Impacts of residential PV installations on MV networks, with and without battery storage

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In 2015, Digsilent Buyisa was appointed to provide technical support to four selected municipalities under a project sponsored by DANIDA (Danish Renewable Energy Programme). During this project it became clear that there was much misunderstanding and anxiety about the impacts of small scale embedded generation (SSEG), in particular photovoltaic (PV) installations, would have on the technical and financial performance of the municipality. Much of the anxiety was not founded leading to 'wild' statements such as, "the voltage in the network is going to fluctuate drastically resulting in HV/MV transformer taps burning out", "The power quality is going to be so bad that the lights are going to flicker like a nightclub", etc. Clearly these statements were made due to a lack of proper understanding of the impacts of PV on the LV and MV networks.

In order to address these issues, Digsilent Buyisa undertook an extensive study to quantify the impacts of PV installation on the electrical networks [1]. Two actual networks in the Polokwane municipality were chosen for study. These networks were ideal in that the customer base was known thus allowing the load profiles of the network to be accurately modelled and simulated. Adding varied levels of PV installations, according to NRS 097-2-3 guideline [2], the impacts of the PV installations, both technically and financially, were quantified.

Following on from this study, it is now clear that storage will add an extra dimension to the technical and financial performance of the municipal networks. As such the authors have undertaken further studies to quantify:

- The impact of storage only on MV network performance, both technically and financially
- The impact of both storage and PV installations on the same network

The objective of the studies are to provide results on two real networks as an example of the kind of results that can be obtained in such studies. This will provide planning and operations staff of MV networks with increased knowledge of the topic so that they can better plan and operate their networks.

Simulation model and assumptions considered

The network chosen for study was Flora Park in the Polokwane Municipality. The network was identified to have approximately 87% residential customers and 13% light commercial customers. The network has a total installed MV/LV transformer capacity of 13 225 kVA. All customers are on a shared LV feeder supply, and all MV feeders are operated radially. There is no active metering of load consumption at each of the MV/LV transformers. For the study purposes it is assumed that the MV/LV transformers can load up to 100% of its installed capacity. No diversity is applied to the loading, and loading is based on the customer load profile connected to that transformer.

All studies were done using DIgSILENT's PowerFactory software, Version 2017.

Load profiles

The output of PV installations is variable, i.e. for PV the output starts in the morning, peaks typically at midday and reduces back to zero by the evening. Output is also dependent on sunny or cloudy days. During a typical day, the customer load profile also varies. In order to simulate all possible load and generation variability, the load and generation profiles must be modelled over a fixed period. In these studies the period considered is 24 hours.

Different customer classes have different load profiles. Once the customer classes were identified, typical load (consumption) profiles were derived for each customer class. All load profiles were normalised. Fig. 1 shows the typical load profile of a residential client with an evening peak occurring between 18h00 and 19h00, and Fig. 2 shows the load profiles used for commercial customers in the studies with a typical midday peak [3].

It is assumed that maximum network loading occurs in winter, and minimum network loading occurs in summer. The minimum summer peak is assumed to be 40% of winter peak load (from mid-December to mid-January when most people are on holiday and company shutdowns).

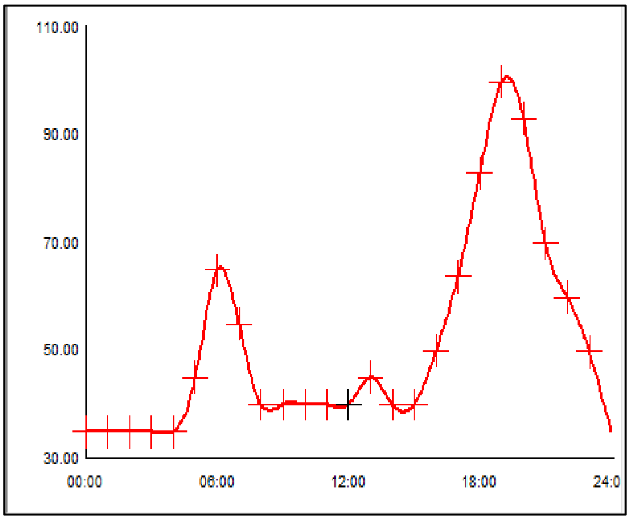

Fig. 1: Residential load profile [3].

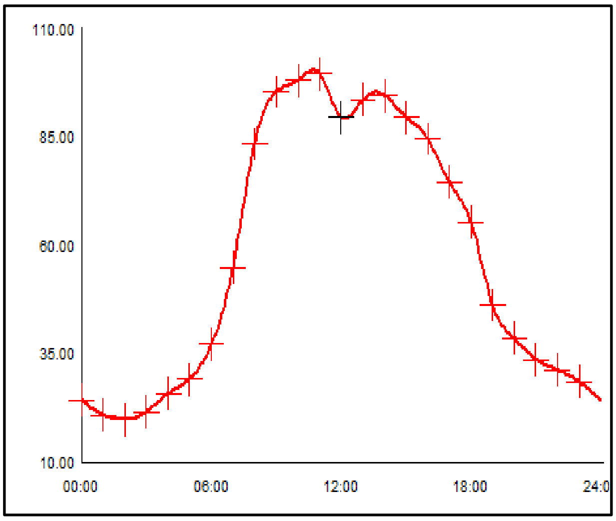

Fig. 2: Commercial load profile [3].

Assumption on installed battery capacity

Battery storage for domestic use is becoming more readily available. With so many different manufacturers on the market, studying the impact on electrical networks with different manufacturer types is practically impossible. As such the battery installation assumed to be installed at all clients, for all studies was a 52 V – 460 Ah – 24 kWh, Li-ion type. Based on commercially available inverter datasheets for inverters compatible with 52 V batteries, the maximum rated input from the grid is 3,64 kW and maximum rated output is 7,28 kW for each battery.

It is further assumed that all customers will have a battery system installed and when, for example a 40% study is done, then it is assumed that all the batteries discharge only 40% of their capacity. No stochastic charging/discharging of batteries was considered in the network.

Battery charge/discharge profiles

The usage of the batteries is also unknown as different customers may setup their installations differently. As such different battery charge and discharge profiles were developed to try to cater for as many of the possible usages i.e.

- *Full discharge*: In this case, batteries can only discharge their full rated output during peak periods (06h00 – 10h00 and 18h00 – 20h00) till the battery reaches 10% of its maximum energy capacity regardless of the load value. The charge/discharge profile for this case is shown in Fig. 3. Discharge into the grid is possible.

- *Load following discharge:* In this case, inverters allow batteries to discharge during peak periods (06h00 – 10h00 and 18h00 – 20h00) till the battery reaches 10% of its maximum energy capacity. However, the dispatch is such that it matches the load value subjected to its maximum rated output limit. The charge/discharge profile for this case is shown in Fig. 4. No discharge into the grid is possible.

- *Conservative discharge:* In this case, the battery discharge is limited to 50% of its maximum rated output, regardless of the load demand. The discharge takes place during peak periods (06h00 – 10h00 and 18h00 – 20h00) till the battery reaches 10% of its maximum energy capacity. The charge/discharge profile for this case is shown in Fig. 5. Discharge into the grid is possible.

Batteries charge from the grid during off peak times till they reach 80% of their maximum energy capacity.

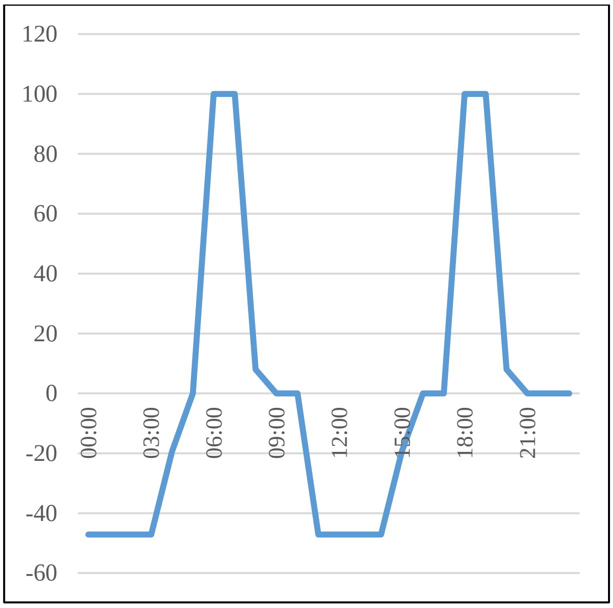

Fig. 3: Full discharge mode: Normalised battery charge and discharge profile.

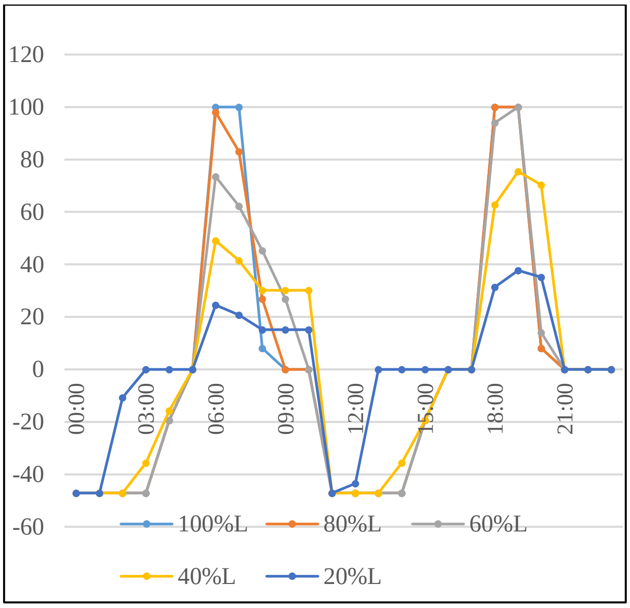

Fig. 4: Load following mode: Normalised battery charge and discharge profile.

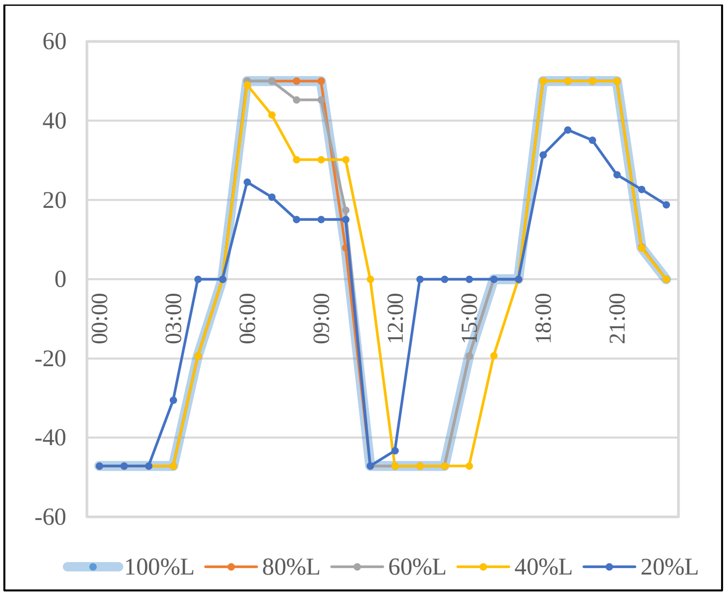

Fig. 5: Conservative discharge mode: Normalised battery charge and discharge profile.

Studies with battery storage only

Impacts on voltage regulation

The first set of studies focused on the impact the varied levels of battery penetration will have on the voltage regulation of the MV feeders. Speculation is that PV installations will cause "the voltage to vary tremendously causing the taps to burn out" on the HV/MV transformers. The results of a previous study that did not consider battery storage [1] showed that in this network the voltage variation, with and without PV installations, was less than 1%. This then raises the question, what will be the impact of battery storage on voltage regulation of the MV network. In the first instance, the first set of studies focuses on voltage regulation in a system with battery storage but no PV installations.

Figs. 6 to 11 show the variance in voltage at the end of Flora Park's longest feeder, for both minimum and peak loading, with and without battery storage. The results had to also consider the different discharge profiles of the battery storage systems.

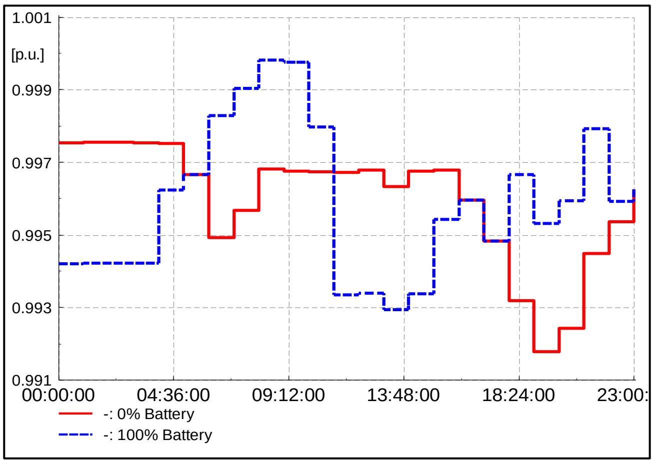

Fig. 6: Conservative discharge mode: Voltage variation with minimum network loading, with and without battery storage.

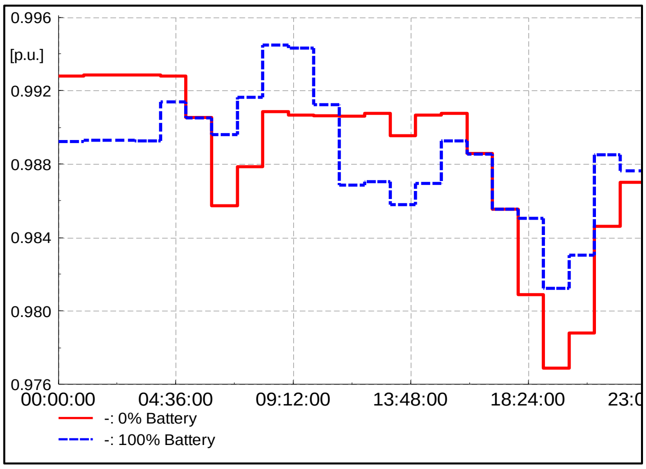

Fig. 7: Conservative discharge mode: Voltage variation with maximum network loading, with and without battery storage.

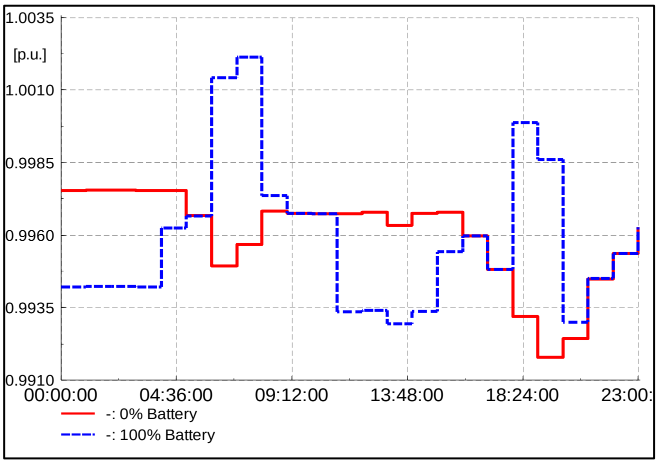

Fig. 8: Full discharge mode: Voltage variation with minimum network loading, with and without battery storage.

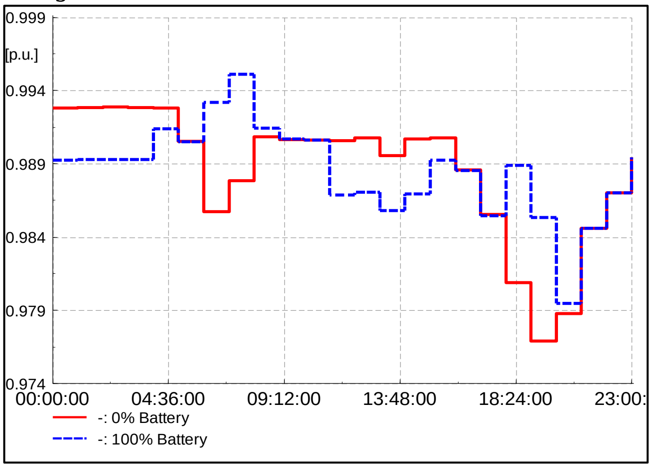

Fig. 9: Full discharge mode: Voltage variation with maximum network loading, with and without battery storage.

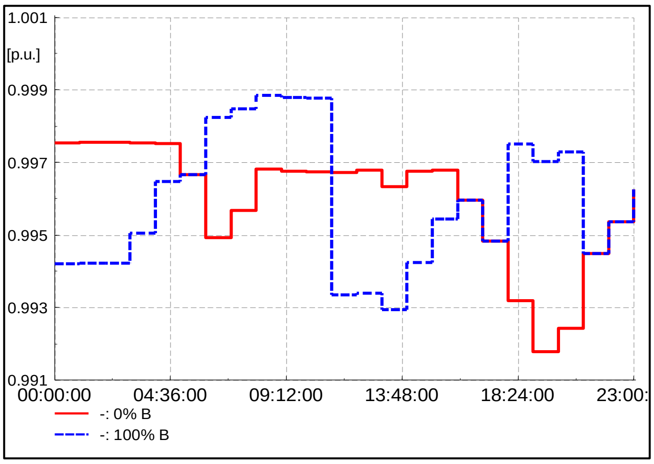

Fig. 10:.Load following discharge mode: Voltage variation with minimum network loading, with and without battery storage.

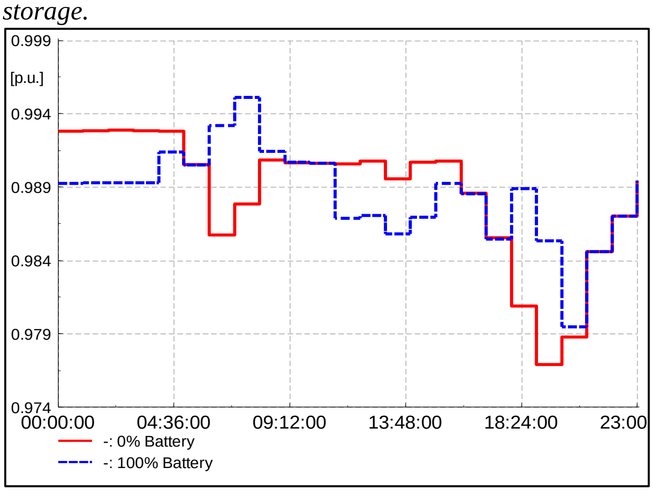

Fig. 11: Load following discharge mode: Voltage variation with maximum network loading, with and without battery storage.

The results of the studies show two distinct results i.e.

- The voltage variation is <1% for all cases studied
- There is a distinct shift in the voltage profile with battery storage and the shift is dependent on the charging and discharging profile of the battery. As expected the full discharge profile can cause the 'largest' voltage variation with the load following profile providing the most conservative profile.
- The battery storage certainly assists the network voltage during the peak loading period 18h00 to 19h00 hours by increasing the voltage however for the morning peak the voltage with battery is higher than cases with no batteries.

Thus, it can be summarised that for this particular network under study, while the introducing of battery storage has change the voltage profile markedly, that overall impact on voltage regulation is minimal. However, the same impact cannot be guaranteed for a weaker network.

Impacts on power flows

There is also concern regarding the impact that varied levels of battery penetration will have on the power flows into the MV network (and associated energy sales). As such the power at the infeed into the HV/MV transformer was monitored, when considering varied levels of battery penetration.

- *Maximum network loading:*

  Figs. 12 to 14 show the variation in the power flows into the Flora Park networks when considering peak loading. The results show that the introduction of batteries led to a significant reduction in the evening and morning peaks. The profile has shifted such that there is an increased demand during off-peak times of early morning and noon.

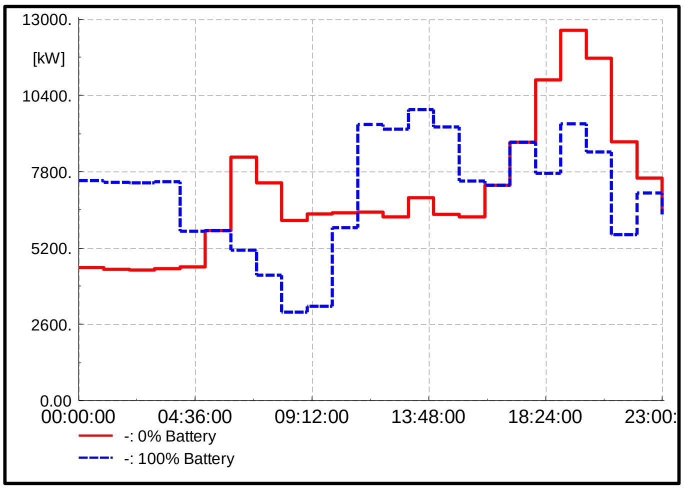

Fig. 12: Conservative discharge mode: Power flow with maximum network loading, with and without battery storage.

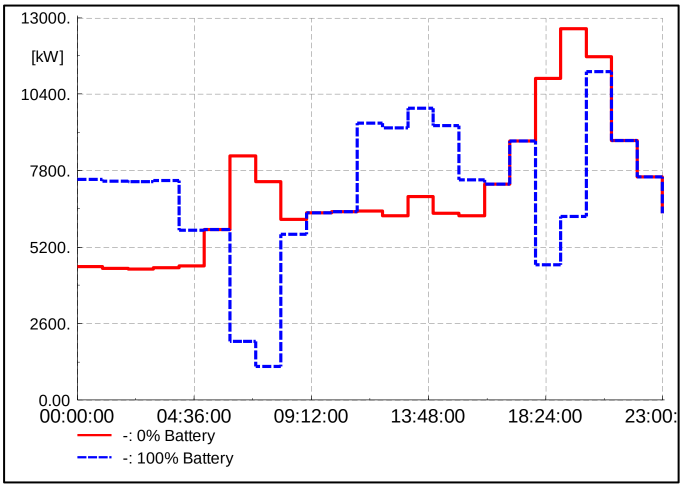

Fig. 13: Full discharge mode: Power flow with maximum_network loading, with and without battery storage.

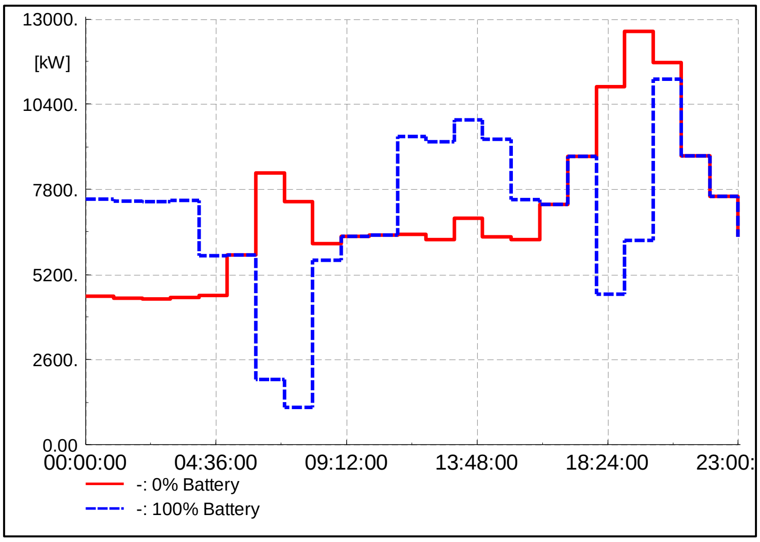

Fig. 14: Load following discharge mode: Power flow with maximum network loading, with and without battery storage.

- *Minimum network loading:* The impact of battery penetration was also considered for minimum network loading that occurs in December/January. The studies show very interesting results in that when the batteries are in full discharge mode, there is now power flow from the MV to the HV network. Figs. 15 to 17 show the power flow for Flora Park network. There is considerable peak shaving that occurs with the introduction of batteries, along with a shift in load demand from peak periods to off-peak periods. However the peak network loading now occurs just after midday when the batteries are charging and not in the evening (with no batteries), regardless of the charging/discharge profile used.

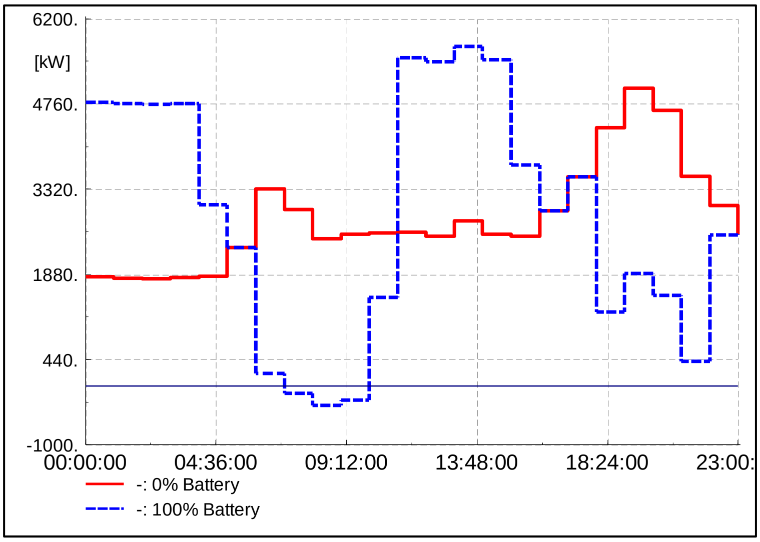

Fig. 15: Conservative discharge mode: Power flow with minimum_network loading, with and without battery storage.

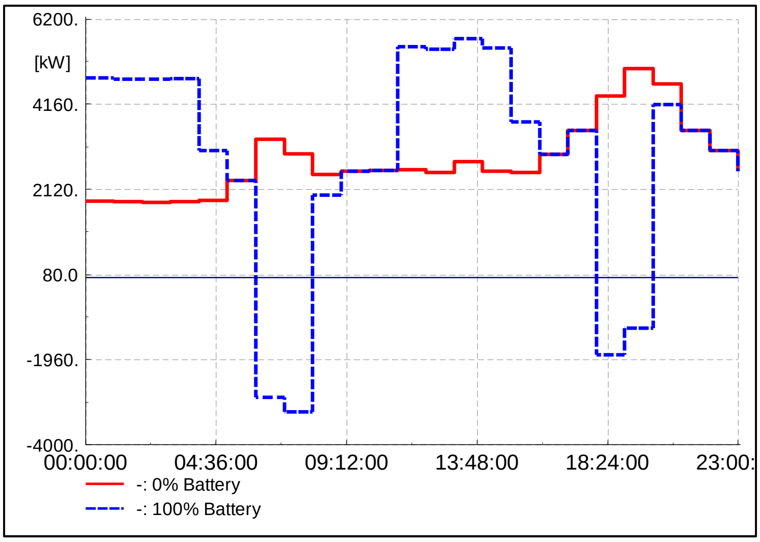

Fig. 16: Full discharge mode: Power flow with minimum network loading, with and without battery storage.

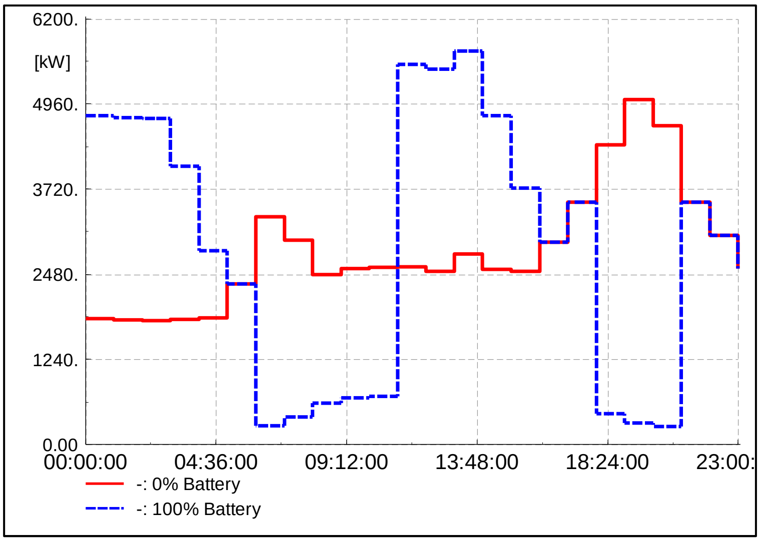

Fig. 17: Load following discharge mode: Power flow with minimum network loading, with and without battery storage.

Impacts on energy and revenue

The batteries clearly cause a significant shift in the power flow in the network from peak to off-peak times. This then raises the question "Do batteries cause a difference in the total energy sold to the customers?" To quantify this question, the total energy sold in a day, with and without batteries, for the different charge/discharge profiles were calculated. A summary of the energy flow over 24 hours is shown in Table 1.

Type of battery operating mode	**Conservative discharge (kWh)**	**Full discharge (kWh)**	**Load following discharge (kWh)**	**No batteries (kWh)**
Maximum network loading	169 258	169 309	169 309	169 313
Minimum network loading	68 100	68 194	68 089	67 987

Table 1: Total units of energy supplied by the utility into the Flora Park network in one day for different battery operating modes.

The results show that the introduction of batteries does not change the amount of energy sold in a day. In fact it is estimated that the amount of energy sold will increase as the assumption in these studies is that the batteries are completely lossless. Since the introduction of batteries did not alter the total energy in the network, its impact on energy sold by the utility is expected to be negligible. Taking into consideration the efficiency rating of battery systems, it can be expected that more energy will be bought from the grid.

To confirm the impact on revenue, the total income was also calculated for a typical day. For these studies all domestic and commercial clients are on a fixed tariff i.e. no time of use tariff is considered. The fixed tariff rates assumed for the sale of energy is shown in Table 2, and the expected daily income from energy sold in the Flora Park network with and without battery systems for different loading levels and modes of battery operation is shown in Table 3.

Customer type	Tariff (c/kWh)
Domestic	177
Commercial	151

Table 2: Tariff used by the municipality.

	Daily income from energy sales			
Type of battery operating mode	**Conservative discharge**	**Full discharge**	**Load following discharge**	**No batteries**
Maximum network loading	R293 865	R293 955	R293 955	R293 962
Minimum network loading	R118 235	R118 399	R118 243	R118 040

Table 3: Approximated daily income for the network for different loading levels and types of battery operation.

Studies with PV and battery storage

With the previous studies showing that batteries only have no impact on the total energy sold in the network and causes shifts in the load and voltage profiles, the next step is to investigate the impact of both PV and battery installations on the MV network.

Assumptions for the PV installations

The article [1] gives a detailed explanation of the study of PV installations only on the Flora Park network. Below is a summary of the key assumptions;

- NRS 097-2-3 [2] was used as the main guide to size the PV installations.
- Residential customers are connected using a 60 A connection breaker (notified maximum demand = 13,8 kVA). These customers are on shared LV feeders as such a residential customer will be limited to 25% of the total NMD, i.e. the PV installation is limited to 3,45 kVA (3,45 kW).
- All commercial customers are also on shared LV feeders hence will also be limited to maximum PV installation size of 3,45 kVA (3,45 kW).
- NRS also stipulates in the simplified criteria that the embedded generation should be limited to less than or equal to 15% of the MV feeder peak. Since there is no active monitoring of the MV feeder peak, to apply this criteria is not possible. As such it could not be considered in the studies.
- PV penetration levels are considered as follows;
  - All clients are assumed to have PV installed on site and the installed size is the maximum allowable size
  - 0% penetration means no PV is generating power regardless of the time of day.
  - 100% penetration means that every customer's PV installation is generating power up to a maximum allowed by the PV generation profile.
  - For PV penetration levels between 0 and 100%, the generation at each of the customer's PV installation is limited to the specified percentage and also limited to the maximum allowed by the PV generation profile.

For these studies only PV installations are considered. Utilising publicly available generation records from SMA [4], typical daily profiles from SMA inverters installed within the Polokwane network was downloaded and analysed. The generation profiles of the inverters were based on a 4 kWp, Sunny Tripower 6000TL-20 model. The daily generation profiles were then statistically analysed and typical daily generation profiles were created considering summer and winter as well as cloudy and sunny days. The PV generation is shown in Fig. 18.

In winter the peak PV generation was found to be less than in summer i.e. it was approximately 80% of the summer peak.

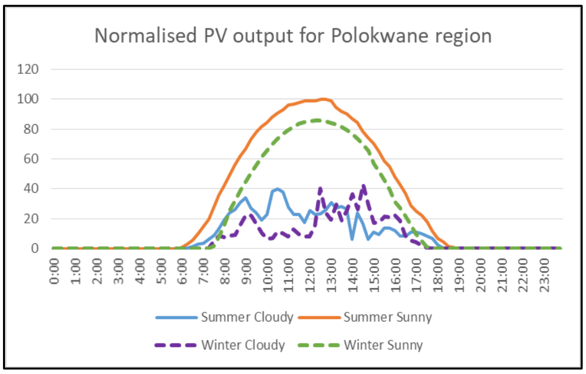

Fig. 18: Normalised PV generation profiles for PV inverters in the Polokwane region.

Impacts on voltage regulation

The results of the studies in [1] showed less than 1% impact on the voltage regulation. The same was found in the studies with batteries only. As such it can be deduced that with both PV and battery in the network, the impact on voltage regulation would be minimal.

Impacts on real power flows

The impact on the power flow in the network when PV installations are introduced was analysed for different scenarios- with full penetration of PV and batteries (100% PV, 100% Battery), with full penetration of PV only, without any batteries (100% PV, 0% Battery) and lastly, for comparative purposes, without PV and batteries (0% PV, 0% Battery). The study was also done for the three different battery operation modes, and the results are shown in Fig. 19 to Fig. 24.

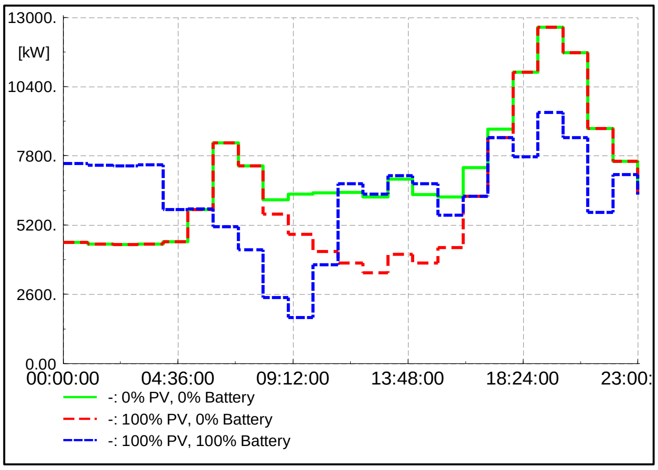

Fig. 19: Conservative discharge mode: Power flow with maximum network loading for different PV and battery penetration levels.

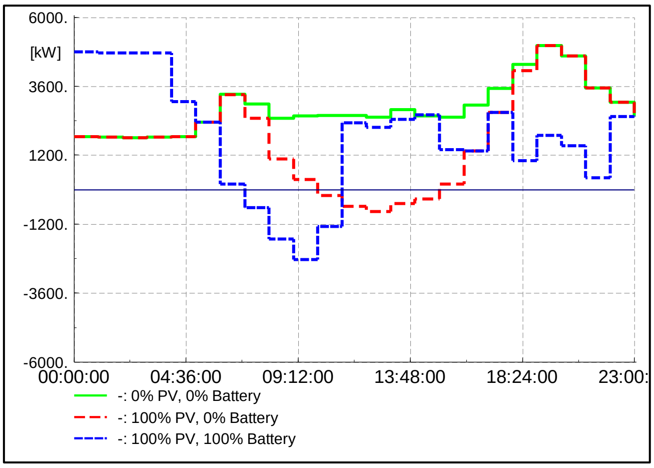

Fig. 20: Conservative discharge mode: Power flow with minimum network loading for different PV and battery penetration levels.

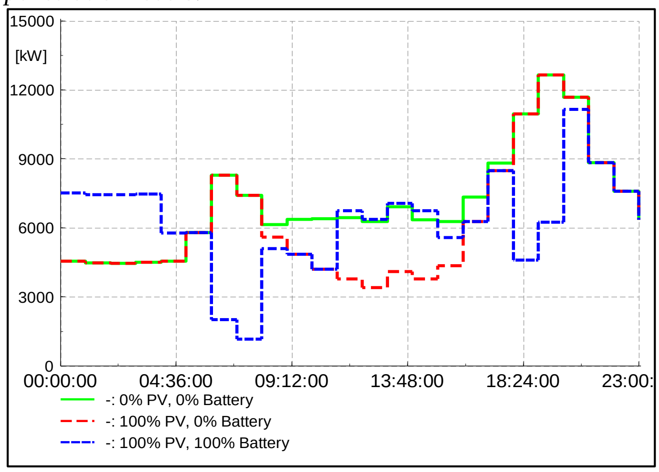

Fig. 21: Full discharge mode: Power flow with maximum network loading for different PV and battery penetration levels.

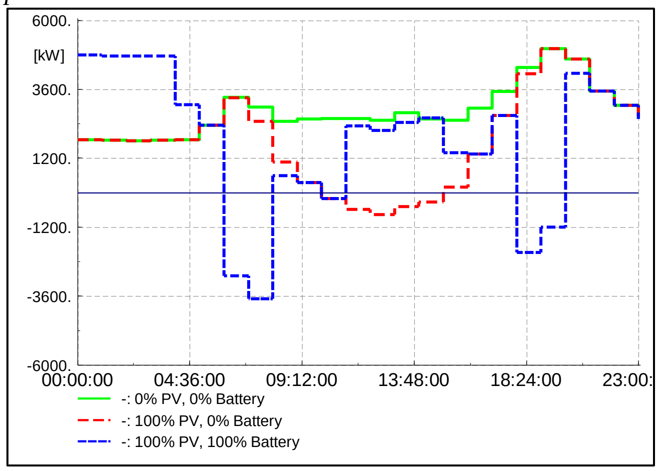

Fig. 22: Full discharge mode: Power flow with minimum network loading for different PV and battery penetration levels.

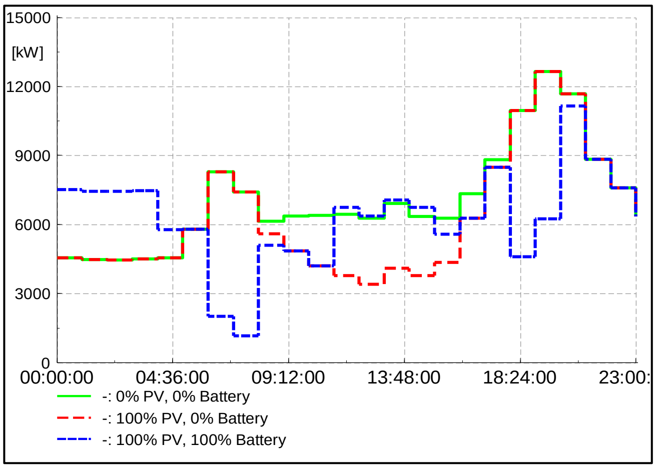

Fig. 23: Load following discharge mode: Power flow with maximum network loading for different PV and battery penetration levels.

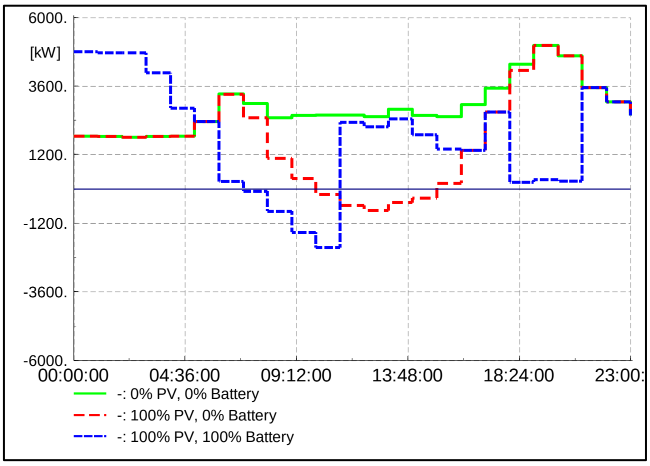

Fig. 24: Load following discharge mode: Power flow with minimum network loading for different PV and battery penetration levels.

Impacts on energy and revenue

The studies in [1] showed that for high levels of PV installation in the network, the negative impact on the energy sold and subsequent revenue can be as high as 37% under certain loading conditions. The results of this study have shown that the battery only installations have no impact on the energy sold. In fact there will be a slight increase in the energy sold to account for the losses in the battery storage systems.

Based on the results of the two studies, it can be deduced that the PV installation will still remain the dominant factor in the reduction of energy sold by the municipalities. The battery storage will simply result in a shift in the usage of that energy.

However these revenue costs are based on a fixed tariff charge for electricity. Should a time of use tariff be introduced, then the impact on the revenue can be different since the clients will charge their batteries during the night (from the grid at a cheap rate) and during the day (from the PV systems) Then the client will discharge the battery during the peak periods (when electricity from the grid is the most expensive) thus further reducing the income to the municipality.

Conclusions and recommendations

The results of the studies have shown:

- Even with the introduction of batteries in every consumer household in the Flora Park network, the impact on the voltage regulation of MV feeders is minimal and within acceptable variation levels.
- The level of battery penetration and mode of battery operation does have an impact on the power flow in the network, and it is important to accurately model the load profiles of customers in the network to accurately determine the expected changes in power flows.
- With batteries only, the amount of energy sold in the network is approximately the same as the network without batteries. In fact energy sales should increase when taking into account efficiency of the battery operation.
- The introduction of PV and batteries into the network again showed minimal impact to the network voltage, for the network studied.
- The municipalities can quantify the expected reduction in energy sales due to PV integration, and this can then be used to determine accurate fixed network charges in order to minimise the effect of reduced energy sales.
- It is recommended that the load following discharge profile is implemented on battery storage systems. Even with a conservative discharge profile, there may be large power variations and reverse power flow.

References

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