European Town Microgrid and Energy Storage Application Study

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Abstract--**The aim of this paper is to size a vanadium redox flow battery energy storage system (VRB-ESS®) for a midsized European town microgrid project in order to minimize grid purchases and reduce spilled wind energy. HOMER™, Matlab® and Simulink® software tools have been used for the analysis. The model inputs are based on one year negative secondary reserve requirement data, extrapolated 5 months load data, multiple sites wind generation data and sourced from HOMER™ PV generation data. Simulation results show that by utilizing 3MW×4hours VRB-ESS®, the benefit to the customer is €1.206 million/year; Grid purchase frequency (649 times/year without VRB-ESS®) is decreased by 54.1%; simultaneously, grid independency (75.8% without VRB-ESS®) is increased by 6.2%; and the amount of spilled wind energy is reduced by 13.1%. As a result, a 2 to 3 MW VRB-ESS®, with between 4 to 6 hours of storage duration, is recommended.**

Index Terms—**Energy storage, HOMER™, Hybrid power systems, Matlab®, Simulink®, Optimization, VRB-ESS®.**

I. Abbreviations

P_wind: wind power
P_pv: PV power
P_load: load
P_wpl: P_wind + P_pv – P_load
P_wl: P_wind – P_load
P_vrb: VRB-ESS® charge/discharge power, '+' represents discharge, '-' represents charge
Cap_SOC: capacity SOC of VRB-ESS®
P_char: maximum chargeable power of VRB-ESS®
P_disc: maximum dischargeable power of VRB-ESS®
P_cp: VRB-ESS® charging power
P_srr: negative secondary reserve requirement, response required within 20 seconds of command
EEX: European Energy exchange
MV: Medium Voltage
PV: Photovoltaic
VRB-ESS®: Prudent Energy Vanadium Redox flow Battery Energy Storage System

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II. Introduction

WITH the growing penetration of renewable energy resources in several European countries and the likely reduction in existing base load generation plants, combined with reducing subsidies for renewable energy generation, there is a significant potential to examine hybrid semi islanded microgrid consisting of renewable generation and energy storage systems which can reduce the dependence on the grid, reduce or hedge against future energy prices increases and to a certain extent help balance the grid excess energy during low loads and peak renewable generation periods. This study is based on a location in northwestern Europe. The customer intends to reduce grid purchase by utilizing wind, PV and VRB-ESS®. The hybrid power system configuration [1]-[3] in Homer™ is shown below Fig. 1:

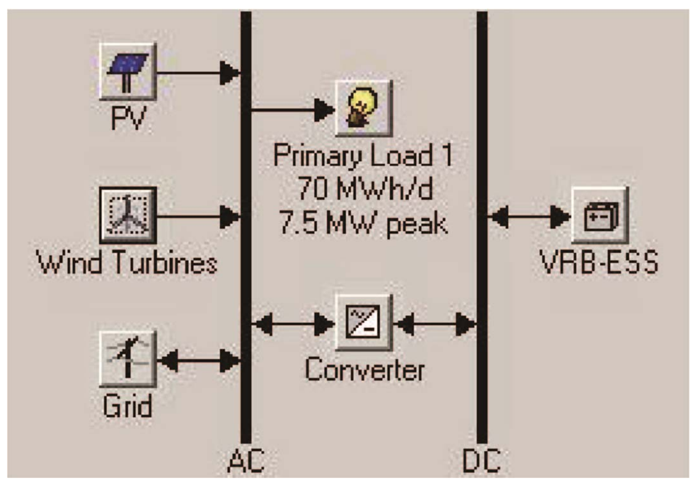

Fig. 1. Hybrid power system configuration.

The current grid purchased electricity price is €25 cents/kWh, the wind grid sale price is €9 cents/kWh, and the PV grid sale price is €20 cents/kWh. The distribution line capacity is 15MW. Our target is to maximize locally generated wind and PV energy to supply local demand by storing it for use when required and to sell excess wind and PV energy to the grid. We also assume that the PV energy is NOT stored but rather sold to grid if not used locally because the current price of PV is high enough to promote direct sales not storage. However excess PV can be stored if grid conditions require it or market price signals change.

The system consists of 21MW of wind power generation, 6MW of PV generation and a load with a peak of 7.5MW which also includes individual PV installations mounted on residential household roofs. The grid interconnection is MV with a 15MW capacity.

A. Energy Storage system: VRB-ESS®

The simulations consider using the VRB-ESS® which is a flow battery, electrical energy storage system based on a REDOX regenerative fuel cell that converts chemical energy into electrical energy, and vice versa. Energy is stored chemically in a vanadium electrolyte solution which is initially the same on both sides of the cell. The electrolyte is pumped from separate plastic storage tanks into flow cells across a proton exchange membrane (PEM) where one form of electrolyte is electrochemically oxidized and the other is electrochemically reduced. The reaction is reversible allowing the battery to be charged, discharged and recharged an unlimited number of times at 100% depth of discharge, with high efficiency and fast response [4].

The VRB-ESS® consists of its chemical conversion and energy storage elements, a power electronics converter and its overall control system. At present in all power grids there are no standards for the interconnection of bi-directional, four quadrant, power converter topologies, capable of supplying and absorbing both real and reactive power, other than harmonic voltage limits. Each installation is analyzed on a case by case basis. Various standards bodies are examining this at present.

The VRB-ESS® is modeled for interconnection purposes, as either a voltage or current source depending upon its selected mode of operation. In islanded grids it may well switch between modes. Models for power electronic converters are well known but are generally unidirectional such as for PV and wind power generation. In the case of the VRB-ESS®, its internal chemistry can be considered as an ideal source (or load) capable of instantaneous response (850 μs) to charge and discharge requests, across its whole operating range at its rated power. This means that the power electronic converter is the controlling element for simulation purposes, which in turn means that very fast (non-inertial) responses are possible. Fault level contributions are limited to approximately 2 p.u. of the storage system power rating.

III. THE OBJECTIVES OF THIS STUDY

There were 4 objectives which we set for the study and project as a whole.

- grid independence: we wished to reduce the dependence on the grid for both supply and support
- reduction in grid purchases of energy
- economic returns of less than 7 years for the energy storage on a simple payback basis
- reduction in spilled wind lost in the microgrid

IV. DISPATCH STRATEGY AND SIMULATION RESULTS

We have used Matlab®, Simulink® and Homer™ software tools to model and simulate the results.

To investigate the effect of VRB-ESS® in this project, we considered two dispatch scenarios. The first one without storage and the second with a 3MW×4hours =12MWh VRB-ESS®. The actual load curve data has been measured over a period of five months and extrapolated over one year, wind power has been determined using data from multiple sites in the region over several years whilst PV data was sourced through Homer™.

A. without VRB-ESS®

The dispatch strategy without the VRB-ESS® in the project is shown below Fig. 2:

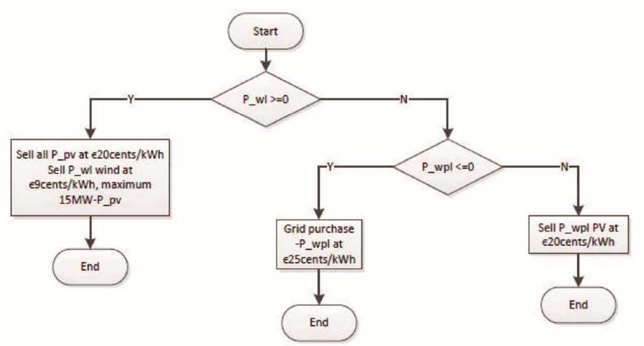

Fig. 2. Dispatch strategy without VRB-ESS®

Simulated aggregated power of wind, PV and load without VRB-ESS® is shown below Fig. 3:

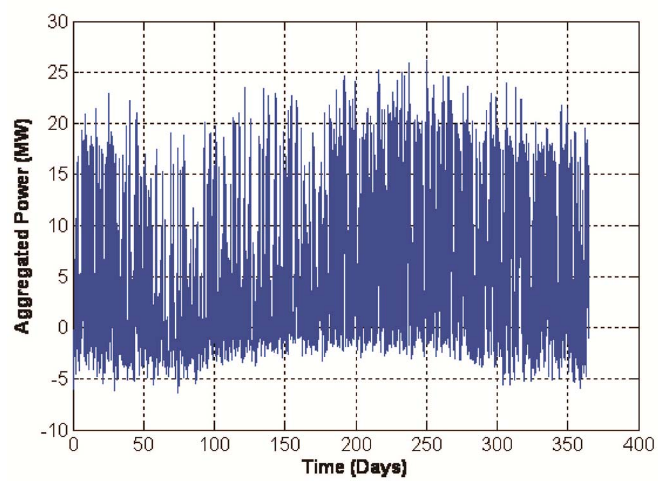

Fig. 3. Aggregated power of wind, PV and load without VRB-ESS®

The aggregated power above and below zero indicate excess (export) and shortage (import) of power individually. When the aggregated power is zero, the supply and demand is balanced within the local microgrid.

Due to maximum 15MW distribution line capacity, excess power that could be sold to the grid cannot exceed 15MW.

Wind and PV grid sales without VRB-ESS® are shown below Fig. 4 and Fig. 5:

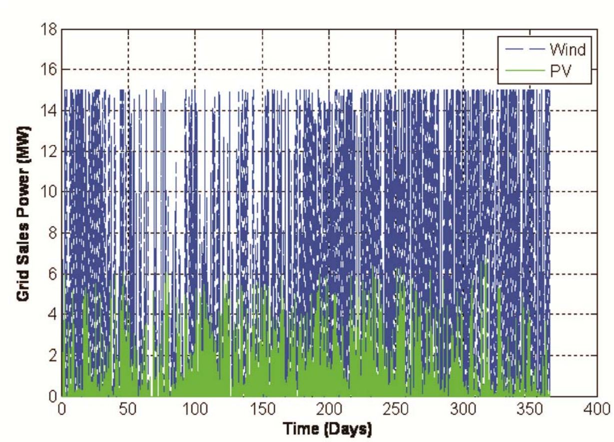

Fig. 4. Wind and PV grid sales without VRB-ESS® over 1 year

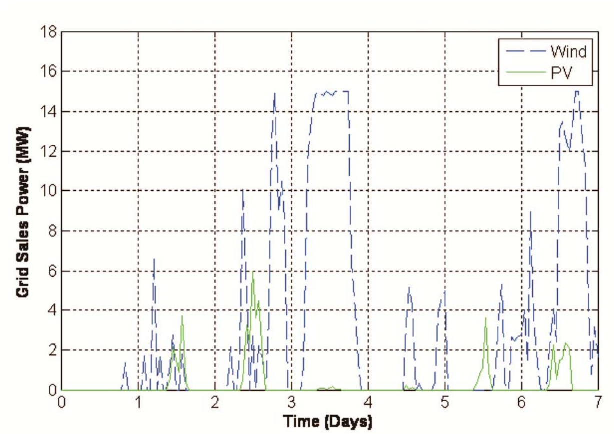

Fig. 5. Wind and PV grid sales without VRB-ESS® over 1 week

Grid purchase: 649 times/year, cumulative 3328 hours/year (37.99% of the whole year);

Energy purchase: 6152 MWh/year;

PV grid sale: 4868MWh/year;

Wind grid sale: 37004MWh/year;

Spilled wind energy: 4404MWh/year.

Grid purchase cost is determined to be = 6152MWh/year × €250/MWh = €1.538 million

Grid sales revenue is determined to be = 4868MWh/year × € 200/MWh + 37004MWh/year × € 90/MWh = € 4.304 million/year

Net benefit of wind and PV connected to the grid without VRB-ESS® is determined to be = €2.766 million/year

B. with 3MW×4hours VRB-ESS®

We have determined through additional simulation that the optimal size for the application is a 3MW×4hours VRB-ESS®. Because of the VRB® technologies ability to scale energy storage independently of power, we are able to simulate multiple sizes and determine benefits rapidly. In practice it is also possible to change the duration of storage by adding additional electrolyte as required.

The dispatch strategy with VRB-ESS® in the project is shown below Fig. 6:

Simulated aggregated power of wind, PV, load and 3MW × 4hours VRB-ESS® is shown below Fig. 7:

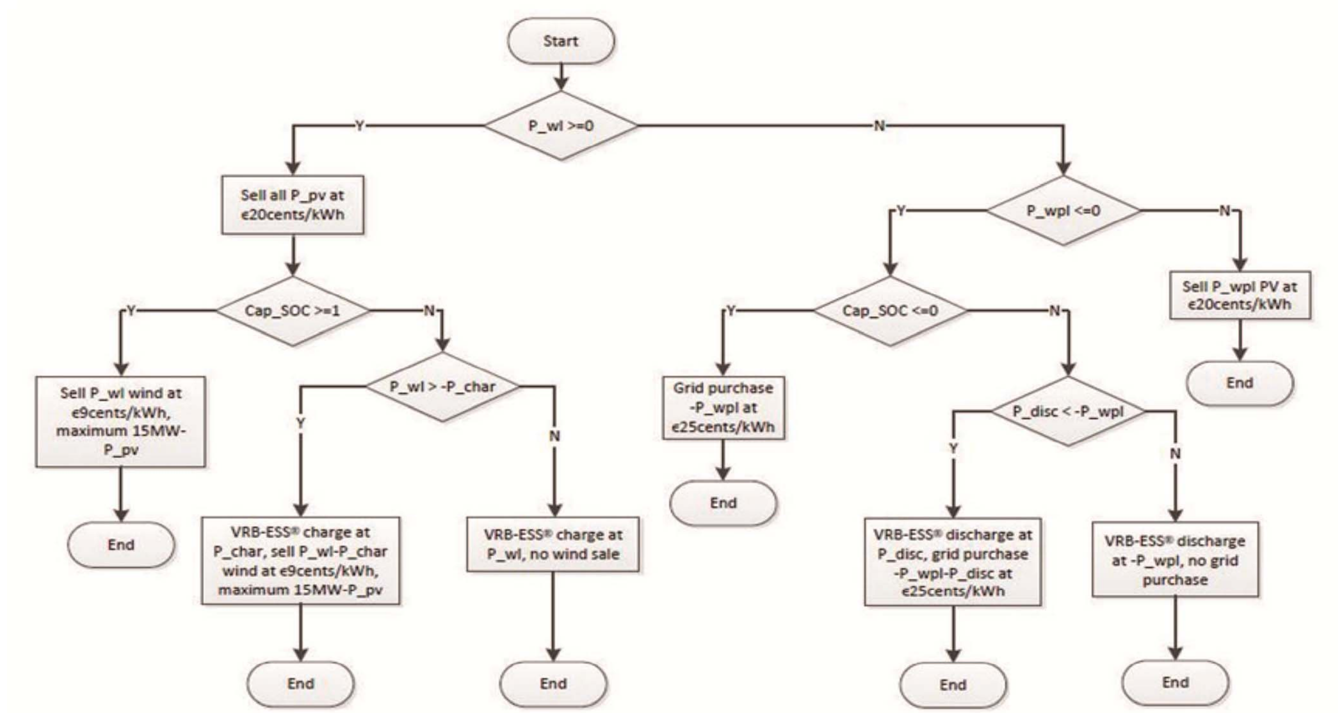

Fig. 6. Dispatch strategy with VRB-ESS®

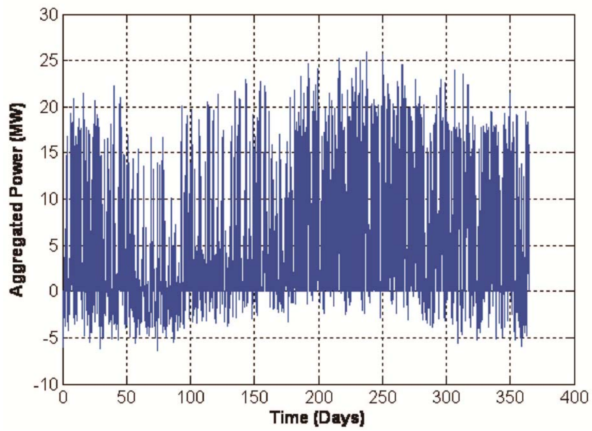

Fig. 7. Aggregated power of wind, PV, load and 3MW×4hours VRB-ESS®

The aggregated power above and below zero indicate excess (export) and shortage (import) of power individually.

When the aggregated power is zero, the supply and demand is balanced within the local microgrid.

Due to maximum 15MW distribution line capacity, excess power that could be sold to the grid cannot exceed 15MW.

Wind and PV grid sales with 3MW×4hours VRB-ESS® are shown below Fig. 8 and Fig. 9:

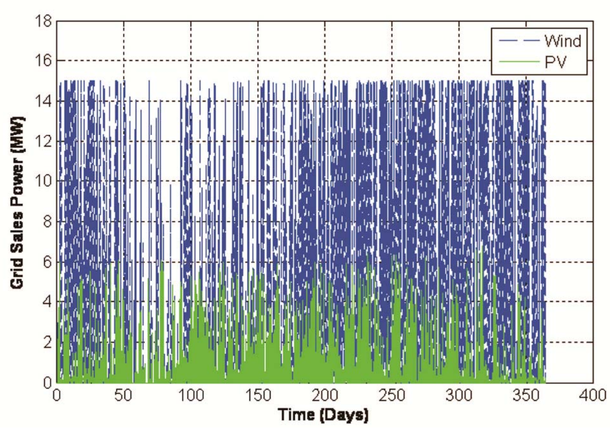

Fig. 8. Wind and PV grid sales with 3MW×4hours VRB-ESS® over 1 year

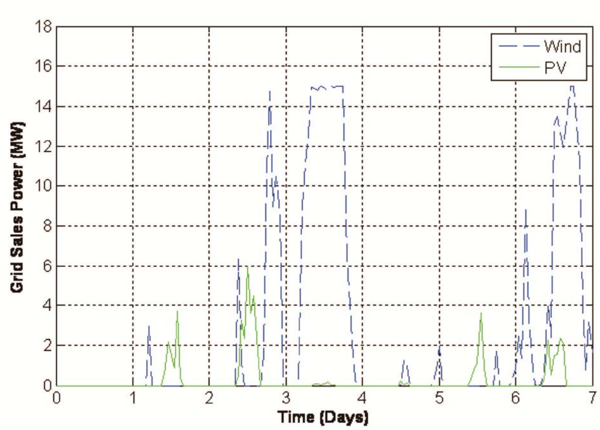

Fig. 9. Wind and PV grid sales with 3MW×4hours VRB-ESS® over 1 week

To analyze the benefit from providing negative secondary reserve service, 3MW×4hours VRB-ESS® charging power curve and negative secondary reserve requirement curve (for the region as a whole – "EEX") are plotted and shown below Fig. 10 and Fig. 11:

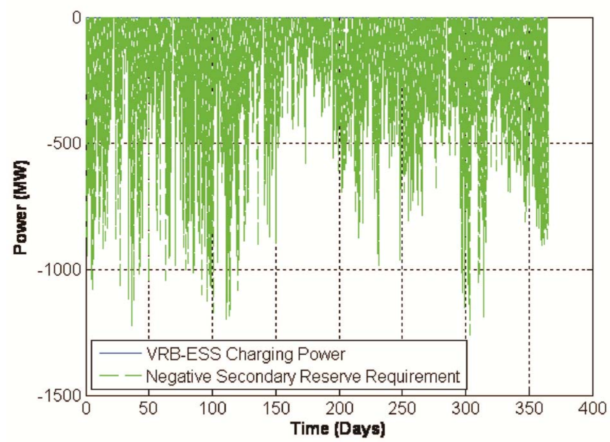

Fig. 10. VRB-ESS® charging power and negative secondary reserve requirement for the region over 1 year

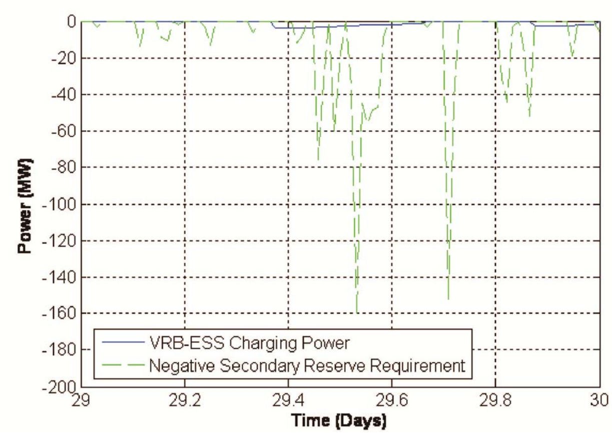

Fig. 11. VRB-ESS® charging power and negative secondary reserve requirement for the region over 1 day

From the above Fig. 11, it is found that sometimes |P_cp| is less than |P_srr|. This means that the VRB-ESS® only partially satisfies the negative secondary reserve requirement; when |P_cp| is greater than |P_srr|, this means VRB-ESS® satisfies all negative secondary reserve requirement. During these periods it is required to charge partially |P_cp| - |P_srr| from the wind farm and to pay €9cents/kWh to the wind farm.

It is assumed that:

- When |P_cp| < |P_srr|, €30cents/kWh bonus is received from the EEX for the amount of VRB-ESS® charging power |P_cp|;
- When |P_cp| >= |P_srr|, €30cents/kWh bonus is received from the EEX for the amount of VRB-ESS® charging power |P_srr|; €9cents/kWh payment is sent to the wind farm for the amount of VRB-ESS® charging power |P_cp| - |P_srr|.

Grid purchase: 298 times/year, cumulative 1741 hours/year (19.88% of the year)

Energy purchase: 3,599 MWh/year

PV grid sale: 4,868MWh/year

Wind grid sale: 3,3293MWh/year

Spilled wind energy: 3,828MWh/year

Grid purchase cost is determined to be = 3,599MWh/year × €250/MWh = €0.900 million

Grid sale revenue is determined to be = 4,868MWh/year × €200/MWh + 33293MWh/year × €90/MWh = €3.970 million/year

Payment to the wind farm for VRB-ESS® charging power is determined to be = 985MWh/year × €90/MWh = €0.089 million/year

Value received from the EEX for providing negative secondary reserve service is determined to be = 3,302MWh/year × €300/MWh = €0.991 million/year

Net benefit of wind and PV connected to the grid with 3MW×4hours VRB-ESS® is determined to be = €3.970 million/year + €0.991 million/year - €0.900 million/year - €0.089 million/year = €3.972 million/year

Therefore the benefit that 3MW × 4hours VRB-ESS® brings is determined to be = €3.972 million/year - €2.766 million/year = € 1.206 million/year; the capital cost is estimated to be €9.174 million, yielding a simple payback of 7.6 years; In addition, grid purchase is reduced by 351 times/year and 1587hours/year; spilled wind energy is reduced by 575MWh/year.

Finally we simulate different sizes VRB-ESS® for this application.

Benefits from VRB-ESS® are shown below Table I: (unit is €millions/year)

TABLE I
BENEFIT FROM VRB-ESS®

MW rating/ duration	2hours	4hours	6hours	8hours
1MW	0.387	0.550	0.660	0.742
2MW	0.665	0.928	1.123	1.260
3MW	0.852	1.206	1.438	1.600
4MW	1.020	1.421	1.659	1.831
5MW	1.144	1.576	1.829	1.984

It is found that the benefit from VRB-ESS® increases both when VRB-ESS® power rating and storage durations increase.

Simple payback year is shown below Table II: (unit is years)

TABLE II
VRB-ESS® SIMPLE PAYBACK YEAR

MW rating/ duration	2hours	4hours	6hours	8hours
1MW	6.2	5.6	5.6	5.9
2MW	7.2	6.6	6.6	7.0
3MW	8.4	7.6	7.8	8.2
4MW	9.4	8.6	9.0	9.6
5MW	10.5	9.7	10.2	11.0

It is found that for certain VRB-ESS® power ratings, 4 hours storage duration results in quickest payback; for certain storage durations, simple payback periods increase when VRB-ESS® power rating increases. The reason is when power rating increases; the utilization rate of VRB-ESS® reduces.

Reduced grid purchase frequency are shown below Table III: (unit is times/year)

TABLE III
REDUCED GRID PURCHASE FREQUENCY

MW rating/ duration	2hours	4hours	6hours	8hours
1MW	130	122	113	111
2MW	249	253	256	256
3MW	310	351	377	388
4MW	347	410	446	474
5MW	375	456	483	511

Grid purchase cumulative duration reduction is shown below Table IV: (unit is MWh/year)

TABLE IV
GRID PURCHASE CUMULATIVE DURATION REDUCTION

MW rating/ duration	2hours	4hours	6hours	8hours
1MW	455	537	571	591
2MW	923	1121	1261	1363
3MW	1248	1587	1812	1959
4MW	1486	1911	2150	2305
5MW	1642	2112	2353	2494

It is found that grid purchase frequency and cumulative duration both reduce when VRB-ESS® power rating and storage durations increase. 1MW cases are the exceptions. The reason is for 1MW, long storage duration VRB-ESS®; we sometimes still require grid purchase even when VRB-ESS® is discharging because 1MW power is insufficient to supply the load itself. However, for 1MW with long storage duration the VRB-ESS® charges and discharges for longer time, so grid purchase cumulative duration reduces.

Spilled wind energy reduction is shown below Table V: (unit is MWh/year)

TABLE V
SPILLED WIND ENERGY REDUCTION

MW rating/ duration	2hours	4hours	6hours	8hours
1MW	104	267	395	488
2MW	190	457	650	787
3MW	226	575	776	933
4MW	292	628	826	987
5MW	314	663	861	1000

It is found that there is less spilled wind energy with both large VRB-ESS® power rating and long VRB-ESS® storage duration.

V. CONCLUSION

The study highlights several factors. Firstly that by including energy storage, capable of both rapid and repeated deep, long duration cycling, it is practical to reduce the grid dependence of local communities and to more effectively utilize renewable generation. Most importantly this reduces costs and yields sensible economic returns. If energy prices continue to increase at the expected rates of close to 5 to 6%/annum, the returns on investment will be improved further, to close to 4 years. Furthermore the net grid wide impacts will be material. The justifiable utility and grid operator concerns related to distributed generation on the networks can be greatly alleviated as storage reduces both the fluctuations and reverse power flows. By examining this further on a macro grid basis, policies and tariffs can be established that fairly reward and price the locational value of storage used in such a distributed manner.

In the cases above, VRB-ESS® with between 2 to 3MW power rating and 4 to 6 hours of energy storage meets the objectives established of economic return, reduced grid purchases, independence enhancements and reduced spilled wind. Grid purchase frequency decrease by up to 58.1%/year, grid independency (75.8% without VRB-ESS®) of energy increases by up to 7.1%, and the amount of spilled wind energy is reduced by 10.4% to 17.6%/year.

VI. Acknowledgment

The authors gratefully acknowledge the contributions of Georg Von Kriegsheim for his work on the wind, load and negative secondary reserve requirement raw data acquisition.

VII. References

[1] A. A. Setiawan, Y. Zhao, and C. V. Nayar, "Design, economic analysis and environmental considerations of mini-grid hybrid power system with reverse osmosis desalination plant for remote areas," *Renewable Energy*, vol. 34, pp. 374-383, 2009.

[2] M. M. Hoque, I. K. A. Bhuiyan, R. Ahmed, A. A. Farooque and S. K. Aditya, "Design, analysis and performance study of hybrid PV-diesel-wind system for a village Gopal Nagar in Comilla," *Global Journal of Science Frontier Research Physics and Space Sciences*, vol. 12, issue 5, version 1.0, 2012.

[3] J. B. Fulzele, and S. Dutt, "Optimium planning of hybrid renewable energy system using HOMER," *International Journal of Electrical and Computer Engineering*, vol. 2, no. 1, pp. 68-74, Feb. 2012.

[4] [Online]. Available: http://www.pdenergy.com/products_whatisvrb.html

VIII. Biographies

Hongfeng [Jack] Li was born in Hubei province, P.R.C., on July 27, 1981. He received his BSc Eng. from Harbin Institute of Technology and MSc Eng. from University of Chinese Academy of Sciences.

His employment experience included HiRain Technologies, ENSKY Technology, and Prudent Energy Inc. His special fields of interest included VRB-ESS® sizing, renewables integration application study, technical and economical analysis, control system modeling, control algorithm design and verification.

Timothy Hennessy was born in Durban South Africa, on 24 November 1960. He received his BSc Eng. from the University of Natal and MSc Eng. from WITS University in South Africa.

His employment experience includes former CEO of VRB Power Systems Inc., a commercial pioneer of the VRB® technology. Before VRB Power, he served as Vice President of Engineering and Operations and Managing Director of LECTRIX LLC (a Bechtel Siemens, AEP JV), Vice President of PacifiCorp's Energy Services Division, and Quality of Supply Manager for ESKOM. He was also a founder and Principal of Power Quality Technology, an independent consulting firm.

He is an IEEE member. He holds 26 patents, has published and presented more than 25 scientific papers, and was the editor of the Power Quality Blue Book (South Africa), a text for utility engineers.