Modelling and optimisation studies for generator dispatch strategies for deployment of an off-grid micro-grid in South Africa

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***Abstract* - This paper presents the modelling of an off-grid micro-grid situated in a remote rural village in Eastern Cape province in South Africa. The modelling looks at the optimization studies for control dispatch strategies for the integration of wind power into the existing micro-grid which comprises an electric load supplied by photovoltaic power, battery bank for energy storage and a diesel generator. The optimization studies are performed using HOMER Pro® and aims to identify the best possible dispatch strategy for the dispatchable generation i.e. (diesel generator and battery storage) that minimizes load shedding and excess energy production in a system where the all the generation has been sized already. Four dispatch strategies built into HOMER Pro®, namely Cycle Charging, Load Following, Combined Dispatch and HOMER Predictive Strategy are tested. The aim of this paper is therefore to test and find which of the above dispatch strategies is the best fit for the rural village. Once the best-fit strategy has been determined, it is further customised and optimised for the rural village load profile.**

Index Terms- HOMER Pro®, optimization, dispatch strategies

I. INTRODUCTION

A pilot project was initiated to electrify a micro-grid situated in a remote village in the province of Eastern Cape in South Africa [1]. The GPS coordinates of the site are 32°34'46.7"S 26°33'33.8"E. The South African national electric grid has a constrained energy supply and as such, remote villages are commonly one of the last groups to be electrified by the national grid when electricity networks are expanded due to larger cities/towns being taking precedence [1]. A micro-grid is a small hybrid semi or fully autonomous electrical power system that comprises the load supplied usually by renewable energy generation i.e. photovoltaic power, battery bank for energy storage, and diesel generator [1]. In the absence of connection to the power grid of South Africa, distributed generation which is predominantly renewable energies, then plays a significant role in supplying remote communities. The existing micro-grid takes advantage of solar resources as renewable energy only and thus, wind power integration into the existing micro-grid is another important renewable energy to explore.

The aim of the optimization study is to determine an optimal dispatch strategy of the various dispatchable generation sources, given that the sizes of the respective generation are pre-determined already, so as to minimise the occurrence of load-shedding and excess energy [1]. This paper also comparatively assesses the implications of wind integration into the existing system [1]. A practical algorithm to implement the optimal dispatch strategy controlled by the micro-grid controller in the system is also presented and it functions to control the balance of energy in the system [2]. The software used for modelling and optimization is HOMER Pro® (Hybrid Optimization of Multiple Electric Renewables). The study also investigates (if cases of load shedding or excess energy occur) the feasibility of additional battery storage.

II. GENERATION SPECIFICATIONS

Table 1 is a summary of the specifications of the generation in the micro-grid [1].

TABLE I: MICRO-GRID GENERATION SPECIFICATIONS

Generation	Specification	Size/ Capacity
Diesel generator (DG)	Cummins S3.8 G6 CoolPac	55 kVA (48 kW maximum)
Photovoltaic (PV) array	Art Solar Si-Poly panels	75 kWp (240 units rated at 320 W each)
Wind generation	Kestrel Wind Turbine Generators	21 kW (6 × 3.5 kW)
Battery storage	Lithium Ion Yttrium Phosphate batteries - Blue Nova BN52V-770	130 kWh (2 × 65 kWh)

III. MODELLING ASSUMPTIONS

The method in which the study has involved first analysing a base case (existing deployed system) which consists of the electric load, PV power, DG, inverter and battery storage (shown in Figure 1 [1]) and identifying an optimal dispatch strategy. The wind integration case consisting of all the elements of the base case plus wind generation included, is then analysed to identify an optimal dispatch strategy then compare it to the base case [1]. It must be noted that at this point when the optimization studies are carried out and informed by previous reporting, the base case has shown to result in excess energy produced [3]. Thus, further cases that include the wind integration are analysed that consider additional battery storage.

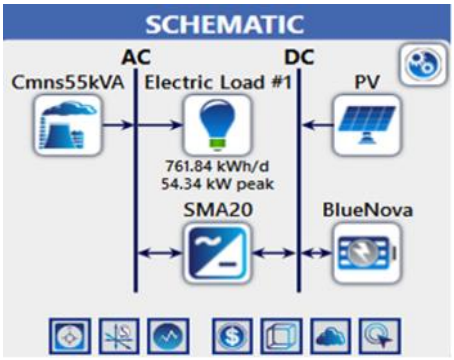

Figure 1: Base case - Electric load, PV array, battery storage, diesel generator, inverter [1]

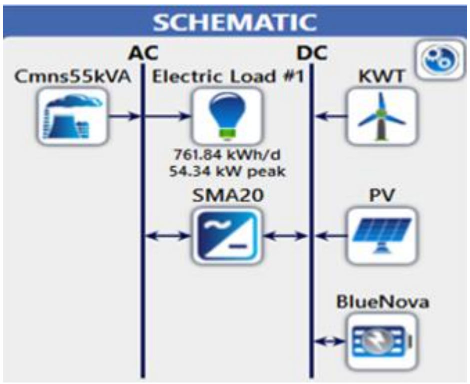

Figure 2: Wind integration case into base case [1]

When modelling the micro-grid in HOMER Pro® the following assumptions were made:

For the PV arrays, a derating factor according to [1] is set at 80 % thus the rating for the panels is effectively 60 kWp. Solar radiation data is obtained from HOMER Pro® taking into account GPS data, and this is obtained from the National Renewable Energy Lab's national solar radiation data base [1]. The PV panels are tilted at 30° and placed at an azimuth angle of 0° [4].

For the inverters, a converter block is what is used to represent them [1]. HOMER Pro® allows for a single converter block to account for all inverters in a system by specifying the size in kW. In this system, the DC/AC converters are collectively 60 kW (3 × 20 kW).

The wind turbine model specified in table 1 is not available in the HOMER Pro® database, but the software does allow for creation of custom components, thus it is a custom model which was specified using the wind turbine data sheet [5]. The wind data for the wind generation is obtained from the NASA Surface meteorology database [1].

The project lifetime is 25 years [4].

IV. VILLAGE ELECTRIC LOAD

As the village that is non-electrified, historical data about electrical load is unavailable [1]. Thus the assumptions about the load are such that:

- Peak demand is modelled at 55.2 kW [1] but diversification is not accounted for in the area, thus a load diversification of 80 % is assumed for the base load.
- As the village is a part of the greater Bisho customer load network, the Bisho demand profile (peak of ~ 650 MW) is used to model the forecasted demand profile for the village by scaling it down.
- Load data is specified with the fidelity of one hour between each data point (average load data for each hour of the day), resulting in 8760 hours (1 year) of data. as input to HOMER Pro®.
- The load consists primarily of residential homes with two distinct peaks (smaller one in the morning and larger one in the evening) as shown in figure 3; it depicts the average load for each hour of the day for one year.
- Figure 4 depicts the average load for each month of a year for the village with expected higher demand during Winter months (June- August).

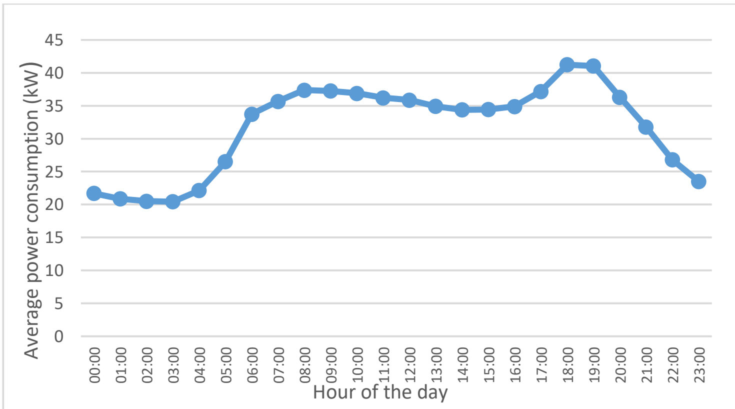

Figure 3: Average hourly load profile for village

V. METHODOLOGY

A. Dispatch strategies

A dispatch strategy determines the control of how the dispatchable generation i.e. the DG and battery storage is used when the non-dispatchable power (i.e. renewable energies) in the micro-grid is insufficient [1]. Depending on the time step fidelity required by the user, HOMER Pro® allows for one hour down to one minute for analysis of system resources and load to obtain an optimal dispatch strategy. With greater fidelity comes more accuracy but for the renewables and electric load in this micro-grid a fidelity of one hour to between each dispatch strategy decision is deemed sufficient [6].

The dispatch strategies of interest and that are offered by HOMER Pro® are Cycle charging, HOMER Combined Dispatch, Load Following and HOMER Predictive Strategy [7].

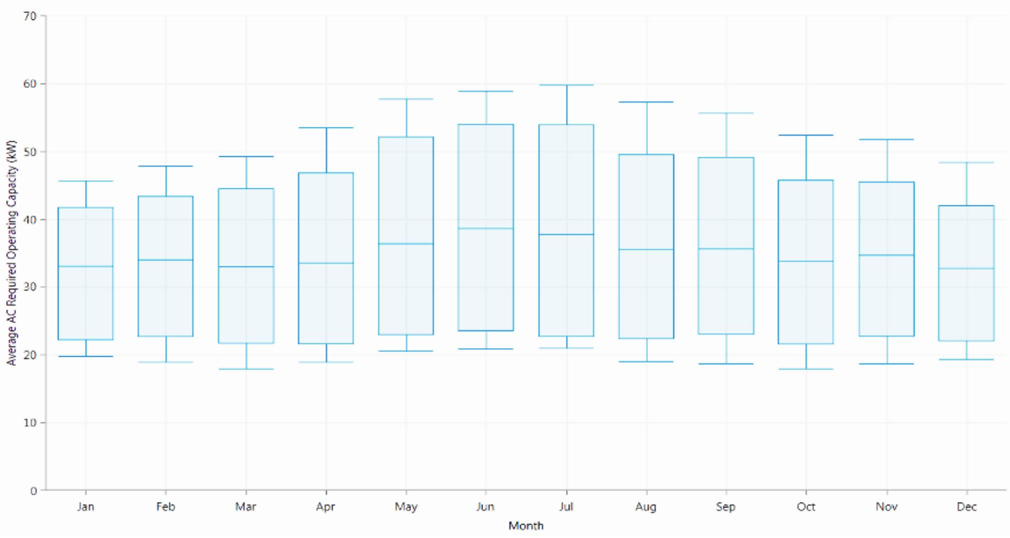

Figure 4: Average monthly load throughout the year for the village

Cycle Charging (CC) dispatch strategy refers to when the DG operates at full capacity to meet the net load (original load minus the renewable energies) and any excess power from the DG is used to charge the battery bank [1]. This strategy often proves to be optimal in cases where renewable energy penetration is low/absent in the system thereby aiming to save fuel costs storing energy in the batteries for future periods to enable the batteries to be dispatched more often [1].

Load Following (LF) dispatch strategy involves the DG used only to meet the net load and any energy used in charging of the batteries is supplied excess renewable energy [1]. LF tends to be optimal in systems where renewable energy penetration is considerable (renewables produce more than the electric load needs) [7].

Combined Dispatch (CD) is a strategy that combines the logic of CC and LF. It uses each respective dispatch strategy depending on if the net load is high or low [7]. It aims to make use of the advantages of LF and CC. In a given time step, a comparison in terms of lower cost is made between the cost of charging the battery using the DG with the cost of charging the battery using excess energy generated by renewables [7]. The restriction in HOMER for this strategy is to have only one DG in the system, one custom selected component but the amount and type of renewables in the system are unrestricted [7]. Three main decisions are made which are either that the net load is met: by the battery solely, by the DG at full capacity while it also charges the battery as much as it can or by the DG running at a capacity sufficient only to serve the net load [7].

HOMER Predictive Strategy (PS) where the strategy employed involves knowledge of the future load demand and energy sources (48 hour forecast on HOMER) and functions to maximise self-consumption of excess energy to minimize any possible energy curtailment of excess energy produced by the renewables [1]. It achieves self-consumption by discharging the batteries in anticipation for times when excess renewable energy will be available in the future so the batteries can absorb it as much as is possible [1]. The success of this type of dispatch strategy is largely dependent on accurate forecasting and the battery capacity [1].

B. *Modelling constraints*

Some modelling constraints are taken into account. The battery state of charge set point is a parameter that is needed to minimize the number of charge/discharge cycles on the battery storage. If it is applied, the DG charges the batteries until the set-point state of charge is reached thereby ensuring that the battery is not discharged as soon as the load requires it-this avoids shallow discharge/charge cycles that ultimately diminishes battery life [7]. The charging cycles set for the battery storage is set at 5000 cycles over its life of 15 years, and a depth of discharge of 80 %. The set-point state of charge of is 100 % and aims to make more use of the batteries to reduce diesel fuel costs [1].

As stated, the capacity of the generation in the system are pre-selected when performing the optimization studies. The DG has a fuel tank capacity of 280 L thus and if surpassed, reserves are used [1]. It operates in Emergency Standby Mode which in this case for this DG means that it can only do 4000 hours in its lifetime of 20 years (200 hours/year) operating at maximum power output [4]. The optimal dispatch strategy chosen must account for this constraint [1].

VI. RESULTS AND ANALYSIS

A. *Base case versus wind integration case*

Figure 5 shows a summary of the results of the HOMER simulation. In the base case, the dispatch strategy that proves to be optimal given the system resources and load is the PS, the Levelised Cost of Energy (LCOE) is R2.74 and the excess energy comes to 2542 kWh/year [1]. The optimal dispatch strategy for wind implementation is also PS, with a LCOE of R2.59 and excess energy of 6362 kWh/year [1]. The various dispatch strategies in section V (CC, CD) are also shown in figure 5 for comparison purposes and they show higher amount of excess energy (14 858 kWh/year and 77 240 kWh/year) and the CC strategy is the only strategy that shows load shedding which is a peak value of 4.7 kW [1]. The LCOE for CC and CD strategies are R 2.73 and R 3.56. It must be noted that the basis for computing the LCOE is the capital costs of the components of the system including diesel costs of approximately R15 /L [8].

The fuel savings for the wind integration cases with different dispatch strategies compared to the base case are shown in figure 6 with the optimal wind implementation case (PS) showing the most fuel savings among the cases. The CD strategy fuel savings is shown as negative and this means that more capital would need to be spent than the base case to meet the load with this specific dispatch pattern [1]. It must be noted that there is no data for the LF case as through HOMER simulation, no feasible configuration of the system made use of LF thus it is not present in the results. The unavailability of a LF configuration does not influence the results as it just means that given the system resources and their limits, an LF configuration would result in a violation of one or more of these limits thus making it infeasible.

As there is excess energy production in both the base case and optimal wind implementation case, it does fit that the recommended dispatch strategy is PS, as its aim is to maximise self-consumption of excess energy. It attempts to make the best use of excess energy produced by the renewables in the system [1].

Other important results to note are that the DG is operating below the limit of 200 hours at full capacity per year for every case [1]. In the base case, the amount of time operating at full capacity, as informed by HOMER is 108 hours, in the wind implementation case with PS, it is 70 hours, in the wind implementation case with CD strategy it is 116 hours in the year and the wind implementation case with CC strategy it is 6 hours in the year [1].

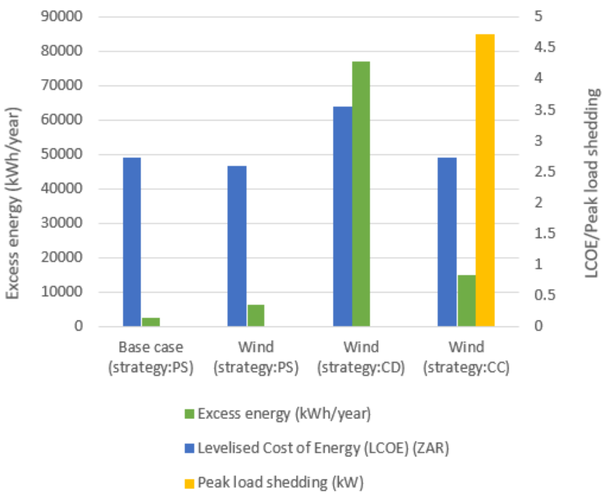

Figure 5: Optimisation results for the different cases

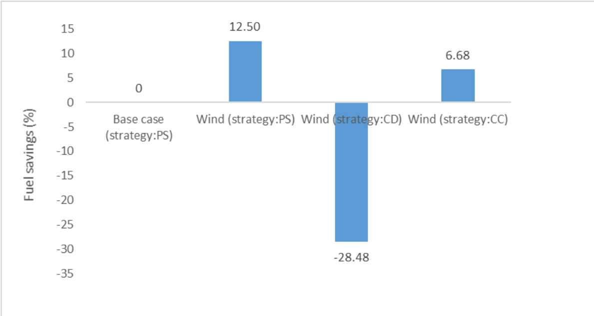

Figure 6: Fuel savings for various cases

B. *Investigation into additional battery storage*

As there is excess energy present in the system when wind power is implemented, several scenarios where additional battery storage is added to the optimal wind power case (PS) were investigated to determine the implications on the excess energy produced. The most significant decrease in excess energy is from the wind implementation case of 2 batteries to 4 batteries (2 additional batteries added to the optimal wind implementation case with the recommended dispatch strategy PS) as shown by figure 7. Thereafter, the decrease in excess energy is not as notable, thus the conclusion is that more than 4 batteries would make the battery storage oversized. This fact is also notable in the fuel savings shown in Figure 8 relative to the wind integration case with 2 batteries. Greater than 4 batteries, the savings remain relatively constant thus the capital costs would outweigh the benefits of having more than 4 batteries in the system. It must also be noted that the LCOE for 4, 6 and 8 batteries in the system are R2.74, R2.98 and R3.22 respectively. The LCOE for 4 batteries with the wind implemented under PS is the same as the base case with PS.

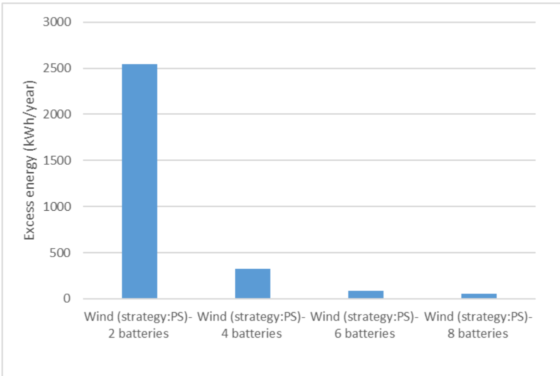

Figure 7: Excess energy versus increase in battery storage

A. *Control logic for implementation of Predictive Dispatch Strategy*

Although HOMER recommends dispatch strategies and a basic structure of what the strategies entail, it does not detail any specific implementation of the strategies. As such, an algorithm was required to be written to achieve this for the micro-grid controller in the village. The optimal dispatch strategy (PS) control logic is proposed in this section.

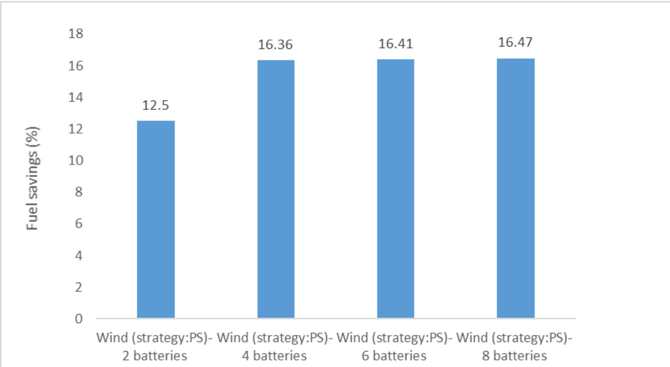

Figure 8: Fuel savings for different battery storage sizes

Using the basic concept of the PS detailed by HOMER Pro®, this algorithm is designed to use a forecast of 24 hours instead of the 48 hours suggested by HOMER. The design algorithm makes use of a reserve margin (E_{Excess}) for the battery which aims to avoid battery discharge when exceptionally low excess energy is forecasted for the upcoming 24 hours. E_{Excess} takes into account the mean daily consumption $E_{Consumption}$ of and designed such that the total excess energy in the forecasted 24-hour period, will charge the battery bank to a SOC of charge of at least 80 % from the minimum state of charge of the battery i.e. SOC_{mIn}. The mean daily consumption of the village is 272.8 kWh/day for the whole load. To obtain the condition of at least 80 % SOC for the battery (1) is considered:

$$E_{Total} \geq E_{Excess} + E_{Consumption} \qquad (1)$$

Where E_{Total} is the total forecasted energy generated by the renewables for 24 hours and E_{Excess} is chosen to be 30 % of $E_{Consumption}$. In summary it means that the future total energy for 24 hours, needs be greater than/equal to the mean daily load plus the reserve margin in order for the battery to be charged to at least 80 % SOC from SOC_{mIn}. The complete logic diagram of this algorithm is presented in Figure 9. The cost of discharging the battery bank and the cost of running the DG are detailed in (2) and (3):

The cost of discharging the battery bank is given by:

$$C_{disch} = C_{batt,wear} = \frac{C_{batt,rep}}{N_{batt} Q_{life} \sqrt{\eta_{rt}}} \qquad (2)$$

Where:

C_{disch} = Cost of discharging the battery bank

$C_{batt,rep}$= Battery replacement cost

N_{batt}= number of batteries in storage bank

Q_{life}= single battery throughput (kWh)

η_{rt}= battery round trip efficiency

The cost running the generator which operates at a capacity only to serve the load is given by:

$$C_{gen} = \frac{F_{con} F_{price}}{L_{served} G_{output}} + \frac{C_{gen,rep}}{L_{served} G_{lifetime}} + \frac{C_{gen,O\&M}}{L_{served}} \quad (3)$$

Where:

F_{con} = fuel consumption [L/hour]

F_{price} = fuel price [R/L]

L_{served}= total load [kW]

G_{output} = generator output [kW]

$C_{gen,rep}$ =replacement cost of the [ZAR/kWh]

$G_{lifetime}$ = DG lifetime

$C_{gen,O\&M}$ =Operation and maintenance costs of the DG.

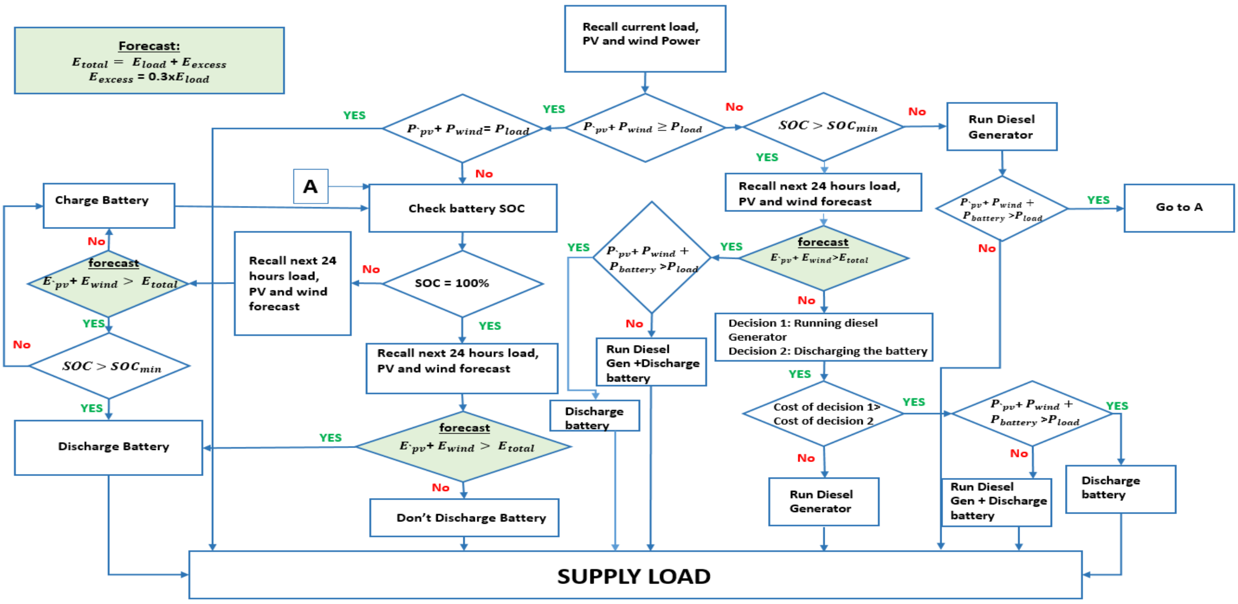

Figure 9: Control logic for Predictive dispatch Strategy

VII. CONCLUSION

Simulations from HOMER Pro® have shown that the optimal dispatch strategy for both the base case and wind implementation case is a Predictive Strategy that uses system resources and forecasting of renewable energy production to aim to maximise self- consumption of excess energy. The optimal wind implementation case results in fuel savings relative to the base case of 12.5 % but produces 2.5 times excess energy.

The CC strategy has shown not to be optimal as it produces more excess energy than the PS and relatively lower fuel savings and there is some load shedding. The CD strategy is not optimal as it produces more excess energy than the PS and actually would require more fuel expenditure. The investigation in additional battery storage to minimize excess energy production has shown that more 4 batteries would make the batteries oversized for the system and that the benefit of fuel savings and excess energy reduction is far outweighed by capital costs of adding the batteries. It must be noted that the assumed load for the village is applicable only to the initial year of electrification and that it may increase in future as consumption goes up.

VIII. RECOMMENDATIONS

From the studies conducted it is recommended that if wind power is integrated more battery storage be used i.e. 2 additional batteries with dispatch strategy PS and the control logic presented. An investigation into adding battery storage has shown that the cost of purchasing the battery storage far outweighs the benefits of fuel savings although excess energy decreases. If increased capital costs are deemed acceptable, at most 2 additional batteries are recommended. If further capital cannot be spent, then the system as it stands will sufficiently meet the load without wind integration with the PS.

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