Optimal Investment Decision for Cotton Farm Microgrid Design

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***Abstract*— The integration of renewable energy sources (RESs) into distributed microgrid systems has been widely applied in agriculture, and in particular in cotton farms. Due to the specific irrigation periods and non-irrigation periods during cotton growth, and the inherent intermittent characteristics of RESs, the design of a cotton farm microgrid system becomes challenging. Finding the optimal size of the RESs for a cotton farm microgrid needs to consider not only the energy demand for cotton irrigation but also the investment cost and the payback period. This paper presents an optimization model for cotton farm microgrid design, which explores available RESs and energy storage options to ensure reliable power supply from renewables. Furthermore, the designed microgrid utilizes solar photovoltaic (PV) units and wind turbine generator as RESs together with battery storage and demonstrates the supply and demand relationship between the microgrid and pump loads. By using RES power supply, renewable energy is optimally utilized to satisfy the seasonal loads demand, and the grid power is used as a backup power source. The objectives of optimization include investment cost, operating cost and simple payback period. In order to solve the underlying optimization problem, this paper adopts YALMIP MATLAB Toolbox. A case study is undertaken using historical energy consumption data for a cotton farm in Gunnedah, New South Wales, to verify the applicability of the proposed approach.**

Keywords*— *Cotton farm, Pump load, Time of use, PV, Wind turbine, Battery storage

I. INTRODUCTION

Cotton industry is one of Australia's largest export earners in rural areas. It provides thousands of job opportunities in Australia [1]. There are over 1400 cotton farms with more than 427 thousand hectares of cotton planted, which contributed a record AU$2.3 billion for the national economy in 2017/2018 [2]. However, cotton cultivation is a high energy demand industry, and the international cotton market is extremely competitive. Therefore, the continuous rise in energy prices has become one of the critical barriers to the development of the cotton industry. In order to reduce the energy cost of cotton farms and simultaneously reduce carbon emissions, this paper aims to develop a design method for cotton farm microgrids including photovoltaic (PV) systems, wind turbine (WT), battery storage, and backup grid connection. It intends to utilize the power generated from wind and PV energy sources and reduce the grid power usage to save irrigation energy costs and shorten the investment payback period.

II. LITERATURE REVIEW

A. Related work

Rural grid-connected microgrids are quite common in Australia; for example, Ref. [3] designed a grid-connected microgrid using PV and battery storage for an area with limited grid power supply in Uttar Pradesh, India. It can support various loads when the grid power is insufficient, and the technical and economic analysis was implemented. In [4], a small grid-connected PV-wind hybrid energy system was studied, which is a RES optimal design to satisfy fifteen homes' energy consumption in a downtown community in Chile. However, the cotton farm microgrid is different from others because the irrigation demand is not constant, and indeed, it is only seasonal as it has to match cotton-growing periods. This is to say, the size of the designed microgrid has to be properly determined for cotton farms. Thus, it is essential to find an optimal size of the microgrid that is suitable for the seasonal and high-power demand of cotton farm irrigation pumps. In addition, the maximum demand charge from the utility needs to be considered in the grid-connected mode [5]. Existing studies have developed methods to reduce time-of-use (TOU) energy tariff charges and maximum demand charges. For example, Ref. [6] maximized loads shifting via demand-side management (DSM) techniques to minimize the TOU charge, while [7] used a closed-loop optimal control strategy to reduce both the TOU charge and maximum demand charge. DSM for a hybrid microgrid consisting of PV and battery storage was proposed in [8]. Ref. [9] presented a mathematical model and a multi-agent system model for the energy management system and proved that DSM can help to reduce domestic energy consumption.

From the aforementioned studies [6-9], the method of grid-connected management of renewable energy in rural microgrids has been paid attention to, while few studies have discussed the seasonal loads and intermittent power sources working together. Targeting at these problems, this paper proposes a new microgrid design method for cotton farms which will consider the seasonal usage of water pumps and intermittent solar and wind energy sources. The microgrid components will be chosen from PV, WT, and battery storage, and the microgrid is connected to the utility grid to provide additional power support. The properly sized battery storage plays an essential role in peak demand management, RES power absorption, and load management under time-varying feed in tariff (FIT). To facilitate this design, a multi-objective optimization methodology is designed to minimize the weighted sum of the operational cost, investment cost, and payback period of the grid-connected microgrid. A case study pertaining to Kensal Green cotton farm is analyzed to verify the effectiveness of the proposed methodology.

B. Main contributions

The main contributions of this paper are listed below.

- A multi-objective cotton farm microgrid design model is presented considering seasonal irrigation pump load, weather conditions, Australian renewable energy policies, electricity tariffs as well as time-varying FITs.
- The cotton farm design model also includes the relationship between the pump power consumption, and the farmland water demand during an irrigation cycle.
- A case study of a real cotton farm discusses the impact of tariff and FIT change on the microgrid operation and investment. The case study also reveals that installing a 10kW WT in an Australian cotton farm is not economically viable.

The remaining part of this paper is organized as follows. Section III presents the RES components for the cotton farm microgrid in Australia, and a power balance model for RESs and load is also formulated. The Yalmip [10] solver along with MATLAB optimization tools is used to solve the microgrid optimization problem for a case study on the Kensal Green cotton farm in Section IV. Numerical results and the discussion of the economic implications are presented in Section V. Section VI summarizes this paper and draws the conclusion.

III. Optimal Design of Cotton Farm Microgrid

Fig. 1 shows the grid-connected microgrid model. The pump loads can be supplied by the grid, battery storage, PV and WT. $P_g(t)$ is the power purchased from the grid for the pump loads at the t^{th} hour; $P_{m1}(t)$ is the power from the PV and WT to the pump loads at the t^{th} hour; $P_{b1}(t)$ is the battery discharged power to the pumps at the t^{th} hour. Besides supplying pump loads, the PV and WT can also feed excess energy into the grid and charge the battery. $P_{m2}(t)$ represents the power from the PV and WT to charge the battery at the t^{th} hour, and $P_{m3}(t)$ is the power from the PV and WT to the grid at the t^{th} hour. When irrigation is not required, the battery storage also releases energy sold to the grid to accelerate the payback period; $P_{b2}(t)$ is the battery power fed back into the grid at the t^{th} hour. Hourly samples are taken in the model.

Fig. 2 illustrates the cotton farm water irrigation system. According to the water demand, pumps are set up to lift water from bore or river through ditches to turkey nest dams for storage. Then the water flows to cotton farms by gravity siphon irrigation. In Fig. 2, $P_{pump,k}(t)$ is the rated power consumption of the k^{th} pump at the t^{th} time; and $F_0(t)$ is the water flow from the storage to field by gravity at the t^{th} time.

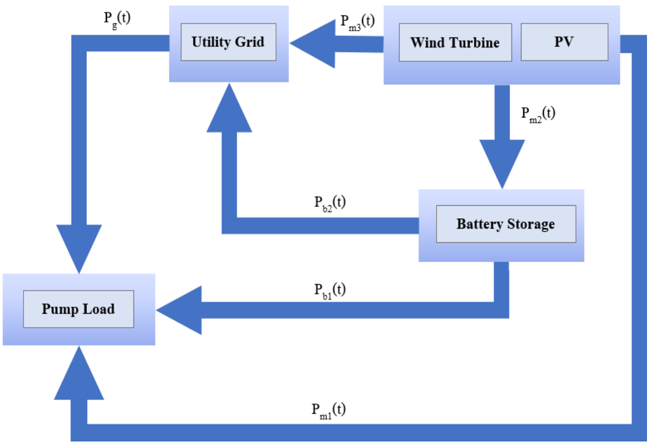

Fig. 1. Grid-Connected Microgrid Model

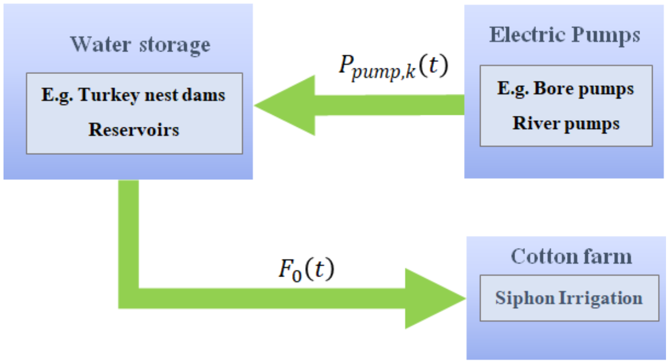

Fig. 2. Cotton Farm Irrigation Model

A. Objective functions

Based on the microgrid system model, the design objectives can be represented by (1), (2), and (3).

$$f_{op} = \sum_{t=1}^{T} \beta_1(t) \cdot P_g(t) - \sum_{t=1}^{T} \beta_2(t) \cdot \left(P_{m3}(t) + P_{b2}(t)\right) + C_0 \quad (1)$$

$$f_{invest} = \sum_{p=1}^{L} k_{1p} \cdot m_{1p} \cdot x_{1p} + \sum_{q=1}^{M} k_{2q} \cdot m_{2q} \cdot x_{2q} + \sum_{r=1}^{N} k_{3r} \cdot m_{3r} \cdot x_{3r} \quad (2)$$

$$f_{payback} = \frac{f_{invest}}{Cost_{org} - f_{op}} \quad (3)$$

In (1), f_{op} is the one-year operational cost of the cotton farm microgrid system, $\beta_1(t)$ represents the electricity tariff rate at time t charged by the grid, T=8760 is the total number of hours in a year, $\beta_2(t)$ represents the rate of FIT per kWh at the time t, and C_0 is the entire system's maintenance cost over one year. Eq. (2) represents the investment cost of the microgrid system, where k_{1p} is the p^{th} type of PV unit price in AU$/kW, $m_{1p}$is the rated power output (in kW) of the p^{th} type of single PV panel, x_{1p} is the total number of the p^{th} type of PV panels to be installed, and the L is the total types of PV panels; k_{2q} is the q^{th} type of WT unit price in AU$/kW, m_{2q} is the rated power output (in kW) of the q^{th} type of WT, x_{2q} represents the number of the q^{th} type of WTs to be installed, and the M is the number of WT types; k_{3r} is the r^{th} type of battery unit price in AU$/kWh, m_{3r} is the single unit battery capacity of the r^{th} type in kWh from the specifications, and x_{3r} represents the number of r^{th} type of batteries in the system, and N is the total types of battery storage. The simple payback period ($f_{payback}$) can be calculated by (3), and $Cost_{org}$ is the original annual operational cost without installing the microgrid system.

The objective functions in (1), (2), and (3) can be combined into a single-objective function (4) with weights λ_1, λ_2, and λ_3. Yalmip solver [10] is applied to solve this optimization problem. Three weights λ_1, λ_2, and λ_3 are assigned to each objective function to represent the percentage of each scalar function, and they are constrained by (5). The optimization model will help the decision-maker select the best actions to obtain the minimal cost.

$$\min\,(\lambda_1 \cdot f_{op} + \lambda_2 \cdot f_{invest} + \lambda_3 \cdot f_{payback}) \tag{4}$$

$$\lambda_1 + \lambda_2 + \lambda_3 = 1 \tag{5}$$

B. System constraints

Pump load balance equation is given in (6) and the microgrid power balance is shown in (7):

$$P_p(t) = P_{m1}(t) + P_{b1}(t) + P_g(t) \tag{6}$$

$$P_{m1}(t) + P_{m2}(t) + P_{m3}(t) = P_{PV}(t) + P_{WT}(t) \tag{7}$$

where

- $P_p(t)$ is the total power demand of all the water pumps at the t^{th} hour;
- $P_{PV}(t)$ is the PV generated power at the t^{th} hour; and
- $P_{WT}(t)$ is the WT generated power at the t^{th} hour.

C. Battery storage constraints

Energy storage of the microgrid is chosen as battery packs, the battery storage state of charge (SOC) in each interval can be expressed by (8), and the constraints of the SOC is expressed as (9).

$$SOC(t) = SOC(t-1) + \frac{P_{m2}(t) - P_{b1}(t) - P_{b2}(t)}{\sum_{r=1}^{N} m_{3r} \cdot x_{3r}} \tag{8}$$

$$SOC_{min} \le SOC(t) \le SOC_{max} \tag{9}$$

where

- $SOC(t)$ is the battery state of charge (SOC) state at the t^{th} time;
- SOC_{min} is the minimum allowed SOC, in this study SOC_{min} = 20%; and
- SOC_{max} is the maximum SOC, in this study SOC_{max} = 90%.

D. Grid-connected constraint

Grid-connected feed-in power constraint can be expressed by (10)

$$P_{m3}(t) + P_{b2}(t) \le Q_1 \tag{10}$$

where Q_1 is the maximum allowed feed-in power.

E. PV generation constrains

Eq. (11) show that PV power generation satisfies the following relations:

$$P_{PV}(t) = \sum_{p=1}^{L} x_{1p} P_{PV,p}^{0}(t) \tag{11}$$

where $P_{PV,p}^{0}(t)$ is the forecasted power generation by a single PV panel at the t^{th} hour.

F. Wind generator constraints

Wind power generation satisfies constraints (12) - (13):

$$P_{WT}(t) = \sum_{q=1}^{M} x_{2q} P_{WT,q}^{0}(t) \tag{12}$$

$$\sum_{q=1}^{M} m_{2q} x_{2q} \le 10\ (kW) \tag{13}$$

where $P_{WT}^{0}(t)$ is the forecasted power generation of a single WT of type q at time t. Eq.

(13) means that the installed WT capacity must not exceed the maximum 10 kW threshold set by the Australian government for small-scale wind systems.

IV. CASE STUDY: KENSAL GREEN COTTON FARM

In order to verify the effectiveness of the proposed optimal planning methodology, the model and algorithm are combined with the historical data from real cotton farms for a case study.

A. Farm information

The Kensal Green cotton farm is located in the south of Gunnedah, New South Wales (Latitude: 30.97°S, Longitude: 150.253°E), and the cotton farm irrigation area is 300 hectares in 2016 [11]. The farm has three sub-bore electricity pumps with nominal power of 75 kW, 75 kW, and 37 kW, respectively. All related information about this case study, including water demand, cotton-growing period, and the pump load profile, is summarized below.

The annual energy consumption of the three bore pumps and the total cost without the microgrid are displayed in Table I. Table I shows the original operational costs under a time of use tariff (Ergon Energy rural TOU Tariff 65 is used). Time-varying and flat FIT schemes are illustrated in Table II.

TABLE I. COTTON FARM ORIGINAL OPERATION COST WITH ERGON ENERGY TOU TARIFF [a]

	Peak	**Off-peak**	**Cost**
	(AU$0.406/kWh)	***(AU$0.223 /kWh)***	***(AU$)***
Pump 1	17,201.5 (kWh)	7,471.79 (kWh)	24,673.29
Pump 2	14,727.0 (kWh)	6,094.00 (kWh)	20,820.97
Pump 3	2,947.2 (kWh)	1,252.45 (kWh)	4,199.67
Total cost (AU$/year)			49,693.93

a. https://www.ergon.com.au/retail/business/tariffs-and-prices/farming-tariffs

TABLE II. FIT SCHEME

Ergon Energy FIT scheme (AU$ / kWh)		
Time-varing FIT	Peak period (3pm-7pm daily)	0.13730
	Off-peak (Remaining hours)	0.05796
Flat rate FIT	All exports	0.07842

B. Microgrid Components and Costs

Table III gives the data of a popular PV model. Table IV provides information regarding small-size WTs that can be found on the Australian market, and Table V shows the corresponding data of a popular battery storage product from Tesla®.

TABLE III. SOLAR GENERATOR SPECIFICATIONS OF THE CASE STUDY

Smart Panel® 60-cell SPV310-60MMJ PV [b]	
Panel power (kW)	0.253
Dimensions (L x W x H) (mm)	1650 x 992 x 40
Panel efficiency	18.9%
Performance ratio	0.75
Warranty (years)	15 years
Average maintenance cost (AU$/year/panel)	5
Unit price (AU$/panel) (Inverters included)	250

b. https://www.solaredge.com/sites/default/files/se_smart_module_monoperc_aus.pdf

TABLE IV. WT SPECIFICATIONS

Atlantis Solar [c]	*ASWT-2kW*	*ASWT-5kW*	*ASWT-10kW*
Rated power (kW)	2	5	10
Cut-in speed (m/s)	3	2.5	3
Rated wind speed (m/s)	9	10	10
Generator efficiency	0.8	0.8	0.85
Design life (years)	20	20	20
Generator efficiency	0.8	0.8	0.85
Average maintenance cost (AU$/year)	800	1000	1500
Unit price (AU$/unit) (Installation and inverter included)	10K	60K	100K

c. https://www.atlantissolar.com/turbine_10kw.html

TABLE V. BATTERY SPECIFICATIONS

Tesla® Powerwall 2 Lithium AC battery system [d]	
Usable capacity (kWh)	13.5
Dimensions (L x W x H) (mm)	1150 x 755 x 155
Max charge and discharge (kW)	6.99
Warranty (years)	10
Round trip efficiency	90%
Average maintenance cost (AU$/year/unit)	300
Unit price (AU$/unit)	10,600

d. https:// www.tesla.com

V. RESULTS AND DISCUSSION

This case study is conducted to assess the validity of the proposed microgrid model, and the results of this study are discussed in the following three subsections. Yalmip toolbox [10] and MATLAB fmincon are adopted for this multi-objective optimization model. In this case study, the parameters of the cotton farm are listed in Table VI. Here, the 2016 energy consumption data of pumps are used to simulate the irrigation of cotton farms. The water demand is based on the average water application rate of cotton farms in the Murray Darling Basin area in 2016, and rainfall as a source of supplementary water is approximately 33% [12] of the total irrigation in this study.

TABLE VI. KENSAL GREEN COTTON FARM'S PUMPS AND FARMLAND PARAMETERS

Parameters	***Value***
Pump 1 energy consumption (kWh)	75,812
Pump 2 energy consumption (kWh)	63,551
Pump 3 energy consumption (kWh)	12,865
Farm size (Ha)	300
Average pumping head (m)	25
Average energy consumption of lifting 1ML water to 1-meter height (kWh/ML/m)	4.55
Water-use efficiency	80
Average irrigation demand (ML/Ha)	6.5
Maximum allowed water usage (ML/year)	1500
Reservoir capacity (ML)	1200
Rainfall percentage of entire irrigation	33.33%
Annual average wind speed at a height of 10-15m (m/s)	3.42
Daily average solar irradiation in 2016 (kWh/m^2)	5.02
Annual operational cost (with TOU tariff) (Au$)	49,694

A. Base Case: Implementation of the proposed optimization methodology on the cotton farm

In the microgrid design of this case study, power balance and microgrid design models mentioned in Section III are applied. The Smart Panel branded PV panels are used, and each panel is rated at 253W. Tesla Powerwall-2 Lithium-ion battery packs are used as battery storage, and each battery pack has a capacity of 13.5 kWh. For WTs, Atlantis Solar series 2kW, 5kW and 10kW WTs are used. Table VII lists the comparison between the original situation and the Base Case, including the microgrid configuration, investment cost and simple payback period. The original situation is for the case that RESs are not installed on the cotton farm. The Base Case ($\lambda_1 = 0.6, \lambda_2 = 0.2$ and $\lambda_3 = 0.2$) solves the optimization problem in (4) with TOU tariff and TOU FIT to optimize the microgrid configuration. Fig. 3 demonstrates that the RESs generate power to pump loads, but it is not enough to satisfy the load demand even at different combinations. Therefore, grid power is the backup to satisfy the energy deficit. On the other hand, the excess energy from the microgrid system can be fed into the grid during the off-peak irrigation period.

Through this Base Case, it can be found that the irrigation time of cotton farms was concentrated in the first 45 days, and then intermittent irrigation was applied from the 260th day to the 365th day of the year. However, from the 46th day to the 259th day, the total working time of the pumps were less than 7 days. Therefore, the energy consumption of water pumping in cotton farms was mainly used in the spring and summer in Australia for about 90 days. For nearly 3/4 of the year, pumps were not used. This infrequent utilization of pump/microgrid system leads to a longer simple payback period than normal.

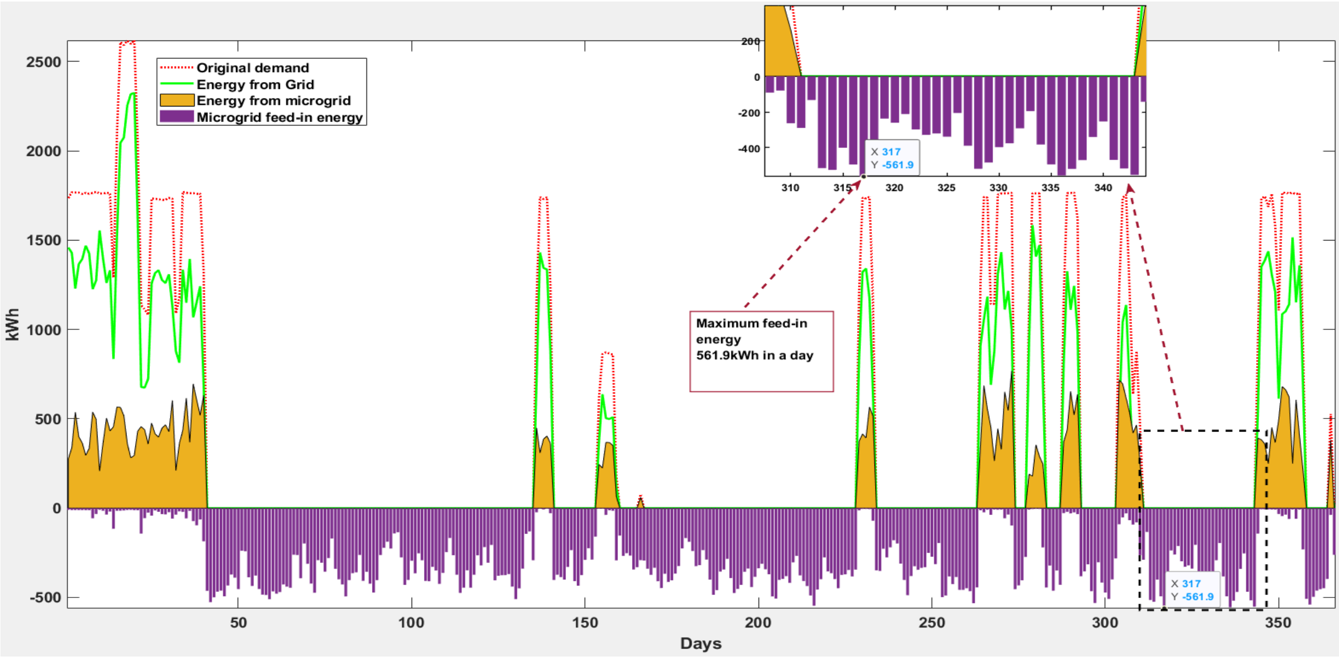

Fig. 3. Microgrid energy distribution in the Base Case

TABLE VII. OPTIMAL DESIGN RESULTS OF COTTON FARM MICROGRID

	Original situation	*Base Case*
Energy purchased from grid in a year (kWh)	152,228	107,793
TOU operational cost (AU$)	49,694	25,251
Pump energy from Microgrid system	0	49.2%
Installed PV size (kW)	0	88.55
Installed WT (kW)	0	2 x 5 kW
Installed battery (kWh)	0	270
Investment total (AU$)	0	420,550
Feed-in to grid energy in a year (kWh)	0	91,103
Simple payback period (Years)	-	17.20

B. *Impact of weighting coefficients sensitivity analyses*

Considering the configuration of the microgrid system design in the Base Case, sensitivity analyses for different factors affecting the optimal configuration of the microgrid system are conducted, i.e., in Scenario 1, the weighting factors are set as λ_1=0.3, λ_2=0.3 and λ_3=0.4. The rest of the model parameters are same as the Base Case. The results obtained for this scenario are shown in Table VIII. In the Base Case, λ_1= 0.6 represents the largest weight of operating costs, and the microgrid generates most of the energy, which can make the operating cost smaller. For Scenario 1, because the differences among λ_1, λ_2 and λ_3 are smaller, the energy generation and investment costs of the microgrid are less than the Base Case. Also, the simple payback period of Scenario 1 is shorter than the Base Case.

TABLE VIII. OPTIMIZED MICROGRID DESIGN RESULTS OF BASE CASE, SCENARIO 1

	Base Case (λ_1=0.6, λ_2=0.2, λ_3=0.2)	*Scenario1 (λ_1=0.3, λ_2=0.3, λ_3=0.4)*
PV panel number (e.a.)	350	351
WT number	2 × 5kW	2 × 5kW
Battery pack number (13.5 kWh/ea.) (e.a.)	20	17
Total operational cost (Au$)	25,251	25,277.5
Save from original TOU operating cost	49.19%	49.13%
Total Investment (Au$)	420,550	389,000
Simple payback period (years)	17.20	16.13

VI. CONCLUSION

This paper proposes a microgrid optimal design method for Australian cotton farms. The methodology is to formulate the design problem as a multi-objective optimization problem, and it seeks the trade-off among multiple objectives. By using the historical data, the configuration of the renewable energy system is optimized. In addition, sensitivity analysis is explored by changing weighting factors to explain their impact on the simulation results. In the case study at Kensal Green cotton farm, the simulation results show that for the 300-hectare case study cotton farm, the operating cost can be reduced by 49% with the designed micrograds in comparison with the existing energy consumption at the farm. The simple payback period is 17-18 years. The grid-connected microgrid can feed the excess energy back into the grid to accelerate the payback period, which depends on particular FIT tariffs.

ACKNOWLEDGMENT

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