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AUTHORITY FOR ELECTRICITY REGULATION, OMAN

# Public Consultation on Residential PV in Oman

# Annex B: Methodology

May 2017

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## A: Introduction & Overview

### Modelling

Modelling was undertaken using Excel 365 and bespoke simulation procedures written in Visual Basic for Applications (VBA).

In addition to Excel functions, simulation models incorporate an Excel AddIn: Simtools, developed and distributed by the University of Chicago (http://home.uchicago.edu/rmyerson/addins.htm).

User Defined Functions were developed in VBA to facilitate scenario and sensitivity analysis.

### Data Sources

The Authority sought to ensure the analysis utilised Oman data to the maximum practical extent to reflect the characteristics of electricity demand in Oman and measured solar radiation in Oman. Accordingly, the analysis makes extensive use of the following data:

| Sl | Data Description | Source |
|---|---|---|
| 1 | Residential Customer Accounts Database (2014) incorporating monthly kWh consumption for individual Residential customer accounts for each of the five licensed suppliers (Muscat, Majan, Mazoon, DPC & RAEC). | Authority for Electricity for Electricity Regulation, Oman |
| 2 | 2016 hourly system demand data for the Main Interconnected System and the Salalah System. | Authority for Electricity for Electricity Regulation, Oman |
| 3 | Solar Radiation hourly data measured at sites in Adam & Manah in 2015 and 2016.<br>http://omanpwp.com/new/Documents.aspx?Pid=84 | Oman Power and Water Company S.A.O.C |

### Overview

The analysis objective was to estimate the production potential of Residential PV systems of varying size installed at residential premises reflecting measured Global Horizontal Irradiance (GHI, $Wm^2/h$) in Oman. PV electricity production over a 25-year horizon (incorporating annual PV panel degradation), was modelled to estimate gas benefits arising from lower grid supplied centrally dispatched electricity. Gas benefits are expressed in terms of: volume (standard cubic metres ($Sm^3$)), cost savings (Rial Omani), and potential $CO_2$ emission reductions (tons of carbon and carbon tax revenues @ \$25 ton of $CO_2$).

Benefit streams are discounted at an assumed real social rate of time preference for Oman of 4% (central case) with High/Low sensitivity values of 6% and 2%, respectively. Benefit present values are compared to the reported cost of Residential PV systems (components and installation costs) to estimate potential net benefits.

The Consultation Paper presents results for the Main Interconnected System (MIS) only.

This annex describes the principal analysis assumptions, the methodology used to derive results, the models used and the scope of sensitivity analyses and results.

## Assumptions & Sensitivity Analysis

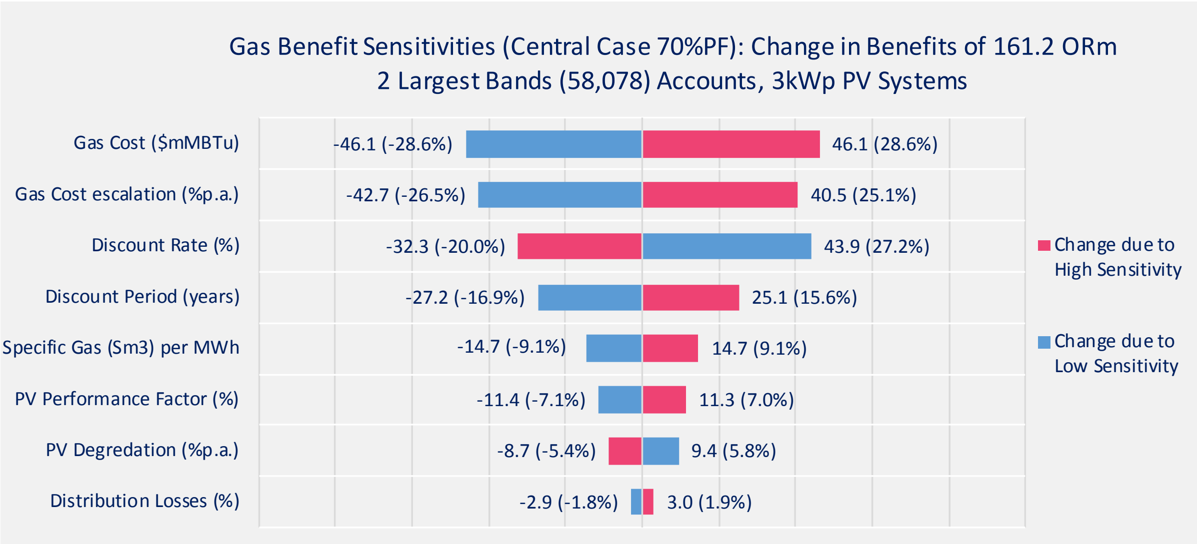
Figure 1 presents the Central, High and Low assumptions of key analysis variables.

*Figure 1: Central Assumptions & High / Low Sensitivities*

| Sensitivity Item | Sensitivity Values | | |
|---|---|---|---|
| | Low | Central | High |
| Gas Cost ($mMBTu) | 5.0 | 7.0 | 9.0 |
| Gas Cost escalation (%p.a.) | 0.0% | 3.0% | 5.0% |
| Discount Rate (%) | 2.0% | 4.0% | 6.0% |
| Discount Period (years) | 20 | 25 | 30 |
| Specific Gas (Sm3) per MWh | 250 | 275 | 300 |
| PV Performance Factor (%) | 65.0% | 70.0% | 75.0% |
| PV Degredation (%p.a.) | 0.0% | 0.5% | 1.0% |
| Distribution Losses (%) | 4.0% | 6.0% | 8.0% |

Figure 2 illustrates the scope of results derived for each analysis Group, in this case Group 2 (2 largest Bands) reflecting the simulated output of 58,078 3kWp PV systems over 12 months.  Results are most sensitive to gas price and annual gas escalation, and least sensitive to assumed distribution system losses and annual PV panel degradation.

*Figure 2: Sensitivity Analysis Results – Group 2 (Bands 6 & 7) & 3kWp PV Systems*




| Sensitivity Item | Sensitivity Values | | | | Results OR million | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Low | Central | High | | Cng: Low | Low | Central | High | Cng: High |
| Gas Cost ($mMBTu) | 5.0 | 7.0 | 9.0 | | -46.1 | 115.2 | 161.2 | 207.3 | 46.1 |
| Gas Cost escalation (%p.a.) | 0.0% | 3.0% | 5.0% | | -42.7 | 118.5 | 161.2 | 201.7 | 40.5 |
| Discount Rate (%) | 2.0% | 4.0% | 6.0% | | 43.9 | 128.9 | 161.2 | 205.2 | -32.3 |
| Discount Period (years) | 20 | 25 | 30 | | -27.2 | 134.0 | 161.2 | 186.3 | 25.1 |
| Specific Gas (Sm3) per MWh | 250 | 275 | 300 | | -14.7 | 146.6 | 161.2 | 175.9 | 14.7 |
| PV Performance Factor (%) | 65.0% | 70.0% | 75.0% | | -11.4 | 149.8 | 161.2 | 172.6 | 11.3 |
| PV Degredation (%p.a.) | 0.0% | 0.5% | 1.0% | | 9.4 | 152.5 | 161.2 | 170.6 | -8.7 |
| Distribution Losses (%) | 4.0% | 6.0% | 8.0% | | -2.9 | 158.3 | 161.2 | 164.3 | 3.0 |

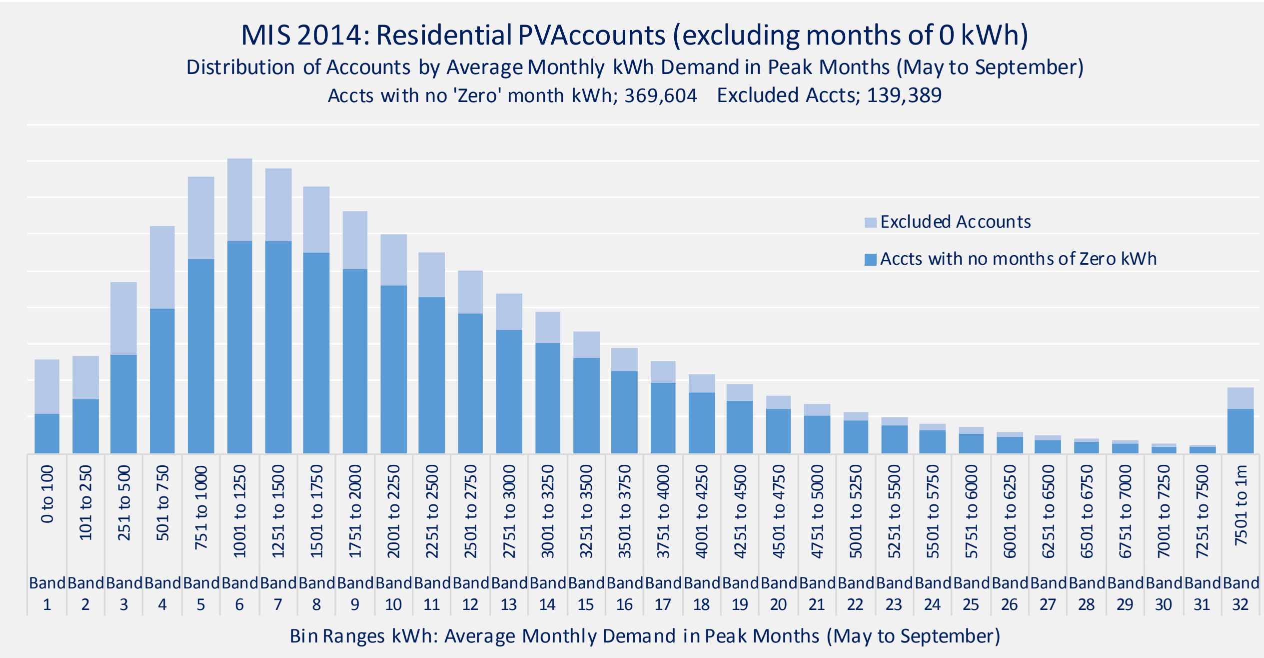
Appendix A presents sensitivity analysis results for Group 2, Group 7 and Group 10, and 3kWp systems.

## B: Data & Methodology

### Residential Accounts Database (2014)

The Authority's 2014 Customer Accounts database provided monthly consumption data for 695,818 Residential accounts, of which 610,380 (88%) are supplied from the MIS. For MIS accounts, screening excluded accounts with four or more months of zero consumption. The remaining 508,993 accounts were sorted into bin ranges reflecting average monthly kWh consumption in the 5 peak summer months (May to September) of the MIS bulk supply tariff. Further screening excluded accounts with one or more months of zero consumption to avoid bias when estimating how much PV output would be consumed by customers (self-supply) or exported. The resulting histogram of analysis data is shown in Figure 3.

*Figure 3: Histogram of MIS Residential Accounts – by Average Monthly kWh (May to September)*



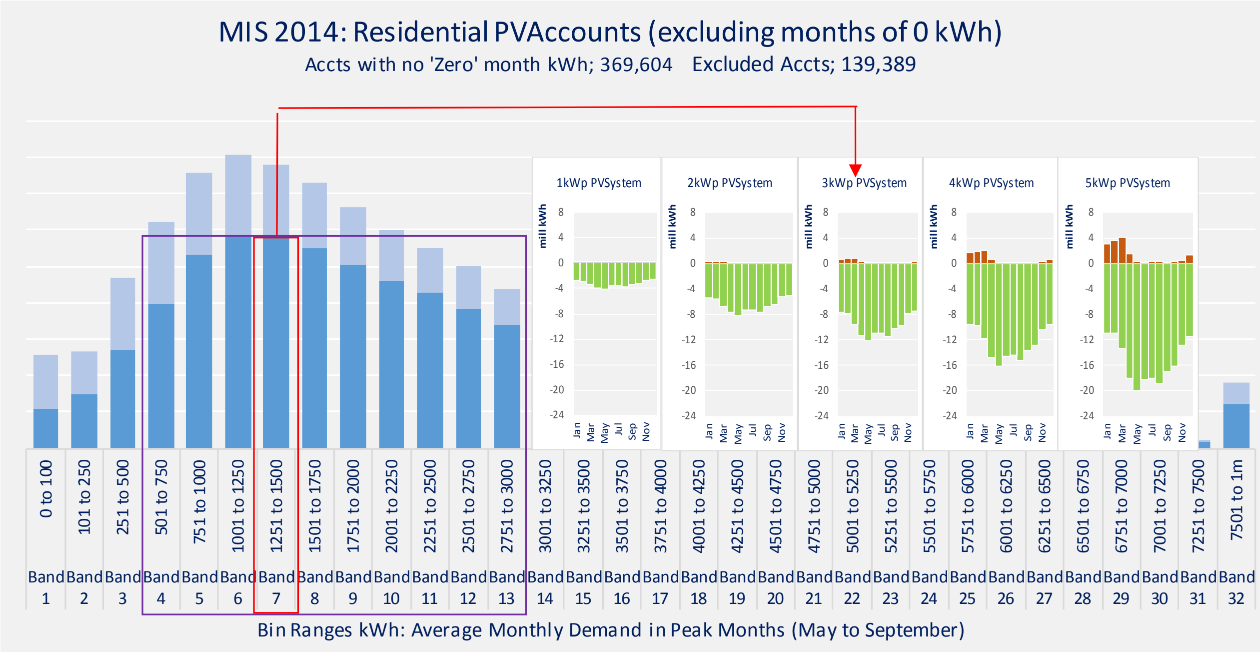

The analysis focused on the 10 largest bands (bands 4 to 13) organised into 10 Groups: Group 1 = largest band, Group 2 = the two largest bands, and so on) shown in Figure 4. This allow the Authority to assess the optimal size of a Residential PV initiative.

*Figure 4: MIS Residential Account Groups & Constituent Bands*

| Groups | Bands | #Accts | % 2014 MIS Accts |
|---|---|---|---|
| *Group 1* | *7* | 29,080 | 5% |
| *Group 2* | *6 & 7* | 58,078 | 10% |
| *Group 3* | *6 to 8* | 85,503 | 14% |
| *Group 4* | *5 to 8* | 112,018 | 18% |
| *Group 5* | *5 to 9* | 137,328 | 22% |
| *Group 6* | *5 to 10* | 160,323 | 26% |
| *Group 7* | *5 to 11* | 181,673 | 30% |
| *Group 8* | *4 to 11* | 201,612 | 33% |
| *Group 9* | *4 to 12* | 220,868 | 36% |
| *Group 10* | *4 to 13* | 237,820 | 39% |
| *All Bands* | *1 to 32* | 369,604 | 61% |

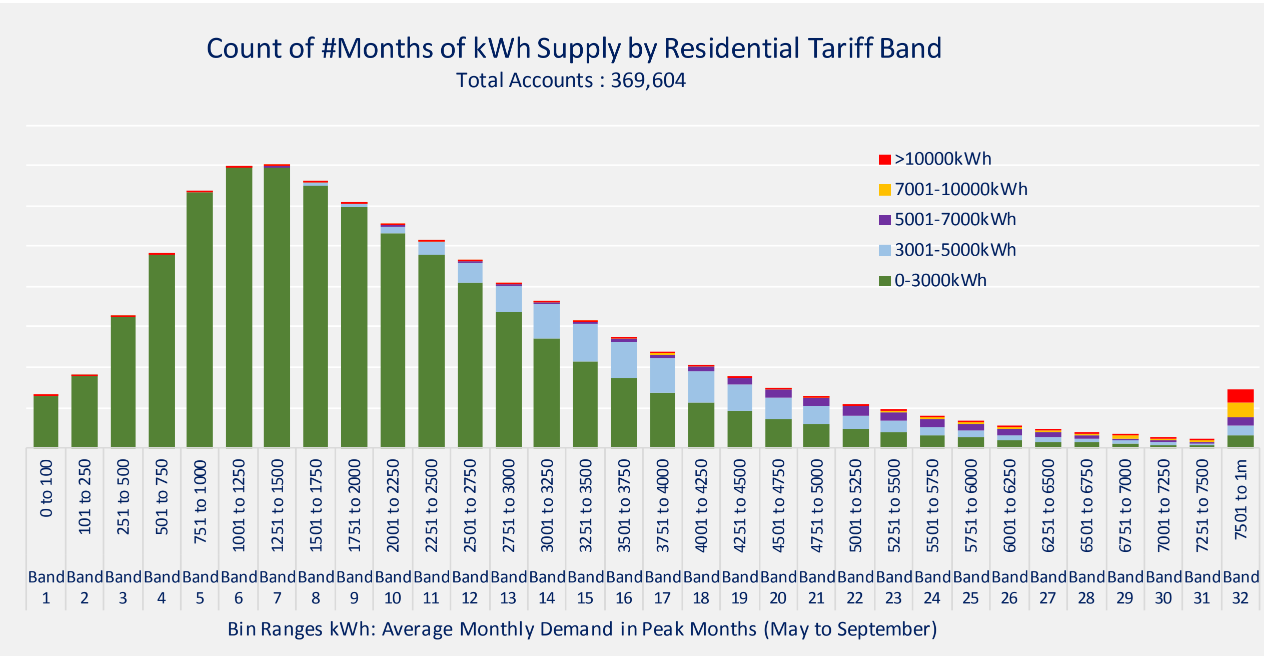
Representative outputs of 1kWp, 2kWp, 3kWp, 4kWp, and 5kWp PV systems were applied to the monthly consumption of individual accounts in each Group to derive estimates of PV output consumed by customers (self-supply) and/or exported to a distribution system, as illustrated in Figure 5.

*Figure 5: Estimating Monthly PV Self-Supply & Export by Account Band*




The 2014 Residential accounts database was evaluated to identify the number of months in 2014 in which monthly consumption fell within each block of the Residential Tariff – the resulting histogram is presented in Figure 6.

*Figure 6: Residential kWh Consumption by Residential Permitted Tariff Band*




For the 10 largest bands (bands 4 to 13) monthly consumption was between 1 - 3,000kWh in 96% of months. Residential customers would have paid 10 baiza per kWh in these months.

### Adjustments for Distribution System losses

PV system production is adjusted for distribution system losses:

1: PV production consumed by customers as self-supply is increased by 6% to reflect avoided losses from lower centrally dispatched electricity;

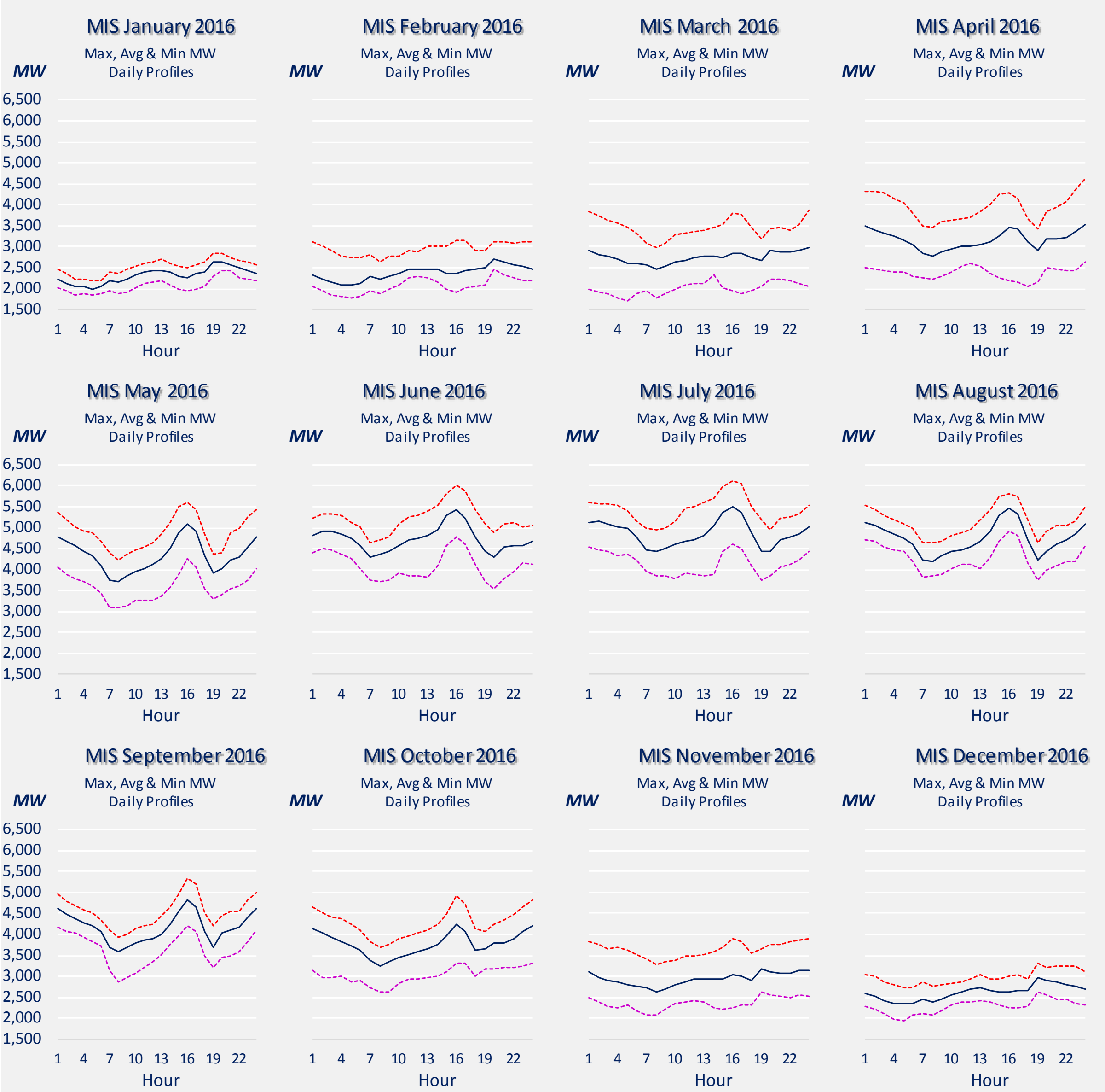
2: PV production exported to a distribution system is reduced by 6% to reflect losses transporting PV electricity across a distribution system.

Losses were subject to sensitivity analysis using High/Low values of 8% and 4%, respectively.

### MIS Hourly Demand (MIS 2016)

To assess how Residential PV production might change the hourly profile of MIS demand average, maximum and minimum demand profiles for each month were derived using 2016 MIS hourly data, as shown in Figure 7.

*Figure 7: MIS Representative Day System Demand – Max, Average and Min 2016*

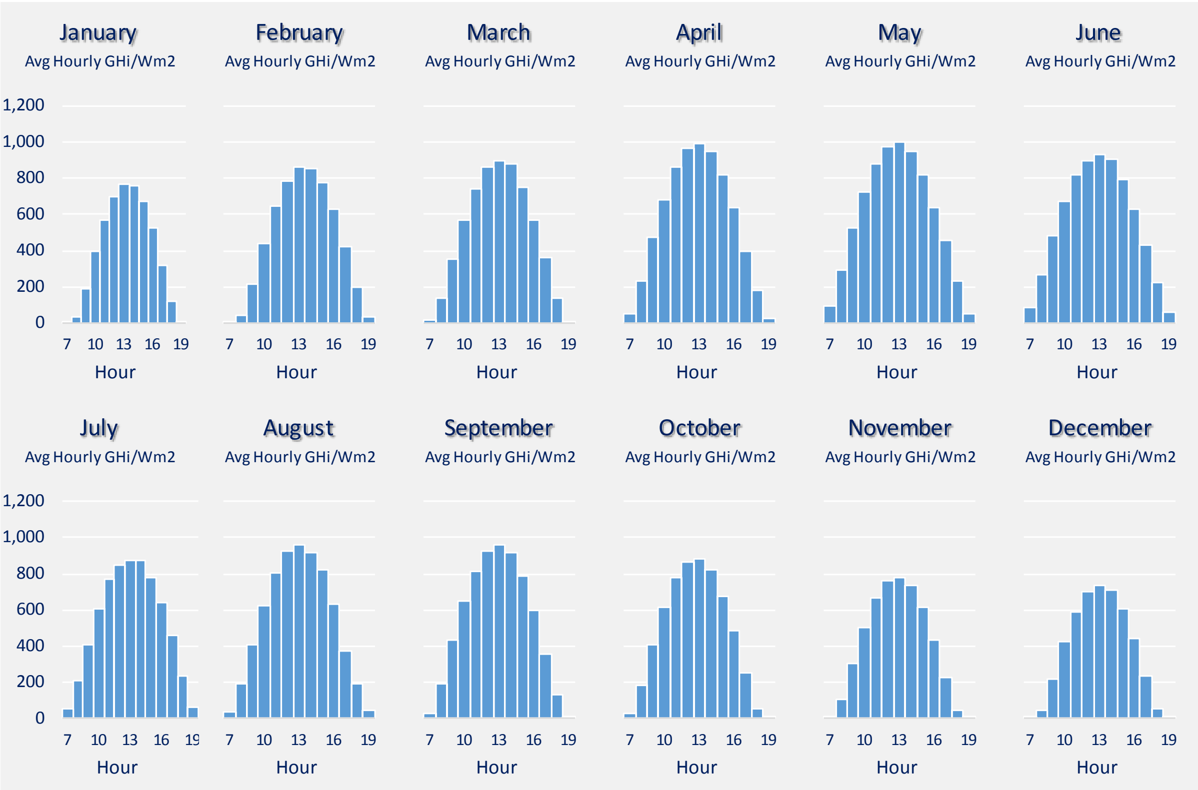



The use of actual system data ensures the characteristics of MIS demand in each month is reflected in the analysis and particularly when aligned to Oman GHi.

## Solar Irradiance Data (Adam & Manah GHi Measurements for 2015 & 2016)

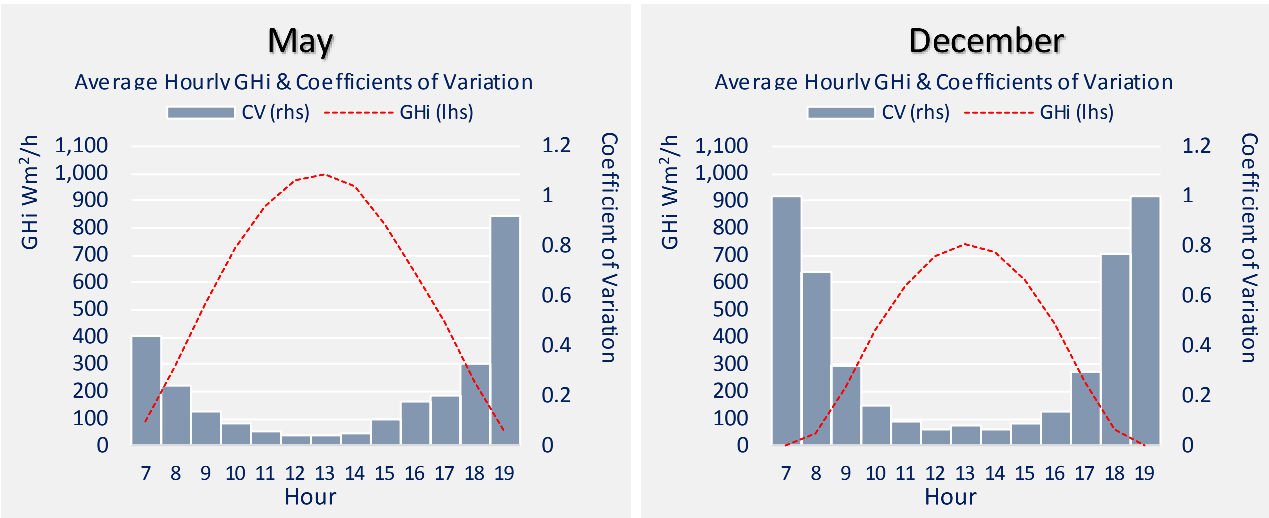
The analysis utilises solar irradiance data measured at monitoring sites in Adam and Manah during 2015 and 2016. The monitoring sites are now supervised by OPWP to support the wider deployment of commercial scale solar technologies in Oman. For the Residential PV analysis, hourly GHi measurements from Adam and Manah were pooled, the resulting hourly average GHi for each month are shown in Figure 8.

*Figure 8: Average Hourly Solar Irradiance (GHi) – Adam & Manah 2015/16*




GHi is highest in May and lowest in December. An interesting characteristic of the GHi data are hourly coefficients of variation (CV = standard deviation $GHi\_{m/h}$ ÷ mean $GHi\_{m/h}$).

*Figure 9: Average Solar Irradiance (GHi) and Hourly Coefficients of Variation – December & May*




As shown in Figure 9, variation around hourly mean GHi is highest in early and later hours of the day, but falls significantly during the day when GHi levels are at their highest.

## C: PV System Modelling Methodology

PV System electricity production is calculated using the following formula[1]:

$$W_{m/h} = GHi\_{m/h} * Xm^2 * PanelEff\_\% * PVLosses\ (PF) \qquad (1)$$

Where:

***$W\_{m/h}$*** is Watts of electricity produced in hour h in month m

***$GHi\_{m/h}$*** is the solar resource (GHi) in hour h in month m derived as follows:

$$Norm.Inv\ (Rand(), Mean\_GHi\_{m/h}, StDev\_GHi\_{m/h}) \qquad (2)$$

Where:

Norm.Inv and Rand() are Excel functions;

Mean_GHi is average GHi in month m and hour h drawn from pooled hourly measurement data from Adam and Manah in 2015/16; and

StDev_GHi is the standard deviation of GHi in month m and hour h drawn from pooled hourly measurement data from Adam and Manah in 2015/16.

***$Xm^2$*** is the $m^2$ panel surface of relevant PVSystems where 250Wp = $1.6^2$.

1 kWp system = 6.4 $m^2$

2 kWp system = 12.8 $m^2$

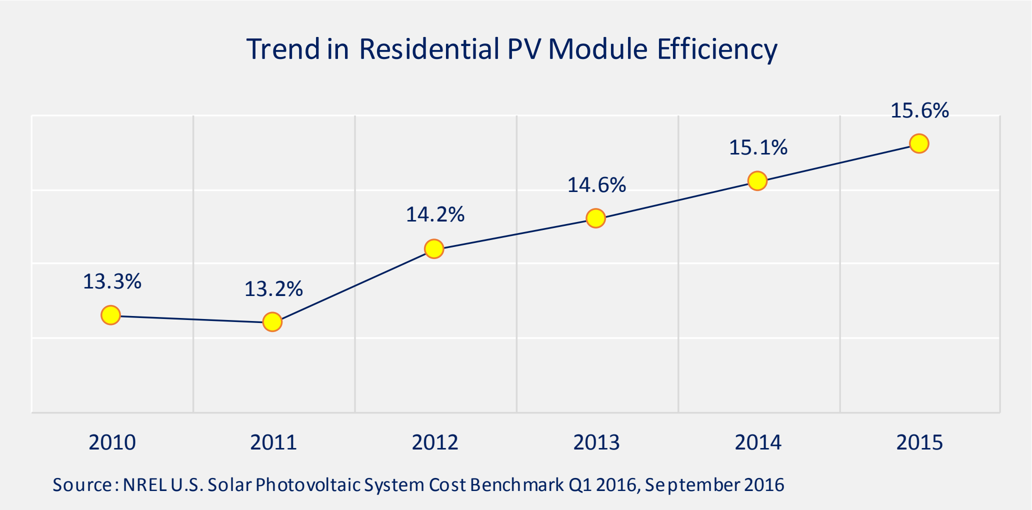
3 kWp system = 19.2 $m^2$

4 kWp system = 25.6 $m^2$

5 kWp system = 32.0 $m^2$

***PanelEff_%*** is the conversion efficiency of PV panels = 15.6%. Source: NREL U.S. Solar PV System Cost Benchmark Q1 2016, September 2016.

*Figure 10: Trend in Residential PV Module Efficiency*

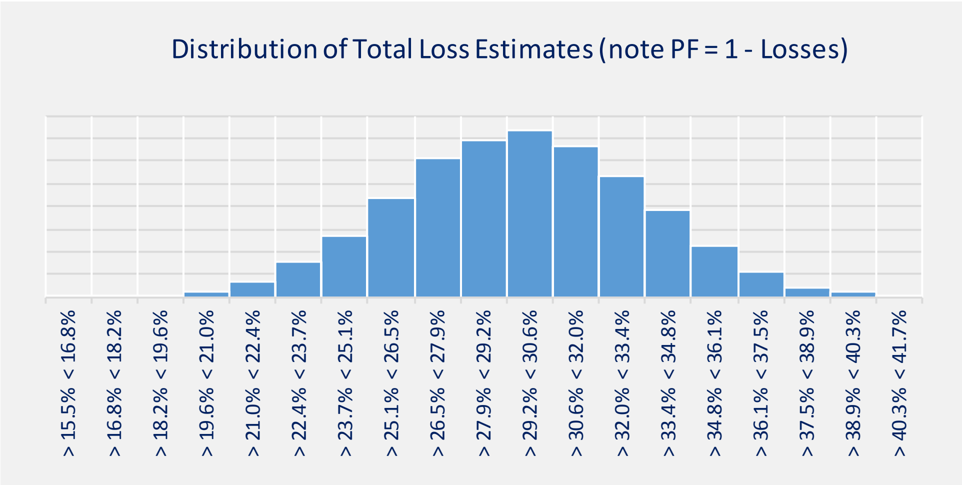



[1] Derived from www.photovoltaic-software/PV-solar-energy-calculation.php

***PVLosses (PF)*** is a performance factor reflecting the aggregation of seven categories of loss, including: Invertor Losses; Temperature Losses; DC Cable Losses; AC Cable Losses; Shading Losses, Weak Radiation Losses, and Dust Losses. PF is calculated as 1 – Sum(losses).

Simulation of High, Likely and Low values of each category of loss returned the distribution of total losses shown in Figure 11 (n=100,000).

*Figure 11: Distribution of Simulated PV System Losses*




The distribution in Figure 11 has a mean of 0.3 and standard deviation of 0.036, providing a central case PF value of (1 - 0.3) = 0.7. High and Low PF values of 0.75 and 0.65, respectively, were applied in sensitivity analysis.

## Monthly PV System Models

Simulation of the calculation methodology described above was used to derive monthly kWh production profiles for 1kWp, 2kWp, 3kWp, 4kWp and 5kWp PV Systems, details of each PV system model is presented in Figure 12.

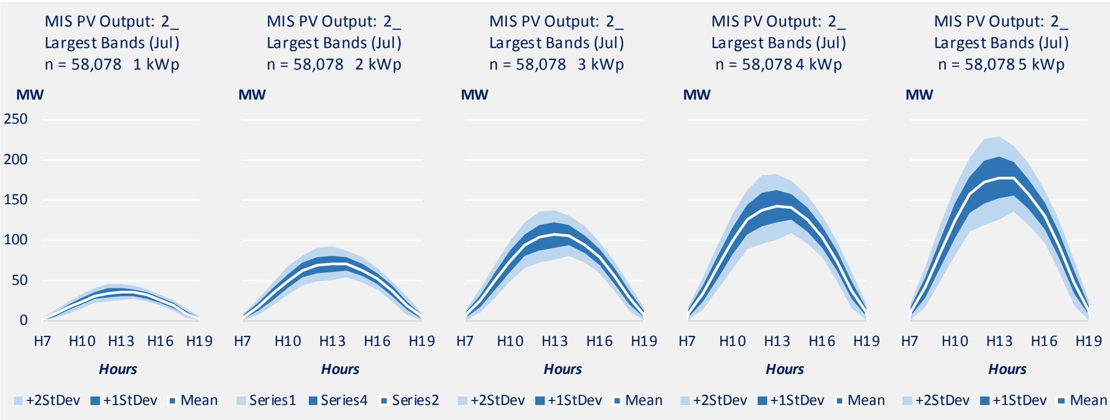
*Figure 12: Representative PV System Models: Monthly kWh (Reflecting Adam/Manah GHi 2015/16, Average PF Factor = 70%, n=50,000)*

| **1 kWp** | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Max_kWh | 198.6 | 222.3 | 271.7 | 267.5 | 267.5 | 297.9 | 268.5 | 263.5 | 218.8 | 205.1 | 195.0 | 179.0 | 2,855.2 |
| Mean_kWh | 109.7 | 119.9 | 136.3 | 152.6 | 165.8 | 150.5 | 147.9 | 150.3 | 142.5 | 131.2 | 108.8 | 103.8 | 1,619.3 |
| Min_kWh | 42.7 | 57.4 | 28.9 | 61.5 | 84.3 | 30.3 | 47.9 | 63.9 | 85.7 | 71.8 | 50.2 | 48.6 | 673.1 |
| StDev_kWh | 17.8 | 18.8 | 27.0 | 22.8 | 21.0 | 29.9 | 24.0 | 22.8 | 14.7 | 15.3 | 16.4 | 14.9 | |
| **2 kWp** | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
| Max_kWh | 397.2 | 444.7 | 536.8 | 542.3 | 538.6 | 613.1 | 534.2 | 524.6 | 435.9 | 418.3 | 384.9 | 355.5 | 5,726.1 |
| Mean_kWh | 219.4 | 239.9 | 272.6 | 305.2 | 331.5 | 301.0 | 295.9 | 300.7 | 285.0 | 262.3 | 217.6 | 207.6 | 3,238.7 |
| Min_kWh | 85.7 | 112.6 | 53.6 | 129.0 | 164.8 | 63.5 | 95.4 | 128.3 | 174.6 | 139.9 | 98.2 | 94.2 | 1,339.8 |
| StDev_kWh | 35.5 | 37.7 | 54.0 | 45.8 | 42.1 | 59.8 | 47.8 | 45.6 | 29.4 | 30.6 | 32.7 | 29.8 | |
| **3 kWp** | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
| Max_kWh | 592.4 | 668.5 | 809.1 | 826.5 | 805.8 | 896.8 | 803.6 | 805.0 | 665.5 | 622.1 | 575.1 | 538.4 | 8,608.8 |
| Mean_kWh | 329.2 | 359.8 | 408.9 | 457.7 | 497.4 | 451.7 | 443.8 | 451.1 | 427.5 | 393.5 | 326.4 | 311.4 | 4,858.3 |
| Min_kWh | 127.5 | 170.4 | 79.4 | 191.5 | 245.9 | 97.7 | 146.7 | 193.9 | 262.9 | 209.1 | 147.5 | 141.5 | 2,013.9 |
| StDev_kWh | 53.4 | 52.8 | 81.0 | 66.3 | 63.1 | 86.9 | 71.9 | 68.4 | 42.7 | 45.9 | 47.5 | 44.6 | |
| **4 kWp** | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
| Max_kWh | 794.5 | 890.9 | 1,080.9 | 1,073.9 | 1,084.3 | 1,214.0 | 1,059.1 | 1,045.4 | 872.3 | 823.9 | 783.5 | 718.5 | 11,441.2 |
| Mean_kWh | 438.8 | 479.6 | 545.4 | 610.4 | 663.1 | 602.0 | 591.6 | 601.5 | 570.0 | 524.6 | 435.1 | 415.1 | 6,477.3 |
| Min_kWh | 179.0 | 225.0 | 108.9 | 263.9 | 319.6 | 130.9 | 190.7 | 254.9 | 335.9 | 286.3 | 207.2 | 189.1 | 2,691.5 |
| StDev_kWh | 71.1 | 75.2 | 108.0 | 91.3 | 84.2 | 119.7 | 95.8 | 91.2 | 58.7 | 61.2 | 65.4 | 59.5 | |
| **5 kWp** | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
| Max_kWh | 992.8 | 1,126.4 | 1,378.0 | 1,358.9 | 1,357.6 | 1,515.2 | 1,340.5 | 1,328.7 | 1,096.9 | 1,032.2 | 967.2 | 900.7 | 14,395.0 |
| Mean_kWh | 548.8 | 599.6 | 681.7 | 762.8 | 828.7 | 752.9 | 739.5 | 751.9 | 712.4 | 655.8 | 544.0 | 518.9 | 8,097.0 |
| Min_kWh | 223.7 | 277.6 | 119.9 | 326.3 | 403.1 | 171.9 | 226.5 | 311.6 | 430.0 | 346.5 | 251.3 | 227.4 | 3,316.0 |
| StDev_kWh | 88.8 | 94.0 | 135.0 | 114.3 | 105.2 | 149.7 | 119.8 | 114.0 | 73.5 | 76.5 | 81.7 | 74.5 | |

## Hourly PV System Simulations

Equation (1) on page 9 was used to simulate hourly PV production for each PV system size, with the number of simulations equalling the number of accounts in each group. Figure 13 presents results for Group 2 (2 largest bands = 58,078 accounts) and July GHi: dark blue areas around central white lines indicate +/- 1 standard deviations of PV output, light blue areas indicate +/- 2 standard deviations of PV output.

*Figure 13: Hourly PV System Simulations – July GHI (1kWp to 5kWP, 2 Largest Bands, n = 58,078)*




| 1kWp | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| +2StDev | 4.4 | 13.4 | 23.6 | 33.2 | 40.5 | 45.1 | 45.9 | 43.7 | 39.1 | 32.6 | 25.0 | 15.1 | 5.1 |
| +1StDev | 3.3 | 10.9 | 20.2 | 28.9 | 35.9 | 39.8 | 40.7 | 39.5 | 35.3 | 29.4 | 21.8 | 12.3 | 3.8 |
| Mean MW | 2.2 | 8.4 | 16.7 | 24.7 | 31.3 | 34.5 | 35.6 | 35.4 | 31.5 | 26.1 | 18.6 | 9.4 | 2.6 |
| -1StDev | 1.1 | 5.9 | 13.2 | 20.5 | 26.8 | 29.3 | 30.4 | 31.3 | 27.8 | 22.9 | 15.4 | 6.6 | 1.3 |
| -2StDev | 0.0 | 3.4 | 9.7 | 16.2 | 22.2 | 24.0 | 25.2 | 27.2 | 24.0 | 19.6 | 12.2 | 3.8 | 0.0 |

| 2kWp | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| +2StDev | 9.0 | 26.7 | 47.3 | 66.6 | 81.2 | 90.0 | 91.7 | 87.3 | 78.3 | 65.2 | 49.8 | 30.3 | 10.3 |
| +1StDev | 6.7 | 21.7 | 40.3 | 58.0 | 71.9 | 79.5 | 81.4 | 79.1 | 70.7 | 58.7 | 43.4 | 24.6 | 7.7 |
| Mean MW | 4.5 | 16.8 | 33.3 | 49.4 | 62.7 | 69.1 | 71.1 | 70.9 | 63.1 | 52.2 | 37.1 | 18.9 | 5.2 |
| -1StDev | 2.2 | 11.9 | 26.4 | 40.8 | 53.5 | 58.6 | 60.8 | 62.6 | 55.5 | 45.7 | 30.8 | 13.2 | 2.6 |
| -2StDev | 0.0 | 6.9 | 19.4 | 32.2 | 44.2 | 48.2 | 50.6 | 54.4 | 47.9 | 39.2 | 24.5 | 7.5 | 0.0 |

| 3kWp | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| +2StDev | 13.4 | 40.1 | 71.0 | 99.8 | 121.6 | 135.2 | 137.8 | 131.1 | 117.5 | 97.9 | 74.8 | 45.4 | 15.4 |
| +1StDev | 10.1 | 32.7 | 60.5 | 87.0 | 107.8 | 119.4 | 122.2 | 118.7 | 106.1 | 88.2 | 65.2 | 36.9 | 11.6 |
| Mean MW | 6.7 | 25.3 | 50.1 | 74.1 | 94.0 | 103.6 | 106.7 | 106.2 | 94.7 | 78.4 | 55.7 | 28.4 | 7.7 |
| -1StDev | 3.3 | 17.8 | 39.6 | 61.3 | 80.2 | 87.8 | 91.1 | 93.8 | 83.3 | 68.7 | 46.2 | 20.0 | 3.9 |
| -2StDev | 0.0 | 10.4 | 29.2 | 48.5 | 66.3 | 72.0 | 75.6 | 81.4 | 72.0 | 58.9 | 36.7 | 11.5 | 0.1 |

| 4kWp | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| +2StDev | 17.9 | 53.6 | 94.8 | 133.0 | 162.0 | 180.3 | 183.2 | 174.6 | 156.4 | 130.4 | 99.6 | 60.7 | 20.5 |
| +1StDev | 13.4 | 43.6 | 80.8 | 116.0 | 143.6 | 159.2 | 162.7 | 158.1 | 141.3 | 117.4 | 86.9 | 49.3 | 15.4 |
| Mean MW | 8.9 | 33.7 | 66.7 | 98.9 | 125.3 | 138.2 | 142.1 | 141.5 | 126.1 | 104.4 | 74.2 | 37.9 | 10.3 |
| -1StDev | 4.4 | 23.8 | 52.7 | 81.8 | 106.9 | 117.1 | 121.6 | 125.0 | 111.0 | 91.4 | 61.6 | 26.5 | 5.2 |
| -2StDev | 0.0 | 13.8 | 38.6 | 64.7 | 88.6 | 96.0 | 101.0 | 108.4 | 95.8 | 78.4 | 48.9 | 15.2 | 0.1 |

| 5kWp | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 | H16 | H17 | H18 | H19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| +2StDev | 22.4 | 66.7 | 118.4 | 166.5 | 202.5 | 225.3 | 229.3 | 218.2 | 195.5 | 162.9 | 124.6 | 76.0 | 25.6 |
| +1StDev | 16.8 | 54.3 | 100.9 | 145.1 | 179.5 | 199.0 | 203.5 | 197.7 | 176.6 | 146.7 | 108.7 | 61.7 | 19.3 |
| Mean MW | 11.2 | 41.9 | 83.5 | 123.6 | 156.6 | 172.6 | 177.7 | 177.1 | 157.6 | 130.5 | 92.8 | 47.4 | 12.9 |
| -1StDev | 5.5 | 29.6 | 66.0 | 102.1 | 133.7 | 146.2 | 151.9 | 156.6 | 138.6 | 114.3 | 76.9 | 33.1 | 6.5 |
| -2StDev | 0.0 | 17.2 | 48.5 | 80.6 | 110.7 | 119.9 | 126.1 | 136.0 | 119.6 | 98.1 | 60.9 | 18.9 | 0.1 |

Hourly PV model outputs were applied to the representative MIS hourly profiles in Figure 7 to assess how a Residential PV initiative might impact system demand (as discussed in the consultation paper).

## D: Modelling Changes in Permitted Tariff Revenue & Customer Bills

Monthly PV System models in Figure 12 were applied to individual customer accounts to estimate potential reductions in average electricity bills for customers at whose premises PV systems are installed. Tariff revenue was calculated by applying the increasing block Residential Permitted Tariff to each account. The calculation was repeated for each individual account after subtracting the PV system outputs in Figure 12.

*Figure 14: Residential Permitted Tariff Revenue with and without PV – Rial Omani & % Change*

| | | | A: Residential Tariff Revenue - RO m | | | | | | B: Reductions in Tariff Revenues - % | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Groups* | *Bands* | *Accounts* | *NO PV* | 1kWp | 2kWp | 3kWp | 4kWp | 5kWp | 1kWp | 2kWp | 3kWp | 4kWp | 5kWp |
| *Group 1* | *7* | 29,080 | 3.4 | 3.0 | 2.5 | 2.1 | 1.7 | 1.4 | -14% | -27% | -39% | -50% | -59% |
| *Group 2* | *6 & 7* | *58,078* | 6.3 | 5.3 | 4.4 | 3.6 | 2.9 | 2.3 | -15% | -29% | -42% | -53% | -63% |
| *Group 3* | *6 to 8* | 85,503 | 10.0 | 8.7 | 7.4 | 6.1 | 5.1 | 4.1 | -14% | -27% | -39% | -50% | -59% |
| *Group 4* | *5 to 8* | 112,018 | 12.1 | 10.4 | 8.7 | 7.1 | 5.8 | 4.6 | -15% | -29% | -41% | -53% | -62% |
| *Group 5* | *5 to 9* | 137,328 | 16.2 | 14.0 | 11.9 | 9.9 | 8.2 | 6.7 | -14% | -27% | -38% | -49% | -59% |
| *Group 6* | *5 to 10* | 160,323 | 20.3 | 17.7 | 15.3 | 13.0 | 10.9 | 9.1 | -13% | -25% | -36% | -46% | -55% |
| *Group 7* | *5 to 11* | *181,673* | 24.6 | 21.6 | 18.8 | 16.2 | 13.8 | 11.6 | -12% | -23% | -34% | -44% | -53% |
| *Group 8* | *4 to 11* | 201,612 | 25.8 | 22.5 | 19.5 | 16.6 | 14.1 | 11.8 | -13% | -25% | -36% | -45% | -54% |
| *Group 9* | *4 to 12* | 220,868 | 30.1 | 26.5 | 23.1 | 20.0 | 17.1 | 14.6 | -12% | -23% | -34% | -43% | -52% |
| *Group 10* | *4 to 13* | 237,820 | 34.3 | 30.4 | 26.7 | 23.3 | 20.2 | 17.4 | -11% | -22% | -32% | -41% | -49% |

For Group 2 (Bands 6 & 7) with 3kWp systems tariff revenue falls from RO 6.3 million to RO 3.6 million, a reduction of 42%. These results provide important insight to how a Residential PV initiative would impact the annual revenues of Licensed Suppliers and annual subsidy requirements.

Further calculations identified the implied reductions in average electricity bills for each Group, results are shown in Figure 15. No allowance is made for remuneration of surplus electricity exported to a distribution system – the resulting changes in tariff revenue shown in Figure 14 are due to self-supply only.

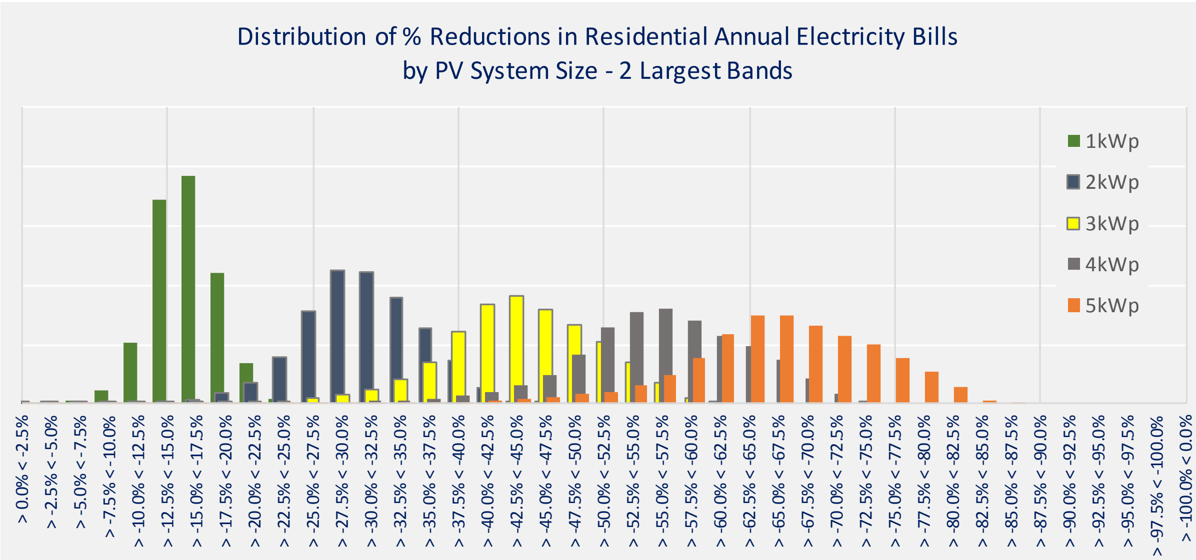
*Figure 15: Reductions in Annual Average Residential Electricity Bills with PV*

| | | | Tariff Rev | Avg Bill (no PV) | A: Reductions in Annual Average Bills - % | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Group | Bands | #Accts | RO million | 12 mths RO | 1kWp | 2kWp | 3kWp | 4kWp | 5kWp |
| *Group 1* | *7* | 29,080 | 3.4 | 118.0 | -14% | -27% | -39% | -50% | -59% |
| *Group 2* | *6 & 7* | 58,078 | 6.3 | 107.8 | -15% | -29% | -42% | -53% | -63% |
| *Group 3* | *6 to 8* | 85,503 | 10.0 | 117.5 | -14% | -27% | -39% | -50% | -59% |
| *Group 4* | *5 to 8* | 112,018 | 12.1 | 108.4 | -15% | -29% | -41% | -53% | -62% |
| *Group 5* | *5 to 9* | 137,328 | 16.2 | 117.8 | -14% | -27% | -38% | -49% | -59% |
| *Group 6* | *5 to 10* | 160,323 | 20.3 | 126.7 | -13% | -25% | -36% | -46% | -55% |
| *Group 7* | *5 to 11* | 181,673 | 24.6 | 135.2 | -12% | -23% | -34% | -44% | -53% |
| *Group 8* | *4 to 11* | 201,612 | 25.8 | 127.9 | -13% | -25% | -36% | -45% | -54% |
| *Group 9* | *4 to 12* | 220,868 | 30.1 | 136.3 | -12% | -23% | -34% | -43% | -52% |
| *Group 10* | *4 to 13* | 237,820 | 34.3 | 144.2 | -11% | -22% | -32% | -41% | -49% |
| *All Accts* | *1 to 32* | 369,604 | 90.0 | 243.5 | -7% | -14% | -20% | -26% | -32% |

The average bills of Group 2 accounts (Bands 6 & 7), with 3kWp PV Systems decline from RO 108 to around RO 63, a 42% reduction.

Average bill reductions in Figure 15 mask significant variation in the underlying distributions of percentage bill reductions. Figure 16 presents histograms of percentage bill reductions for Group 2 accounts for each PV system size.

*Figure 16: Distribution of Annual Reduction in Average Electricity Bills by PV System Size*




| *2 Lgst Bands* | Avg Bill | 1kWp | 2kWp | 3kWp | 4kWp | 5kWp |
|---|---|---|---|---|---|---|
| +2StDev | | -21.5% | -41.1% | -57.9% | -72.1% | -84.0% |
| Average | 107.8 | -15.7% | -30.5% | -43.9% | -55.6% | -65.8% |
| -2StDev | | -9.8% | -19.9% | -29.8% | -39.1% | -47.6% |
| StDev | 68.2 | 2.9% | 5.3% | 7.0% | 8.2% | 9.1% |
| n | 58,078 | | | | | |

It would be misleading to expect all customers to benefit from the average reductions reported in Figure 15. For a given annual kWh consumption, the percentage reduction in annual bills will tend to increase with PV system size. However, the significant overlap of distributions suggests percentage bill reductions for customers with large PV systems may sometimes be lower than for customers with smaller PV systems, reflecting variations in customer consumption within each Group.

The reported bill reductions provide some insight to how the installation of PV systems at residential premises might affect customer bills, but the reported reductions should be considered in the context of the analysis and treated with caution.

## E: Modelling Gas Benefits ($Sm^3$)

The gas benefits of a Residential PV initiative are sensitive to the assumed amount of gas required to generate 1 MWh supplied from the MIS. Data in Authority Annual Reports suggests an average value of around 260 $Sm^3$ per MWh for the MIS. While this may be an accurate reflection of the overall system average, Residential PV will not displace average generation but will displace marginal gas plant.

Figure 17 presents estimates of the specific gas content of four OCGT plant whose output is likely to be displaced by Residential PV in the medium term: Manah, Wadi Jizzi, Al Kamil and Al Rusail. Data is from Authority Annual Reports for 2014 and 2015.

*Figure 17: Specific Gas Content of MIS (OCGT) Marginal Plant – 2014 & 2015*

Residential PV MIS Gas Efficiency Checks

| Item | Year | Manah | Wadi Jizzi | Al Kamil | Al Rusail |
|---|---|---|---|---|---|
| Nat Gas $Sm^3$ million | 2014 | 366 | 204 | 417 | 1,259 |
| | 2015 | 419 | 149 | 194 | 1,241 |
| MWh (gross) | 2014 | 1,110,785 | 573,741 | 1,252,347 | 3,694,883 |
| | 2015 | 1,303,166 | 415,692 | 584,968 | 3,682,283 |
| $Sm^3$ /MWh | 2014 | 329 | 356 | 333 | 341 |
| | 2015 | 322 | 358 | 332 | 337 |
| GWh/$Sm^3$ | 2014 | 3.0 | 2.8 | 3.0 | 2.9 |
| | 2015 | 3.1 | 2.8 | 3.0 | 3.0 |

Figure 18 compares the MIS average gas content and the 4-plant average over 2014/15.

*Figure 18: Comparison Specific Gas Contents: MIS Average & Four OCGT Plant*

| | | |
|---|---|---|
| Average MIS specific gas content | 260 | MWh/$Sm^3$ |
| Average 4 OCGT MIS plant 2014/15 | 338 | MWh/$Sm^3$ |

The gas content of marginal OCGT plant is significantly higher than the MIS average as a significant proportion of MIS electricity is produced by highly efficient CCGT. Valuing Residential PV gas benefits using the MIS average would significantly underestimate potential gas savings, as highlighted in Figure 19.

*Figure 19: Potential Underestimate of Gas Saving Benefits*

| | *Residential PV Bands: (inc Dloss)* | | Largest | 2-Largest | 7-Largest | 10 Largest |
|---|---|---|---|---|---|---|
| *1* | 1 Yr PV production | *MWh* | 149,200 | 297,600 | 932,600 | 1,220,100 |
| *2* | 1 Yr Gas Saving | *$Sm^3$ mill* | 38.8 | 77.4 | 242.5 | 317.2 |
| *3* | | *$Sm^3$ /MWh* | 260 | 260 | 260 | 260 |
| *4* | Solar Gas as % Total MIS Gas 2015 | | 0.5% | 1.0% | 3.3% | 4.3% |
| *5* | Solar Gas as % 4 plant Gas 2015 | | 1.9% | 3.9% | 12.1% | 15.8% |
| *6* | Solar gas *@ 4-Plant 2014/15 ($Sm^3$ m* | | 50.5 | 100.7 | 315.6 | 412.9 |
| *7* | MIS average Vs 4 Plant 2014/15 | | -23.2% | -23.2% | -23.2% | -23.2% |

Line 1 in Figure 19 is MWh PV production for various bands, line 2 is the estimated gas saving assuming 260 $Sm^3$/MWh. For the 2 largest bands gas savings equate to 1% of total 2015 MIS gas use and 4% of the gas used by the 4 OCGT plant. Line 6 shows gas savings assuming the 4-plant average 338 $Sm^3$/MWh, line 7 shows that gas savings are 23% lower using the MIS rate than the 4-plant average.

The analysis reflects a central assumption of 275 $Sm^3$/MWh with High/Low values of 300 $Sm^3$/MWh and 250 $Sm^3$/MWh, respectively, applied in sensitivity analysis.

## F: Modelling $CO_2$ Emissions

An important assumption when valuing emission reduction gas benefits is the emission factor used to estimate $CO_2$ per kWh displaced by Residential PV.

Estimates of natural gas $CO_2$ per kWh are sensitive to the fuel conversion efficiency of facilities whose output is displaced by Residential PV.

$CO_2$ emission factors typically assume a fuel conversion efficiency of around 33%. The MIS in Oman is served by many highly efficient CCGT with efficiencies of up to 60%. $CO_2$ emission factors were derived for a range of gas plant efficiencies – the calculation steps and assumptions are shown in Figure 20.

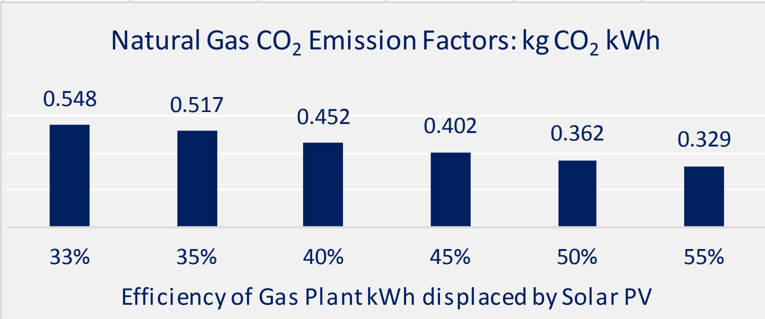
*Figure 20: Natural Gas $CO_2$ Emission Factors*

Pounds of $CO_2$ per billion BTU of energy: 117,000

*Source: https://www.physics.uci.edu/~silverma/units.html*

| | |
|---|---|
| 117 | lb/MBTu expressed as lb per million Btu |
| 0.00011700 | * $10^{-6}$ to Convert to lb/mMBTu |
| 0.00099743 | * by 8.5 to estimate Btu per 1 Wh (40.0% Efficiency) |
| 0.00000045 | * 1/2205 to convert lbs to tonnes of $CO_2$ for 1Wh |
| 0.00045235 | * 1000 for tonnes $CO_2$ per kWh |
| 0.45234694 | * 1000 for ktonnes **or** kg $CO_2$ per kWh |
| 40% | Efficiency of NatGas kWh displaced by PV |

| | Fuel Efficiency of Facility/System kWh displaced by Solar PV | | | | | |
|---|---|---|---|---|---|---|
| | 33% | 35% | 40% | 45% | 50% | 55% |
| kg $CO_2$ kWh | 0.548 | 0.517 | 0.452 | 0.402 | 0.362 | 0.329 |




Our central estimate of $CO_2$ emission reductions reflects an emissions factor of 452 kg/kWh consistent with an assumed gas conversion efficiency of 40%.

## G: Modelling Carbon Tax Revenues

A carbon tax of US$25 per ton of $CO_2$ was applied to derive an estimate of avoided environmental damage due to Residential PV. Details of the tax calculation are presented in Figure 21.

*Figure 21: Carbon Tax Calculations*

Pounds of $CO_2$ per billion BTU of energy: 117,000

*Source: https://www.physics.uci.edu/~silverma/units.html*

| | |
|---|---|
| 117 | lb/MBTu expressed as lb per million Btu |
| 0.00011700 | * $10^{-6}$ to Convert to lb/mMBTu |
| 0.00099743 | * by 8.5 to estimate Btu per 1 Wh (40.0% Efficiency) |
| 0.00000045 | * 1/2205 to convert lbs to tonnes of $CO_2$ for 1Wh |
| 0.00045235 | * 1000 for tonnes $CO_2$ per kWh |
| 0.45234694 | * 1000 for ktonnes **or** kg $CO_2$ per kWh |

| | |
|---|---|
| 40% | Efficiency of NatGas kWh displaced by PV |
| 25 | US$ t $CO_2$ |
| 0.0113 | Carbon Tax $/kWh |
| 0.0044 | Carbon Tax OR/kWh |
| | Exchange Rate 1US$ =0.384883 OR |

| | Baisa/kWh | Fuel Efficiency of Facility/System kWh displaced by Solar PV | | | | | |
|---|---|---|---|---|---|---|---|
| | | 33% | 35% | 40% | 45% | 50% | 55% |
| Carbon Tax US$ tCO2 | 10 | 2.1 | 2.0 | 1.7 | 1.5 | 1.4 | 1.3 |
| | 15 | 3.2 | 3.0 | 2.6 | 2.3 | 2.1 | 1.9 |
| | 20 | 4.2 | 4.0 | 3.5 | 3.1 | 2.8 | 2.5 |
| | 25 | 5.3 | 5.0 | 4.4 | 3.9 | 3.5 | 3.2 |
| | 30 | 6.3 | 6.0 | 5.2 | 4.6 | 4.2 | 3.8 |

A carbon tax of $25US per ton of $CO_2$ from generating plant with an assumed efficiency of 40% equates to 4.4 baiza/kWh.

## H: Analysis Questions

The modelling framework was developed to provide answers to the following analysis questions:

i. How much electricity could residential PV systems ranging in size from 1kWp, 2kWp, 3kWp, 4kWp and 5kWp produce given measured solar irradiance in Oman?

ii. What would be the distribution and monthly profile of Residential PV in terms of (a) self-supply (b) export of surplus kWh to a distribution system?

iii. How would Residential PV affect the hourly profile of system demand, in each month at times of maximum and minimum demand?

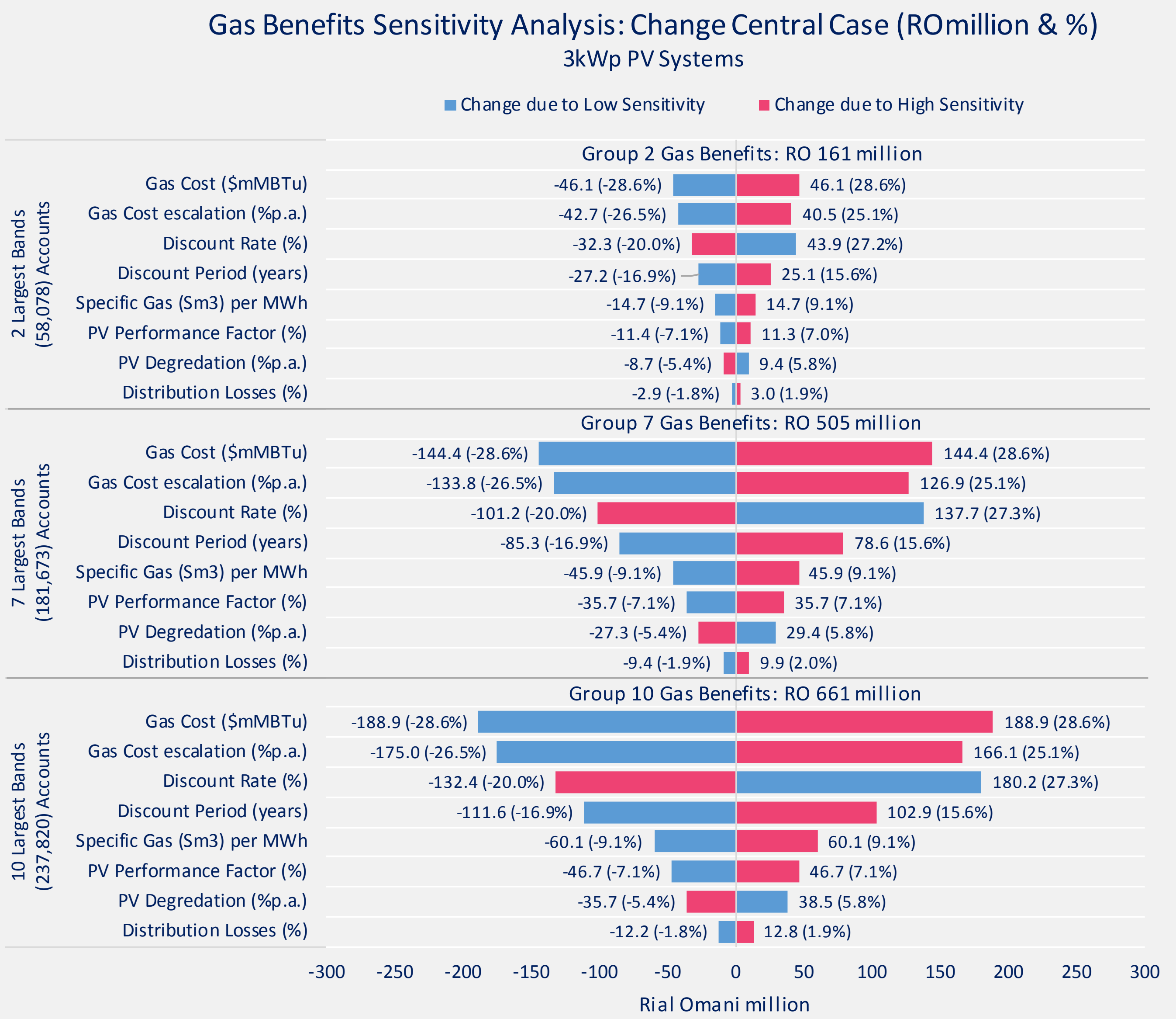
iv. What would be the likely magnitude of fuel savings (natural gas) in terms of volume ($Sm^3$) and economic cost (Rial Omani)?

v. By how much could Residential PV reduce natural gas related $CO_2$ emissions in Oman?

vi. How would Residential PV affect tariff revenues and Customer electricity bills?

vii. How would Residential PV affect distribution companies' ability to recover network costs?

## Appendix A: Group 2, Group 7 & Group 10 Sensitivity Analysis




| Sensitivity Item | Sensitivity Values | | |
|---|---|---|---|
| | Low | Central | High |
| Gas Cost ($mMBTu) | 5.0 | 7.0 | 9.0 |
| Gas Cost escalation (%p.a.) | 0% | 3% | 5% |
| Discount Rate (%) | 2% | 4% | 6% |
| Discount Period (years) | 20 | 25 | 30 |
| Specific Gas (Sm3) per MWh | 250 | 275 | 300 |
| PV Performance Factor (%) | 65% | 70% | 75% |
| PV Degredation (%p.a.) | 0.0% | 0.5% | 1.0% |
| Distribution Losses (%) | 4% | 6% | 8% |