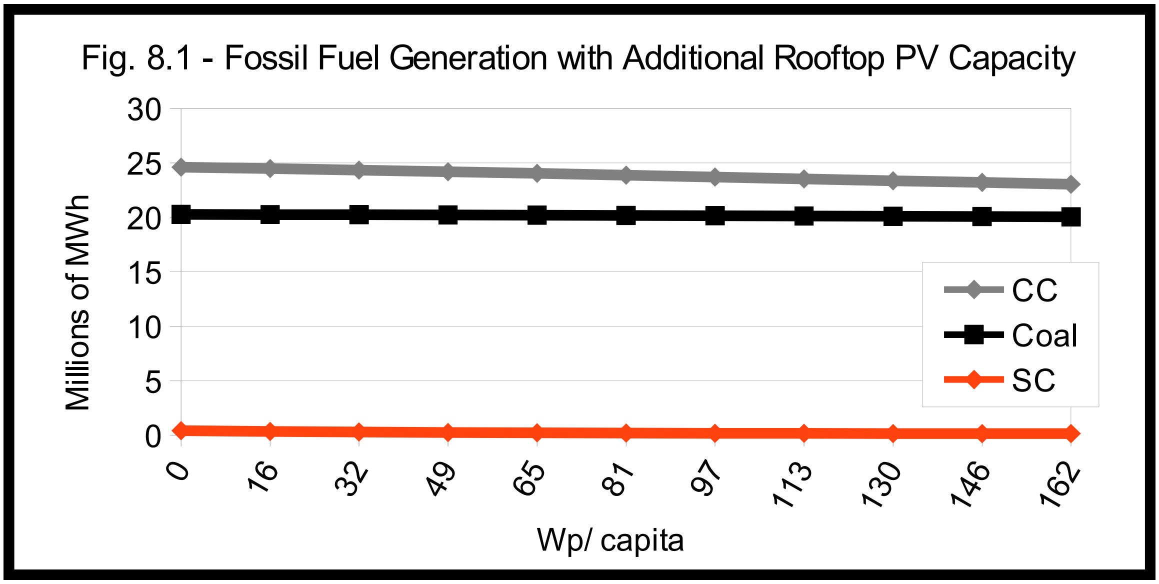
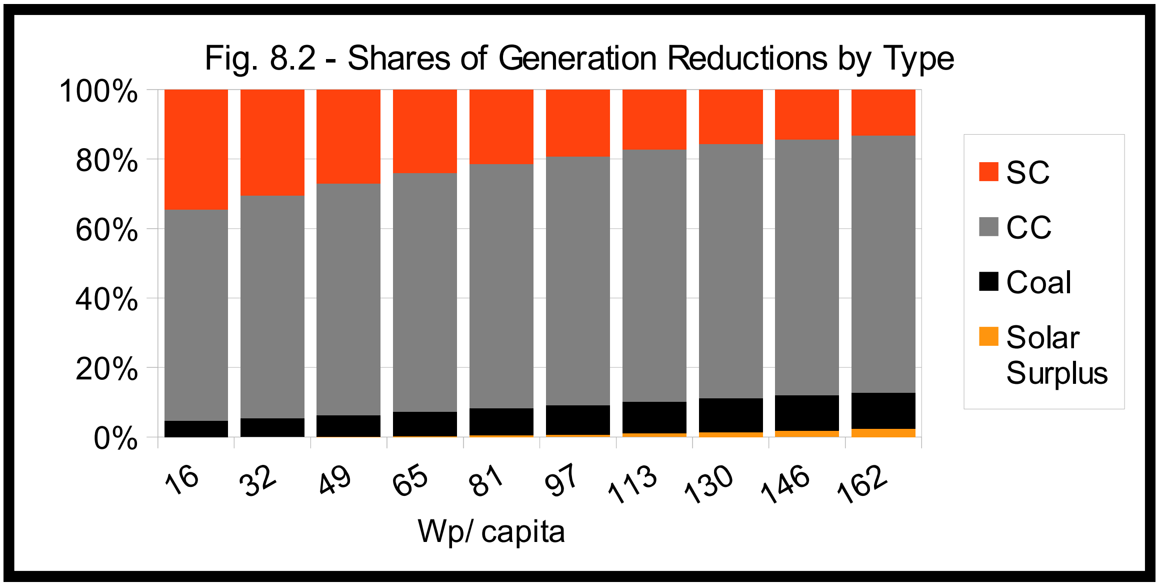


Fig. 8.2 illustrates Table 8.1 rows for "% of Total Reduction".



Additional Capacity of 1.62 – 16.2 Wp/ capita

The rooftop PV impacts for 1.62 – 16.2 Wp/ capita are a good indicator of the current and near-term impacts of additional rooftop PV capacity in the region. These impacts indicate the marginal generating sources during hours with rooftop PV generation. About 95% of the impacts of rooftop PV capacity are reductions of natural gas generation.

Although SC generated only 0.40% of the region's fossil fuel electricity, because it is assumed to be the most-marginal generation, and because a large fraction of SC generation occurs mid-day, during summertime, with 1.62 Wp/ capita of rooftop PV capacity, 31% of the generation reductions impact SC generation.

Most of the generation reductions impact CC generation because it operates on the margin throughout most of the year. Coal is least flexible, and compared to natural gas generation, rooftop PV impacts on coal are small and only occur when there is little or no natural gas generation. With 1.62 Wp/ capita only about 5% of rooftop PV impacts are reductions of coal generation.

Additional Capacity of 16.2 – 48.6 Wp/ capita

These multiples are equivalent to 10 to 30 times the rooftop PV capacity in 2009, equivalent to 200 - 600 Wp/ capita.[1] With increasing multiples of rooftop PV capacity, a smaller share of the impacts affect SC generation, and a greater share of the rooftop PV impacts affect CC and coal generation. With 48.6 Wp/ capita, a small amount of solar surplus could impact other sources of electricity that are not included in the model.

Additional Capacity of 48.6 – 162 Wp/ capita

If rooftop PV capacity expanded by an additional 30 – 100 times its 2009 capacity, the impacts shift away from SC generation and towards CC, coal, and the solar

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[1] For comparison, the Boardman coal plant or a large natural gas generator have nameplate capacities of about 600 MWp (equivalent to 48.6 Wp/ capita).

surplus. The share of rooftop PV impacts on SC drop from 31% to 6% and rooftop PV impacts on coal generation rise from 5% to 11%. About 2% of rooftop PV impacts are solar surplus.

Impacts on Fossil Fuel Generation

Impacts on Natural Gas Generation

As an illustration, Fig. 8.3 shows SC generation and rooftop PV impacts for 162 Wp/ capita for one week (168 hours) in August.

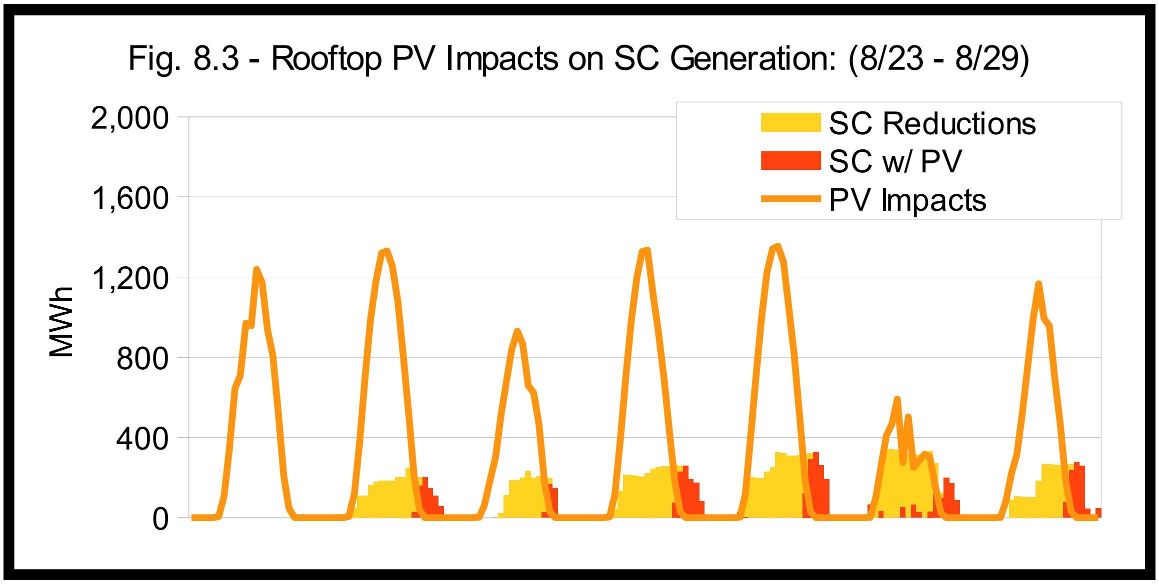
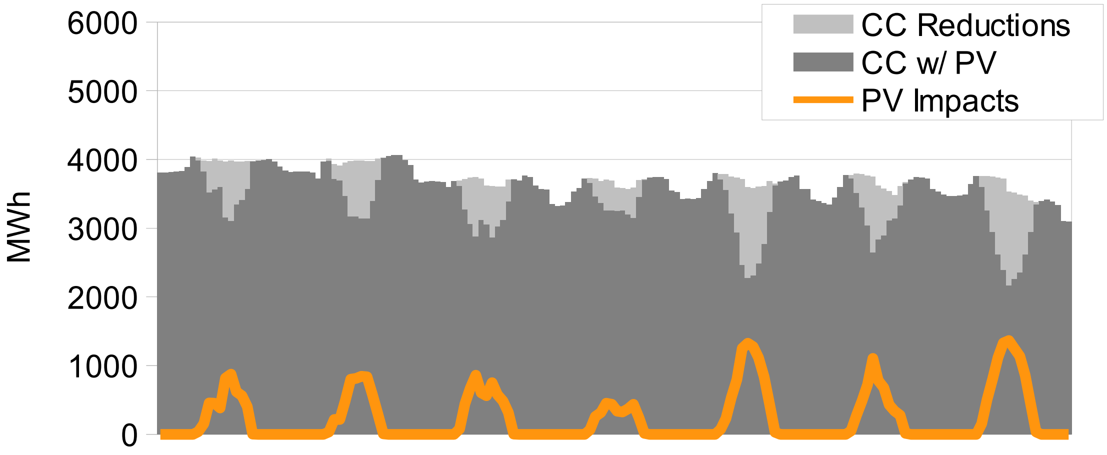


Fig. 8.3 - Rooftop PV Impacts on SC Generation: (8/23 - 8/29)

SC generation was not used on Aug. 23. With this level of rooftop PV capacity, the peak of generation exceeded SC generation every day. Most notably, while rooftop PV capacity completely obviated SC generation during the day, it was not available to offset SC generation during early evening hours. This is discussed further in the conclusions below.

A similar pattern is found for CC generators, although the impacts are usually less dramatic because of the much larger quantity of CC generation. During summertime rooftop PV impacts also cause peak-demand reductions of CC generation. During winter, however, natural gas generation often exhibits dual daily peaks at morning and evening (for heating and lighting demand), and because rooftop PV impacts fall during mid-day they may created greater variability. Fig. 8.4 shows CC generation and rooftop PV impacts for 162 Wp/ capita for one week (168 hours) in February.

Fig. 8.4 -- Rooftop PV Impacts on CC Generation (2/14 - 2/20)



This increase of variation could increase the demand for ancillary services.

Rooftop PV Impacts on Coal Generation

To some extent, coal is a load-following source of electricity that adjusts to meet demand, but adjusting coal generators increases their costs and their rate of CO2 emissions. Denholm and Margolis (2007) find diminishing economic returns from additional PV capacity when PV generation begins to impact inflexible baseload generators. Therefore, policies that promote rooftop PV capacity as a solution to CO2 emission should also consider limits of effectiveness or supplementary investments into storage or transmission capacity. This topic of the optimal quantity of PV capacity is the subject of substantial research (Jo et al., 2010; Denholm & Margolis, 2007a & 2007b), however, in the Pacific Northwest, there is probably enough flexibility from hydro-power and CC generation to manage a large amount of additional rooftop PV capacity.

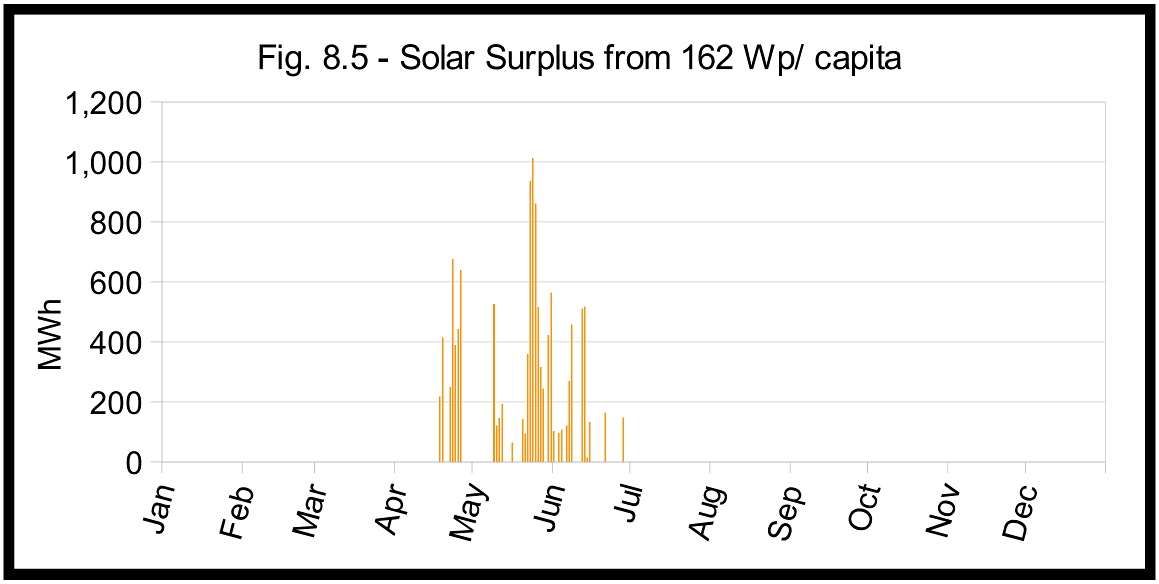
Total Generation Reductions

Overall, even large additions of ideal rooftop PV capacity create small impacts relative to the total regional fossil fuel generation. An additional 162 Wp/ capita produces total rooftop PV impacts of about 2,130,000 MWh, compared to a total of 45,305,000 MWh of fossil fuel generation. Consequently, even this extreme expansion could only reduce fossil fuel generation by about 4.7%.

Oversupply Conditions

Oversupply occurs when wind and hydropower exceed the demand for electricity, and the BPA must compensate generators for lost revenues. Oversupply usually occurs during spring at night, when hydropower and wind power are active and demand is low. Even though rooftop PV impact occur during the day, and oversupply usually occurs at night, when fossil fuel generation is low, rooftop PV capacity could complicate oversupply conditions on some sunny days or the evenings thereafter.

The solar surplus is a measure of when and how much rooftop PV capacity exceeds regional fossil fuel generation. Fig. 8.5 shows the solar surplus from 162 Wp/ capita.



The solar surplus occurs around April, May and June, when both fossil fuel generation and electricity demand are low, and it indicates when rooftop PV capacity could exacerbate the oversupply of electricity and cause negative impacts on some primary sources. The growth of wind power (Fig. 1.3) has increased the likelihood of oversupply, and although oversupply from wind-power usually occurs at night (EIA, 2011), if rooftop PV capacity displaces hydropower during the day during oversupply conditions, then it indirectly impacts wind power at night. Power system operators would prefer to utilize oversupplies, but sometimes hydropower is spilled and wind power is curtailed (NPCC, 2011). These consequences raise the costs of electricity. Fortunately, even during 2010 and 2011, when streamflows were strong, wind displacement was not a significant expense (NPCC, 2012). There are mechanisms to accommodate oversupply, and some of them would also facilitate additional rooftop PV capacity. For example, to relieve oversupply, NPCC (2012a) recommends lowering reserve requirements for hydropower reservoirs, increasing system flexibility by increasing capacity for curtailment at night, and developing thermal resistive loads to use excess power.

While some solar surplus could displace other fossil fuel generators (such as other natural gas or coal generators), late-spring is typically a time when the region is exporting electricity. Therefore, the solar surplus may also indicate when and how much rooftop PV capacity increases the region's ability to export electricity to other regions. EIA (2011) shows that these months (May, June, and July) exhibit increased flows of power out of the Pacific Northwest, corresponding to increased flows of power to California. Alvarado and Griffin (2007) explain:

> Northwest transmission power-flow data shows that California imports daily peak power throughout the year, imports little power off-peak, and imports more power in the spring during the hydro run-off season and in the summer during periods of high California demand. (p. 17)

By means of power trading schemes, this would enable the region to import more low cost power from California during winter, but opportunities for power trading are limited by transmission, and adding transmission capacity reduces the likelihood of power surpluses and wasted power. Yet, even with 162 Wp/ capita, the magnitude of the solar surplus is only 0.12% of the annual fossil fuel generation (50 MWh / 43,227 MWh), and unlikely to seriously affect oversupply conditions.

9. Rooftop PV Impacts on CO2 Emissions

CO2 emissions reductions are calculated by reducing the hourly emissions proportionately to the hourly generation reductions:

(CO2 Emissions (tons)) x (generation reduction (%)) =

CO2 Emissions w/ PV (tons)

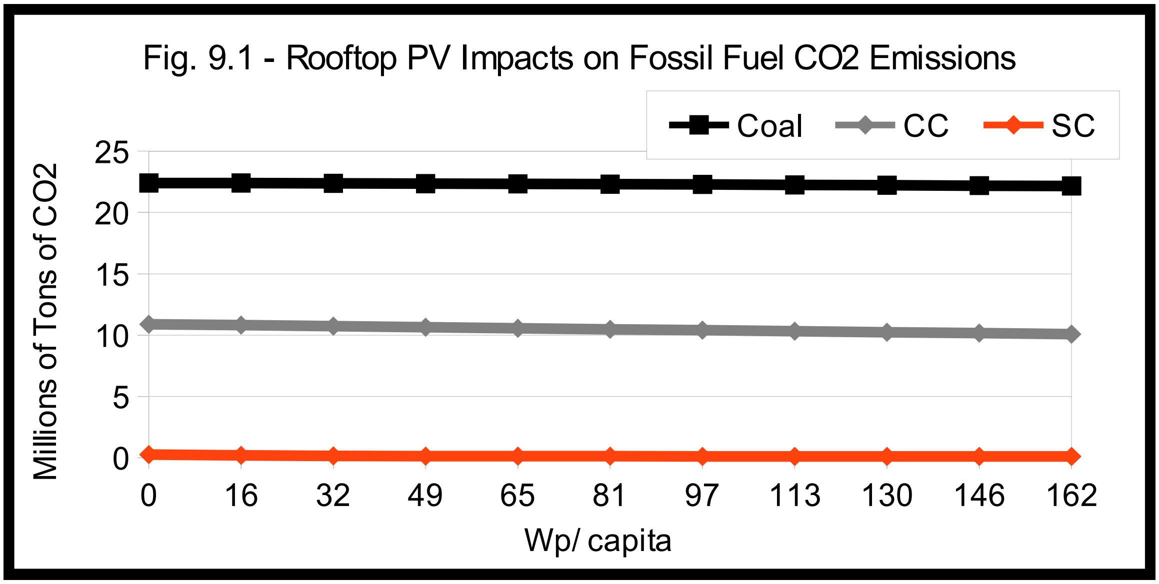
The relationship between electricity generation and CO2 emissions is not linear, yet this method assumes, for example, that a 10% reduction of generation from a particular source corresponds with a 10% reduction of emissions from that source. In reality, however, from hour to hour, rooftop PV impacts would have larger or smaller impacts on these CO2 emissions. Yet, by using hourly emissions data, variations of heat rates for changes of fossil fuel generation are partially captured by the CEMS measures of the emissions from each unit. And because regional variations of load are usually distributed amongst a number of marginal generators (instead of one, single "most-marginal" generator), pooling generators by type is not a bad approach. Table 9.1 shows the impacts of additional rooftop PV capacity on fossil fuel CO2 emissions. Rooftop PV Impacts from Table 8.1 are included for reference.

Table 9.1 – Rooftop PV Impacts on Fossil Fuel CO2 Emissions

Multiple	Base	1	10	20	30	40	50	60	70	80	90	100
Regional Wp/ capita	**0**	**1.62**	**16.2**	**32.4**	**48.6**	**64.8**	**81.0**	**97.2**	**113**	**130**	**146**	**162**
Regional MWp	0	20	201	402	603	804	1,005	1,206	1,407	1,608	1,809	2,010
PV Impacts	**(1000's of MWh)**											
PV Generation	0	19	194	387	581	775	969	1,162	1,356	1,550	1,743	1,937
T&D Savings	0	2	19	38	57	77	96	115	134	153	172	192
PV Impacts	0	21	213	426	639	851	1,064	1,277	1,490	1,703	1,916	2,129
CO2 Reductions	**(1000's of tons)**											
SC	0	11	76	114	132	141	146	150	153	155	157	158
CC	0	7	69	149	232	316	399	480	560	638	715	791
Coal	0	1	11	24	42	64	89	117	147	177	207	236
Total	**0**	**19**	**156**	**286**	**406**	**521**	**635**	**748**	**860**	**971**	**1,079**	**1,185**
CO2/ Wp/ capita	**0**	**11.6**	**9.6**	**8.8**	**8.4**	**8.0**	**7.8**	**7.7**	**7.6**	**7.5**	**7.4**	**7.3**
CO2 w/ PV	**(1000's of tons)**											
SC	260	249	183	146	128	119	113	109	107	105	103	102
CC	10,872	10,865	10,802	10,723	10,639	10,555	10,473	10,392	10,312	10,234	10,156	10,080
Coal	22,399	22,398	22,389	22,375	22,357	22,336	22,310	22,282	22,252	22,222	22,192	22,163
Total	33,531	33,512	33,375	33,244	33,125	33,010	32,896	32,783	32,671	32,560	32,452	32,345
% Reduction by Type	**(change from 0 Wp/ capita)**											
SC	0.0%	-4.3%	-29%	-44%	-51%	-54%	-56%	-58%	-59%	-60%	-60%	-61%
CC	0.0%	-0.1%	-0.6%	-1.4%	-2.1%	-2.9%	-3.7%	-4.4%	-5.1%	-5.9%	-6.6%	-7.3%
Coal	0.0%	0.0%	0.0%	-0.1%	-0.2%	-0.3%	-0.4%	-0.5%	-0.7%	-0.8%	-0.9%	-1.1%
Total	0.0%	-0.1%	-0.5%	-0.9%	-1.2%	-1.6%	-1.9%	-2.2%	-2.6%	-2.9%	-3.2%	-3.5%
% of Total Reduction	**(each column totals 100%)**											
SC		59%	49%	40%	32%	27%	23%	20%	18%	16%	15%	13%
CC		35%	44%	52%	57%	61%	63%	64%	65%	66%	66%	67%
Coal		5%	7%	8%	10%	12%	14%	16%	17%	18%	19%	20%

Rooftop PV Impacts on CO2 Emissions

Fig. 9.1 and Fig. 9.2 show the region's fossil fuel CO2 emissions with additional rooftop PV capacity.



The impacts are relatively small.

Fig. 9.3 shows that as additional rooftop PV capacity is added, the impacts shift away from SC generation and towards CC and coal generation.

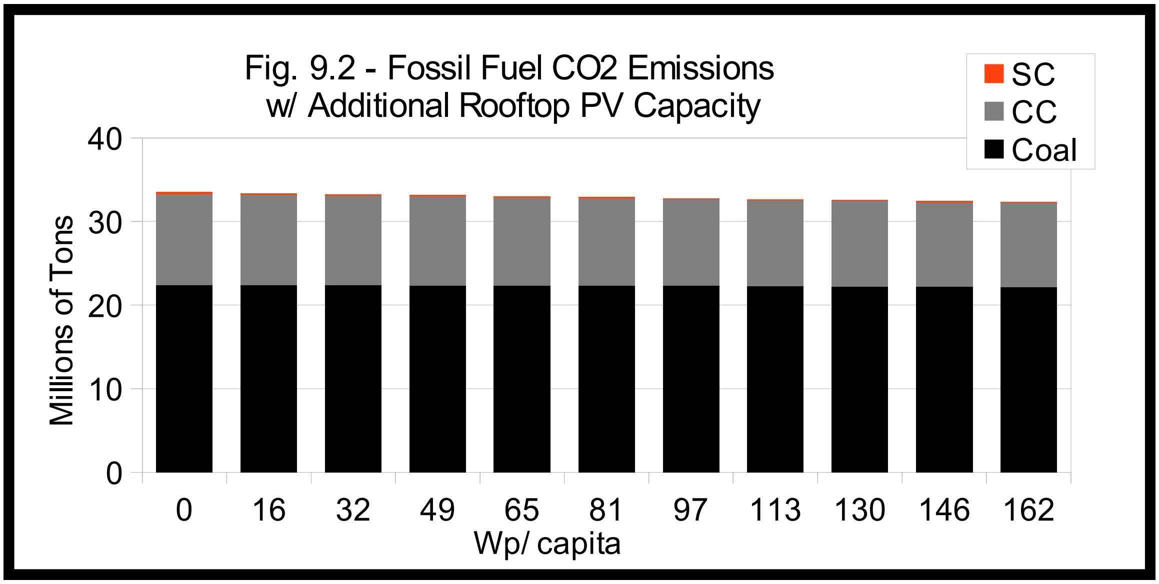


Fig. 9.3 - Shares of CO2 Emissions Reductions

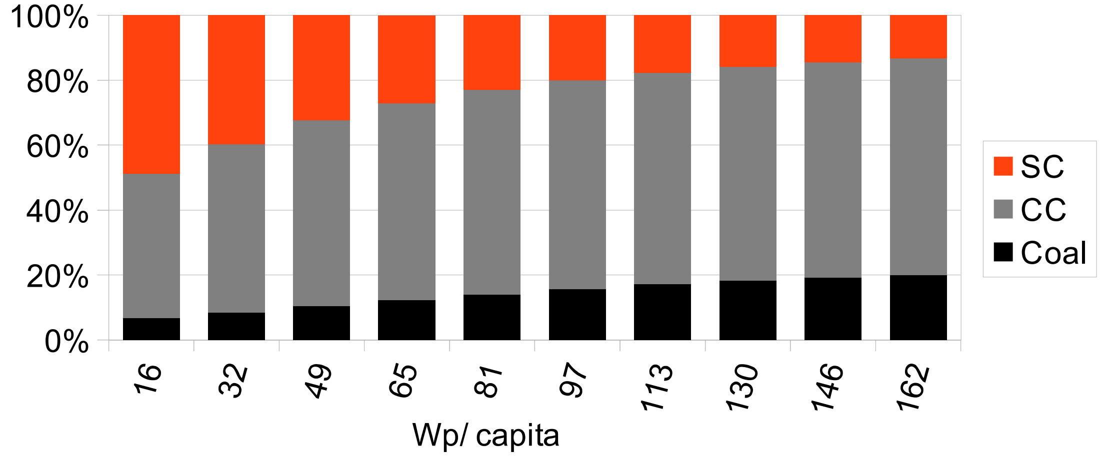
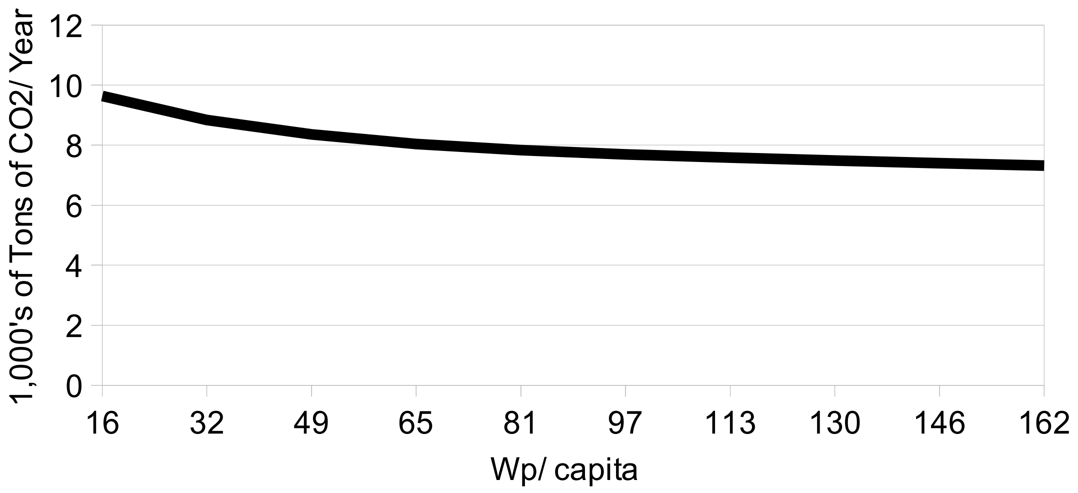


Table 9.1 and Fig. 9.4 show that as rooftop PV density increases from 16.2 – 162 Wp/ capita, the CO2 reductions/ Wp/ capita decline from 9,600 to 7,300 tons/ Wp/ capita. Although additional rooftop PV capacity increasingly impacts coal generation, there is also a progressively larger share of impacts to CC generation, which is the source with the least emissions. That means that additional rooftop PV capacity is progressively less effective at reducing CO2 emissions.

Fig. 9.4 - CO2/ Wp/ Capita



10. Conclusions & Discussion

Summary of Conclusions

In 2009 the region had about 1.62 Wp/ capita of rooftop PV capacity, which reduced electricity generation by about 21 MWh, and reduced CO2 emissions by about 12,000 tons. Oregon had the most rooftop PV capacity, and Idaho had the least.

Based on the regional distribution of rooftop PV capacity in 2009, additional capacity will usually displace natural gas generation, and each Wp/ capita of additional rooftop PV capacity will reduce CO2 emissions by about 7,000 tons per year. If, as planned, the region reduces its consumption from coal generators and continues to invest in conservation and natural gas generation, then it becomes only more true that rooftop PV capacity will displace natural gas generation. While more natural gas generators will facilitate the integration of rooftop PV capacity, they will also reduce the impacts of additional rooftop PV capacity on CO2 emissions.

The impacts of rooftop PV capacity are different during different seasons. During springtime, especially during high-water years, rooftop PV will exacerbate oversupply conditions. However, these impacts will be small and they may be mitigated by the same methods being developed to mitigate oversupply in general. A substantial quantity of rooftop PV generation occurs during high-price months of late-summer, which coincides with the use of air conditioning (which requires reactive power). With the right technology rooftop PV capacity can provide high-value reactive power; and with the right tariff structure the owners of rooftop PV capacity could receive exceptionally high prices for their systems' contributions to the grid.

Regional Energy Policy

Additional rooftop PV capacity will impact CO2 emissions, but there is no regional plan to maximize and focus those impacts. Each state has its own plan, but they share the same regional electricity system. Because it is worthwhile to install rooftop PV capacity in the best circumstances, this thesis offers some recommendations to maximize the impacts of rooftop PV capacity. Furthermore, CO2 emission reductions are one of the primary motivations for additional rooftop of PV capacity, so it is also essential to focus rooftop PV impacts on CO2 reductions. Fortunately, many of these recommendations for integrating rooftop PV capacity into the grid are prudent measures regardless of the extent of additional rooftop PV capacity, so they could be implemented with no regrets. This study calculates the impacts of typical, but idealized rooftop PV capacity. Because some rooftop PV capacity is located in less-than-ideal circumstances, this research probably over-estimates rooftop PV impacts. Yet, an examination of the causes of this over-estimation are revealing about how to achieve ideal results.

Maximizing Rooftop PV Impacts

Technical and social barriers limit the opportunities for additional rooftop PV capacity to a small group of participants. In addition to increasing the quantity of rooftop PV capacity, there are other means of increasing rooftop PV impacts by maximizing the quantity of electric energy generated from each Wp/ capita of rooftop PV capacity (i.e. increasing the ratio of MWh/ kWp). Some noteworthy factors, discussed below, are increasing PV module efficiency, maintenance, and optimal locations. These factors are relative to the rooftop PV capacity and its physical environment.

Module Efficiency

Module efficiency is the physical relationship between the physical quantity of rooftop PV capacity and rooftop PV generation. Early PV modules had very low levels of efficiency and so very physically large rooftop systems were necessary to generate the same quantity of electricity as is generated by modern PV modules. A large part of the recent success of rooftop PV capacity may be attributed to greater module efficiency (Tyagi et al., 2013), however, besides investment in research and development this factor is outside of the range of options available to regional planners. Lots of physical and industrial science investments are devoted to improving module efficiency of mass produced PV modules, and yet, this aspect of PV performance is probably overemphasized by comparison with other factors that also affect rooftop PV generation.

Maintenance

Rooftop PV systems are exposed to the forces of nature, and they require maintenance to sustain their performance. The PV modules are less effective over time due to a natural decay, and they are also subject to obstruction from dust and other debris.

Optimal Distributions

Some places are sunnier than others, so obviously, rooftop PV capacity in sunnier places produces greater impacts. Optimal locations may be identified for a wide scope of geographies.

Optimal Local Distribution

The local distribution refers to the locations of rooftop PV capacity within an urban area. Rooftop PV impacts are reduced when rooftop PV capacity is shaded

(Robinson & Stone, 2004; Vignola, n.d.) and solar resources vary within urban areas, depending upon ground-based obstructions such as tall buildings and tress. As rooftop PV density increases regional PV impacts diminish as ideal and available locations become occupied and rooftop PV capacity is forced to develop into sub-optimal locations. This effect could be mitigated by facilitating development in ideal locations. For example, enabling people with less-than-ideal rooftops to purchase shares of ideally located capacity and also enabling people with ideal rooftops to share their opportunity with other investors.

Rooftop PV generation will be maximized by structuring incentives to motivate the development of rooftop PV capacity on rooftops clear from shading by trees, buildings, or flagpoles. These rooftops are usually above commercial, public, or communal places such as stores, restaurants, offices, apartments, churches, military bases and schools. Some of these facilities have the physical potential to generate much more electricity than they consume.

Optimal Regional Distribution

The geographic distribution of rooftop PV capacity affects its impacts because different urban areas have different solar resources. Optimal regional distribution means encouraging rooftop PV capacity in urban areas with the best solar resources. On a regional scale cloudiness is the major factor determining the solar resource and areas east of the Cascades have better solar resources.

Achieving Optimal Distributions

Ownership Structures for PV Capacity

The rooftop PV capacity distribution is partly determined by the policies and practices at the intersection of the ownership of buildings, the ownership of rooftop PV capacity, and the ownership of rooftop PV generation. Rooftop distribution will be optimized by enabling consumers with less-than-ideal rooftop property to finance and utilize rooftop PV capacity on other rooftops.

Rooftop PV capacity may be owned and operated several different ways, and although a multitude of rooftop PV systems may have similar patterns of electricity generation they may have very different financial outcomes. Markets are intrinsically connected with ownership and transfers of ownership, and the markets for the products of rooftop PV capacity are new and dynamic. Two aspects of rooftop PV ownership that could influence the distribution of rooftop PV capacity are community solar and the structure of incentives.

Community Solar

Community owned solar has made solar ownership feasible for people who do not have ideal roofs (Asmus, 2008; Coughlin, 2010). It enables customers to own shares of PV capacity located away from their homes. Rooftop PV capacity has a physical structure and an ownership structure and the physical system may be 'de-bundled' from the ownership of the electricity that it generates. For example, some community solar models, a single investor finances the purchase and installation of the system, then sells shares of generation. In this way, a utility customer who is unwilling or unable to purchase their own rooftop PV system could buy a short term rent/ lease generation from a system. Community solar enables residents without access to good solar resources to buy shares of PV capacity.

PV systems are limited to consumers who meet all these conditions:

-own their homes

-have good credit or significant disposable income

-have good roofs

-have above average electricity demand (high-occupancy)

-occupy homes with suitable exposure to sunlight

Consequently, rental housing, apartments, low-income households, poor credit households, low-occupancy housing, and housing blocked by trees or buildings are not viable for PV deployment. Conversely, large buildings with high, flat roofs (schools, apartments, churches, offices) frequently have ideal exposure to sunlight, and could provide space for rooftop PV capacity. Hass (1994) notes that the owners of large apartment buildings have rights to lease rooftop space to a utility company, but that the tenants cannot.

Community owned solar enables any electricity customer to buy shares of optimally located solar power systems that are optimally located. Community solar divides the costs and benefits of PV systems so that consumers can choose how much capacity they would like to buy. For example, without community solar options a customer who lives alone in an apartment, or a low-income family renting a home, or a large family living in a home they own on a shaded lot, are be unable or unwilling to invest in PV systems. However, with community solar, each of those households would have more options for investing in rooftop PV capacity.

Incentive Structures

On both local and regional scales, the geographic distribution of rooftop PV capacity would be influenced by a shift away from capacity incentives ($/ kWp) and towards production incentives ($/ kWh).[1] Thereby, rooftop PV investors would receive financial compensation proportionately to their ownership and access to solar resources, rather than their access to rooftop space. By offering production incentives, ideal rooftops would gain value relative to other rooftops. Because the grid in the Pacific Northwest is constrained by both energy and capacity a mix of incentives for capacity and generation would compensate investors for both.

Focusing Rooftop PV Impacts

Maximizing rooftop PV capacity impacts is important, but research has found that rooftop PV impacts on CO2 reductions are even more affected by the coordination and synchronization of rooftop PV impacts and CO2 emissions (increasing the ratio of CO2 reductions/ kWp). This can be achieved by focusing rooftop PV impacts on coal generation and on simple-cycle generation. Coal generation produces the most CO2/ kWh of electricity, and simple-cycle generation is a strong indicator of grid-stress, which is when the grid is least efficient. Transportation is a major source of CO2 emissions and the electrification of transportation is another opportunity for rooftop PV generation to impact CO2 emissions.

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[1] See Oregon (2011, p. 40).

Focus on Coal Generation

Rooftop PV generation primarily reduces natural gas generation, however, CO2 emission reductions could be increased by focusing its impacts on coal generation.

Carbon Taxes

Carbon taxes are a widely regarded method of reducing coal generation because they connect the price of electricity with the cost of CO2 emissions. If the dispatch order discussed in chapter 3 were simply based on the average cost of generation, then carbon taxes could move coal towards marginal generation and increase rooftop PV impacts on coal generation. However, coal is inflexible and using coal for load following incurs additional maintenance costs and raises its CO2 emissions even further. If carbon taxes were sufficient to move coal to the margin, it would probably also motivate the retirement of coal with bio-fuels and natural gas generators. Consequently, carbon taxes are more likely to shift baseload generation to natural gas and therefore rooftop PV woulds still displace natural gas generation. However, additional rooftop PV capacity along with some other changes to the electricity system would reduce coal generation by increasing the likelihood and/or frequency of hours when the demand for electricity is met by a combination of natural gas and rooftop PV generation.

Focus on Simple-Cycle Generation

Rooftop PV impacts may be focused on CO2 emissions by synchronizing rooftop PV impacts with SC generation. That means rooftop PV impacts must become reliable sources of load-following generation. This can be accomplished by: a) shifting the peak-demand on the grid to match rooftop PV generation, and, b) shifting rooftop PV generation to match the grid-peak.

Recommendations to Integrate Rooftop PV Capacity

Denholm & Margolis (2007a, 2007b) identify three basic methods to synchronize rooftop PV generation with high-value opportunities, increased flexibility of generation, load shifting, and storage.[1] These are all methods of adjusting the timing of generation and use of electricity.

Flexibility of Generation

Rooftop PV capacity is one of several generation sources and it can be integrated by changing the capabilities of other generation sources so they can change generation more rapidly and more efficiently. Flexibility can also be improved by improving transmission and distribution networks to increase access to additional sources. The Pacific Northwest already benefits from the flexibility of hydro-power, but that flexibility is increasingly consumed by wind power. Additional flexibility will come from the planned additions of natural gas generation (NPCC, 2012) and new fast-response simple-cycle generation. WECC (2011) also reports that system operators have 'learned' from experience how to use wind power, a phenomena that may apply to rooftop PV. Although additional flexibility will improve the utilization of PV generation, because of morning, evening, and nighttime demands, high-density PV capacity will still require load shifting and/or energy storage (Denholm and Margolis (2007).

Load Shifting

Load shifting is the flexibility of use of electricity, essentially, the demand-side of

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[1] Bebic (2008, p. vi) makes the same claim, there described as, “balancing the generation portfolio, load control, and energy storage”.

generation flexibility. Increasing the flexibility of the timing and intensity of electricity consumption will focus rooftop PV capacity on CO2 emissions. Load shifting changes the pattern of electricity use and moves activities from high-cost hours to low-cost hours. As NPCC (2010a) explains:

> while the costs of providing electricity vary with power system circumstances that change from hour to hour and season to season, electricity consumers seldom see prices that reflect these "real time" costs. This disconnect leads to higher consumption at high cost times than is optimal, with over-investment in peaking capacity. (p. H-2)

There several mechanisms to compel load shifting, including voluntary changes, time of use (TOU) pricing, mandatory curtailments. Voluntary changes may be part of information and suggestion campaigns by utilities to persuade customers to reduce peak-use without financial incentives. Consumers may be compelled to take responsibility for some of the social costs of the timing of electricity use. Generally, these programs will be most successful for changes that have low costs for consumers. TOU pricing adds financial incentives to compel greater load-shifting, essentially offering participating customers a larger share of its benefits. Rooftop PV owners benefit from TOU rates that correlate to the system-benefits provided by PV capacity. Similarly, interruptible loads pay lower rates for their acceptance of limited reliability, and mandatory curtailments (such as rolling brown-outs) prevent the extraordinarily high costs of systemic failures. Spees & Lave (2008) found that:

> half of all possible customer savings from load shifting are obtained by shifting only 1.7% of all MWh to another time of day, indicating that only the largest customers need be responsive to get the majority of the short-run savings. (p. 111)

At certain times of year rooftop PV generation shifts daily peaks to different times of day.

Customers could be paid a higher rate for positive net electricity generation during peak-hours (Hass, 1994), a possibility with new smart meter technologies. This would provide the double benefit of avoiding the highest priced consumption and receiving the highest prices for generation.

Load shifting could be facilitated by developing methods of easily shifting thermal loads, which are sometimes flexible over the course of a few hours. Solar surpluses from rooftop PV systems can be used to heat water, which may be tedious to apply to residential water heaters, yet it would be feasible for larger commercial and industrial heating and refrigeration loads, or for district heating systems at institutions or municipal facilities. For example, by synchronizing and staggering the timing of thermal loads (e.g. refrigerators and water heaters) the demand for electricity can be moderated without significant variations of temperatures. This is probably a more cost-effective mechanism than battery storage of electricity.

Peak-demand/ load shifting is the subject of substantial research, because of its wide-ranging potential to improve several aspects of electrical system efficiency. Namely, it would improve the utilization of existing generation and transmission capacity, improve reliability, and reduce costs of operation. Yet, after numerous studies, regional planners are reluctant to affirm its potential for large savings (NPCC, 2010a, Chapter 5).

Energy Storage

Storage is a buffer between generation and consumption. Energy storage systems have many possible sizes and different configurations, and they may be located anywhere in the electricity system between fuel sources and final uses. For example, natural gas, coal, and hydro-electric reservoirs are all stores of energy, so are batteries and flywheels, and so are the banks of electric capacitors located in most substations. Energy storage raises the cost-effectiveness of rooftop PV by collecting electricity when it is most available and using it when it is most valuable. Energy has many forms, and depending upon the circumstances some are more easily stored than others. Rooftop PV capacity generates electricity and so the mechanisms that store its photo-voltaic energy must utilize electricity. Electricity storage (as electric charge, i.e. capacitors) has high cost, so the electric energy from rooftop PV capacity is usually used immediately as it is generated, transmitted to the grid, or converted into other forms of energy.

Storage has been bolstered by a recent notice from FERC regarding energy storage as a “recognized asset” (Gies, 2012). Therein, storage facilities are included in energy markets as power producers, which increases the opportunities to utilize otherwise wasted oversupplies and earn greater returns on intermittent electricity by moving it to displace the costliest generators.

Electricity storage delays the use of electricity, and because the summertime peak-demand for electricity usually extends past sundown, distributed daily-scale storage could effectively extend rooftop PV impacts into early evening hours. Batteries are one type of electricity storage, and they may be more cost-effective if they are integrated with electric vehicles. They may be charged by day at work-places, and then provide electricity after sunset.

Because seasonal oversupplies usually coincides with minimum prices for wholesale power, “ideally” people could develop storage capacity that carries springtime surpluses forward to expensive late-summer and wintertime demands. But holding electricity for that long is prohibitively expensive by comparison with the alternatives, such as additional peak-generator capacity or transmission, so although it is reasonable to use electricity storage to shift hourly and daily variations, it is not a viable option for seasonal variations (Eyer & Corey, 2010).

Flywheels are another storage option found to reduce emissions by providing voltage regulation and reducing the use of natural gas generation. Eyer & Corey (2010, p. E-8) predict that, “high-speed flywheel storage systems have a good chance of being a financially viable regulation resource.” Coupling batteries and fly-wheels with rooftop PV capacity could provide a low-impact option to optimize PV generation.

And yet, overall, most urban areas have sufficient demand for electricity during daylight hours that large quantities of energy storage are not especially valuable for the integration of grid-connected rooftop PV capacity. Eyer & Corey (2010) explain, “for situations involving grid-connected solar generation, a lot or even most electricity is produced when energy is already valuable, making energy time-shift relatively unattractive.” With net-metering, the grid provides a type of 'virtual storage' for electricity that is not useful at the site where it is generated. Thereby, a financial accounting mechanisms is used to store and spend the electricity from rooftop PV capacity.

Micro-grids

Overall, the best solution to maximize and focus rooftop PV impacts on CO2 emissions will be a mix of these mechanisms. Micro-grids coordinate generation flexibility, demand-shifting, and storage together relative to the electricity grid. Developing micro-grids is one way of reducing the variability of rooftop PV impacts managing local demands for ancillary services. Micro-grids include generation, coordinated patterns of electricity consumption, and storage capacity.

Rooftop PV generation will add electric energy to the grid, but without attention to integration, it will probably increase the need for ancillary services. With the correct mix of technologies, however, rooftop PV capacity could actually provide ancillary services to the grid (Braun, 2008; Andreotti, Del Pizzo, Rizzo, & Tricoli, 2010). Rooftop PV capacity has been shown to be able provide both active and reactive power (Clastres, Ha Pham, Wurtz, & Bacha et al., 2009), and because power factor corrections must be provided by generators located close to demand, that distributed energy resources like rooftop PV capacity are well-positioned to provide them (Vizoso, Piegary, & Tricoli, 2010). They (ibid.) explain that PV inverters can be designed to provide real-time reactive power without signals from the system operator and explain that, "many major power outages are at least partially attributable to problems related to transmitting reactive power to load centers." Therefore, when distributed generation can provide reactive power it can improve grid reliability. And although the details of using rooftop PV capacity for reactive power compensation are not well understood, Eyer & Corey (2010) propose that:

> there are exploitable synergies between the localized need for reactive power (usually near loads) and increasing emphasis on DER [distributed energy resources]. Perhaps more importantly, aggregated DER capacity (if dispatched in a coordinated way) could be part of a robust approach to region-wide grid stability during major power interruptions involving declining area-wide or system-wide voltage. (p. C-5)

They (ibid.) also note that because air conditioning equipment is a major cause of reactive power, rooftop PV capacity could be a valuable component of voltage regulation during hot summer days when the grid is most stressed.

Extensions of this Research

This research has identified some questions without obvious answers.

Locational Differences

This thesis has concluded that most of the region's rooftop PV capacity is located around the urban areas of Portland and Seattle. These areas receive the least sunlight, and rooftop PV capacity located in these areas is less productive than the same capacity located in eastern areas of the region. How significant are the differences of solar resources with regard to rooftop PV impacts on CO2 emissions? Would it be worthwhile to structure the region's rooftop PV policies to compel more development in the eastern areas of the region?

Predictability

Rooftop PV generation is currently unpredictable, and its variations become less problematic if they are more predictable. Dragoon & Schumaker (2010) assert that partly-cloudy days are the most problematic for PV integration. Basically, on sunny days, PV is a variable but predictable resource that could be incorporated into load forecasts. Vignola, Grover, Lemon, & McMahan (2012) explain the importance of accurate solar datasets to improve the reliability of predictions of PV generation and raise the likelihood of investment in PV capacity. More research into predicting rooftop PV generation would improve its viability as a regional source of electricity.

Variability

WECC (2012, p.3) suggests that grid operators could indirectly manage variable generation by, "transferring some of the responsibility for managing the variability and uncertainty of the resource to the load". By transferring responsibility, both producers and consumers of electricity would pay for variability, and get paid for reducing it. What mechanisms are most effective for measuring variability?

Probability

Because rooftop PV is a variable resource, another approach to estimating rooftop PV impacts is statistical probability analysis. Power system reliability has always included an element of probability and power system managers continuously adjust generation and transmission resources to accommodate unexpected variations. Meyer & Luther (2010) have found that PV capacity corresponds with high wholesale prices, and a similar approach could be developed to determine correlations between the hours with "peak-sunlight" and the hours with peak demand for fossil fuel generation.

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Appendix A. Fossil Fuel Generation Profile Details

The data for the fossil fuel generation profile is from the U. S. Environmental Protection Agency's (EPA) Continuous Emission Monitoring System (CEMS) (EPA, 2009 – 2010). The CEMS includes hourly data for generation (MW) and CO2 emissions (tons) for all electric generation emissions sources over 25 MWp. CEMS data is an accurate measure of fossil fuel generation and emissions (Holland & Mansur, 2008). CEMS data is better than modeled generation and emissions data because it provides actual outputs, instead of hypothetical outputs. For the region defined in this thesis, the CEMS data includes 42 fossil fuel turbines at 24 facilities. Additional information about these turbines was obtained from the NPCC "Projects" database (NPCC Projects, n.d.).

Fig A.1 orders the regional generators by their average heat rates, and shows that most CC generators have the same heat rate (around 7,000 Btu/ kWh), and that coal and SC generators have higher heat rates.

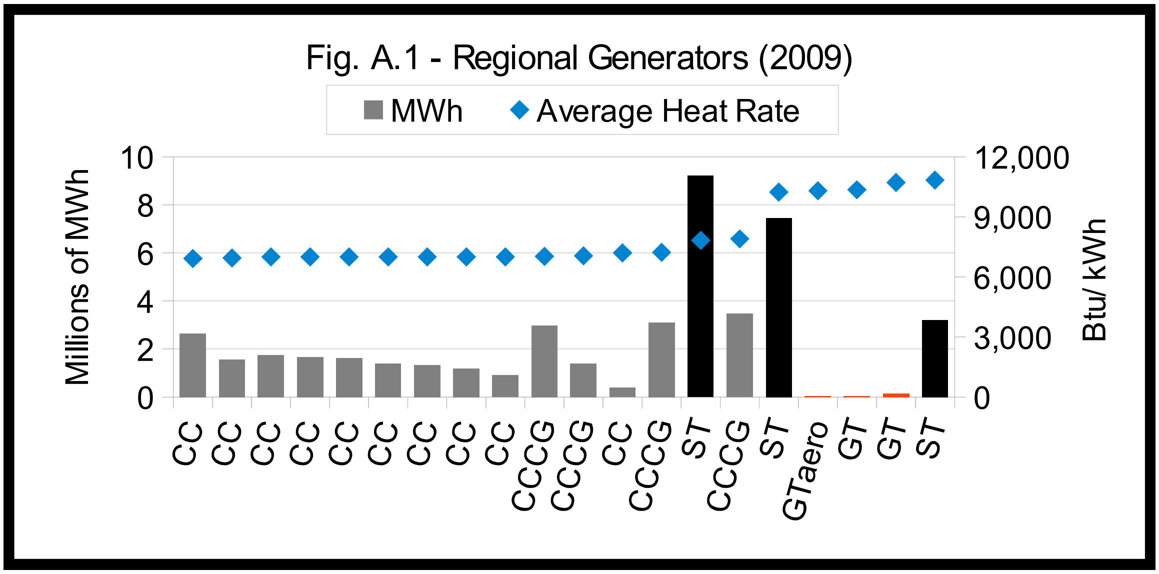
Fig. A.1 - Regional Generators (2009)

Table A: Regional Generators

NPCC Unit ID	EPA CEMS Unit ID	CEMS Name	State	Initial Service Year	Type	Nameplate Capacity (MW)	Average Heat Rate (Btu/kWh)	NPCC 2009 (Mwh)	NPCC 2009 (Mwh%)
COAL STEAM TURBINES									
1107-8	1,2,3,4	Colstrip*	MT	1975	ST	502	7,819	9,208,424	20.24%
1086-7	BW21, BW22	Centralia	WA	1972	ST	730	10,240	7,450,380	16.37%
1044	1SG	Boardman	OR	1980	ST	601	10,840	3,200,203	7.03%
COMBINED-CYCLE COMBUSTION TURBINES									
1248	CTG-1, CTG-2	Hermiston Power Plant	OR	2002	CCCG	689	7,900	3,466,420	7.62%
1246	1, 2	Hermiston	OR	1996	CCCG	235	7,220	3,098,149	6.81%
1290	CT1, CT2	Klamath Cogeneration Project	OR	2001	CCCG	536	7,020	2,981,729	6.55%
1443	PWEU1	Port Westward	OR	2007	CC	399	6,925	2,648,148	5.82%
1089	CT1, CT2	Chehalis Generation Facility	WA	2003	CC	593	7,000	1,747,270	3.84%
1228	1, 2	Grays Harbor Energy Center	WA	2008	CC	650	7,000	1,675,175	3.68%
1475	1	River Road	WA	1997	CC	248	7,000	1,624,892	3.57%
1131	CGT2	Coyote Springs	OR	2003	CC	287	6,950	1,559,368	3.43%
1368	CTG1	Mint Farm Generating Station	WA	2008	CC	319	7,000	1,392,577	3.06%
1130	CTG1	Coyote Springs	OR	1995	CCCG	266	7,050	1,391,263	3.06%
1219	CT-1	Goldendale Generating Station	WA	2004	CC	280	7,000	1,340,543	2.95%
1305	CTGEN1	Rathdrum Power, LLC	ID	2001	CC	270	7,000	1,187,856	2.61%
1200	F1CT	Frederickson Power LP	WA	2002	CC	318	7,000	911,040	2.00%
1028	30, 40, 50, 60	Centralia	WA	2002	CC	322	7,200	378,695	0.83%
SIMPLE-CYCLE NATURAL GAS TURBINES									
1201	CT3, CT4	Fredonia Generating Station	WA	1984	GT	129	10,710	149,533	0.33%
1467	1, 2	Rathdrum Comb. Turbine Project	ID	1994	GT	83	10,350	44,326	0.10%
1291	GT1, GT2, GT3, GT4	Klamath Energy LLC	OR	2002	GTaero	50	10,300	42,836	0.09%
TOTALS	**37**	**20**				**7,508**		**45,498,827**	**100%**

The data from CEMS and from the NPCC do not match perfectly, mostly because they use different methods to measure co-generation facilities. However, they are very close. For 2009 the total fossil fuel generation recorded by CEMS was 44,779,178 MWh (Table 1.2), which is 98.4% of the generation data recorded by the NPCC (45,498,827 MWh). Hourly CEMS data for generators in MST were shifted to PST.

Exceptions

Most of the electricity generated by these turbines is distributed and used by residents of the region. There are three exceptions:

Encogen

The Encogen natural gas turbine is excluded because it is part of a must-run co-generation facility that is unaffected by changes of system-load (NPCC Correspondence).

Colstrip

Although the Colstrip coal generation facility is located outside of the geographic region (Fig. 1.2), it is included as a regional generator because most of its capacity is owned by utilities in the region, and its electricity is transmitted to utilities in the region. Shares are owned by Puget Sound Electric (Seattle & Tacoma), Portland General Electric (Portland), Avista (Spokane), NorthWestern (Missoula), and Pacific Power(Yakima & Redmond). The generation from Colstrip to the region is adjusted as follows (NPCC Correspondence):

Units 1 & 2: 50%

Units 3 & 4: 70%

Southern Idaho Peakers

The "peaker" SC generators located in southern Idaho (Bennett Mountain Power Project and Danskin/ Evander Andrews Power Complex) are excluded from the regional generators because they are not well connected with the rest of the region. These generators were built for that reason, to provide peak power to southern Idaho. Furthermore, Idaho has a very small share of regional rooftop PV capacity, and the rooftop PV impacts from other areas would probably not reduce generation there. This constraint would be alleviated by the completion of the proposed Boardman, OR to Hemingway, ID transmission line project (B2H), which would also enable SC generation in Idaho to serve loads in Oregon and Washington (BPA, 2012).

Appendix B. Rooftop PV Generation Profile Details

The rooftop PV generation profile is created by applying solar resource data to the urban rooftop PV capacity profile. This process has three main steps.

First, hourly solar radiation data from 2009 for the twelve urban areas (Table 4.2) was retrieved from the 1990—2010 National Solar Radiation Database (National Renewable Energy Laboratory, 2012). Their data includes modeled, hourly, Global Horizontal Irradiance (GHI) data that is widely used to simulate solar resources. The SUNY data set was selected for its accuracy and consistency (Wilcox 2012, p. 3).

Second, these solar radiation data were input into the NREL's Hybrid Optimization Model for Electric Renewables (HOMER) and converted into hourly PV generation profiles. HOMER has been used in a number of studies of PV generation (Lambert, Gilman, & Lilienthal, 2006; Denholm & Margolis, 2007a & 2007b; Fantidis, Bandekas, Potolias, & Vordos, 2013)), and it has been found to produce similar outcomes as other PV system models and to accurately model actual PV systems (Lee, Frearson, & Rodden, n.d.). Rooftop PV generation from 1 kWp of capacity was calculated for each urban area (Fig. 5.1). Rooftop PV capacity was assumed to be typical, but idealized, rooftop PV systems (unshaded, well-maintained, fixed-axis PV capacity, tilted at latitude). Although they overestimate rooftop PV generation, these are typical assumptions for the analysis of PV impacts (Asano, Yajima, & Kaya, 1996). The derate factor adjusts the AC output from the PV systems to account for electricity used by the PV systems' wiring and electronics. The physical characteristics for the rooftop PV systems were copied from the default values for the PV Watts solar power estimator

(Changing System Parameters, n.d.):

– Nameplate, Mismatch, DC wiring, AC wiring, System Availability = 0.89 (89%)

– Inverter Efficiency = 0.90 (90%)

– No adjustments for soiling or for aging

Total Derate Factor Adjustment = 0.80 (80%)

Third, each urban area's rooftop PV generation profile was multiplied by its corresponding rooftop PV capacity (Table 4.2). These twelve profiles were then combined into a single, regional, urban rooftop PV generation profile (Fig. 5.3).

Caveats

Because this profile is developed from hourly averages of solar radiation, it essentially removes intra-hourly variations of rooftop PV generation and shows the rooftop PV impacts abstracted into hourly totals. Although intra-hourly variations of rooftop PV generation are a worthwhile concern, they will probably not have major impacts upon the regional generators. Some research has found that the helpful and harmful impacts of intra-hourly variations on ancillary services depend upon the configuration of the rooftop PV systems. It is more likely that these generators will be affected by whatever rooftop PV impacts are sufficient to cause the demand for electricity to vary from one hour to the next. These hourly variations are usually characterized by a mid-day peak. However, the ancillary services that facilitate hourly variations, such as spinning-reserves and dispatch orders, are more likely to be affected by the hourly variations shown by this model.

Also, because this model is comprised of twelve point sources across the region, instead of showing the impacts of thousands of variously sized rooftop PV systems scattered around the region, it probably overestimates the variations of rooftop PV generation. In reality, a broad spatial distribution of PV capacity has less variation than any one system, because intra-hourly variations of intermittent resources over a broad area tend to balance out (Dragoon & Schumaker, 2010, pp. 7 – 9).