Solar Enablement

Review of Python Code

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Victoria Power Networks (VPN, CitiPower and Powercor)

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Executive Summary

CitiPower and Powercor (also referred to as Victoria Power Networks or VPN) have engaged Jacobs to provide a review of four key functions of the Python code. These functions are utilised to determine the feasibility, in respect to customer benefits, of undertaking investment in the distribution network and allow for the enablement of rooftop solar PV that would otherwise have been constrained.

Jacobs have relied entirely on the information provided by VPN and have reviewed the Python model using several methods including direct review of the code and assessment of the outputs by running (parts) of the code. Jacobs did not review every single line item and/or function of the code but focussed on the major and most critical functions of the code.

Overall the code is well written and based on the tests conducted by Jacobs as per the scope of work set out in this document, the Python code runs according to the specifications outlined by VPN.

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The sole purpose of this report and the associated services performed by Jacobs is to review the Python code of the Solar Enablement project in accordance with the scope of services agreed and set out in the contract between Jacobs and CitiPower & Powercor.

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1. Introduction

1.1 Background

This report discusses the results from the Python model review Jacobs conducted for VPN as part of the Solar Enablement project.

In an earlier engagement Jacobs assisted VPN with the estimation of potential market and carbon emission reduction benefits of enabling residential rooftop solar PV through CitiPower and Powercor's distribution networks. The results from this market benefit analysis were key inputs into the Solar Enablement model VPN developed.

The Solar Enablement model aims to determine the rise in network voltages as a result of increased solar export. When network voltages rise sufficiently, customers' solar inverters likely trip off and stop generating for both in-home consumption and for exports. As part of the modelling VPN aims to determine the economic feasibility, from a customer perspective, to augment the distribution network to allow for connection without solar export constraints. This is done at the distribution transformer level, where the cost of transformer augmentation is assessed individually against the market and carbon emission reduction benefits.

The VPN Solar Enablement model was developed in Python, an open source statistical and programming tool, and includes the following main functions:

I. Load the rooftop solar PV uptake projections from 2018 to 2030 and allocate these to the appropriate distribution substations;

II. Load the current voltage distribution profiles of the distribution substations. The voltage distribution profiles are based upon 15-minute blocks of data over a representative month for Summer and Winter, and two months to represent the shoulder season. The voltage rise for each of these substations is the forecast based on the rooftop solar PV uptake projections;

III. Determine the new voltage distribution of each distribution transformer and the increased levels of tripping (in kWh per annum) of residential rooftop solar PV. This is achieved via a linear transformation of the current voltage distribution profiles, based upon the expected voltage rise as a function of the projected increase in rooftop solar PV; and

IV. Apply the economic test for each of the distribution transformers to determine whether there would be a benefit for removing solar constraints at that location.

The aim of the above model analysis is that solar constraints would only be removed at distribution substations where the cost of augmentation is fully offset by market and carbon emission benefits.

This report discussed the work Jacobs was contracted to conduct for VPN, reviewing the above main functions of the Solar Enablement model. The next sections will address the scope, approach and review outcomes and conclude with a summary of the review.

1.2 Scope

VPN have engaged Jacobs to provide a review of four key functions of the Python code. These functions are utilised to determine the feasibility of undertaking investment in the distribution network and allow for the enablement of rooftop solar PV export, that would otherwise have been constrained.

As the main objective of this review, VPN have engaged Jacobs to determine that the program functions and associated outputs are according to the specifications as presented to Jacobs. A secondary objective is the provision of commentary about the structure of the code.

To conduct the review, Jacobs has relied on the information provided by VPN. We also attended briefings to understand the objective of the review, the Solar Enablement model and the core specifications. We have reviewed the Python model using several methods including direct review of the code and assessment of the outputs by running (parts) of the code. Jacobs did not review every single line item and/or function of the code but focussed on the major and most critical functions as described in the previous section and briefly discussed below.

The review conducted by Jacobs is to determine whether the key functions investigated are according to specifications. The review does not include any assessment on the merits of the modelling approach to enabling more solar, e.g. whether the modelled approach (including associated equations) is the correct or best approach. The review also does not assess the correctness of the input data.

The full Python model specification is conducted over several stages, the first of which is a data preparation step. We have assumed that the data provided from this stage utilised for the remaining functions is correct. The key stages in the overall model investigated in this study are outlined below:

- Solar Forecast
- Voltage Rise
- Application of Voltage Rise
- Economic Test

The entire model coded in Python was extensive, and due to the handling of large datasets required hours to run to completion using advanced computing power. It was therefore not appropriate to run the full model for the purposes of reviewing. Instead key functions within the code were identified and reviewed in a manner that we were satisfied that they fulfilled the specifications. Reviewing the code involved a combination of carefully interpreting some functions and running some functions through Python to analyse the outputs.

2. Approach

2.1 Activities

The following activities were undertaken during the review process:

- Initial discussions and meetings
- Data collection
- Detailed discussions and workshop with VPN Manager of AI and Data Analytics
- Development of review approach
- Report outline presented to VPN for comments
- Review of the Python code
- Draft Report
- Review and discussion
- Final Report

Following the draft report, VPN provided comments on some of our findings, which we have reproduced in this final report where indicated. Jacobs have not confirmed the accuracy nor analysed the content of these comments.

2.2 Data collection

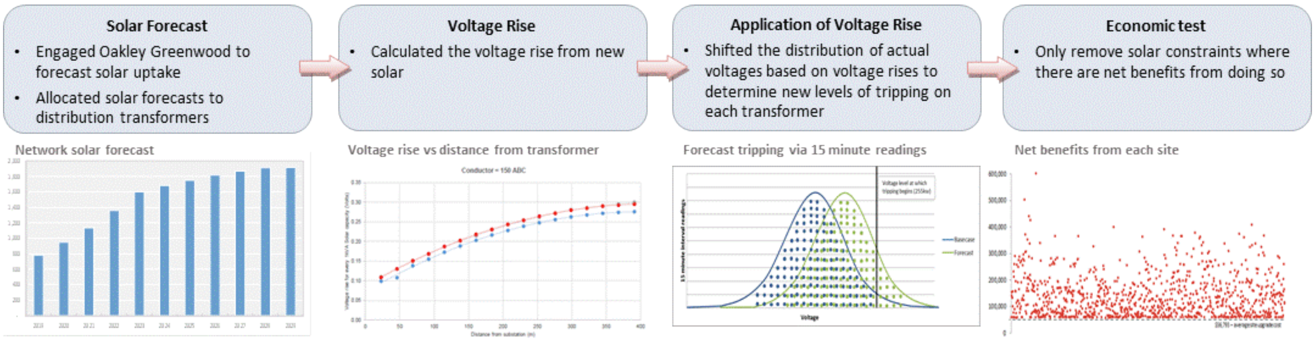
The below outlines the data supplied by VPN for the purposes of reviewing the Python model.

- Five sets of python code in Jupyter notebook format, one of which was a duplicate updated version.
- One Python script containing the main functions that were called upon via the notebooks.
- A PowerPoint presentation and word document outlining the key steps undertaken in the model.
- A set of 114 folders representing CitiPower and Powercor Zone Sub Stations containing forecasted information on PV installations for each respective ZSS in Parquet format. These were based upon projections supplied to VPN by Oakley Greenwood (OGW).
- 20 CSV files containing input data to the functions, primarily relating to the attributes of individual VPN transformers.
- CSV files containing the voltage distribution of each individual transformer for four months representing the seasonal voltage behaviours in 2018 and 2019.

2.3 Review approach

We conducted the review following the main structure and steps as outlined in Figure 1.

Figure 1: Main functions of the Python Solar Enablement Model



Source: VPN

To be able to conduct the review in a reasonable time-frame, we selected two Zone Sub Stations (ZSS) as the targets for investigation. We then conducted a review of the expected outputs on connected distribution transformers to determine if the code was working according to specifications.

The code is programmed to apply the same logic to each of the ZSS and underlying distribution transformers in the VPN distribution area and therefore we were able to save significant time to limit the investigation to these two ZSS.

The “BAS” Zone Sub Station was selected to analyse the “Solar Forecast” and “Voltage Rise” sections of the code. Some basic analysis of the input CSV supplies files shows the following attributes of the BAS ZSS:

1. The BAS ZSS has 4,662 different distribution transformers connected.
2. Total customers connected to the BAS ZSS include:
    - 33,949 Residential customers
    - 2,644 commercial customers
    - 797 A customers, 1361 DF customers, 642 I customers, 7 public lighting (P) customers
3. Customers with PV installations fed into the BAS ZSS include:
    - 4,516 Residential customers
    - 111 commercial customers
    - 18 agricultural (A) customers, 173 domestic farm (DF) customers, 117 industrial (I) customers with PV installations.

A second ZSS “TK” and subset of its transformers was selected to conduct analysis on the “Application of Voltage Rise” and “Economic Test” functions within the code.

3. Review

3.1 Solar Forecast – allocate solar forecasts to distribution transformers

3.1.1 Forecasting residential PV capacity installed to individual ZSS

Function name: zss_predictions

This function determines the ZSS projections of solar PV for residential properties on existing network infrastructure.

Review results: function according to specifications

The function was reviewed and found according to specifications.

The function includes three key steps, these are:

1. The OGW solar PV forecasts by ZSS was loaded into the function.
2. A linear estimation was performed for each ZSS based on the first and last values.
3. The linear forecast was then adjusted for greenfield developments and commercial installations were removed at 3.6% compounded annually and 22% respectively.[1]

The function returned the following outputs:

- A dataset including a timeseries of the forecasted solar PV penetration per ZSS in MVA, based on the OGW and linear forecasts.
- The linear rate of increase (slopes) for each of the ZSS, provided in VA per year.
- A dataset with the projections of solar PV penetration per ZSS in MVA (adjusted for greenfield and commercial developments. An example of this output for the BAS ZSS is shown below. The adjusted growth of PV installations output in this dataset was used by other functions within the model to estimate the future PV installation capacity per individual distribution transformer connected to the ZSS.

Table 1: Example output for the expected MVA/year added to the BAS zone substation

Year	Forecast MVA/year	Cumulative MVA	Adjusted growth MVA/yr	Adjusted cumulative MVA
2018	12.19207	22.8995	9.509811	22.8995
2019	12.19207	35.09156	9.070897	31.97039
2020	8.207619	43.29918	5.800357	37.77075
2021	9.254436	52.55362	6.182568	43.95332
2022	11.32353	63.87715	7.111582	51.0649

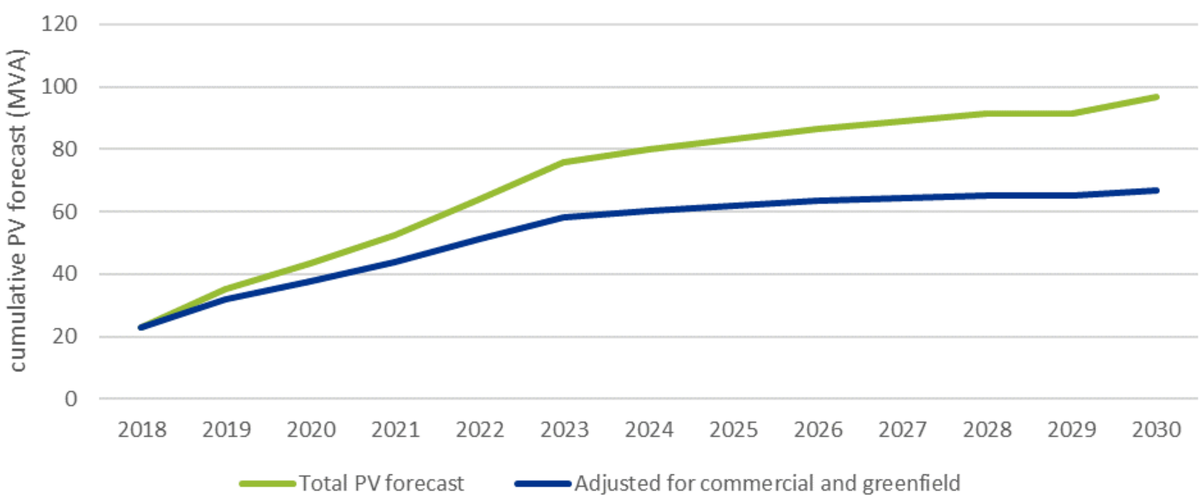
[1] VPN informed us that the 3.6% was obtained via historical analysis of greenfield development PV installation over the past 3 years. The 22% reduction for commercial customers was obtained from the OGW forecast.

Year	Forecast MVA/year	Cumulative MVA	Adjusted growth MVA/yr	Adjusted cumulative MVA
2023	12.03139	75.90853	7.05719	58.12209
2024	4.11082	80.01935	2.234647	60.35674
2025	3.308989	83.32834	1.651486	62.00822
2026	3.316404	86.64475	1.502259	63.51048
2027	2.515112	89.15986	1.019137	64.52962
2028	2.118713	91.27857	0.753653	65.28327
2029	0.239457	91.51803	0.0729	65.35617
2030	5.129679	96.64771	1.289182	66.64535

Comments:
Jacobs reviewed outputs from running the function and analysing the results for the BAS Zone Substation. The output dataset represents for the BAS ZSS were validated against by manually checking the annual growth rate from the OGW forecasts.

The average yearly growth rate, as determined by the OGW forecast was used to project the uptake of PV for individual transformers. These were then adjusted for commercial and greenfield developments. It is noted that while the linear uptake of PV installation for each ZSS was also calculated, this was only used for the last year of the forecast (to extend it by one year). Using the adjusted OGW forecast directly provides a more accurate year on year growth figure compared to the linear uptake approximation. This is highlighted in the figure below for the BAS ZSS.

Figure 2: Cumulative PV forecast for BAS ZSS



3.1.2 Forecasting residential PV capacity installed to individual transformers

Function name: zss_transformer_forecasts

This function determines individual transformer projections of solar PV for residential properties on existing network infrastructure.

Review results: function according to specifications, minor comments on approach

The function was reviewed and found according to specifications.

The key inputs into this function are:

- List of ZSS names.
- List of ZSS rate of PV uptake forecasts prior to commercial/greenfield adjustments (from function 1).
- Dataset containing ZSS solar forecasts following greenfield/commercial adjustments MVA (from function 1).

Additional data inputs were supplied by the following csv files:

- Transformer_inverter.csv : historical list of each PV installation on record, including date of installation, inverter size, customer type, transformer id and feeder (ZSS).
- Tx_feeder_rating_type.csv: list of transformers including the feeder (ZSS), rating and configuration.
- Customer_count.csv: list of the customer types (eg residential, commercial) for each of the transformers and number of customers within each category.

The key steps performed by this function are outlined below:

1. The historical list of VPN customer installed solar PV was loaded into the function, including date of installation and size (capacity) of inverter installed and type of customer (e.g. residential, commercial).
2. These installations were allocated to the respective ZSS based on feeder information and sorted based on installation date.
3. For each distribution transformer, if there is more than 1 installation for the transformer, the installations are sorted by installation date and a new cumulative sum of PV capacity is calculated.
4. Rate of solar PV uptake is then calculated for each transformer (slope) based on the first and last installation in the historical dataset.
    a. If there is only one installation, then the gradient is set at the rate of installation taken from the time of that installation until the end of 2018.
    b. If the gradient is zero (no installations), then a small slope of 1 is assigned to the transformer. This was done so that the slope was non-zero as a zero slope would prevent the transformers from ever being allocated PV in the future.
    c. If gradient is negative, then it is updated to be a positive gradient.
5. A new dataset is created containing information on transformer id, the historical rate of uptake, the number of solar customers assigned to the transformer, the year and capacity of first PV and last PV installation on record.

6. A second set of data loaded into the function, containing the transformer rating linked via transformer id. A linear value is added to the dataset based on the rate of uptake of solar PV for each transformer, as calculated in previous steps.

7. Each distribution transformer connected to the ZSS is then allocated a priority based on several factors. These include:

    a. The historical slope of the transformer (historical rate of uptake in MVA/annum).

    b. The proportion of customers for each distribution transformer as a percentage of the total ZSS customer base.

        i. transformer customers/total ZSS residential customers

        ii. Total ZSS residential customers for BAS in the function was confirmed to be 33,949.

        iii. The transformer's share of the ZSS was noted to be the total transformer customers (whether residential/commercial/I/DF/P/A/B) divided by the total residential customer number of the ZSS. This is slightly inconsistent.

    c. Availability factor or PV saturation of each respective transformer. This is calculated as the proportion of customers for each transformer that do not have PV installed:

        i. (the total transformer customers – transformer solar customers)/ (total transformer customers +1)

8. The total number of customers forecast assigned to each ZSS was calculated by utilising the average forecast yearly rate of uptake (provided from the first function) divided by the average residential customer system size. For BAS, the rate of uptake for 2018 was 9.5098 MVA/year. Divided by the average of 6kVA/customer, this gives a total allocation of 1,585 customers for 2018. It should be noted that elsewhere projections for average systems size are between 3.09 and 5kVA.

VPN Response 1

The solar forecast undertaken by Oakley Greenwood found 'data from the Clean Energy Regulator's (CER) website indicates that the average size of each installation installed in 2018 in Victoria was around 6.9KW'. In their conservative view, OGW assumed future systems would be 6KW.

First, the VPN model calculates the number of new installations that will occur, hence to be internally consistent with OGW, VPN divided the forecast capacity by 6. However, in forums, stakeholders pointed out that not all customers generate 6KW. Therefore, in setting the amount of solar generated, VPN have ratcheted the amount up from 3.09KW in 2019 to 5KW by 2025 as discussed in its business case (noting that customers are typically installing more solar panels than their inverter capacity meaning that by 2025 it is likely customers will generate the full 5KW from a 5KW inverter).

VPN has indicated that this is a conservative and internally consistent approach; by dividing the solar forecast by 6KW but assuming customers will generate less than this.

9. The list of forecast customers per year for each ZSS along with the list of prioritised transformers was then passed through a function that allowed the projected growth of customers for the ZSS to be allocated to a transformer based upon the transformer's "priority". Outputs from this function were confirmed to allocate the correct number of projected customers to the BAS Zone Substation for the forecasting period.

Table 2: BAS ZSS customer PV forecasts for years 2018-2031

Year	ZSS PV growth (MVA/year)	PV customer growth/ year (based on 6kVA av.)
2018	9.509811	1,585
2019	9.070897	1,512
2020	5.800357	967
2021	6.182568	1,030
2022	7.111582	1,185
2023	7.057190	1,176
2024	2.234647	372
2025	1.651486	275
2026	1.502259	250
2027	1.019137	170
2028	0.753653	126
2029	0.072900	12
2030	1.289182	215
2031	1.289182	215

The function returned the following outputs:

1. Dataset with the date and capacity of each PV installation, the respective distribution transformer id, aggregated to each ZSS.

   In the case of the BAS ZSS, 4,963 records were returned displaying each PV installed to the BAS ZSS, the date and capacity of installation, and the distribution transformer id to which it was installed at. Table 3 contains an example of this output.

Table 3: Example output showing the date and capacity of PV installed at transformers for the BAS zone substation

Installed PV	transformer_id	feeder	cust_class	pv_capacity	pv_install_date
123119	20048110	BAS024	R	2475	31/12/2012
72541	20048110	BAS024	R	1500	7/05/2013
95067	20048110	BAS024	R	4000	31/08/2014
123120	20048110	BAS024	R	3000	8/03/2018

2. Dataset containing the average rate of uptake of each transformer (slope), as determined by the first and last PV installation on record and cumulative PV installations, the availability factor and total number of customers per transformer.

In the case of the BAS ZSS, 4,662 records were returned representing each of the distribution transformer feeding from the BAS ZSS. A sample of this output is shown in the table below.

Table 4: Example output for the expected rate of PV growth (slope) for individual transformers in the BAS zone substation

Installed pv	Slope	Solar customers	Trans-former id	x1	x2	y1	y2	Total tx customers	Share of zss	Availability factor
22475	3333	7	20048110	31/12/12	28/11/18	2475	22475	59	0.002	0.87
45945	5618	17	20048121	26/07/10	15/08/18	1000	45945	123	0.004	0.85
44010	6073	16	20048132	31/08/11	26/08/18	1500	44010	154	0.005	0.89
0	1	0	20054037	0	1/01/18	0	0	15	0.000	0.94

3. Dataset representing the forecast customer and PV growth for each distribution transformer in the ZSS for each year of the forecasting period.

   Table 5 represents the BAS ZSS for final year of forecasting. As expected, for each solar PV customer the solar PV growth is 5 kVA. The sum of customers added for the BAS ZSS for 2031 is 214, which is also as expected. The sum of customer growth was calculated for each year and was found equal to the expected customer growth projected for the total ZSS for each year, indicating that the customer growth output for each ZSS has been allocated as specified.

Table 5: Example output displaying the rate of uptake of PV, forecast growth in PV capacity, projected number of solar customers and availability factor calculated for individual transformers in the BAS zone substation

Customer growth	Forecast	Forecast growth (VA)	Installed pv	Share of zss	Slope	Solar customers	Total tx customers	Trans-former id	Year	Availability factor
0	74610	0	74610	0.001738	3333	16	59	20048110	2031	0.728814
1	215178	5000	215178	0.003623	5618	50	123	20048121	2031	0.593496
1	282718	5000	282718	0.004536	6073	61	154	20048132	2031	0.603896
0	10117	0	10117	0.000442	1	0	15	20054037	2031	1

Comments

The calculation of customer numbers in historic data is based upon an average system size of 6 kVA. Historically, this appears to be smaller e.g. 3.09 kVA. This could possibly lead to an underestimation of solar customer growth per year for each ZSS. However, VPN has addressed this issue, refer to textbox VPN Response 1.

The transformer's share of the ZSS was noted to be the total transformer customers (residential, commercial, other) divided by the total residential customer number of the ZSS. This is inconsistent.

3.2 Voltage rise – calculate the voltage rise from new solar

3.2.1 Projecting whether transformers both need to and can be tapped down to lower voltages

Function name: calc_pv_effects

This function determines the requirements for augmentation of individual distribution transformers, based on the projected increase in solar PV penetrations supplied by previous functions and parameters of the individual transformer.

Review results: function according to specifications, some recommendations to refine code

Inputs into this function include:

- Dataset for each ZSS containing the yearly forecasted uptake of solar customers and PV capacity for each distribution transformer, as supplied by the previous function.
- List of starting 95th percentile voltages of each transformer (tx_volt).
- List of number of circuits for each distribution transformer (tx_switches).
- The expected voltage rise per new customer with rooftop PV for each distribution transformer.
- The number of tap changes allowed per distribution transformer.
- The voltage limit that dictates whether the distribution transformer requires some form of mitigation (e.g. tap changes, augmentation).

The key steps performed by this function are outlined below:

1. Obtain input information for each distribution transformer based on the starting voltage, average voltage rise per customer (previously calculated based upon length of feeder and type of conductor), number of switches per distribution transformer, number of times each distribution transformer can be tapped. These inputs were provided in csv format and were calculated as part of the data preparation stages by VPN. The forecasted installation of solar PV for each transformer as calculated in the previous function also formed a part of the input.

2. The function firstly creates datasets for each distribution transformer, containing information on the forecast amount of PV and number of customers for each year in the projection period.

3. The data is then passed into a function, which calculates the voltage rise per distribution transformer per year. Information on the number of circuits per transformer is utilised in combination with the voltage rise per distribution transformer. The function assumes that PV installation are evenly spread across circuits and phases and only causes a voltage rise once a customer has been added to each circuit and phase. It does this by multiplying the number of circuits for the distribution transformer by three phases. If the forecast number of new PV customers is less than this value for a given year, then no voltage rise is assumed for that year, but the number of customers is carried forward and added to next year’s forecast customer growth. The actual voltage rise is then calculated as a product of the number of voltage rises, the voltage rise per customer and the number of kVA forecast per customer. Individual distribution transformers were checked, and this function performed as expected. The table below represents a distribution transformer with 4 circuits, a voltage rise of 0.15 per customer and an expected 5 kVA average PV installation per customer. One voltage rise is expected for every 12 customers added, and this is observed in the output.

Table 6: Example computations of the function displaying the expected customer growth and associated voltage rises per distribution transformer

Year	Customer growth	Forecast	Forecast growth	Solar customers	Total tx customers	Number of voltage rises	Voltage rise
2018	0	132881.7	0	14	197	0	0
2019	20	194681.7	61800	34	197	1	0.75
2020	12	235581.7	40900	46	197	1	0.75
2021	13	284028.4	48446.67	59	197	1	0.75
2022	14	340658.4	56630	73	197	1	0.75
2023	14	401745	61086.67	87	197	2	1.5
2024	4	420471.7	18726.67	91	197	0	0
2025	3	435471.7	15000	94	197	0	0
2026	3	450471.7	15000	97	197	0	0
2027	2	460471.7	10000	99	197	1	0.75
2028	1	465471.7	5000	100	197	0	0
2029	1	470471.7	5000	101	197	0	0
2030	2	480471.7	10000	103	197	0	0
2031	2	490471.7	10000	105	197	0	0

4. The next step investigates the possibility of tapping the distribution transformer to mitigate voltage rises. It includes calculations on the impact that tapping has on the voltage rise of each distribution transformer and estimates the year that this will need to occur.

   Results on expected voltage rises from the previous step are added to the starting voltage input for each distribution transformer to create the total expected 95th percentile voltage for each distribution transformer. Once the voltage breaches the nominated voltage limit, the transformer is assumed to be tapped and the voltages are then reduced accordingly. If the distribution transformer can only be tapped once, voltages are reduced by 2.5% from the year of the breach. If distribution transformers can be tapped twice, voltages are reduced by 5% from the year of the breach.

5. The function then determines whether augmentation is required based upon the list of tap adjusted forecasted 95th percentile voltages for each distribution transformer i.e. it checks whether there is a constraint, but augmentation is not flagged unless the transformer passes an economic test as discussed later. These voltages are fed into another function which compares these voltages for each year against the voltage limit. If this is breached, the year of the breach is recorded (but subject later to an economic test), and voltages from this year onwards are changed to 240 to represent the effects of augmentation.

   Both the year of breach (if applicable) and the list of projected voltages for each transformer are returned. If no breach is found, then a high number is returned (9999) to represent that no augmentation is expected in the foreseeable future.

Outputs from this function include:

1. Time series of projected voltage increases for each transformer following both tap changes and augmentation if applicable.

2. List of years when tap changes and augmentations are expected to occur for each transformer.

Comments

Parameters fed into the function were repeated throughout the code several times, such as the estimated size of residential PV inverter capacities. This increases risks of mistakes during future updates, e.g. the programmer may not update the correct variables.

There are several functions within this section which have been superseded and should be deleted.

3.3 Application of voltage rise

3.3.1 Determining whether an augmentation is needed

Function name: process_percents

This function shifts the distribution of the spread of voltages of individual transformers in a linear manner according to the expected voltage rise. It then calculates the expected number of hours that voltages are expected to breach given thresholds following the application of the voltage rise.

Review Results: function according to specifications

Inputs into this function include:

- Dataset for each ZSS containing the yearly forecasted uptake of solar customers and PV capacity for each of the distribution transformers. This was supplied by the previous function.
- Voltage distribution 'bins' for each distribution transformer. These datasets contain information on the number of 15-minute block voltage levels across individual transformers of one month for each season (summer, winter, spring and Autumn). The histograms depict number of times each 15-minute block of voltage data is represented across a range of voltages.
- Solar PV generation output data in normalised ½ hourly blocks. Utilised to establish the relative daily PV generation output for each season (e.g. summer, winter, and shoulder seasons).

The key steps performed by this function are outlined below:

1. The function firstly obtains information on the normalised dataset of relative PV generation profiles for both CitiPower and Powercor. Then the average normalised generation output is determined for a typical summer's day (January), a typical winter's day (July) and a typical shoulder period day in March and October. These factors were then escalated so that the maximum generation output was 3.09-5KW (over time) in accordance with VPN's generation profile (refer to VPN Response 1). The normalised generation profiles are summed over the daytime period and divided by the number of hours to provide a relative proportion of daily solar generation output for each season.

2. Data for each ZSS and the connected individual distribution transformers is then passed into the function containing information on the voltage rise forecast per annum from 2019 to 2031. This includes voltage rises expected in the default scenario where no tapping or augmentation is conducted, and the voltage rise expected if the transformer is tapped. This data was supplied from the previous function.

3. The next step in the function is to calculate the percentage of time the 15-minute blocks of voltage breach the voltage threshold. This forms the basis for the expected percentage of solar PV trips each year. To calculate this, nested loops are run for each voltage threshold (253 to 257), for each scenario (default, tapped), for each season (shoulders, winter, summer), for each distribution transformer and for each forecast year. A function then subtracts the expected cumulative voltage change from the voltage threshold and then sums the percentage of data points that fall above this altered threshold value. This serves to essentially shift the voltage distribution in a linear manner by the expected voltage rise each year.

4. This adjustment of the voltage distribution and change was examined for distribution transformer #11028637. The voltage change was manually added each year, and percentage of values exceeding the threshold 253 was found to match the output from the function. Results from this analysis are outlined in Table 7 and the output from the function were found to be according to specifications.

5. The percentage of solar PV trips forecast for each distribution transformer was then used to calculate the total number of kilowatt hours of trips expected for each season. The trips in kWh (per season) is calculated via the following formula:

   Trips (kWh) = percent trips * solar customers * day length * system size * days per season * solar profile factor for respective company and season.

   The number of days per season is 90 for both summer and winter and 180 days for the shoulder seasons. A 7-hour daytime period is calculated for the day length. The results of these are returned in a dataset which includes results from individual distribution transformers connected to each ZSS.

Outputs from this function include:

The key outputs from this function include a CSV file for each ZSS, for each scenario (default or tapped) and for each threshold value.

These files include the estimated cumulative voltage change for each distribution transformer, the estimated cumulative number of customers for the specific transformer and forecast average size of inverters as calculated in previous functions. Additionally, this output includes the percentage of tripping that occurs for each year, each season and scenario for the respective distribution transformer and the actual number of kWh of trips is then presented based on the seasonal PV factor for each of the companies (CitiPower and Powercor). A sample of the output is provided in the table below for transformer 11028637 in feeding into the TK zone substation for the tapped scenario and a 256V threshold.

Table 7: Example of key output from the function displaying values for transformer #11028637 for the tapped scenario

Year	Day length	Percent trips	Season days	Solar customers	System size	Trip kwh	Trip kwh escalated	Trip kwh mean	Trip kwh mean escalated	Trip kwh median	Trip kwh median escalated	Voltage change
2019	7	0.000	90	10	3.09	0	0	0	0	0	0	0
2020	7	0.024	90	19	3.63	577	722	388	484	402	502	4.95
2021	7	0.578	90	29	3.9	22741	28427	15266	19082	15834	19792	9.9
2022	7	0.899	90	41	4.18	53623	67029	35996	44995	37335	46669	16.5
2023	7	0.962	90	53	4.54	80515	100644	54048	67560	56059	70073	23.1
2024	7	0.978	90	57	4.72	91554	114443	61458	76823	63745	79681	26.4
2025	7	0.982	90	60	5	102502	128127	68807	86009	71367	89209	28.05
2026	7	0.984	90	63	5	107795	134743	72360	90450	75052	93815	29.7
2027	7	0.984	90	65	5	111217	139021	74657	93321	77435	96793	29.7
2028	7	0.985	90	66	5	113125	141406	75938	94922	78763	98454	31.35
2029	7	0.985	90	66	5	113125	141406	75938	94922	78763	98454	31.35
2030	7	0.985	90	68	5	116553	145691	78239	97799	81150	101438	31.35
2031	7	0.987	90	71	5	121895	152369	81825	102282	84870	106087	33

3.4 Economic Test

3.4.1 Projection of benefit of augmentation of transformers in zone sub stations

Function name: generate_output

This function removes transformers that are not considered for augmentation such as those in the CBD and transformers with a rating of less than 63 kVA. It then calculates the levelized economic benefits that an augmented transformer would bring in relation to the avoidance of tripped hours.

Review results: function according to specifications

Inputs into this function include:

- Dataset containing information on the number of tripping hours per transformer per season, as obtained via the previous function.

The key steps performed by this function are outlined below:

1. Information on number of tripping hours calculated per distribution transformer per season for each scenario (default/tap) is passed into the function.

2. The cost of the tripping hours for each distribution transformer is calculated by multiplying the total tripping hours over all seasons by the implied market and carbon benefits of $46.71 per MWh.

3. The percentage of tripping hours per ZSS is then calculated, as the sum of tripping hours per distribution transformer divided by the number of solar customers for the ZSS by number of hours per day (7) by number of days per season by the system size.

4. The list of distribution transformers and their ratings are fed into the function. These are grouped and sorted by their rating size to provide a distribution of 29 sizes with the number of transformers falling into each size category. Distribution transformers with a rating of less than 63 kVA are removed from this list.

5. The list of CBD transformers is passed into the function from an input csv file. These distribution transformers are removed from the original list of transformers. The distribution transformers are also identified as being either part of CitiPower or Powercor.

6. The function then passes the list of yearly benefits as derived from multiplying the tripped generation in kWh by $4.67 *cents* per kWh into a function. For the years 2019 to 2031, these are depending on the tripping hours associated with the projections from the modelling. An NPV value is then calculated over a 30-year period. The remaining 17 years after the forecasting year of 2031, the cost of tripping hours is assumed to remain constant. The NPV is based on a discount rate of 2.75%.

7. The previous step is performed for each of the seasonal factor variations. The list of 30 benefit cash flow values was confirmed to be correct for transformer id, by assessing the cash flow list from within the subfunction (calc_benefits), from adding the cash flow benefit values for the same transformer in the csv files for each season, for each respective year.

8. A list of transformers that can be tapped by increasing the lower threshold[2] is then loaded into the function. The transformers in this list are removed from the main augmentation benefit dataset. From a

[2] Tapping will reduce the overall voltage levels and therefore a breach of the lower voltage threshold may be the result. By increasing the lower threshold level tap changes may still be applied and thus the respective distribution transformer does not need to be augmented.

subset of transformers Jacobs analysed, 4 transformers were removed of the total of 60 distribution transformers connected to the "TK" ZSS.

VPN Response 2

> When VPN considered whether transformers could be tapped rather than augmented, they originally did not account for the impact of a dynamic voltage management system (DVMS) in the tapping analysis. As a DVMS increases voltages at times minimum volts are experienced, this means that VPN understated the number of transformers that could be tapped downwards and overstated the amount of augmentation needed. Therefore, VPN undertook a post model adjustment; it recalculated which transformers could be tapped (based on the impact of DVMS) and then removed these incremental transformers from the augmentation list. VPN considers this to be a very conservative assumption as transformers that can be tapped may also need to be augmented later.

9. For the remaining list of transformers, the present value of benefits from augmentation is included in a csv file. The benefit that is presented each year results from the augmentation that occurs in that particular year.

Key outputs from this function include:

- A dataset summarizing the total number and percentage of tripping hours per ZSS per season per year for the forecasting period.
- A list of the number of distribution transformers by size, benefitting from augmentation per ZSS for each year.
- A list with the number of distribution transformers by size that have a net economic benefit after augmentation per ZSS each year once the augmentation costs are considered, as outlined in the example in Table 8.

Table 8: Example output for TK substation on number of transformers that would have a net economic benefit of augmentation for the years of the projection

Year	Economic benefits	Measure	Owner	Scenario	tx_rating	ZSS
2019	1	economic_benefits	Citipower	tap	300	TK
2019	1	economic_benefits	Citipower	tap	400	TK
2019	2	economic_benefits	Citipower	tap	500	TK
2019	1	economic_benefits	Citipower	tap	750	TK
2019	1	economic_benefits	Citipower	tap	1000	TK
2020	1	economic_benefits	Citipower	tap	300	TK
2020	1	economic_benefits	Citipower	tap	400	TK
2020	2	economic_benefits	Citipower	tap	500	TK
2020	1	economic_benefits	Citipower	tap	750	TK
2020	1	economic_benefits	Citipower	tap	1000	TK
2021	1	economic_benefits	Citipower	tap	300	TK
2021	1	economic_benefits	Citipower	tap	400	TK
2021	2	economic_benefits	Citipower	tap	500	TK
2021	1	economic_benefits	Citipower	tap	750	TK

Year	Economic benefits	Measure	Owner	Scenario	tx_rating	ZSS
2021	1	economic_benefits	Citipower	tap	1000	TK
2022	1	economic_benefits	Citipower	tap	300	TK
2022	1	economic_benefits	Citipower	tap	400	TK
2022	2	economic_benefits	Citipower	tap	500	TK
2022	1	economic_benefits	Citipower	tap	750	TK
2022	1	economic_benefits	Citipower	tap	1000	TK
2023	1	economic_benefits	Citipower	tap	300	TK
2023	1	economic_benefits	Citipower	tap	400	TK
2023	2	economic_benefits	Citipower	tap	500	TK
2023	1	economic_benefits	Citipower	tap	750	TK

3.4.2 Determining net economic benefit of augmenting distribution transformers

Occurs within main function and determines the net economic benefits of augmenting distribution transformers.

Review results: net benefit calculations according to specifications with recommendations on coding layout

The remainder of economic calculations occurs largely within the main Python function.

The levelized benefit of each distribution transformer in the ZSS is run through two sequential loops. The first loop determines all transformers that would benefit from augmentation – that is a total count of all transformers that exhibit any number of customer tripping hours. The second loop only counts those transformers where the benefits outweigh the average cost of the augmentation process.

Table 9 shows an example of output of the benefits of tripping hours per transformer as calculated via previous functions, and represents the benefit if augmentation is feasible. For the purpose of the review, the function was performed on a subset of the TK ZSS distribution transformers. Manual calculation of the number of transformers that would benefit from augmentation having a net positive benefit was performed on this subset and confirmed against outputs from the function. Similarly, the correct number of transformers whose augmentation benefit exceeded the cost of augmentation ($93,714.49) was tested manually and found to be correct.

Table 9: Example output data displaying the levelized economic benefits expected from augmenting transformer #11028637

Year	Owner	Transformer id	Tx rating	Economic benefits	Economic benefit escalated	Economic benefits mean	Economic benefit mean escalated	Economic benefits median	Economic benefits median escalated
2019	Citipower	11028637	750	215766	269707	112624	140780	110153	137692
2020	Citipower	11028637	750	227614	284518	118810	148513	116204	145254
2021	Citipower	11028637	750	239687	299609	125116	156395	122372	152965
2022	Citipower	11028637	750	249647	312059	130328	162910	127472	159340
2023	Citipower	11028637	750	256495	320619	133918	167397	130984	163730
2024	Citipower	11028637	750	260552	325690	136044	170055	133065	166332

Year	Owner	Transformer id	Tx rating	Economic benefits	Economic benefit escalated	Economic benefits mean	Economic benefit mean escalated	Economic benefits median	Economic benefits median escalated
2025	Citipower	11028637	750	263571	329464	137623	172029	134610	168263
2026	Citipower	11028637	750	265488	331860	138625	173282	135591	169489
2027	Citipower	11028637	750	266881	333601	139354	174192	136304	170380
2028	Citipower	11028637	750	267936	334920	139906	174883	136845	171056
2029	Citipower	11028637	750	268821	336026	140369	175461	137298	171622
2030	Citipower	11028637	750	269730	337163	140845	176056	137763	172204
2031	Citipower	11028637	750	270289	337861	141137	176421	138049	172561

The remaining code within the main function was largely based around aggregating, testing and presenting results. This part of the code was not thoroughly reviewed.

Comments

There are a few comments we would like to raise in relation to this function, these are:

- Step 8 in the function described above removes a set of distribution transformers for augmentation assessment whilst increasing the lower voltage threshold. This was not discussed in the specifications but has been addressed by VPN in VPN Response 2.
- The loop to calculate counts of transformers that would benefit from augmentation is repeated twice.
- The average augmentation cost for both companies, CitiPower and Powercor are repeated numerous times throughout the code.
- The final economic benefit calculation, checking and aggregation of results contains many repeated steps. There are many hard-coded variables within this section such as the generation costs, which are also repeated numerous times.
- The last section of the code also has limited commentary.
- It is highly recommended that the last portion of the code is consolidated into subfunctions, and hard-coded values are replaced with variables that are set in one location.

4. Summary of Review

Overall the code is well written, and based on the tests conducted by Jacobs and as per the scope of work defined in section 1.2, the Python code runs according to the specifications outlined by VPN.

Furthermore, the functions in general contain a good level of data checks to ensure that calculations are only performed on numeric variables, that no division by zero is encountered and that infinite loops are avoided.

The code is very complex, and the overall layout should be simplified to avoid risks for future updates of the code, particularly if the key programmers were no longer available.

The following outlines some basic steps that could be implemented to help minimise the risk of future updates:

- Removal of obsolete functions and pieces of code.
- Avoidance, removal and consolidation of hardcoding variables within functions.
- Avoidance of setting variables multiple times within the code and consolidation of current variables.
- Setting the key input and output directories at the beginning of the main function and only refer to these variables within the code.
- Adding detailed commentary throughout all sections of the code.

Appendix A. Voltage distribution shift

2019 base	distribution	2020	2021	2022	2023	2024	2025	2026	Cum % >253
		4.95	**9.9**	**16.5**	**23.1**	**36.4**	**28.05**	**29.7**	
219	5	223.95	228.9	235.5	242.1	245.4	247.05	248.7	1.1%
220	8	224.95	229.9	236.5	243.1	246.4	248.05	249.7	1.2%
221	8	225.95	230.9	237.5	244.1	247.4	249.05	250.7	1.2%
222	5	226.95	231.9	238.5	245.1	248.4	250.05	251.7	1.3%
223	7	227.95	232.9	239.5	246.1	249.4	251.05	252.7	1.4%
224	10	228.95	233.9	240.5	247.1	250.4	252.05	253.7	1.5%
225	9	229.95	234.9	241.5	248.1	251.4	253.05	254.7	1.6%
226	6	230.95	235.9	242.5	249.1	252.4	254.05	255.7	1.7%
227	9	231.95	236.9	243.5	250.1	253.4	255.05	256.7	1.8%
228	15	232.95	237.9	244.5	251.1	254.4	256.05	257.7	2.0%
229	29	233.95	238.9	245.5	252.1	255.4	257.05	258.7	2.3%
230	43	234.95	239.9	246.5	253.1	256.4	258.05	259.7	2.8%
231	41	235.95	240.9	247.5	254.1	257.4	259.05	260.7	3.3%
232	45	236.95	241.9	248.5	255.1	258.4	260.05	261.7	3.9%
233	40	237.95	242.9	249.5	256.1	259.4	261.05	262.7	4.4%
234	54	238.95	243.9	250.5	257.1	260.4	262.05	263.7	5.0%
235	44	239.95	244.9	251.5	258.1	261.4	263.05	264.7	5.5%
236	74	240.95	245.9	252.5	259.1	262.4	264.05	265.7	6.4%
237	99	241.95	246.9	253.5	260.1	263.4	265.05	266.7	7.6%
238	136	242.95	247.9	254.5	261.1	264.4	266.05	267.7	9.2%
239	137	243.95	248.9	255.5	262.1	265.4	267.05	268.7	10.9%
240	205	244.95	249.9	256.5	263.1	266.4	268.05	269.7	13.4%
241	245	245.95	250.9	257.5	264.1	267.4	269.05	270.7	16.3%
242	366	246.95	251.9	258.5	265.1	268.4	270.05	271.7	20.7%
243	414	247.95	252.9	259.5	266.1	269.4	271.05	272.7	25.7%
244	600	248.95	253.9	260.5	267.1	270.4	272.05	273.7	32.9%
245	676	249.95	254.9	261.5	268.1	271.4	273.05	274.7	41.0%
246	1020	250.95	255.9	262.5	269.1	272.4	274.05	275.7	53.2%
247	1033	251.95	256.9	263.5	270.1	273.4	275.05	276.7	65.6%
248	1306	252.95	257.9	264.5	271.1	274.4	276.05	277.7	81.3%
249	805	253.95	258.9	265.5	272.1	275.4	277.05	278.7	91.0%
250	543	254.95	259.9	266.5	273.1	276.4	278.05	279.7	97.5%
251	153	255.95	260.9	267.5	274.1	277.4	279.05	280.7	99.3%
252	48	256.95	261.9	268.5	275.1	278.4	280.05	281.7	99.9%
253	4	257.95	262.9	269.5	276.1	279.4	281.05	282.7	100.0%
254	3	258.95	263.9	270.5	277.1	280.4	282.05	283.7	100.0%