IB Extended Essay

"The Potential of Residential Solar Power Systems to Meet the Grid Demand in Canberra, Australia"

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Abstract

The aim of this IB Extended Essay is to investigate the potential of residential photovoltaic (PV) solar power systems to best meet Canberra's own grid demand. Canberra, the capital of Australia, experiences an arid and sunny highland climate. In addition, it has a lot of residential roof space to suit PV systems. The electrical grid demand in Canberra is very seasonal, with strong winter morning and evening peaks and summer afternoon demand shoulders. This investigation looks at the possibility of contributing the most amount of solar energy to the Canberra grid from many distributed residential PV systems but without ever having to export or store solar energy due to overproduction.

To achieve such grid saturation by solar power, one would need to limit the total capacity of all PV systems to cover Canberra's grid demand at the point where maximum solar irradiation and minimum grid demand coincide, being on or around the summer solstice. Having assessed true grid demand and weather data for a full year (FY0809), the maximum possible net solar power generation capacity and net solar energy contribution to the grid for summer solstice were calculated to be 153MW and 41.5% respectively. This amount of solar power generation can be met easily, using only a quarter of the available residential roof area in Canberra. When operating such a distributed PV system all year round, the maximum net *annual* solar energy contribution would reach 25%. Furthermore, it was found that the net solar energy contribution cannot be increased by changing panel orientations towards east or west because grid demand around noon is flat and irradiation peaks only shift by about one hour compared to using "solar-perfect" north-facing roofs. Ultimately, the annual solar contribution could be significantly increased when combining with the Snowy Mountains Scheme for energy storage.

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Statement of Authenticity

I confirm that this IB Extended Essay is entirely my own work and that I have acknowledged information provided by, and/or used from third-parties.

Acknowledgements

I would like to thank Louise from the Bureau of Metrology and Marina from ActewAGL for the supply of the respective climate and grid demand raw data for Canberra, my essay supervisor Cate Rosier for her input, my family for their patience and especially my father for giving me the opportunity to jointly install and monitor our own residential PV system, which inspired me to write this essay.

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1. Introduction

Energy is present everywhere. It can be found in the form of heat, light, mobility or as food. The human lifestyle adopted in developed nations has adapted itself so much that, as shown in Figure-1, it relies heavily and increasingly on energy consumption. Power stations generate electricity, motorcars use transport fuels and factories continuously produce products we use daily. The majority of these processes, however, use some sort of fossil fuel. In Australia electricity is made mainly from coal, most cars are powered by fuels derived from crude oil, and factories use electricity and/or natural gas to manufacture their products.

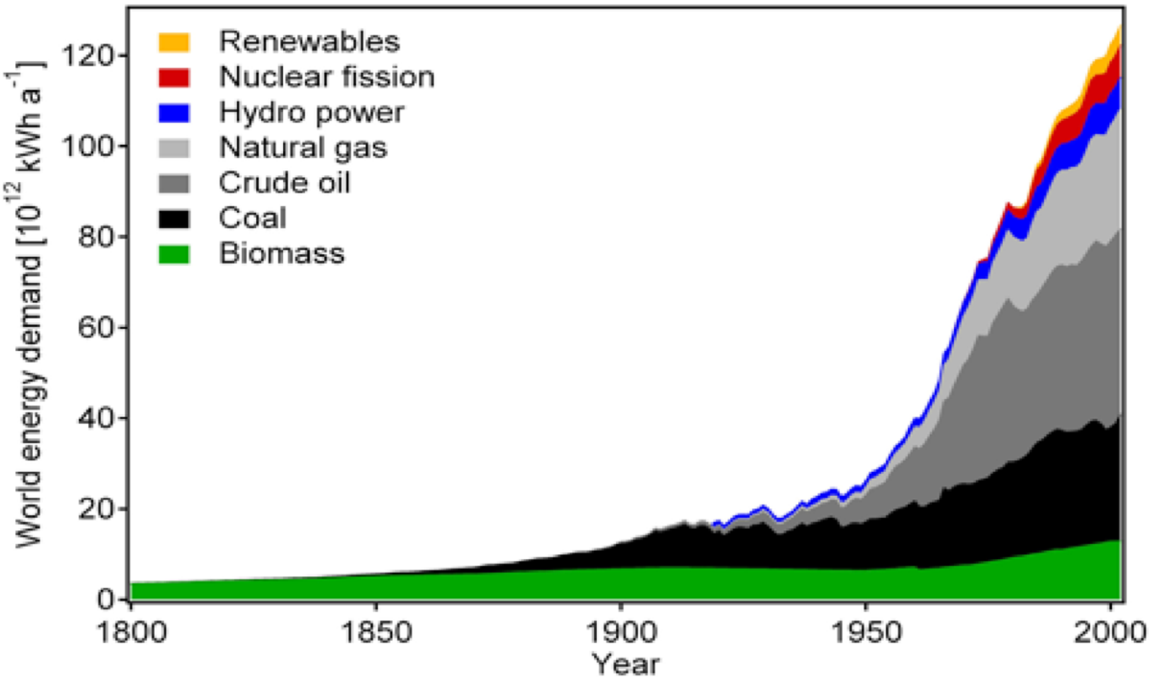

Figure-1: World energy demand growth: The graph shows the historical development of the world energy demand growth over the past two hundred years, confirming the very heavy dependence on fossil fuel energy resources being mainly coal, crude oil and natural gas [Source of graph: Hydropole, 2010].

We use more and more fossil fuels for our daily needs. All these fossil fuels are burned, which not only produces energy but also pollutants. In addition to this they all release greenhouse gases, most commonly carbon dioxide (CO_2). These greenhouse gases trap the heat in the earth's atmosphere. The end result is climate change in general and global warming in particular. In addition and on a global scale, fossil fuels are becoming more and more scarce. This means that from an environment and society point of view the world has to start to focus on renewable energies, like wind power, solar energy, ocean energy from waves or tides, biomass and geothermal energy [Rutherford, 2009].

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As part of this picture and as individuals, we can and should focus on the use of residential photovoltaic (PV) solar power systems. Such systems involve a collection of PV solar panels that are connected to the electricity grid by means of a smart power inverter. In most cases and particularly in Canberra, roof-mounted PV systems can easily cover the electricity consumption of a residential dwelling.

Being the capital of Australia, Canberra is a city with around 350’000 inhabitants. It is a planned city that started back in 1913 as the result of an international competition among city planners and architects. Canberra is growing steadily and receives all of its energy from interstate. The local government introduced a Feed-in-Tariff (FiT) in March 2009, primarily for small renewable energy generators including residential PV systems and for the reasons of stimulating the installation of such systems.

What would happen if the number of residential PV systems dramatically increased? What challenges would this bring to the electricity infrastructure? Could Canberra even cover all of the grid demand by PV systems? These are some “big-picture” type questions, which cannot be answered in the scope of this essay.

Instead, this assessment focuses rather on the general question of how much solar power could be produced on existing residential dwellings and without changes to the grid, energy storage or import-export options.

2. Method & Assumptions

In order to study and understand the potential of residential PV systems in Canberra, some boundary information must be given and assumptions defined. Firstly, an understanding of the photovoltaic effect and how residential PV systems work is considered helpful. Secondly, since this project focuses specifically on the case of Canberra, it is necessary to generate an overview about available residential dwellings and the orientation of their roofs with respect to suitability for residential PV systems. In addition and thirdly, a basic understanding of Canberra's location and average climate is required. More specifically, it was chosen to study Canberra's climate data as measured by Australia's Bureau of Meteorology (BoM) for the most recent full-year period available, being the financial year 2008-2009 (FY0809). Finally, the solar irradiation data is vital to quantify the performance of residential PV systems and to compare their performance directly with Canberra's real grid demand data that has been supplied by ActewAGL Pty. Ltd. (ActewAGL) for FY0809.

2.1. Photovoltaic Systems

The discovery of the photovoltaic (PV) effect dates back to the 19th century. Becquerel accidentally stumbled across the photovoltaic effect in his experiments from 1839. However, it was in 1887 that Hertz established that the combination of specific metals with semiconducting properties would result in an electric charge when hit by electromagnetic waves [PV Resources, 2010]. Figure-2 illustrates and explains how the PV effect works.

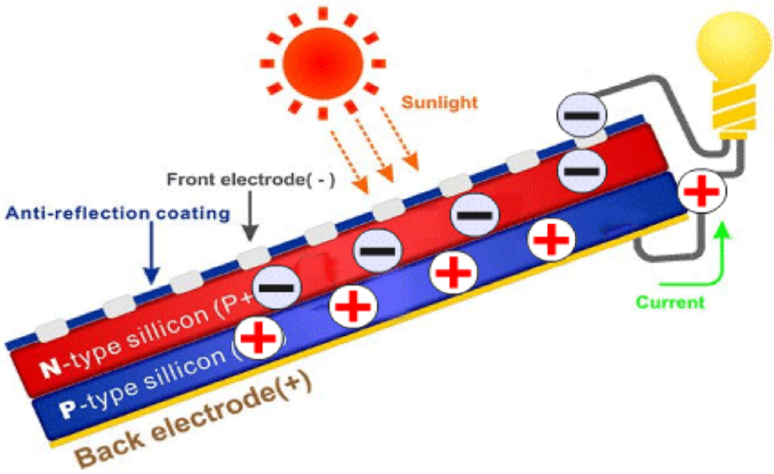

Figure-2: Photovoltaic effect: Modern PV panels employ two individually polarised semiconductor layers that are combined in a so-called junction. One layer is negatively (n) polarised or charged, the other positively (p). When sunlight hits the junction, it excites the electrons in the vicinity of the junction and generates an amount of free electrons that are drawn to the n-conductor. This surplus of electrons in the n-conductor flows toward the negative front electrode and through a load of an external electrical circuit when connected to the positive back electrode of the PV cell. The PV effect only works with a specific high-energy range of light from the solar spectrum such as the visible and near-infrared light, very much depending on the semiconductor materials chosen [Source of graph and information: Sunnywin Energy, 2010].

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Figure-3 shows a residential PV system installed on the roof of a Canberra home. These systems respond very quickly and highly linear to the amount of solar irradiation that the solar panels receive. PV panels therefore operate very reliably from sunrise to sunset.

Figure-3: Residential PV system: Such systems comprise a number of roof-mounted solar panels, which are connected in series to produce direct current (DC) of around 200-300 Volts. An inverter (red box on the left of the house) accepts the DC power, converts it to alternating current (AC) and synchronises with the electrical grid to feed AC solar power back into the supply network of the electricity utility via switchboard (grey box next to the red inverter) [Source of picture: Own photo].

According to a report by the Worldwatch Institute [Worldwatch Institute, 2010], a cumulative amount of 21 Gigawatt (GW) of PV power has already been installed worldwide by the end of 2009. This power generation capacity is comparable with Australia's nationally installed coal-fired power generation capacity, hence capable of delivering clean solar power to more than 20 million people. Market trends continue to show continuous growth for PV systems.

2.2. Residential Buildings in Canberra

The Australian Bureau of Statistics (ABS) distinguishes between four different types of residential dwellings, namely separate houses, semi-detached houses, townhouses and flats. According to its 2006 Census [Australian Bureau of Statistics, 2010], there were 83'447 residential dwellings in Canberra. Of these the vast majority, 71'120 or 85%, were separate houses with a typical floor area of between 150 and 180 m^2. Residential houses in Canberra are generally single-story brick-veneer designs with gable roofs.

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If considered from a solar energy aspect, there are basically two main types of suburbs in Canberra namely well-established older ones and newer ones. Most importantly for this study, however, is the fact that the amount of shade from trees differs strongly. Studying Canberra's suburbs from the air via Google Maps (refer to Figure-4), it is considered a fair assumption that both types of suburbs comprise roughly half of the total residences given in the 2006 Census, hence around 35'000 separate private dwellings each.

Maps removed for copyright reasons

Figure-4: Canberra suburbs: Aerial views of two typical residential suburbs (on the left hand side an older suburb, Garran, built some 30-50 years ago and featuring fully-grown trees that provide ample shade, and on the right hand side a more recent suburb, Ngunnawal, with comparably limited gardens and vegetation): It is common for private residences in Canberra to face the street, with suburban roads designed in a non-structured manner, resulting in Canberra not having a prevailing house orientation. In both views shown above, magnetic north is at the top of the page [Source of aerial pictures: http://maps.google.com.au, last accessed on 4th of July 2010].

Overall and for the purpose of this study, it was therefore assumed that:

- Canberra has some 70'000 private dwellings that are potentially suitable for residential PV systems, which are all separate private dwellings. All semi-detached houses, townhouses and flats are not considered any further in this study;
- Of these 70'000 separate dwellings, 35'000 are located in newer suburbs and therefore largely unshaded, while half of the second set of 35'000 dwellings are shaded by large trees and hence not really suitable for residential PV systems. Nevertheless, the rest of this second set of dwellings (17'500) are also assumed to be largely unshaded and therefore suitable for residential PV systems; and
- The average roof size of each private dwelling measures about 160 m^2, of which it was assumed that a quarter each faces approximately north, west, east and south respectively. Considering that PV systems are better not placed to the very edge of the roof lines in order to omit extreme wind forces and to allow access for maintenance, this study further assumes in addition that the available net roof area for PV systems be reduced by 25%, down to 120 m^2 each dwelling.

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These assumptions lead to the cumulative potential of ideal *north-facing* roof areas that are suitable for residential PV systems in Canberra of around 1.575 million m^2. This roof area is equal to about 220 international standard-size soccer fields. In addition, about the same area would be available for both west- and east-facing roofs of private residences in Canberra.

2.3. Weather in Canberra

Canberra is located in the southern hemisphere, in Australia. The city is 580 metres above sea level and lies on the coordinates of 35.30 degrees North, 149.20 degrees East. Although the city enjoys a climate with four distinct seasons, its climate is relatively arid. According to the BoM [Bureau of Meteorology, 2010a], Canberra's annual average number of daily sunshine hours is 7.6 h/d, ranging from 9-10 hours per day in summer to 5-6 h/d in winter.

Particularly relevant for this study in terms of climate, however, are the values for solar irradiation and ambient temperature. This is because the output of the residential PV system is directly and swiftly following the solar irradiation input to the PV panels. In addition, the efficiency of PV panels reduces linearly with increasing ambient and therefore panel temperature, which is called "negative temperature coefficient" (NTC). Depending on PV panel technology, NTCs vary from 0.25% per degree Kelvin (K) to 0.5%/K [Bosch Solar Energy, 2010]. Assuming the same amount of solar irradiation, say blue-sky conditions, PV panels are therefore more efficient in winter when ambient temperatures are low than in summer.

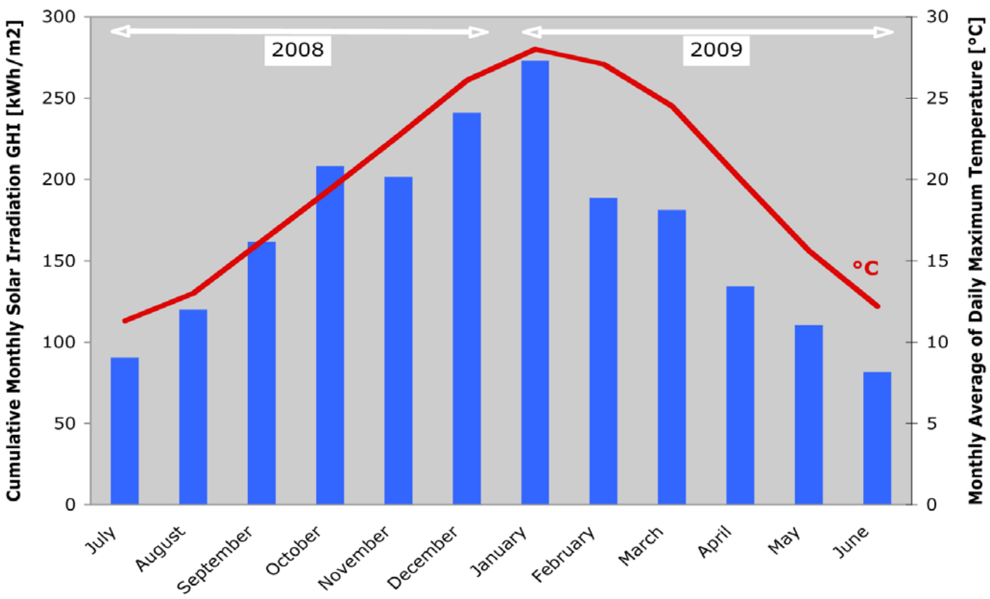

Figure-5: Canberra solar weather: Comparative illustration of cumulative monthly solar irradiation (GHI) and monthly averages of maximum daily ambient temperatures. GHI includes all direct, indirect and diffuse solar irradiation seen by a horizontally mounted radiation sensor. The above data has been compiled using real weather data measured, and supplied for this study, by the Australian Bureau of Meteorology for the period between 1st of July 2008 and 30th of June 2009 (FY0809) [Source of data: BoM; Source of graph: Own graph].

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Figure-5 shows the monthly variations of cumulative solar irradiation in kWh/month and the related monthly averages of maximum daily ambient temperature for Canberra given in degrees Celsius. This data has been selected and prepared using real measured climate data provided by the BoM for the time period of FY0809 [Bureau of Meteorology, 2010b]. As Figure-5 shows, the amount of solar irradiation measured on a horizontal surface (GHI) during peak summer of FY0809 (December and January) was almost three times as much as measured during the middle of winter (June and July).

2.4. Grid Demand in Canberra

The grid demand in Canberra is very seasonally dependent. Maximum demands occur during extreme weather situations in summer and winter while autumn and spring experience relatively balanced grid demands. Figure-6 illustrates calculated average demand curves for each month of FY0809 using raw load data supplied by ActewAGL [ActewAGL, 2010].

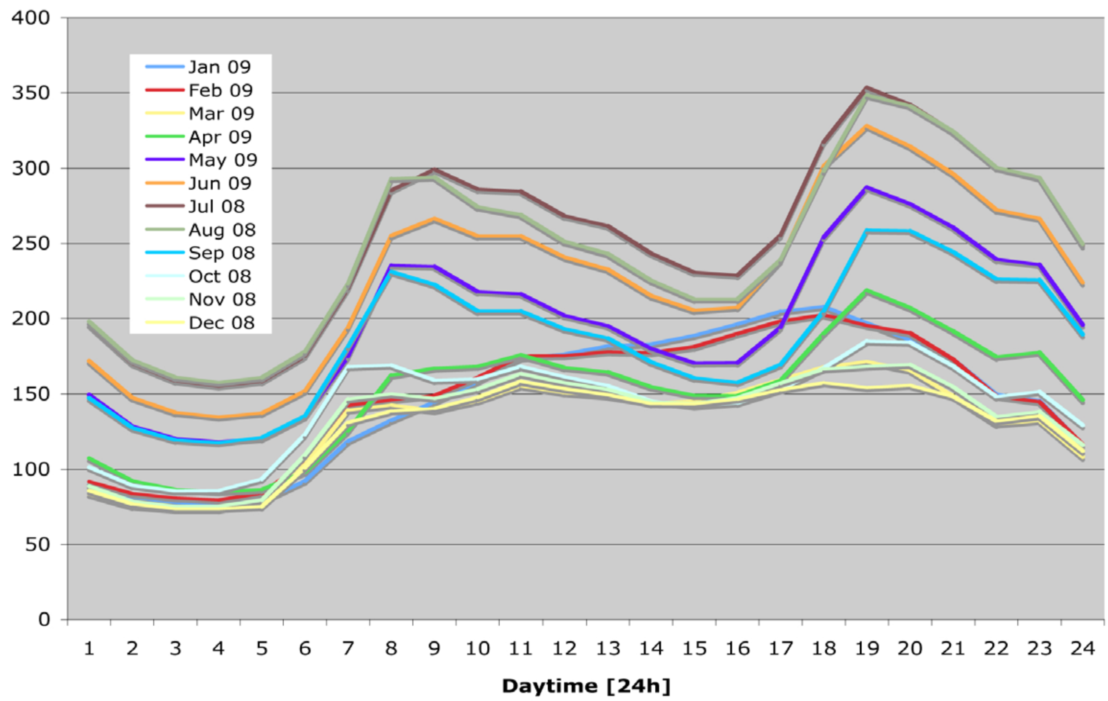

Figure-6: Canberra grid demand: Average monthly grid demand curves during the financial year 2008-2009: In winter, the grid demand has two distinct morning and evening peaks, mirroring much increased power consumption at home before and after work. This is mainly the result of comparably poor housing from an energy-efficiency point of view, which necessitates bursts of space-heating when ambient temperatures are below comfort levels. Autumn and spring experience comparably constant grid demand curves, with large increases only occurring during unexpectedly hot or cold individual days or short periods. In the two main summer months, peak demand shoulders can be observed, which rise steadily from morning to early evening. This is due to air-conditioning. Generally rare and hence not showing up explicitly as part of the average monthly data are demand peaks resulting from short periods of cold snaps or heat waves. [Source of data: ActewAGL, 2010; Source of graph: Own Graph].

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Canberra typically has a morning and an evening demand peak generated by residences. The only exceptions are the two summer months of January and February, during which a gradual ramping up of the demand from morning to evening occurs due to air-conditioning at work, peaking at about 200MW. In stark contrast to summer months, the morning and evening load peaks during winter months are extreme, with morning maxima of up to 300MW and evening peak demands of close to 350MW. The three winter months of June, July and August are most pronounced. During the winter half-year from April to September the morning demand peaks occur at around 8am, whereas for the other months during the summer half-year the morning demand peaks are at around 7am. The shift of the peak demand is due to daylight savings only. At around 7pm, the evening demand peaks, which is shown in most monthly demand curves. Towards the end of the graph between 10pm and 11pm, there is a slight all-year-round shoulder in the demand curve resulting from the initiation of off-peak tariffs.

2.5. Grid Saturation

An additional but very important assumption of this study concerns the limitation of solar power. It was chosen to limit the maximum amount of solar power that can be cumulatively installed on Canberra's residential dwellings by the concurrent load demand of the Canberra grid. This means that the total amount of solar power produced at any given time can only lead to grid saturation and hence there would not be any need or option for energy storage or export to the neighbouring state of New South Wales. All of the solar power would always be used instantaneously for Canberra's own consumption of electricity. Hence there shall not be any over-production.

3. Calculations & Optimisation

Based on the methods and assumptions provided in the previous chapter, it is now aimed to identify the maximum possible PV system capacity that can be installed in Canberra using "solar-perfect" north-facing residential roofs, to quantify the resulting solar power contribution as a percentage of the total grid demand, and to study possibilities of how to optimise the solar output by varying PV panel orientations. This would involve the use of east- and west-facing residential roof areas, either on their own or in combination with north-facing roofs.

3.1. Maximum PV System Capacity

The PV system performance limitation given by the condition of grid saturation (refer to Chapter 2.5) can only be satisfied for the time when maximum solar production coincides with a typical minimum grid demand curve. Following the average grid demand curves shown in Figure-6, minimum grid demand in Canberra occurred in November and December 2008. Given that the longest day of the year and therefore the highest position of the sun in the sky occurs on the 21st of December (summer solstice), the sunniest day around this date and the average grid demand curve for December 2008 were chosen to calculate the maximum PV system design capacity possible for Canberra when using north-facing residential roofs only. In addition and as typical for Canberra, it was assumed that all north-facing roofs are sloping at an angle of 22 degrees. At 12pm noon, when the solar radiation is at its maximum, the average demand profile for December 2008 stood at 153MW (refer to Figure-7).

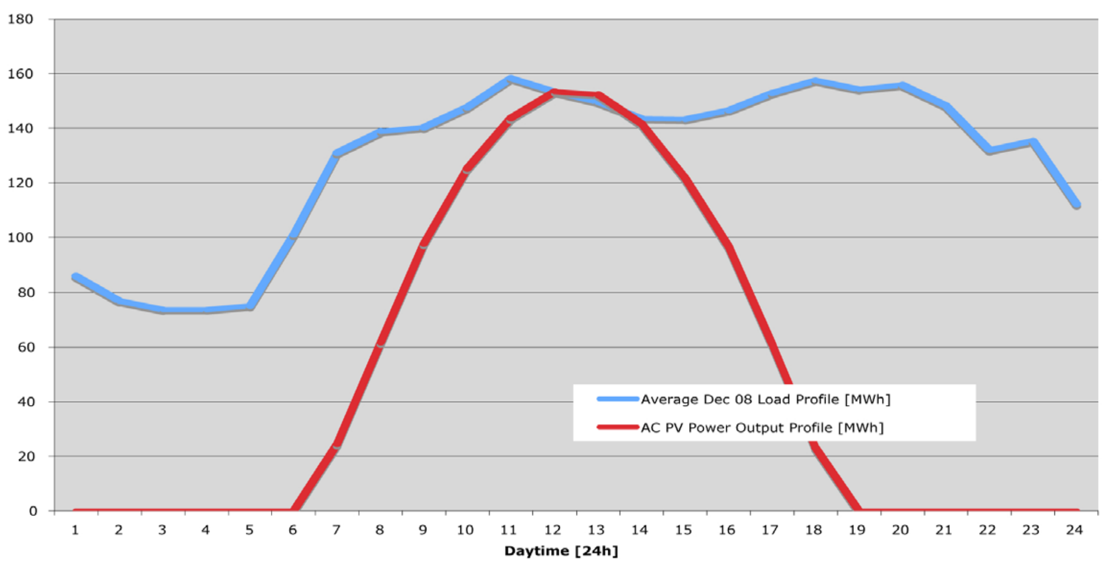

Figure-7: Maximum PV system capacity: Comparison of average monthly load curve for Canberra in December 2008 and calculated net AC power output profile of a hypothetical very large PV array placed on unshaded north-facing residential roofs with 22° tilt angle. "PVWatts" [NREL, 2010] [NREL, 2010] was used to calculate the power output profile. The hypothetical PV "super-array" was sized to exactly match the grid demand without producing any oversupply. The maximum grid load at noon and hence the PV system size chosen were 153MW [Source of graph: Own graph].

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As the experience with our own residential PV system shows, modern PV panels using crystalline silicon have an efficiency of around 16% at Standard Testing Conditions (STC = 1000W/m^2, 25°C, AM1.5). The operating temperature of a PV panel in Canberra's summer though is usually at around 65-75°C. Considering the NTC, the net solar-to-DCelectric conversion efficiency would therefore be reduced to around 12%. At the highest solar position at noon on the 21st of December 2008, the peak solar irradiation shining onto PV panels on a 22°-sloping north-facing roof in Canberra was around 1050W/m^2 [Bureau of Meteorology, 2010b]. Furthermore, the typical conversion efficiency from the DC output of the solar panels to the AC output of the inverter is around 80-85%. Therefore the net AC solar power output per square meter of PV panels on a sunny 21st of December day and for a common Canberra residential dwelling would typically be about 100W/m^2. This means that Canberra would have needed about 1.53 million square metres of solar PV panels placed on unshaded, 22°-sloping, north-facing roofs to satisfy its average grid demand of 153MW that was calculated for the 21st of December 2008.

Based on the assumptions made in Chapter 2.2 about total available unshaded north-facing roof areas on residential dwellings (1.575 million m^2), the required amount of 1.53 million m^2 to produce a net solar power output of 153MW has almost perfectly existed during the Census year of 2006.

In order to produce a *net* peak solar power output of 153MW in the middle of December in Canberra, a total of about 255MW$_p$ (MW$_p$ = Megawatt-peak) worth of PV panels would need to be installed. As explained above, this figure refers to the STC-rating of PV panels, being the standard DC-capacity ratings of PV panels as sold in the shop.

3.2. Solar Contribution of PV Systems

The ratio between the total amount of net solar PV power produced divided by the total amount of grid electricity consumed shall be referred to as solar contribution.

In the case of the 21st of December 2008, for when the maximum PV system capacity has been designed based on the best daily solar irradiation and lowest average monthly grid demand, Canberra's hypothetical residential PV "super-array" system sized for a net output of 153MW would have produced some 1'203 MWh of net solar output. When compared with the total electricity consumption of 2'901 MWh as per ActewAGL data for the same day, a maximum *daily* solar contribution of 41.5% would have resulted.

Using climate data as measured by the BoM for the sunny winter solstice day of the 21st of June 2008, the same hypothetical residential PV "super-array" system was calculated to produce only 656 MWh of net solar power. Combined with ActewAGL's daily winter electricity consumption of 5'247 MWh, the calculations would have resulted in a comparably low *daily* solar contribution of 12.5%.

Ultimately, the annual solar contribution for the period from the 1st of July 2008 to 30th of June 2009 has been calculated with the help of real PV system performance data measured at my home, being very close to 1.5 MWh/kW$_p$/y. Therefore, when multiplied with the total rated PV system size of 255MW$_p$, at total net *annual* solar power output of 382'500 would have resulted. Together with the total electricity consumption data provided by ActewAGL of 1'528'339 MWh/y for FY0809, this means that the annual solar contribution for Canberra under the assumed grid-saturation condition would have been 25.0%.

3.3. PV System Optimisation For Grid Load

The above results from Chapter 3.1 concerning both available and needed roof area show that if virtually all north-facing residential roofs suitable for PV power were covered in PV panels, the net solar output could have covered around 41.5% of the grid demand on the 21st of December 2008. As graphically deductible from Figure-8, an increase of the 41.5% solar contribution is hardly possible under the limiting assumption of grid saturation, regardless of the orientation of the PV panels, including combinations of different orientations. North-, east- and west-facing PV systems on residential roofs with 22°, and even PV systems mounted horizontally on flat roofs, experience very similar daily irradiation profiles and therefore generate about the same amount of solar electricity in Canberra during the summer months.

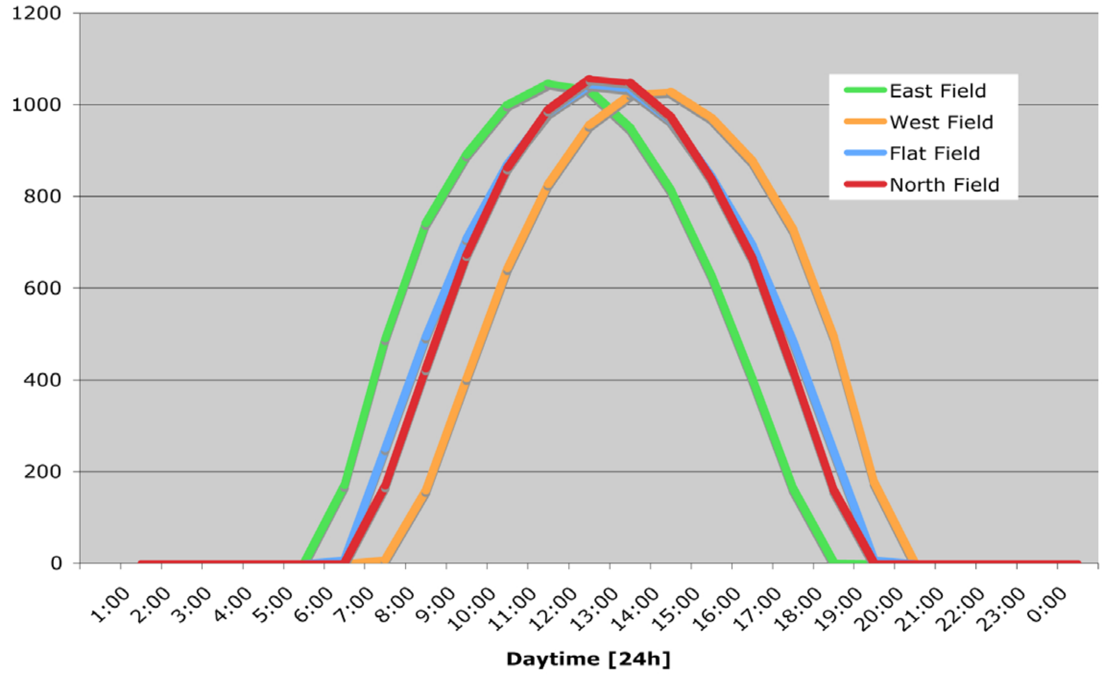

Figure-8: Variation of solar irradiation profiles with PV panel orientation in summer: Based on the PV systems calculator "PVWatts" from the National Renewable Energy Laboratories [NREL, 2010], 22° tilted north-, east- and west-facing PV systems as well as PV systems mounted horizontally on flat roofs experience very similar solar irradiation profiles for Canberra on the 21st of December. As shown in Figure-6, when compared with the virtually flat grid demand profile of December 2008 around midday, changes in the orientation of PV panels away from the "solar-perfect" north-field produce only a small lateral shift of the solar irradiation profile by about one hour, hence do not allow to build larger PV systems under the given grid saturation condition [Source of graph: Own graph].

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Nevertheless, even if there is virtually no scope for PV system size optimisation under the assumed grid saturation limitation, the solar irradiation profiles and hence the solar power production profiles for the same 22° sloping roof orientations but for the shortest day in winter (21st of June) vary in Canberra strongly (refer to Figure-9). On a perfectly sunny day around winter solstice, north-facing roofs receive up to 60% more irradiation useful for PV power systems than the other three roof orientations studied.

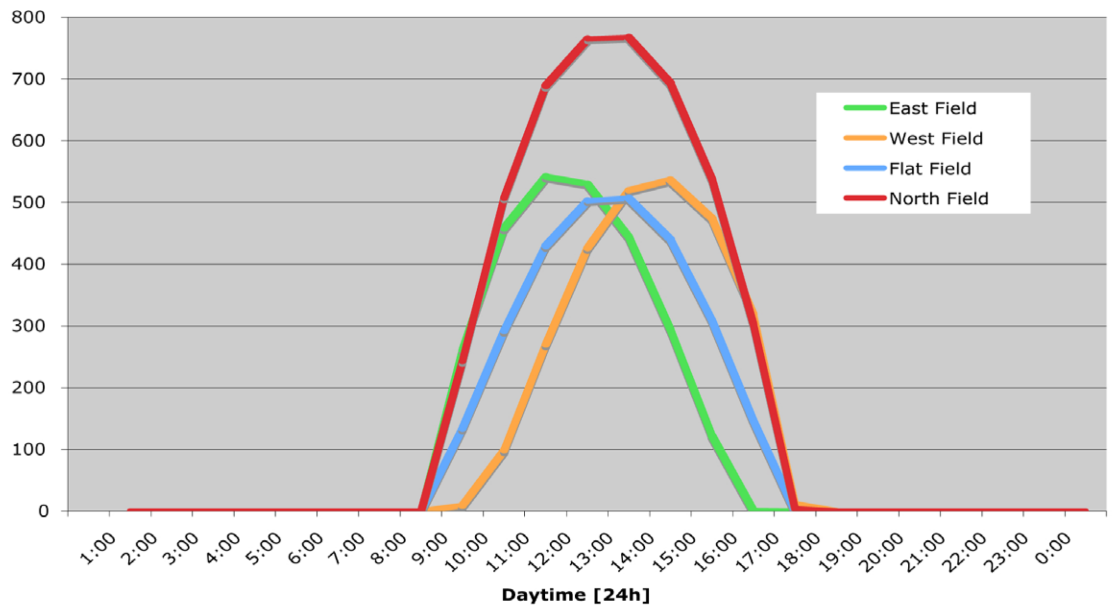

Figure-9: Variation of solar irradiation profiles with PV panel orientation in winter: Based on the PV systems calculator "PVWatts" from the National Renewable Energy Laboratories [NREL, 2010], 22° tilted north-, east- and west-facing PV systems as well as PV systems mounted horizontally on flat roofs experience very different solar irradiation profiles for Canberra on the 21st of June, therefore generate also accordingly different amounts of daily solar electricity [Source of graph: Own graph].

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4. Evaluation of Approach & Results

This Chapter attempts to reflect on the adequacy of the approach taken to evaluate the potential of residential PV systems to meet Canberra's grid demand, the key findings of this study, and on some trends.

4.1. Critical Analysis of Approach

Being a preliminary investigation only, the approach of estimating the roof area available for residential PV systems and combining this with actual solar radiation and grid demand data is appropriate. The same is true for choosing the design point at summer solstice. The maximum load that the grid can absorb must coincide with the period of available peak solar irradiation.

However, the results would be more accurate if the lowest *daily* load profile in December would have been chosen rather than the average *monthly* load profile. This would have been on the 31st of December 2008 (holiday!), when the peak grid demand at midday was only 138MW rather than the calculated monthly average of 153MW. This results in a 10% reduction of the maximum solar PV system capacity presented herein.

Additional inaccuracies also concern the assumptions made about the overall PV system conversion efficiency (overall about 60%, including NTC plus DC-to-AC). A lower efficiency would result in the need for more roof area.

4.2. Contribution of PV Systems to Grid Load

Judging the results presented in Chapter 3.1 and 3.2 above when "thinking big", it is astonishing to find that residential solar PV systems can theoretically make a valuable contribution to the demand of Canberra's electricity grid without any modifications to ActewAGL's electricity network whatsoever. Using only 1.53 million square meters of existing solar-perfect north-facing roof areas on Canberra's residential dwellings and without over-producing at any given time during the FY0809 period, the *annual* solar contribution to the entire grid consumption would have been 25%. This would be achieved with a total installed, DC-rated solar power capacity of $255MW_p$, producing a net AC solar power output of about 153MW.

If Canberra would team up with the very large hydro-power energy storage capacity available at the nearby Snowy Mountains Hydro-Electric Scheme [Snowy Hydro, 2010], the city could probably triple its solar power contribution. It would do so by utilising also east- and west-facing roof areas of residential dwellings and by exporting and storing excess solar power produced during the day for the night and the summer half-year for later use in the winter half-year. Given such export-import energy storage partnership with the Snowy Mountains Scheme, Canberra could even achieve a solar contribution of 100% if additional roof area would be used such as that available on commercial buildings and industrial warehouses.

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4.3. Optimisation Potential of PV System Orientation

As the solar irradiation profiles of Figure-8 show, the solar power production optimisation potential is rather limited when attempting to vary the PV system orientation. In December when solar irradiation is highest and the grid demand is comparably low and flat, the solar irradiation profiles for 22° sloping north-, east- and west-facing roofs all peak within less than 2.5 hours of each other. This means that for the assumptions of no-export and no-storage, neither morning nor evening grid demand peaks could be satisfied by a change in PV panel orientation from north to east or west.

In contrast, in winter the orientation of the PV panels has a strong impact on system performance. East and west fields receive a lot less solar irradiation because the sun is much lower in the sky resulting in less time exposure and less intense irradiation. North-facing roofs receive about double as much irradiation in the middle of winter than the east- and west-facing roofs. Hence they remain preferred roofs.

Overall for Canberra and because summer dominates with irradiation and long days, north-facing PV systems installed on 22° sloping roofs generate only about 12-14% more solar power *annually* than respective east- or west-facing systems [Clean Energy Council of Australia, 2009].

4.4. Trends

Assuming further growth of Canberra as a city combined with warmer summers, more demand for air-conditioning, yet better insulated homes, it is expected that Canberra's grid demand profiles will slowly shift from extreme winter-peaking to increased summer-(afternoon)-peaking. Maintaining the grid-saturation assumption, such a trend would then allow for more solar power to be installed and result in a higher solar contribution toward 50% or more.

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5. Conclusions

The findings of this study about the potential of residential photovoltaic (PV) solar power systems to best match Canberra's grid demand lead to three key conclusions:

Firstly, the choice of the optimum PV system is capped by the lowest grid demand in summer at around noon: Under the assumption that all of the solar power produced on residential homes in Canberra must be consumed by the city concurrently (no surplus power generation and no energy storage), the comparably low grid demand typically experienced at around midday in December dictates the design of the maximum possible solar system for Canberra. Under these assumptions, the maximum PV system capacity that can be installed in Canberra today amounts to about 255MW_p, producing a net total system output of around 153MW.

Secondly, the maximum contribution of solar power generated as part of the grid demand in Canberra varies throughout the seasons: The demand-and-supply limitation given above results in the total amount of PV panels that can be installed on residential homes in Canberra being around 1.53 million m^2. While this equates to using less than one quarter of the existing residential roof area available in Canberra, the resulting *annual* solar contribution would be around 25%.

Thirdly, the orientation of the PV panels is irrelevant from a purely grid-optimisation point of view (disregarding economic aspects): During the summer half-year, the solar irradiation profiles seen by, and hence the solar power output produced from PV systems installed on residential dwellings is nearly identical for north-, east- and west-facing roofs. Even flat roofs offer similar performance. The grid cannot really benefit from choosing any particular orientation.

These findings are encouraging for Canberra since it has been found that a lot of PV systems can be installed before any changes to the grid infrastructure is needed. In addition, PV systems can be installed with a much greater freedom of orientation than anticipated – almost any residential roof is a good solar roof in Canberra.

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