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Optimal energy mix of a microhydro-wind-grid system powering a dairy farm in Western Cape, South Africa.

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Abstract

This paper presents an optimal control strategy of a grid-tied microhydro-wind power system for a rural dairy farm in South Africa. The problem is formulated as a multi-objective optimisation programme in discrete time domain to minimise grid imported energy cost under Time of Use Tariff (TOU) while at the same time maximising revenue generated from the sale of surplus renewable energy to the grid at a specified renewable energy feed-in tariff. The application of the proposed model to a practical case study shows the potential of the model to save the farmer the grid energy cost up to 75.07% in summer and 70.69% in the winter with a discounted repayment period of 3 years and 7 months.

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Keywords: Microhydro system; optimal control; TOU tariff; feed-in tariff; dairy farm; distributed renewable energy.

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1. Introduction

South Africa's electricity consumption in the agricultural sector accounts for approximately 3.8% of the country's total generation [1]. The appreciable share makes the agricultural sector a potential target for energy efficiency investment programmes. In the sector, dairy farming is a cardinal energy consumer due

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to of heavy mechanisation [2, 3]. According to [4], milk cooling, water heating and milking are the main energy consumers on non-irrigated dairy farms accounting for 31%, 23% and 20% of utility bills respectively. On the other hand, water pumping accounts upto 73% of electricity consumption in irrigated dairy farms [5]. These varying levels of energy demand underscore huge potential for energy efficiency improvements, especially in cooling and pumping operations. The effects of time differentiated tariff structure on the energy consumption on dairy farms have been studied in [6, 7, 8]. In [7], a solar photovoltaic-grid system is proposed for a dairy farm application with the option of selling surplus solar power to the grid. There is no work in the current literature that has studied the potential of micro-hydro power systems for powering dairy farms despite close siting of farms near rivers, like in the South African context. The potential of hydrokinetic technology as a renewable energy resource is studied in [9, 10]. This paper proposes a hybrid hydrokinetic-wind-grid system for powering a rural dairy farm. Besides minimisation of grid energy import under TOU tariff, unlike the model presented in [7], the model proposed in this paper allows for the sale of surplus distributed renewable energy (DRE) to the grid under an established DRE feed-in tariff, creating an extra revenue stream for the farmer.

2. Mathematics model formulation

The schematic layout of the proposed hybrid power system is shown in Fig. 1. As shown, it comprises the microhydro generator, the wind generator and the grid supplying power to a dairy farm.

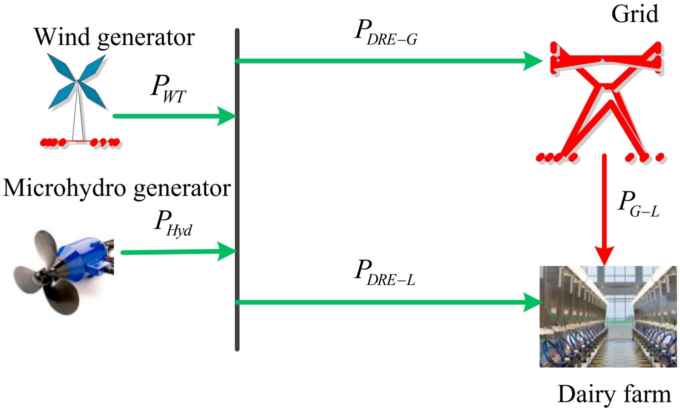

Fig. 1. Schematic Layout of the grid-connected hybrid system

In Fig.1, P_{WT} and P_{Hyd} denote the power flows from the wind turbine and the micro-hydro turbine respectively. The farm power demand, $P_L(t)$, is primarily met by the combined power flow from the wind and the microhydro generator, $P_{DRE-L}(t)$, supplemented by the power purchased from the grid, $P_{G-L}(t)$, when the renewable on-site generator is insufficient to meet the load demand. In occasions when the on-site renewable generation is greater than the load demand, the surplus renewable power, $P_{DRE-G}(t)$, is sold to the grid at an established feed-in tariff to earn an income for the farmer.

2.1. The objective function

The proposed model seeks to minimise the grid energy cost while at the same time maximising the revenue generated from the sale of surplus DRE to the grid over a 24 hour control horizon. The optimisation problem is expressed in discrete time domain as follows:

$$\min J = t_s\left(w_1\sum_{k=1}^{N}\rho_g(k)\,P_{G-L}(k) - w_2\sum_{k=1}^{N}\rho_f\,P_{DRE-G}(k)\right), \tag{1}$$

where t_s is the sampling interval, which is 30 min in this case, k is the k^{th} sampling interval and $w_1 + w_2 = 1$ are the weighting factors. $\rho_g(k)$ is the time-of-use (TOU) tariff, ρ_f is the feed-in tariff for the renewable energy sold to the grid while $N = \frac{24}{t_s} = 48$ is the total number of samples over the control horizon. The objective function expressed by equation (1) is solved subject to the following constraints:

$$P_{DRE-L}(k) + P_{G-L}(k) = P_L(k)\,, \tag{2}$$

$$P_{WT}(k) + P_{Hyd}(k) = P_{DRE-L}(k) + P_{DRE-G}(k)\,, \tag{3}$$

$$P_{WT}^{min} \leq P_{WT}(k) \leq P_{WT}^{max}\,, \tag{4}$$

$$P_{Hyd}^{min} \leq P_{Hyd}(k) \leq P_{Hyd}^{max}\,, \tag{5}$$

$$P_{DRE-L}^{min} \leq P_{DRE-L}(k) \leq P_{DRE-L}^{max}\,, \tag{6}$$

$$P_{DRE-G}^{min} \leq P_{DRE-G}(k) \leq P_{DRE-G}^{max}\,, \tag{7}$$

$$P_{G-L}^{min} \leq P_{G-L}(k) \leq P_{G-L}^{max}\,, \tag{8}$$

where min, max denote the lower and the upper bounds of the continuous power flows between the system sources and the load.

2.2 Case study

The case study is based on a rural dairy farm in the Western Cape Province of South Africa. The farm is situated within proximity of Berg River for ease of access to water for farm use. The cardinal electricity consumers on the farm are the milk coolers, milking machines, water heating system and lighting. Fig.2 shows the aggregated load profile of the farm in summer and winter with a peak value of $15.40kW$ and $17.40kW$ respectively.

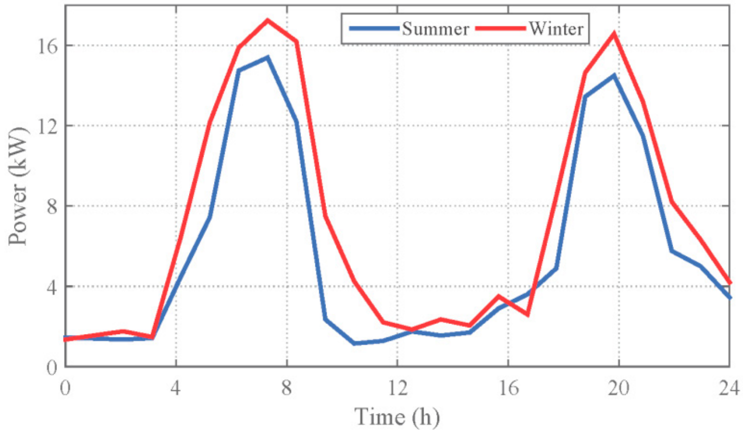

Fig.2. Daily load profile of the dairy farm on a typical day in summer and winter

3. Results and discussions

The problem is a linear optimization problem with linear constraints solvable in MATLAB using *OPTI toolbox* over a 24 h control horizon with a sampling interval, $t_s = 30\, mins$.

3.1 Optimal power flows of the model in summer

Fig. 2 shows the results of the power flow of the model in summer when full optimisation priority is given to the minimisation of grid energy; $w_1 = 1; w_2 = 0$. In this optimisation scenario, the optimal control (OC) maximises the use of the on-site generated energy (DRE) to meet the system load demand and only exports surplus power to the grid after the consumer's demand has been fully met. Also the OC will imports power from the grid only when the load, P_L, is greater than the combined DRE generation as is the case between 06:00 and 09:00 and between 18:00 and 21:00. As shown in Fig.2, the on-site DRE generation is greater than the farmer's demand and as a result, the surplus DRE, P_{DRE-G}, is fed into the grid to generate an income for the farmer between 00:00 and 06:00 and between 09:00 and 18:00.

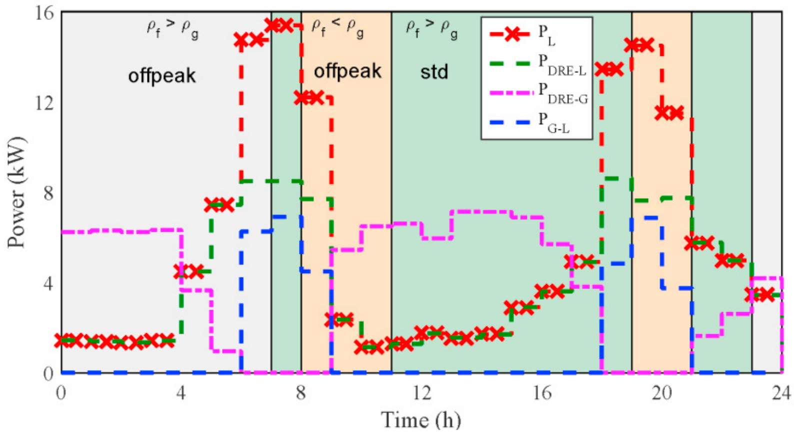

Fig. 3. Optimal power flows of the system in summer

3.2. Optimal power flows of the model in winter

Fig. 4 shows the results of the optimal power flows of the proposed model on a typical day in the winter when $w_1 = 1; w_2 = 0$. Typically, the figure is identical to Fig. 3 except the high P_{G-L} power purchase between 06:00 and 07:00 and between 20:00 and 21:00. This is caused by the high peak power demand of the dairy farm in winter as compared to the demand in summer. Table 1 shows the daily energy and cost savings of the proposed OC model on a typical day in the winter.

Table 1: Daily optimal energy and cost savings in winter

Season	Baseline demand (kWh)	Baseline Cost(R/day)	Optimal cost (R/Day)	Feed-in (R/Day)	Energy savings (kWh)	Energy savings (%)	Cost savings (%)
Summer:	134.76	124.51	31.04	119.09	101.63	75.41	75.07
Winter:	172.14	171.30	50.20	90.22	122.44	71.13	70.69

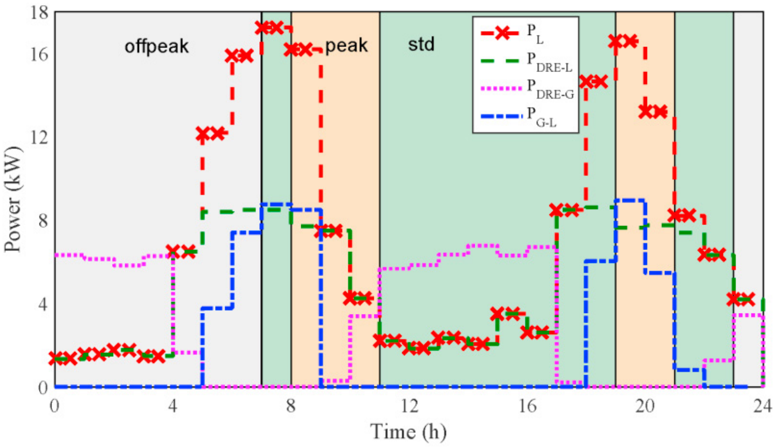

Fig. 4. Optimal power flows of the system in winter

As shown in Table 1, the daily baseline grid energy demand in the summer is $134.76\ kWh$ while the optimal demand is $33.13\ kWh$, resulting in an energy savings of $101.63\ kWh$, which translates to 75.41% in daily energy savings. In the same vein, the daily baseline energy cost in the winter is $R124.51$ while the daily optimal cost after the intervention is $R31.04$, translating to 75.07% in cost savings. Similarly, the proposed model achieves 71.13% and 70.69% in energy and cost savings respectively in winter as shown in Table 1.

4. Economic analysis and payback period

Table 1 and Table 2 give the specifications of the wind generator [†]and the microhydro generator[‡] used in the case study. As shown, the wind and hydrokinetic generators are sized at 3.5kW and 7.5kW respectively, giving a hybrid system of 11kW sized by rule of thumb to meet the farmer's average load.

Table 1.Wind generator parameters

Rated power (kW)	Start-up speed (m/s)	Breaking speed (m/s)	Rated wind speed (m/s)	Survival speed (m/s)	Swept area (m^2)	Service life (yrs)
3.5	2.8	22	11	50	12.6	75

Table 2. Microhydro generator parameters

Rated power (kW)	Rated water speed (m/s)	Frequency(Hz)	Rotary speed (rpm)	Power factor (pf)	Max depth (m)	Service life (yrs)
7.5	3.5	50	1500	0.8	10	20

4.1 Annualised feed-in energy and revenue

In order to effectively determine the reflective energy and revenue generated from the proposed project over a year-long period, simulations are carried out for a typical day in each season to account for

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[†] http://www.angelwindenergy.com/Raum.html

[‡] http://www.yueniao.com/T25-7.5DTF4.html

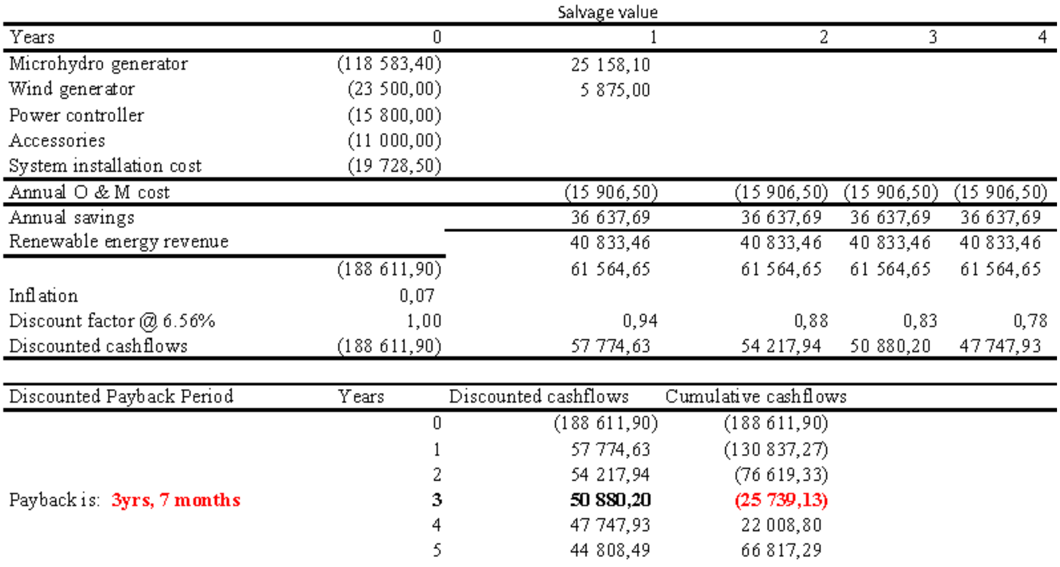
demand variations which varies with changes in seasons. The feed-in energy and revenue are then averaged to determine a single day's value. The average daily value is then annualised to determine the average annual revenue. The energy cost saved after the proposed intervention is then translated as a savings. Table 3 shows the calculated seasonal energy and revenue generated from the proposed intervention. In the case study, the farmer's load profile in spring, summer and autumn is nearly identical and as a result, the feed-in energy and associated revenue are similar as shown in Table 3. From the table, the average daily DRE feed-in is calculated by taking the average of the four seasons. The same can be done for average daily optimal grid energy and revenue from feed-in energy.

Table 3. Seasonal daily renewable energy feed-in and associated revenue

Seasons	Winter	Spring	Summer	Autumn
Feed-in energy (kWh)				
DRE feed-in	72.27	93.27	93.27	93.27
Optimal grid energy	49.69	33.13	33.13	33.13
Revenue (R)				
DRE sales	90.22	119.09	119.09	119.09
Grid savings	122.44	101.63	101.63	101.63

In Table 4, Annual savings refers to the amount of money the end consumer would have spent per year if the proposed intervention was not implemented, which is assumed constant throughout the service life of the project. Similarly, the annual operation and maintenance costs are assumed constant throughout the project life as shown in Table 4. The project has a service life of 20 years with a salvage value of $R25,158.10$ for the micro-hydro generator and $R5876.00$ for the wind generator as shown in Table 4.

Table 4. Present value and discounted payback period



		Salvage value			
Years	0	1	2	3	4
Microhydro generator	(118 583,40)	25 158,10			
Wind generator	(23 500,00)	5 875,00			
Power controller	(15 800,00)				
Accessories	(11 000,00)				
System installation cost	(19 728,50)				
Annual O & M cost		(15 906,50)	(15 906,50)	(15 906,50)	(15 906,50)
Annual savings		36 637,69	36 637,69	36 637,69	36 637,69
Renewable energy revenue		40 833,46	40 833,46	40 833,46	40 833,46
	(188 611,90)	61 564,65	61 564,65	61 564,65	61 564,65
Inflation	0,07				
Discount factor @ 6.56%	1,00	0,94	0,88	0,83	0,78
Discounted cashflows	(188 611,90)	57 774,63	54 217,94	50 880,20	47 747,93

Discounted Payback Period	Years	Discounted cashflows	Cumulative cashflows
	0	(188 611,90)	(188 611,90)
	1	57 774,63	(130 837,27)
	2	54 217,94	(76 619,33)
Payback is: **3yrs, 7 months**	**3**	**50 880,20**	**(25 739,13)**
	4	47 747,93	22 008,80
	5	44 808,49	66 817,29

To ascertain the economic viability of the proposed system, discounted payback analysis was carried out [11]. This method discounts the cash flows (CF) of the project to determine the present value (PV) of the future flows. Then the next step is establishment of the future period when the PV equals the total capital cost (CC). This is the point when the break-even occurs (payback period). From Table 4, the estimated initial capital cost of the project is -$R188,611.90$; the amount in bracket $(188,611.90)$ represents all the initial capital investment and all running (operational) costs of the project. In this paper, the payback period is obtained from the net present value (NPV) of the present value (PV). The present value of the cash flow during the $n-$ th year, $PV(n)$, is formulated as follows:

$$PV(n)=\frac{\text{Cash flow }(n)}{(1+r)^n}, \tag{9}$$

where Cash flow (n) is the cash flow of the $n-th$ year and r is the discount rate (discount factor), which is 6.56% in the case study; a value that indicates the time value of money in South Africa as of May 2017. After obtaining the present value, the NPV is expressed as follows:

$$NPV_{n=1}^{m}=\sum_{n=1}^{m}PV(n)-CC, \tag{10}$$

where CC is the initial capital cost of the project. Finally, the discounted payback period is obtained by the following expression [11]:

$$\text{Payback period}=m_y+\frac{-NPV_{n=1}^{m}}{PV\left(m_y+1\right)}, \tag{11}$$

where m_y denotes the last year with a negative NPV and the results are presented in Table 4. From Table 4, it can be shown, that the discounted payback period of the project is 3 years and 7 months.

5. Conclusion

This paper presented an optimal energy mix and control of the micro-hydro-wind-grid system for powering a dairy farm. The objective of the model was to fully meet the farm's electrical energy demand by the on-site renewable generation and minimise the cost of grid energy importation. The analysis of the results presented in the paper showed a huge energy and cost saving potential of the proposed model under TOU tariff. Besides the projected savings, the model creates an extra income stream for the farmer through the sale of surplus renewable energy to the grid through an established DRE feed-in tariff. A payback period of 3 years and 7 months shows the viability of the model for application in many rural on-grid as well as off-grid scenarios within the vicinity of rivers. Micro-hydro is an emerging renewable technology with a huge potential to alleviate reliance on the depleting fossil fuels because of its high energy density as compared to other intermittent renewable resources.

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