# Effects of time-scale on householder PV economic analyses: over-estimation of self-consumption

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**Abstract**

The economic analysis of when solar roof-top photovoltaic (PV) systems become viable is of great interest to many householders. It is well known that buy-back rates for solar energy are low and in general a PV system only becomes financially attractive if households consume a high proportion of the energy generated, in order to benefit from avoiding the cost of buying electricity at retail rates. Battery storage for most householders remains uneconomic (although prices are trending downwards) making power consumption patterns critical to determining financial viability. Currently householders have access to their power consumption from their retailer in half-hour time periods. If this information is combined with PV generation at the householder's location, a good estimate of the financial viability can be determined.

However, using a half-hour analysis period implies that the power generated and load consumed in the half hour period is constant. The reality can be very different though, as both loads and generation can spike or dip and it is the instantaneous load and generation that determines when power is exported or imported from the grid. To determine the effect of time-scale on self-consumption, values were calculated from one-minute generation and load data for a number of New Zealand installations and compared with calculations for half-hour and hourly data. All households analysed showed some over-estimation of self-consumption when compared with the one-minute baseline data. For a typical 3.5kW PV system, the over-estimation varied between 1% and 8%, depending on the base level of self-consumption and characteristics of the load profile. In addition, the impact of using median load profiles, such as those used by the EECA Energywise™ Solar Calculator on self-consumption values was investigated. The process of creating median load profiles further smooths the load, similar to the effect of using longer-time-scales. When using median load profiles, the self-consumption over-estimation was found to be in the order of 5% for the majority of householder profiles for the various regions specified in the Solar Calculator.

## Introduction

For a householder considering installing a domestic photovoltaic (PV) system, the expected financial value of a PV system is a major factor in their decision. Several tools exist to help householders assess how much electricity they can expect to generate for their location and PV set-up, however there are very few tools that take into account the effect of the householder's pattern of electricity use, which is key to whether a PV system is viable or not. The Energy Efficiency Conservation Authority (EECA) Energywise$^{TM}$ Solar Calculator, which is available on the EECA website [1] is one tool that attempts to address this deficiency. Ideally, to accurately determine a householder's self-consumption, the householder would supply their specific load profile for the calculation. The reality is however, that the majority of householders do not have a yearly profile available on-hand, and for ease of use, representative profiles depending on characteristics of electricity use are used instead.

When calculating the financial benefit of a PV system, another issue that arises is that load profile data is typically only available with half-hourly resolution from smart meters. If this is then used to determine the amount of self-consumption of generated electricity and the amount exported to the grid, inaccuracies may result due to fluctuations in the load and generation at smaller time-scales. This may lead to an over-estimation of the amount of electricity self-consumed and therefore an overstatement of financial benefit of the system with current buy-back rates. This research aims to investigate the scale of this effect.

The issue of longer time-scales not capturing shorter time-scale deviations has also been recognised by Lindemann of Valentin Software [2] who produce the PV*SOL PV design and planning software. The PV*SOL program allows irradiance and load profiles to be synthesized at one-minute resolution from hourly or even longer time-scales.

## Method

This paper is divided into two parts, firstly the effect of data's time resolution on calculating self-consumption is explored. The second part looks at the effect of using a median data profile as a representative profile on the self-consumption. For the first part, data was obtained from the University of Otago's Centre for Sustainability (CSAFE) [3]. This data has high resolution household load data down to one-minute time-scales from Grid Spy monitoring devices, installed as part of the GREEN Grid project. Included within the data are also a small number of households that have PV systems. The second part of this paper analyses the self-consumption of over eighteen thousand household load profiles when compared to a reference generation profile. Self-consumption values are then compared to the representative load profiles generated for different electricity user types for the EECA Energywise$^{TM}$ Solar Calculator.

### Analysis of high resolution (one minute) household data

The first set of data was obtained from CSAFE's GREEN Grid 'hundred-home' trial. It consists of Grid Spy measurements of various electrical circuits within the home at one-minute time increments and is designed to understand the householder's pattern of domestic appliance use. The hundred-home trial contains load data from 37 households, however not all households were suitable for analysis. All households had periods of missing data, ranging from the occasional minute to months of empty data due to metering issues. As a result, some data cleaning was required to convert the data into a more workable from. Some households with significant data gaps were omitted.

Four households in the data-set had PV systems, as summarised in

Table 1. Household 28 was omitted due to insufficient data and only limited analysis was possible for household 23 as the PV with a battery made household 23's generation and load difficult to interpret due to the metering set-up. This left two useable households, however household 19 had essentially independent PV systems.

*Table 1: Summary of one minute data available for PV households*

| Household | Location | Base Panel Size (Watts) | Valid Days Data | Additional Notes |
|---|---|---|---|---|
| **19** | New Plymouth | 2 * 4600 | 354 | Two individual PV Sources, assume sources on separate phases. |
| **23** | New Plymouth | 1350 | 357 | Has a PV source paired with a battery storage, obscuring consumption of PV generated power |
| **24** | Bell Block | 4600 | 357 | Most complete original PV household |
| **28** | Napier | 4600 | 3 | Single PV source, but data set only contains three days of data |

To extend the analysis from the two useable PV households, additional composite PV households were fabricated. Load data for households without PV were merged with PV data from a PV household in the same geographic region. Care was taken to ensure the generation and load data were appropriately synchronized in time. The PV households are summarised in Table 2.

*Table 2: Summary of households used for analysis, including composite households, with loads coupled with PV households and base PV households. The annual energy consumption is extrapolated to 365 days from the number of valid days.*

| Household | Household used for PV Source | Region | Annual Energy Consumption (kWh) | Number of Valid Days of Data |
|---|---|---|---|---|
| **6** | 19 - Panel 1 | New Plymouth | 8822.6 | 349 |
| **8** | 19 - Panel 1 | New Plymouth | 9183.2 | 344 |
| **10** | 19 - Panel 1 | New Plymouth | 5150.4 | 354 |
| **11** | 19 - Panel 1 | New Plymouth | 4684.6 | 344 |
| **13** | 19 - Panel 1 | New Plymouth | 12278.2 | 354 |
| **14** | 19 - Panel 1 | New Plymouth | 3546.7 | 227 |
| **19 (panel 1)** | 19 - Panel 1 | New Plymouth | 2834.7 | 354 |
| **19 (panel 2)** | 19 - Panel 2 | New Plymouth | 2728.2 | 354 |
| **21** | 19 - Panel 1 | New Plymouth | 3859.4 | 338 |
| **22** | 24 | Bell Block | 13864.7 | 353 |
| **24** | 24 | Bell Block | 7410.8 | 357 |
| **25** | 19 - Panel 1 | New Plymouth | 5466.1 | 295 |
| **26** | 19 - Panel 1 | New Plymouth | 5560.0 | 319 |
| **27** | 19 - Panel 1 | New Plymouth | 7563.6 | 327 |

## Data Pre-processing

An example of the raw CSAFE data is shown in Table 3. Note that the data is in units of Watts, not kWh as is standard in most metering applications.

*Table 3 Example of the raw data format from the CSAFE hundred-home trial.*

| Time | Incomer (W) | Hotwater (W) | Oven (W) | Kitchen (W) | Laundry (W) | PV (W) |
|---|---|---|---|---|---|---|
| **29/05/2015 1:45** | -2888.44 | 3067.27 | 38.51 | 0 | 14.76 | -3071.85 |
| **29/05/2015 1:46** | -2860.72 | 2711.53 | 38.51 | 34.38 | 14.76 | -3077.55 |
| **29/05/2015 1:47** | -974.68 | 0 | 1907.94 | 43.44 | 20.45 | -3067.59 |

The first stage of pre-processing was to clean the data. A simple interpolation method was employed to fill small amounts of missing data. The valid data points on either side of a data gap are averaged and used to fill the gap in a linear ramp. However, if one of the two end data points has a value of zero, the missing data is also assumed to be zero – loads being switched on or off instantly is more common than a load slowly being ramped up or down. The amount of interpolated data was tracked and when the data was then split into days, days with more than half an hour of missing data were declared invalid.

To analyze the effect of time-scale, the cleaned data was converted from one-minute to half-hourly and hourly timescales. The half-hourly timescale was chosen as this is the standard period for conventional household metering with smart-meters. Hourly time-periods were of interest as this is the time-period used by the EECA Energywise$^{TM}$ Solar Calculator.
For example, to transform the data to half-hourly samples, the original one-minute data is averaged into thirty minute blocks. Note that the raw data has units of Watts, not Watt-hours as is more standard in metering applications.

$$Incomer\_1_{half\ hour} = \frac{\sum_{i=1}^{30} Incomer_{1_{minute}}(i)}{30}$$

Finally, the household's load and generation profiles were determined. Identifying the total household load was not always obvious however as the electrical monitoring for each household is customized depending on appliances, wiring configuration and the presence of controlled circuits. Individual circuits were monitored in each household to supply information about different appliance use for other research projects. To determine which individual circuits to sum in order to find the total household load, a function was created to graph and overlay each individual circuit for visual confirmation.

Most households would have an Incomer_Uncontrolled column, which was an aggregate of many loads, as well as the PV column:

$$Incomer\_Uncontrolled = PV + Load_1 + Load_2 + Load_3 + Load_4 + Load_5 + \cdots$$

Visual inspection confirmed if the HotWater was a separate controlled circuit or included as a load in an Incomer circuit. For example, the load for the example in Table 3 is calculated as:

$$Load_{Total} = Incomer\_Uncontrolled + HotWater\_Controlled - PV$$

## Calculation of Self-Consumption

For each timescale (i.e. 1 minute, half-hourly and hourly) the annual self-consumption is determined by considering the total PV energy self-consumed, and the total amount of energy generated.

For each time period *i*, of each data set, the PV energy self-consumed by the household is calculated:

$$If\ Generation(i)\ \leq Load(i):$$
$$Self\ Consumption(i) = 100\%$$
$$If\ Generation(i)\ > Load(i):$$
$$Self\ Consumption(i) = \frac{Load(i)}{Generation(i)}$$
$$PV\ Self\ Consumed(i) = Self\ Consumption(i) * Generation$$

The annual self-consumption can then be calculated:

$$\frac{\sum PV\ Self\ Consumed}{\sum Generation}$$

The annual self-consumption results for each of the three time-scales are summarised for each of the 14 households in Table 4. The difference in self-consumption results between the half hourly and hourly time periods are directly compared in columns five and six.

*Table 4: Self-consumption results for 14 households, comparing half hourly and hourly results to the one minute baseline data.*

| Household | 1 min Self-Consumption | 30 min Self-Consumption | 60 min Self-Consumption | Difference in Self-Consumption 30 min – min | Difference in Self-Consumption 60 min – min |
|---|---|---|---|---|---|
| **6** | 34.8% | 36.9% | 38.2% | 2.1% | 3.4% |
| **8** | 34.2% | 36.3% | 37.3% | 2.1% | 3.1% |
| **10** | 25.0% | 27.3% | 28.3% | 2.3% | 3.3% |
| **11** | 18.8% | 19.9% | 20.6% | 1.1% | 1.8% |
| **13** | 46.6% | 48.6% | 49.6% | 2.0% | 3.0% |
| **14** | 21.5% | 22.8% | 23.5% | 1.3% | 2.0% |
| **19 Panel 1** | 22.9% | 23.4% | 23.7% | 0.5% | 0.8% |
| **19 Panel 2** | 18.5% | 18.9% | 19.3% | 0.5% | 0.8% |
| **21** | 15.9% | 17.0% | 17.6% | 1.2% | 1.8% |
| **22** | 50.2% | 54.8% | 56.2% | 4.6% | 6.0% |
| **24** | 42.8% | 45.7% | 48.5% | 2.9% | 5.7% |
| **25** | 21.8% | 26.1% | 27.0% | 4.3% | 5.3% |
| **26** | 20.9% | 24.1% | 25.6% | 3.2% | 4.8% |
| **27** | 28.6% | 30.4% | 31.3% | 1.8% | 2.7% |

From these results, we can see a consistent pattern – for all households, the self-consumption figure for both the half-hourly and hourly time-scale are both larger when compared to the one-minute time-scale. Additionally, for all households the hourly time-scale results in a larger self-consumption figure compared to the half-hourly timescale. The over-estimation of self-consumption varies, from 0.5% to 6%, with the larger over-estimates occurring at higher self-consumptions. The relationship between the over-estimation self-consumption at larger time-scales relative to a household's self-consumption, was explored by artificially scaling the PV panels to provide more self-consumption data points.

## Scaling PV Generation to Shift the Self Consumption Level

To investigate the effect of different self-consumption values, the amount of PV generation was artificially shifted by linearly scaling the PV generation data for household 24. The PV generation data was scaled incrementally from 0.1 up to 4, which equates to varying the household's PV rating from 460W resulting in self-consumption close to 100%, up to 18.4kW which results in very low self-consumption rates. The load data remains unadjusted.

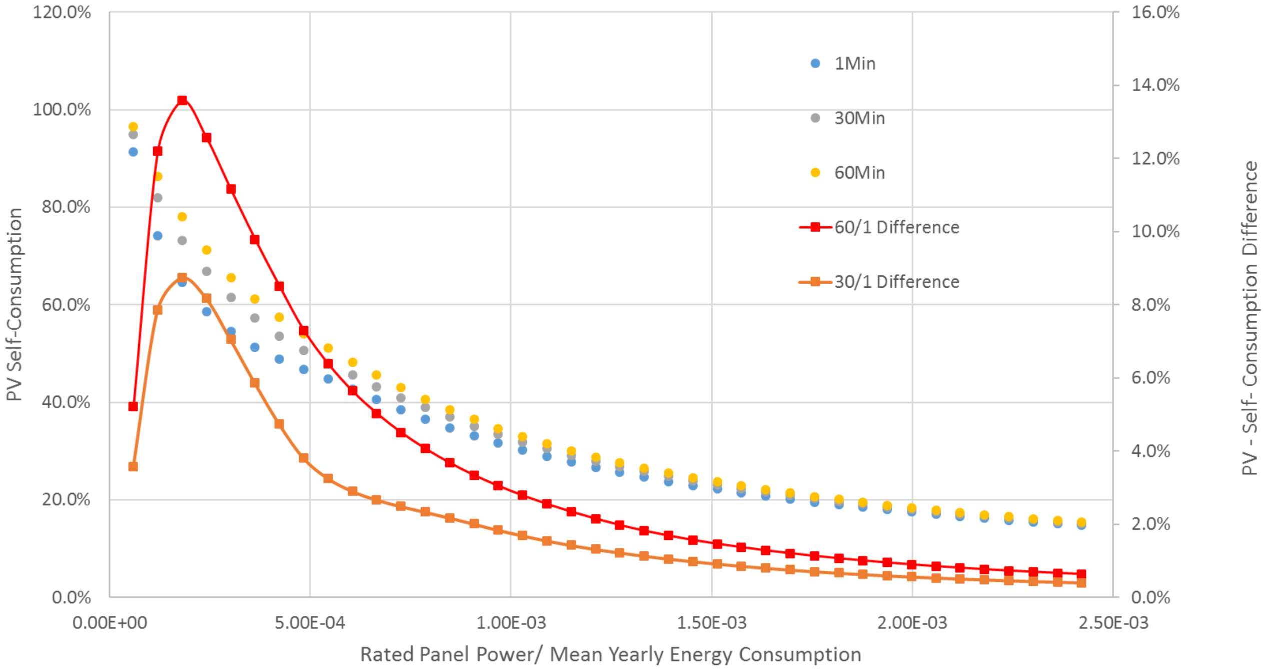


*Figure 1: Household 24's scaled PV self-consumption calculated for different measurement time-periods. The left axis reports the absolute self-consumption and the right axis the difference in self-consumption for the half-hourly and hourly time-period compared to the baseline measurement of one minute metering.*

Figure 1 shows how the self-consumption for household 24 changes as its rated panel power is linearly scaled. The x-axis in Figure 1 is presented as a ratio of the scaled PV panel size and the extrapolated annual energy consumption. The over-whelming trend is that as self-consumption increases, as shown on the left-axis, the PV self-consumption difference (right-axis) increases. This peaks before breaking down as more one-minute time periods fully consume the generated PV.

Data from the other households were similarly analyzed, using household 24's panel power scaled to match the same rated panel power to yearly energy consumption ratios used in Figure 1. The difference in the hourly time-scale compared to the one-minute self-consumption data is plotted in Figure 2, and between half-hourly and one-minute self-consumption data is plotted in Figure 3. The same trends in Figure 1 are evident in Figure 2 and Figure 3 as is evident by the same shapes of the curves, however the over-estimation difference varies strongly by household. Clearly the amount of over-estimation is strongly related to self-consumption. The range in observed values for the self-consumption difference between households likely is the result of each household's different load characteristics, which will result from the different distribution of different household appliances and their associated temporal load profiles. Future work to analyse the frequency components of the load data is expected to provide further insights. Again, the increase in over-estimation of self-consumption is evident between the hourly and half-hourly analyses.

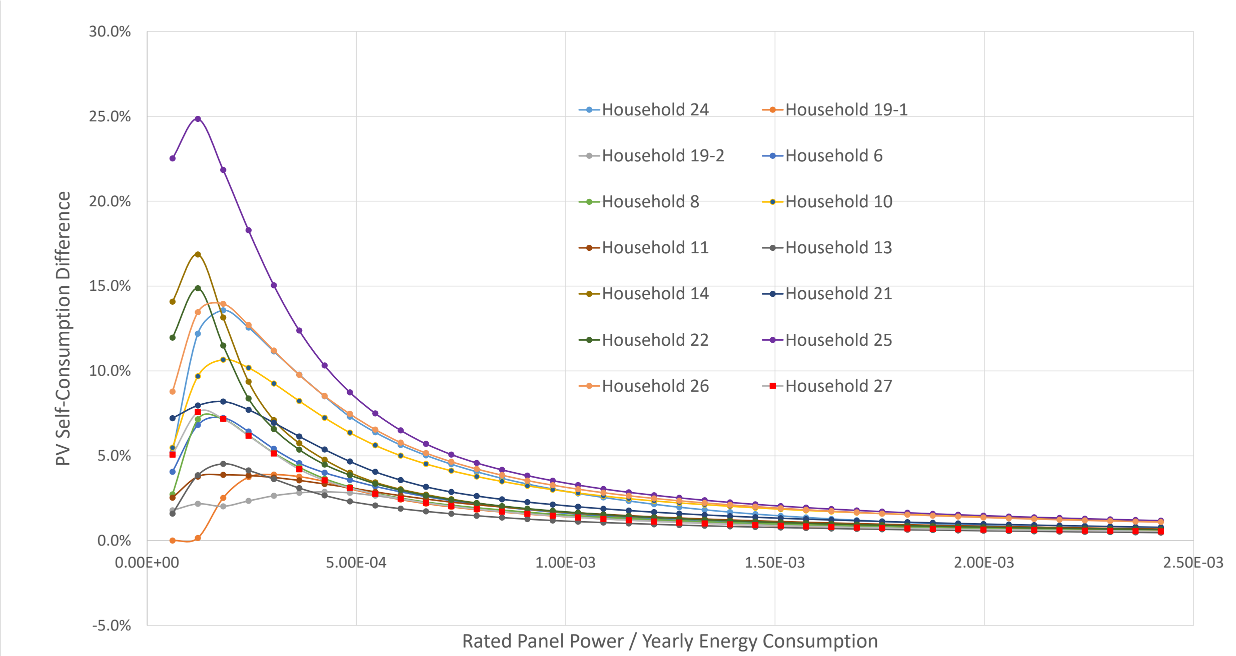


*Figure 2: Plots the difference in self-consumption of generated PV between hourly and one minute time-scales, for composite households created using Household 24's scaled PV generation profile.*

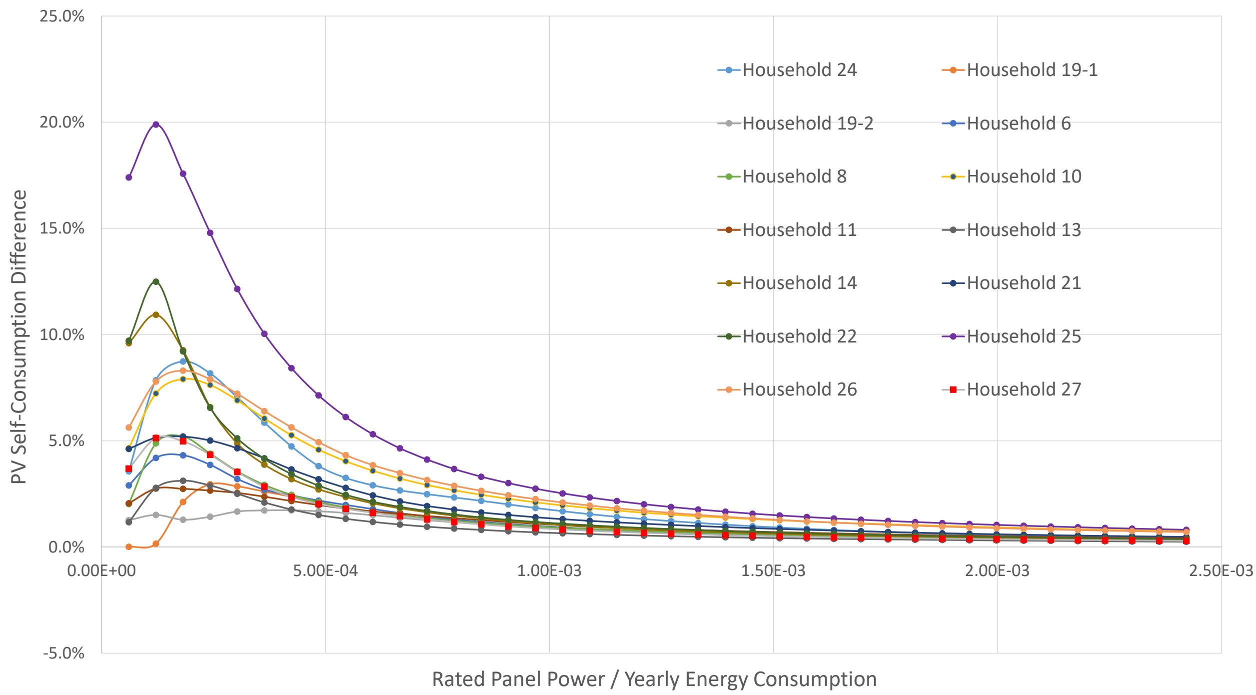


*Figure 3 Plots the PV self-consumption differences between half-hourly time-scales and the one minute baseline, for composite households created using Household 24's PV generation profile. The generation is scaled as described for Figure 1 to probe the effect of different base self-consumption ratios.*

Another interesting point of reference is to consider the typical PV installation size. Table 5 summarises self-consumption difference between the hourly data compared to the one-minute baseline data from Figure 1Figure 2 when the rated panel power is set to 3.5kW. The difference in self-consumption varies between approximately 1 – 8%, just slightly higher the results in Table 4 as expected as with the reduction in system size, the self-consumption increases.

*Table 5 Estimated self-consumption difference between calculations using hourly and one minute time periods assuming a typical PV system of 3.5kW.*

| Household | Rated Panel Power/Yearly Energy Consumption (*E-3) | PV Self-consumption Difference (60 - 1min) |
|---|---|---|
| **6** | 0.39 | 4.3% |
| **8** | 0.37 | 4.3% |
| **10** | 0.68 | 4.5% |
| **11** | 0.72 | 2.3% |
| **13** | 0.28 | 3.8% |
| **14** | 0.64 | 2.9% |
| **19 - Panel 1** | 1.19 | 1.2% |
| **19 - Panel 2** | 1.24 | 1.2% |
| **21** | 0.87 | 2.4% |
| **22** | 0.25 | 8.1% |
| **24** | 0.46 | 7.8% |
| **25** | 0.54 | 7.8% |
| **26** | 0.55 | 6.5% |
| **27** | 0.41 | 3.7% |

## Investigation of the effect of a median load profile on self-consumption

The second part of this paper investigates the effect of using median load profiles on self-consumption values. The EECA Energywise$^{TM}$ Solar Calculator uses a median load profile to act as a representative load profile for a particular user-type in their particular region to assist in estimating when the user is using electricity relative to when their PV panels are generating electricity. In this way, the amount of electricity self-consumed by the householder and the electricity exported can be estimated. The representative load profile is scaled by the annual electricity which the householder enters.

The median load profiles were generated from over eighteen thousand load profiles captured by smart-meters with good coverage across New Zealand. The calculation of the median load profile is described in reference [1]. However, using a median load profile risks losing the higher frequency information in individual profiles, i.e. sharp changes in load are moderated. It was hypothesized that this smoothing could result in an over-estimation of self-consumption.

The load profiles used to generate the representative median load profiles originated from smart-meter data from NZ households, and hence are at half-hourly resolution. The EECA Energywise$^{TM}$ Solar Calculator however, uses hourly resolution, consistent with the PV data available from NIWA's Solarview tool. The load profiles were grouped based on their geographic region and user-type. The user-type separated households depending on whether they had electric hot-water heating, electric space-heating, were a higher or low user of energy (based around their annual energy consumption) and whether they were high users of energy during the day [1].

Each of these groups contains the load profiles of the constituent households in half-hourly and hourly timescales, as well as a single median profile intended to be representative of the load-profile – region pair. The analysis of the second data set focuses on the difference in self-consumption difference between the generated median and the individual load profiles. Additionally, the difference in the self-consumption between the half-hourly and hourly data sets is observed.

## Comparison of Median Self-consumption with Individual Household Self-consumption

For each region and user-type group, self-consumption is calculated for the load profiles used by the EECA Energywise™ Solar Calculator using the PV generation profile from household 24, scaled to the typical residential PV system size of 3.5kW. These were then compared to the self-consumption calculated for the median profile of that specific region and user-type group, again using household 24's generation profile.

Self-consumption values were calculated for both half-hourly and hourly resolution and the difference in self-consumption between the median profile and individual profiles compared. Figure 4 graphs a subset of these results for the five most populated regions and a common user-type profile of high user, electric hot-water and space heating, flat rate tariff and low day use.

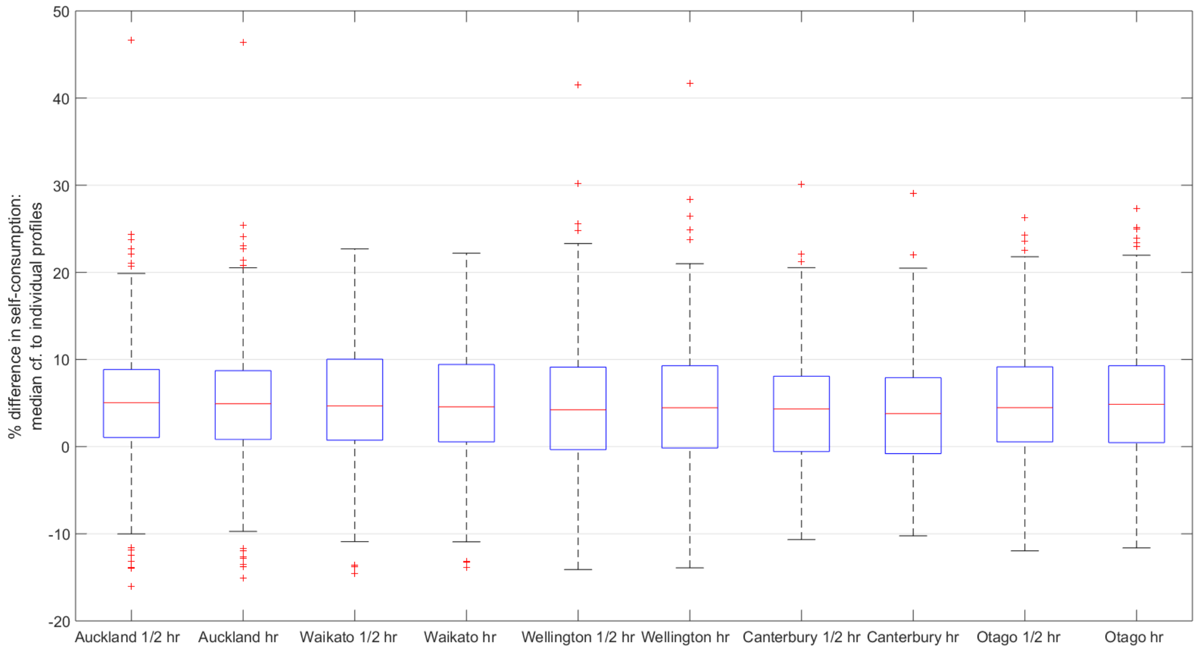


*Figure 4 Box plots representing the distribution of the differences in self consumption for individual household profiles compared to the median profile calculated for that group (region/user type). The red line represents the median value, the blue boxes represent the 25th and 75th percentile, and the whiskers extend 1.5 times the interquartile range from the box edges. The y-axis is truncated at 50%, omitting a small number (<5) outliers.*

The results in Figure 4 consistently show that the median load profile generates a self-consumption that is 5% larger than the median self-consumption of the individual load profiles in each regional/user-type group. The inter-quartile ranges are 10% or less. Interestingly there is very little difference between the half-hourly and hourly data which suggests that the over-estimation from the longer time-scales and the effect of the smoothing with a median profile are largely not additive.

## Conclusions

Key trends identified were that the longer the sample time period, the greater the over-estimation of self-consumption was likely to be. In general, the over-estimation of self-consumption increases with higher self-consumption values and the size of the over-estimation is influenced by the load profile shape.

Low numbers of households with PV represented in the one-minute baseline data set have made broad quantitative conclusions difficult. However, by extending the data-set to include composite households by pairing non-PV households with a PV generation household allowed a greater diversity in household loads to be represented. In this data-set over-estimation of self-consumption for a typical sized PV installation of 3.5kW when using hourly time-scales was between 1% and 8%. This suggests there may be errors in estimating self-consumption, which should be acknowledged when performing economic analyses with half-hourly and hourly metering data. Future work in this area is anticipated to examine the frequency components of the load profiles and look at the appliances that have the greatest influence on over-estimation.

It was also concluded that using a median load profile does bias results to larger self-consumptions, in the order of 5%. However, given that the representative median load profile used by the EECA Energywise™ Solar Calculator is just that, a representative load profile it is probably a small difference compared with the variability of an individual householder's actual load profile. In future, a better method for generating a representative load profile to avoid this skew might employ Markov models to better capture the shape of the load profile without smoothing it.

The combined effect of a relatively long sample period and using a median load profile on the self-consumption was not able to be explored. It is expected that the combined effect is unlikely to be purely additive however.

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## References

[1] Alan Wood, Allan Miller, Sharee McNab and Scott Lemon, "EECA's energywise™ PV Solar Calculator," EEA Conference Wellington, 2016. http://www.epecentre.ac.nz/research/eea%20conference%20papers%202016/UC-GG-16-CP-ARW-01-EEA%20Conference%20Paper%20PV%20Web%20Tool-r24.pdf

[2] University Of Otago. (2017) Centre for Sustainability. [Online]. http://www.otago.ac.nz/centre-sustainability/index.html

[3] Steffen Lindemann. (2015, June) Assessing self-consumption in grid-tied PV systems using PV*SOL. [Online]. http://www.valentin-software.com/sites/default/files/ise2015_valentin_software.pdf