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Optimising fuel efficiency for renewable energy-based systems incorporating hybrid energy storages

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ABSTRACT

Mini-grids powered by renewable energy sources have periods of high and low energy production due to variability in resources. The reliability of power supplied from such systems can be significantly improved by incorporating energy storage systems. This study investigates the use of energy storage – pumped hydro systems and hydrogen fuel cells – in a mini-grid system for operational cost reduction and system reliability improvement. The hybrid system's power output is modelled with the objective of simultaneously minimising fuel costs while ensuring system reliability. The proposed mathematical model is verified using real-world data of KwaZulu Natal site in South Africa. The simulation results show that small-sized pumped hydro systems (PHS), in combination with Hydrogen Fuel Cells (HFC) can significantly reduce fuel costs of diesel generators in off-grid systems by 69% in summer and 34% in winter.

Keywords: Hybrid energy storage, pumped hydro storage, hydrogen fuel cells, renewable energy.

1. INTRODUCTION

Traditionally, major sources of power supply to the central grid has been from nuclear, thermal or gas power plants and hydropower systems. However, the shift in source of supply owing to the increase in power demand, depletion of fossil-based resources and environmental concerns have led to seeking alternative power supply via decentralised mini-grids. These are designed to suit the load profile (residential and commercial loads) using locally-available resources [1], either renewable or non-renewable sources. Renewable energy (RE) sources, especially wind and solar energy, serve as the best alternatives owing to their maturity and ability to meet the growing energy demand in the world [2].

With the wide availability of RE resources, electricity demand in unserved communities can be satisfied with systems such as solar, wind and hydropower, in combination with diesel generators [3][4]. This can easily satisfy the communities' energy demand (usually less than 1MW). Despite these benefits, RE sources are characterized by intermittency, rendering their supply unreliable. A promising solution is through the use of energy storage systems such as battery banks, pumped hydro storage (PHS), hydrogen fuel cells, supercapacitors, or compressed air energy storage (CAES) [5].

Some works of literature have considered the inclusion of storage systems in RE systems. In [6], a solar PV-diesel generator system including Lithium-ion batteries was presented, showing storage contributed to an improvement of rural electrification in South Africa. Similarly, the inclusion of storage systems enhances the system performance and stability of a small wind farm [7].

All storage systems incorporated in microgrids have their specific characteristics and qualities which make some more suitable than others for particular sites and situations. These characteristics include lifetime costs, efficiency, environmental impact, tank capacity, scalability or mobility. For off-grid systems, mobility of the storage is not a critical consideration, like in electric transportation systems. Other factors such as effects of regulations and policies, as well as technical and financial constraints, could also influence the particular energy storage system selected like it was done for a wind farm in Australia[8]. Another wind-farm in Denmark selected storage systems for a hybrid energy storage system based on the combination which gave the highest Net Present Value [9].

Kalinci et al [10] performed the economic analysis of a wind-alone system and a wind-PV system. Results show the inclusion of the PV system decreases the size of the storage tank of the HFC system and economic metrics.

Similar research considering cost and reliability as the optimization criteria [11] included a pumped hydro storage system. Here, the economic and energy balance analysis of the hybrid system was completed and the author opined that RE-based systems, compared to diesel-based systems, would be more competitive in future. Bokabo, et al [3] presented the operation scheduling of a RE-based hybrid system including a diesel generator and PHS system. The obtained results show minimized diesel costs owing to more utilization of RE sources.

This paper presents the application of PHS and HFC systems as viable storage options for small-scale power systems. It proposes an enhanced operational strategy for the hybrid storage system by ensuring that optimal charging and discharging of both storage options are not violated and operation costs are minimized during system operation. The modelling of hybrid power system with realistic resource characteristics demonstrates the impact of solar and wind resource availability on the energy storage capacity, and the attendant effect of the storage capacity on the system optimization.

2. HYBRID POWER SYSTEM COMPONENTS

The hybrid power system under consideration in this study consists of solar photovoltaic (PV) panels, wind turbines and diesel generating units as the power generation sources, while the energy storage options comprise of a pumped hydro storage (PHS) system and a hydrogen fuel cell (HFC) system.

2.1 Solar PV systems

A PV panel's electrical output depends the efficiency of the PV panels as given by the manufacturer (η_{PV}), solar irradiation G(t) in kWh/m^2 which varies hourly depending on the site being studied and the area of one panel, A_{PV} (in m^2) [12]. The total output of the solar PV array is obtained by multiplying the output of one solar panel by the number of panels (N_{PV}).

$$P_{PVT}(t) = N_{PV} * \eta_{PV} * \mathrm{G(t)} * A_{PV} \quad (1)$$

The solar PV panel used in this study is a 72-cell polycrystalline panel rated 320W, with an area of 1.9188m^2 and efficiency of 16.68%.

2.2 Wind turbine systems

Wind speeds cause rotation of the blades of a wind turbine and this leads to electricity generation. The output power of a wind turbine is determined by its rated power, available wind speeds at the site and height above ground. The mathematical model for the wind system's electricity output, P_{WT} is stated as [4]:

$$P_{WT} = N_{WT} * \frac{P_R(V_{wt}^3 - V_{ci}^3)}{(V_{wr}^3 - V_{ci}^3)} \quad \text{for } V_{ci} \leq V_{wt} \leq V_{wr} \quad (2)$$

P_R is the rated power of the turbine (3kW), V_{wt} is actual wind speed at t, V_{ci} is cut-in speed, V_{CO} is the cut-out speed, V_{wr} is the rated wind speed of the turbine and N_{WT} is the number of wind turbines. For wind speeds outside the range in Equation (2), the following assumptions are adopted [4], [13]:

$$P_{WT} = 0 \quad \text{for } V_w < V_{ci} \text{ and } V_w > V_{co} \quad (3)$$

$$P_{WT} = N_{WT} * P_R \quad \text{for } V_{wr} < V_{wt} < V_{co} \quad (4)$$

2.3 Energy Storage Systems

Considering the intermittency of solar and wind electricity outputs, a RE- powered system needs to have a storage system in place for improved reliability.

2.3.1 Pumped Hydro Storage Systems (PHS)

The components of the PHS system include the turbine generator, motor-pump and upper and lower reservoirs. The turbine generator generates power, while the motor-pump is a power consumer. The power generated or consumed by these components of the PHS system is determined by the density of water ρ, the acceleration due to gravity g, the head of the PHS h, defined as the height difference between the upper and lower reservoirs and turbine and motor efficiencies given by η_{TG} and η_{MP} respectively [11], [14]. The volume of water used by the turbine (V_{TG}) or pumped by motor (V_{MP}) is measured in cubic metres (m^3), the power of the pumps (P_{PHS-P}) and turbines(P_{PHS-T}) are rated in W, acceleration due to gravity rated in meters per second (m/s^2) and head h, in meters (m):

$$V_{TG}(t) = \frac{(3.6 * 10^6) * P_{PHS-T}}{\eta_{TG} * \rho * g * h} \quad (5)$$

$$V_{MP}(t) = \frac{(3.6 * 10^6) * \eta_{MP} * P_{PHS-P}}{\rho * g * h} \quad (6)$$

The volume of water in the upper reservoir at any time t V(t), is given by

$$V(t) = V(t-1) + V_{MP}(t) - V_{TG}(t) \quad (7)$$

2.3.2 Hydrogen Fuel Cells (HFC)

The Hydrogen fuel cell (HFC) system consists of an electrolyser, hydrogen storage tank and a stack of fuel cells. The electrolyser is powered by electricity (P_{EL}) from the solar PV, wind turbines or diesel generator to break down water molecules to produce hydrogen which is stored in the tank. When electricity is needed, the hydrogen in the storage tank is used up by the fuel cell and electricity is generated. The mathematical model of the HFC is presented as follows:

$$V_{H2} = \eta_{INV} * \eta_{EL} * P_{EL} \quad (8)$$

$$P_{FC} = \eta_{FC} * V_{FC} \quad (9)$$

In equations (8), (9), V_{H2} represents the volume of hydrogen produced by the electrolyser and stored in the tank, V_{FC} is the volume of hydrogen used up by the fuel cell to generate power, P_{FC}. The efficiencies of the inverter, electrolyser and fuel cells are represented by η_{INV}, η_{EL} and η_{FC} respectively. Typically, the efficiency of the electrolyser is about 0.6, and 0.5 for fuel cell [15].

$$E_s(t) = E_s(t-1) + V_{H2}(t) - \frac{V_{FC}}{\eta_s}(t) \quad (10)$$

The storage system used in this study is a combination of the PHS and HFC systems. PHS systems are characterised by high energy density and long lifetimes. Geographical conditions in obtaining a suitable head is sometimes a challenge, while naturally-existing caverns or unused mineshafts could support their deployment in other areas. In comparison, hydrogen fuel cells also have a high energy density and long lifetimes. This makes them cost-effective as they are not replaced often, and they are also scalable enough for multiple small units to be deployed within a network.

2.3.3 Efficiency of hybrid energy storage system

In this study, the total energy consumed by the motor pumps and electrolyser is compared with the total energy produced by the turbine generators and fuel cells. The overall efficiency of the hybrid energy storage system can be computed as in (11) below [16]:

$$\eta_{ESS} = \frac{\sum (P_{FC} + P_{PHS-P})}{\sum (P_{EL} + P_{PHS-T})} \quad (11)$$

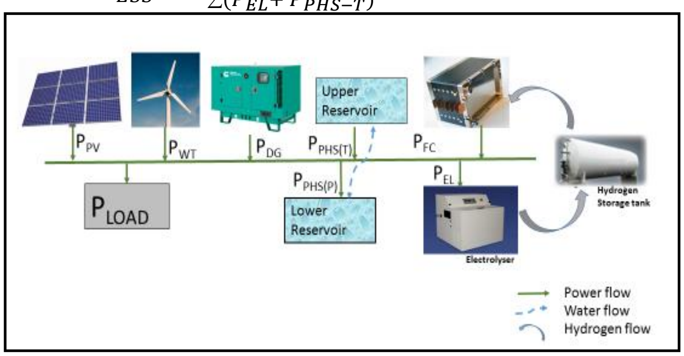

Figure 1: Configuration of the hybrid system and storage.

3. SYSTEM MODELLING

In this hybrid system, we seek to minimize the diesel generator fuel costs, while ensuring system reliability is not violated. The objective function is presented below:

$$\text{Min } C_f * \sum_{t=1}^{N} (aP_{DG}^2(t) + bP_{DG}(t) + c) \quad (12)$$

Here, C_f is the price of diesel per litre [27], N is the number of sampling intervals, t is the sampling time, P_{DG} is the output power from the diesel generator and a, b, c are the diesel generator's fuel cost coefficients [14].

System constraints:

For the overall system, a power balance constraint is applied to ensure that power supply matches demand at every hour.

$$\eta_{INV} * (P_{PVT}(t) + P_{WT}(t)) + P_{FC}(t) + P_{PHS-T}(t) + P_{DG}(t) - P_{EL}(t) - P_{PHS-P}(t) = P_{LOAD}(t) \quad (13)$$

Constraint (14) is set in to ensure the optimal value for the number of panels N_{PV} is an integer and does not exceed the maximum allowed quantity, N_{PVMAX}.

$$0 \le N_{PV} \le N_{PVMAX}; \quad N_{PV} \subset \text{integers} \quad (14)$$

Constraint (15) is set in to ensure the optimal value for the number of turbines, N_{WT} is an integer, and does not exceed the maximum number of wind turbines, N_{WTMAX}.

$$0 \le N_{WT} \le N_{WTMAX} \text{ and } \quad N_{W} \subset \text{integers} \quad (15)$$

Constraint (16) is the limit for the level of water stored in the reservoirs and it ensures that water does not overflow

$$V_{\min} \le V(t) \le V_{\max} \quad (16)$$

For the PHS operation, it is desired that the pump and turbines are not functioning at the same time [14], thus a binary variable *x*, with values of 0 and 1 is introduced, such that:

$$P_{MP}(t) = P_{MP}(t) * x \quad (17)$$

$$P_{TG}(t) = P_{TG}(t) * (1-x) \quad (18)$$

4. CASE STUDIES

For this study, a site at KwaZulu Natal Howard College in the KwaZulu Natal province is used. For operational analysis, both the winter and summer load profiles and the corresponding solar and wind data for these seasons are considered in analysing the fuel used by the diesel generator. The loads range from 9.415kW to 69.58kW on a typical day in summer and 11.73kW to 101kW on a typical winter day. The total energy demand per year is approximately 241.1MWh per annum, considering 275 days of summer and 90 days of winter. Other modelling parameters are presented in Table I.

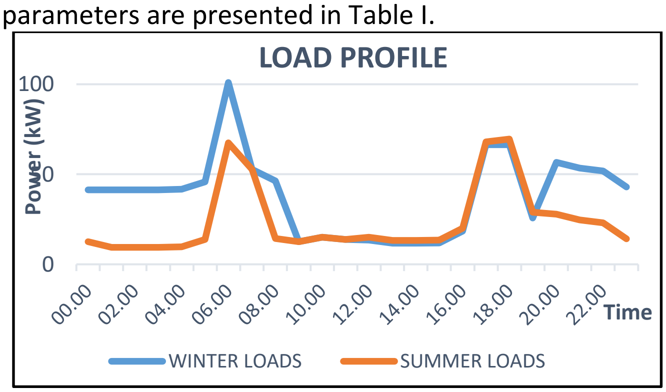

Figure 2: Winter and summer Load profiles

Table I: Parameters used in modelling the system

SOLAR PV		***PUMPED HYDRO STORAGE***	
Area of one panel (m^2)	1.9188	Density of water ρ(kg/m^3)	1000
Efficiency of panel, η_{PV}	0.1668	Acceleration due to gravity g (m/s^2)	9.81
Maximum number of panels	250	Head h (m)	60
DIESEL GENERATOR		Efficiency of turbine generator η_{TG}	0.85
Cost of diesel per litre ($)	0.9	Efficiency of motor pump η_{MP}	0.75
Diesel generator coefficients a, b, c.	0.246, 0.0815, 0.4333	***WIND***	
HYDROGEN FUEL CELL		Rated power of turbine (kW)	3
Efficiency of electrolyser η_{EL}	0.6	Rated wind speed (m/s)	10
Efficiency of fuel cell η_{FC}	0.5	Cut-in speed (m/s)	2
Efficiency of storage tank η_S	0.95	Cut-out speed (m/s)	40
Efficiency of inverter	0.95	Maximum number of wind turbines	100

The data presented in Table I is used in modelling the system using the Advanced Integrated Multidimensional Modelling System (AIMMS) software. The CPLEX 12.7 solver is used to solve the objective function of minimising diesel costs. The system is modelled as a mixed integer quadratic problem (MIQP) with a mix of 365 continuous and integer variables and 267 constraints. The solar radiation G(t) and wind speeds, $V_W(t)$ used in the model were from [17].

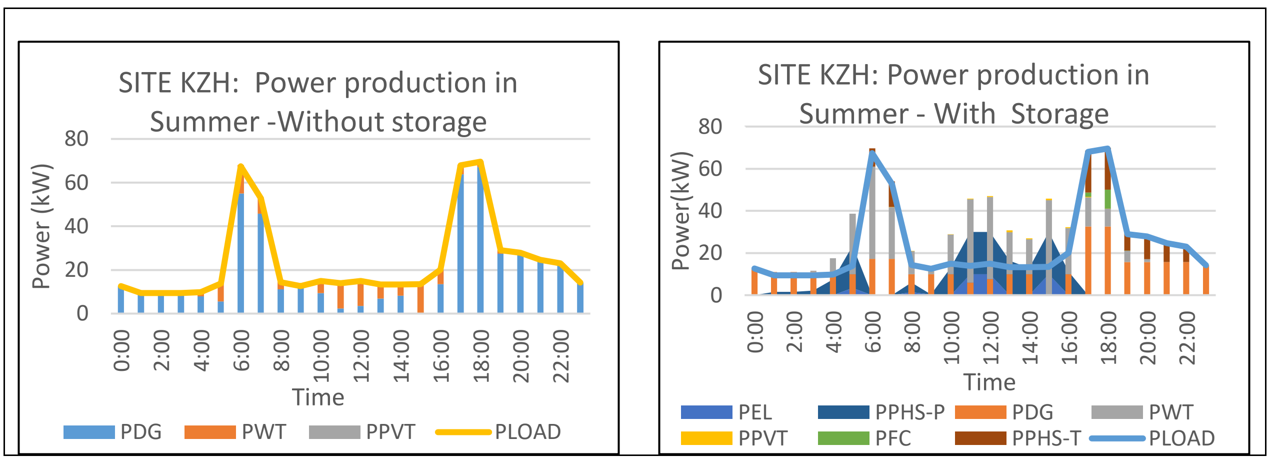

Figure 3: Power generated from solar PV, wind, diesel generators and energy storage systems in summer

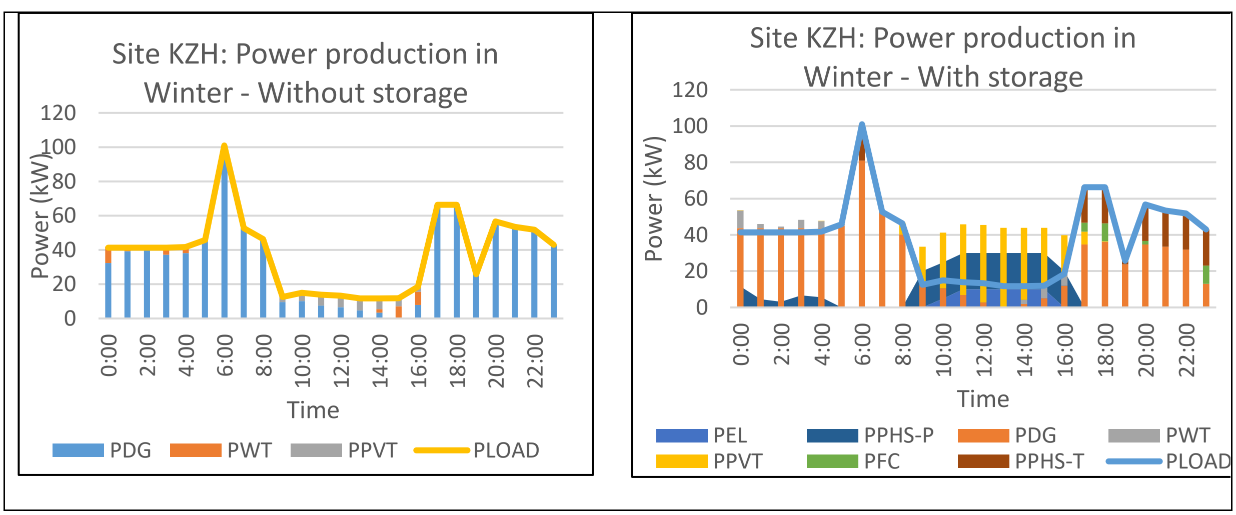

Figure 4: Power generated from solar PV, wind, diesel generators and energy storage systems in winter

Table II: Diesel generator outputs, with and without the energy storage systems.

Time slot	Summer			Winter		
	P_{LOAD} (kW)	Without storage P_{DG} (kW)	With storage P_{DG} (kW)	P_{LOAD} (kW)	Without storage P_{DG} (kW)	With storage P_{DG} (kW)
12:00	12.62	12.62	12.62	41.42	32.33	43.77
01:00	9.42	9.41	10.96	41.42	39.34	43.77
02:00	9.42	9.41	10.96	41.42	40.59	43.77
03:00	9.42	9.23	10.96	41.42	37.19	43.77
04:00	9.78	7.9	10.96	41.78	38.22	43.77
05:00	13.81	5.62	9.97	45.81	44.87	44.86
06:00	67.41	54.96	17.29	101.01	101	81
07:00	52.77	45.74	17.29	52.77	52.75	52.63
08:00	14.41	11.15	9.97	46.41	45.36	40.19
09:00	12.56	11.6	9.97	12.56	9.49	14.31
10:00	14.97	9.43	9.97	14.97	10.06	10.6
11:00	13.85	2.31	5.98	13.85	7.61	6.77
12:00	14.99	3.55	7.62	13.39	6.55	2.74
13:00	13.33	6.91	9.97	11.73	4.73	0.12
14:00	13.33	8.12	9.97	11.73	3.32	1.92
15:00	13.49	0.02	0.06	11.89	0.01	4.98
16:00	20.05	13.4	9.97	18.45	7.97	12.03
17:00	67.93	63.76	32.65	66.33	65.2	34.72
18:00	69.58	67.12	32.65	66.38	66.3	36.16
19:00	28.98	27.41	15.74	25.78	25.77	23.84
20:00	27.93	27.54	15.74	56.73	56.72	34.72
21:00	24.61	24.6	15.74	53.41	53.4	33.4
22:00	23.02	23.02	15.74	51.82	51.81	31.81
23:00	14.22	14.22	14.22	43.02	43.02	13.02
TOTAL ENERGY (kWh)	**571.9**	**469.1**	**316.9**	**925.5**	**843.6**	**698.7**

5. RESULTS

The impact of the energy storage systems on diesel costs are studied and analysed in this section.

The results in Table II above clearly shows the effects of including energy storage systems in the hybrid power system. When the hybrid system has no storage incorporated, all power needed for the loads is provided from solar PV panels and wind turbines, if available, and the diesel generators. With this configuration, the diesel generator is on for most of the hours of the day, incurring higher fuel costs. The inclusion of storage systems causes a reduction in the diesel fuel costs by 69.28% and 33.53% in summer and winter respectively.

From the simulation, six operational scenarios also emerge, where the supply meets demand based on operating constraints and limits in the model. Time slots in which these scenarios occur are presented in Table III.

Table III: Operating scenarios for hybrid power system and storage

S/N	Supply	Demand	Season/Time
1	DG	Loads	Summer:23-24 Winter:05-06
2	DG	Loads, Charging	Summer:01-05
3	PV-Wind-DG	Loads	Summer:08-12
4	PV-Wind-DG	Loads, Charging	Summer:09-17
5	DG-PHS-HFC	Loads	Winter:06-07
6	PV-Wind-DG-PHS-HFC	Loads	Winter:17-24

The overall efficiency of the storage system was also computed and results are presented in Table IV, showing better system efficiency in winter.

Table IV: Power outputs and overall efficiency of the energy storage system

	Summer	Winter
P_{EL}	35.26	54.81
P_{FC}	10.89	26.92
P_{PHS-P}	150.52	191.39
P_{PHS-T}	95.90	141.94
Total power consumed (P_{EL} and P_{PHS-P})	185.78	246.20
Total power supplied (P_{FC} and P_{PHS-T})	106.79	168.86
Overall efficiency	57.48%	68.59%

6. CONCLUSION

Off-grid communities have benefited from electricity supply from renewable energy resources, as these systems can be deployed irrespective of the distance to the central grid. In this study, a hybrid system featuring solar and wind systems with a diesel generator is analysed. In order to ensure system reliability during renewable energy intermittency, pumped hydro storage systems and hydrogen fuel cells are incorporated into the system.

The objective function of this study is the minimization of operation costs of the diesel generator, and is presented as a Mixed Integer Quadratic Program (MIQP) model and solved using CPLEX 12.7 in AIMMS. The developed model is applied to real-world data for KwaZulu Natal province, South Africa. The simulated results reveal that incorporation of storage systems which have a long lifetime of about 20 years significantly reduces the costs of operating the diesel generator by 69.28% and 33.53% in summer and winter respectively, for KwaZulu Natal province.

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