Microgrid Optimal Investment Design for Cotton Farms in Australia

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Abstract

Microgrids (MGs) and distributed renewable energy sources (RESs) have been widely used in Australian agriculture. Because of the irrigation characteristics of cotton plants and the intermittent power generation of RES, the cotton farm MG design problem has become challenging. To optimally design the renewable energy systems of cotton farm MGs, one should consider the energy cost of cotton irrigation, total investment cost and simple payback period simultaneously. This paper proposes an optimization model for the cotton farm MG design, which can identify the best RESs and energy storage configuration to meet the irrigation demand. In addition, the designed MG uses solar photovoltaic units and wind turbine generators as RES, which are further aided by battery storage to maintain energy supply at the least cost. The objectives of MG design include minimization of operation cost, investment cost and a simple payback period, which is formulated as a normalized multi-objective function.

Keywords: Cotton farm, Microgrid, Solar photovoltaic, Wind turbine, Battery storage

1 Introduction

As one of the largest exporters in rural areas, the cotton industry in Australia creates thousands of jobs every year [1]. With more than 427 thousand hectares used to plant cotton among over 1400 cotton farms, the overall revenue in the cotton industry hit a record of AU$ 2.3 billion in 2017/2018 [2]. As an industry with high energy demand, the revenue of the cotton industry is highly sensitive to energy costs. Therefore, reducing operating costs plays an important role in improving the competitiveness of Australian cotton products. This paper aims to reduce cotton farm energy costs by designing the relevant microgrid (MG) equipped with photovoltaic (PV) units, wind turbines (WT) generators, and battery storage. In order to design a more suitable MG for cotton farms, this paper takes operation cost, investment cost and simple payback period as the optimization objectives, and the constraints of the cotton farm such as seasonal irrigation demand, water reservoir, water evaporation, etc. In our preliminary study in [3], a grid-connected MG model is established for a cotton farm pumping system, and a case study was carried out to validate the proposed model. This paper is a further study of our preliminary study in [3], and the multi-objective model is normalized to stabilize the weighting factors to facilitate sensitivity analysis on various key impacting factors.

The Australian cotton farming region is rich in natural resources. The yearly average solar global horizontal irradiation is 4.86 kWh/(m^2· day), the annual average wind speed at 50 m height is 4.2 m/s, and the annual average temperature is 16.04 °C. In the literature, many studies on renewable energy generation have been proposed in agricultural areas. For example, Ref. [4] illustrates a standalone MG case study in which a hybrid power supply system was implemented in a cotton farm at Emerald, Queensland, and the optimal design of irrigation pumps in a cotton farm was achieved by the software Hybrid Optimization of Multiple Energy Resources (HOMER). In [5], an off-grid MG is investigated for a cotton farm in Australia, and HOMER was used to obtain the optimal investment results for energy cost reduction. In the case study of [6], thirteen hybrid MG projects are evaluated, and a sustainability assessment is performed in terms of the institutional, technical, environmental, and social-economic impact on rural Venezuela. Furthermore, rural MGs can be divided into two categories as per operation mode: grid-connected and off-grid MGs [7]. Several papers present an off-grid MG system based on renewable energy sources (RESs) and conventional energy sources. Ref. [8] develops a viable MG system including PV, small hydro, battery storage, and diesel generators for rural electrification in Southern Cameroons. Ref. [9] proposes a methodology based on the energy balance evaluation for a given design period to determine the size of the electrical energy storage in standalone systems. In [10], a hybrid AC/DC off-grid MG planning model is proposed to help select the best technology for each device from the candidate list.

Grid-connected MGs are often applied in rural areas. For example, a grid-connected hybrid MG with PV and wind turbine is reported in [11], which can meet the energy needs of 15 residential houses in rural communities in Chile. A grid-connected MG is recently established in a remote area of Uttar Pradesh, India, and the installed PV and battery storage can support the loads in case of insufficient power from the grid [12]. These MG design results are not directly applicable to the MG of cotton farms because of the seasonal energy demand of water pumping: water needs to be pumped only during irrigation periods, and there is not any water pumping load at non-irrigation periods. Due to this extraordinary characteristic, the scale of the designed MG needs to be appropriately decided for the cotton farm: A MG of a too large size increases the capital cost, while an MG of a too small size leads to instability issues and does not contribute significantly to reducing the operational cost. To solve the aforementioned issue, this paper will study the optimal sizing problem of a cotton farm MG tailored to the irrigation characteristics of cotton farms. Furthermore, the charge from the grid for the maximum demand will be modelled to match the actual situation of the Australian cotton industry [13]. In literature, many existing studies minimise energy costs under the time-of-use (TOU) electricity tariff and charge for the maximum demand. For example, an optimal load shifting strategy is presented in [14] to minimize the operation cost of the conveyor belt systems of a colliery, and a closed-loop optimal control technique is presented in [15] to reduce the TOU cost and maximum demand charges for a water pumping system. Moreover, a multi-agent mathematical model is presented in [16] for energy cost reduction through demand-side management. The results show that the proposed method can significantly reduce domestic energy consumption. A demand-side management model is introduced in [17] for an MG equipped with PV and battery storage to reduce residential energy costs.

However, it is difficult to shift the irrigation pump load for cotton farms, especially in the water high-demand season in which cotton needs to be irrigated continuously for at least two to three weeks, and the pumps are kept running for these weeks. To resolve this issue, the most common method is reducing the maximum demand cost by energy storage, which can be considered for power management and peak demand reduction in the grid-connected MG system. Ref. [18] shows that battery size optimization can ensure a smooth power flow in the MG and reduce peak load demand. [19] takes advantage of the particle swarm optimization method to minimize the MG's total energy and operating cost by optimally adjusting the control variables to satisfy various constraints. Ref. [20] reviews the control strategies of different types of energy storage devices and the corresponding working principles and limitations. Consequently, battery storage can be considered for power management and peak demand reduction in the grid-connected MG system in [21]. By 2025, Australia will have over 15,800 cotton farms and other agricultural consumers connected to the electricity grid [4]. Therefore, the choice of electricity price plays a critical role in shortening the investment payback period for a grid-connected MG. An electricity cost reduction demand side management model based on MG supply chain and TOU tariff is proposed by [22], where end-users are equipped with energy storage. A model is developed in [23] to evaluate the effectiveness of demand response strategies using TOU tariff combined with regional thermal control. Ref. [24] proposes a model to reduce residential electricity demand by considering price elasticity and solar PV power, where Monte Carlo simulation for power flow analysis in low-voltage distribution networks was applied. However, these models have not considered the situation in that power utility purchases energy from MGs. A feed-in tariff (FIT) is one of the incentive schemes envisaged by the Australian government for RES installation. Nevertheless, Australia's Small-scale Renewable Energy Scheme (SRES) limits PV installation to no more than 100 kW and wind systems to a capacity of no more than 10 kW. In this study, the FIT scheme is considered in the objective function to reduce operational costs. Meanwhile, FIT can shorten the payback period for the grid-connected MG during off-irrigation seasons.

For the MG optimization modelling, Ref. [25] develops a model for energy storage management in the distribution network, which can reduce operational costs and improve voltage stability. A stochastic techno-economic MG model is proposed in [26] for a rural MG to assess technical design decisions and financial conditions. Ref. [27] models a hybrid energy system and obtains the optimal configuration with the help of life cycle cost minimization. Furthermore, Ref. [28] establishes a pump storage model based on the hybrid solar-wind system to do the techno-economic optimization for a rural MG.

The aforementioned literature paid attention to the RES integration and management method for rural MGs, but none of them discussed the case that both seasonal pumping loads and intermittent renewable sources appear simultaneously in the same MG. Motivated by the problems mentioned above, this paper presents a new cotton farm MG design method, where the seasonal water pumping demand and intermittent PV and wind power generation are considered. The proposed cotton farm MG is structured with PV, WT, and battery storage. In addition, the proposed MG is assumed to be connected to the power grid to ensure enough power supply for irrigation. PV and wind turbines are energy generators in this MG, and the battery is essential for energy demand management under time-varying FIT. However, the corresponding investment cost is expensive and should not be ignored. Considering all these factors, this study proposes a multi-objective optimization problem to minimize MG's operational cost, investment cost, and payback period. A grid-connected MG cotton farm case study is simulated to validate the design results. Furthermore, the impact of numerical research results in different situations is considered from the perspective of cotton farm stakeholders.

The main contributions of this study are given below.

(1) A multi-objective MG optimal design model is proposed for cotton farms that are able to handle seasonal water pumping loads under various weather conditions, Australia's renewable energy policies, electricity prices, and FITs.
(2) The relationships among pump energy consumption, water storage and irrigation water demand during cotton planting cycles are modelled in the MG design.
(3) Using an actual cotton farm for the case study, the impact of grid electricity tariff and FIT on the initial investment and routine operational costs of the MG is discussed. The case study also indicates that the capacity of the WT should be limited by 10 kW in order to be economically viable.

The rest part of this paper is organized as follows. Section 2 introduces the RES components of MG for Australian cotton farms and establishes design objectives and constraints of RESs and cotton irrigation. Details of a case study are given in Section 3. In Section 4, the Yalmip toolbox [29] is used together with MATLAB fmincon optimization tools to solve the normalized multi-objective MG optimization problem. The numerical results and the economic impact are also discussed in this section. Section 5 summarizes the paper and draws conclusions.

2 Optimal design of cotton farm microgrid

In this section, the energy models of key MG components are briefly reviewed.

Fig. 1 shows the power balance within the MG. The power of water pumps is supplied by the grid, battery storage, PV and WT. In Fig. 1, notation $P_g(t)$ represents the amount of power purchased from the

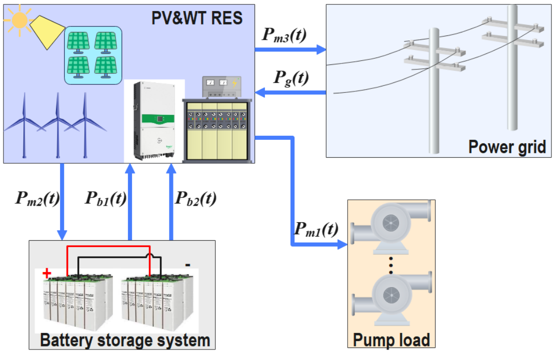

Figure 1: Grid-connected microgrid

grid at time t, i.e., the t^{th} hour since the time is sampled each hour; $P_{m1}(t)$ is the power flowing from the PV and WT to the water pump at time t; $P_{b1}(t)$ denotes the power discharged by the battery at time t to supply the load. Excess power from the PV and WT can be sold to the grid or charged to the battery storage. The notation $P_{m2}(t)$ denotes the power flowing from the PV and WT to the battery storage at time t, and $P_{m3}(t)$ denotes the excess power from the PV and WT to the grid. When water pumps are not switched on, the battery also can sell power (denoted by $P_{b2}(t)$) to the grid to make a profit. The power flows in this diagram are functions of time t. Hourly samples are taken in the models, and each year consists of 8760 hours. The water irrigation system of the cotton farm is illustrated in Fig. 2. To meet the water irrigation demand, pumps lift water from the bore or river through ditches to turkey nest dams. Then the water will flow from the dams to cotton farms by gravity. In Fig. 2, notation $P_{(pump,k)}(t)$ represents the nominal power of the k^{th} pump at time t; and $F_0(t)$ denotes the water flow rate from the dam to the cotton field at time t.

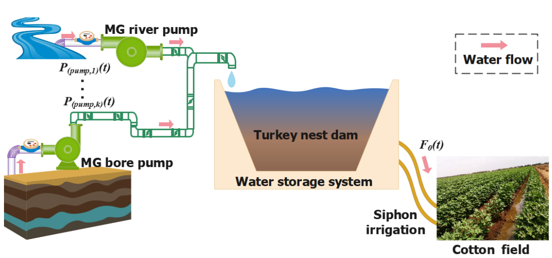

Figure 2: Cotton farm irrigation model

A *Objective functions*

From the system configuration in Fig. 1, the following equations can express the MG design objective functions.

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

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

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

In (1), f_{op} represents the annual operational cost of the MG, $\beta_1(t)$ denotes the grid electricity price at time t, $T = 8760$ is the number of hours in a year, $\beta_2(t)$ is the FIT rate at time t (AU$ /kWh), and C_0 represents the annual maintenance cost of the MG. Eq. (2) calculates the capital investment cost of the MG, where there are L, M, and N different types of PV panels, WTs and battery storage, respectively. Notations k_{1p}, m_{1p}, and x_{1p} are the unit price (in AU$ /kW), rated power (in kW), and the total number of installed panels of the p^{th} type of PV, respectively. Symbols k_{2q}, m_{2q}, and x_{2q} represent the unit price (in AU$ /kW), rated power (in kW), and the number of installed units of the q^{th} type of WT, respectively. Similarly, k_{3r}, m_{3r}, and x_{3r} are the unit price (in AU$ /kWh), single unit battery capacity (in kWh), and the total number of installed battery units of the r^{th} type of battery storage unit. Since x_{1p}, x_{2q} and x_{3r} represent the MG equipment quantity, they need to satisfy integer constraints. Eq. (3) gives the simple payback period ($f_{payback}$), in which C_{org} denotes the baseline annual operation cost before the installation of the MG. The multi-objective functions in (1-3) can be transformed into a single objective function in (4) by weighting factors λ_1, λ_2, and λ_3. However, these objective functions have different magnitudes, so it is convenient to normalize the objectives to obtain an optimal solution consistent with the weighting factor specified by the decision-maker. Therefore, a weighted summation normalization method is adopted to (8) - (13). These objectives are normalized by using the true variation intervals of the objective functions on the Pareto optimal set, and f_{op}^{norm}, f_{invest}^{norm} and $f_{payback}^{norm}$ represent the normalized f_{op}, f_{invest} and $f_{payback}$, respectively;

f_{op}^{min}, f_{invest}^{min} and $f_{payback}^{min}$ are the Utopia points satisfying $f_{op}^{min} = f_{invest}^{min} = f_{payback}^{min} = 0$; and f_{op}^{max}, f_{invest}^{max} and $f_{payback}^{max}$ are the Nadir points of the individual objectives, in which f_{op}^{max} is based on the maximum energy to be purchased to satisfy the irrigation demand; f_{invest}^{max} and $f_{payback}^{max}$ are based on the farm owner maximum investment and payback willingness. Yalmip toolbox is used to solve this optimization problem. The weighting factors λ_1, λ_2, and λ_3 satisfy constraints in (8), Eqs. (9) - (11) are the constraints to ensure all the objective functions satisfy the farm owner's requirement.

$$min(\lambda_1 \cdot f_{op}^{norm} + \lambda_2 \cdot f_{invest}^{norm} + \lambda_3 \cdot f_{payback}^{norm}) \quad (4)$$

$$f_{op}^{norm} = \frac{f_{op} - f_{op}^{min}}{f_{op}^{max} - f_{op}^{min}} \quad (5)$$

$$f_{invest}^{norm} = \frac{f_{invest} - f_{invest}^{min}}{f_{invest}^{max} - f_{invest}^{min}} \quad (6)$$

$$f_{payback}^{norm} = \frac{f_{payback} - f_{payback}^{min}}{f_{payback}^{max} - f_{payback}^{min}} \quad (7)$$

$$\lambda_1 + \lambda_2 + \lambda_3 = 1 \quad (8)$$

$$f_{op}^{min} \leqslant f_{op}^{norm} \leqslant f_{op}^{max} \quad (9)$$

$$f_{invest}^{min} \leqslant f_{invest}^{norm} \leqslant f_{invest}^{max} \quad (10)$$

$$f_{payback}^{min} \leqslant f_{payback}^{norm} \leqslant f_{payback}^{max} \quad (11)$$

B *System constraints*

According to the power flow in Fig. 1, Eq. (12) shows that the pump load is supplied by PV, battery storage and utility, while (13) shows the power balance from PV and WT:

$$P_p(t) = P_{m1}(t) + P_{b1}(t) + P_g(t) \quad (12)$$

$$P_{m1}(t)+P_{m2}(t)+P_{m3}(t) = P_{PV}(t)+P_{WT}(t) \quad (13)$$

where:

- $P_p(t)$ is the total power of water pumps at time t;
- $P_{PV}(t)$ is the power from the PV at time t; and
- $P_{WT}(t)$ is power from the WT at time t.

C *Battery storage constraints*

The state-of-charge (SOC) of the battery storage satisfies the following relation (14) derived from energy balance and is also subject to the boundary constraints in (15).

$$S_{SOC}(t) = S_{SOC}(t-1) + \frac{P_{m2}(t) - P_{b1}(t) - P_{b2}(t)}{\sum_{r=1}^{N} m_{3r} \cdot x_{3r}} \quad (14)$$

$$S_{soc}^{min} \leqslant S_{SOC}(t) \leqslant S_{soc}^{max} \quad (15)$$

where:

- S_{soc} (t) is the SOC at time t;
- S_{soc}^{min} is the minimum bound of SOC and is chosen as 20% in the case study; and
- S_{soc}^{max} is the maximum bound of SOC and is taken as 90% in the case study.

D *Grid feed-in constraints*

When the MG is in grid-connected mode, the feed-in power satisfies the following constraints in (16)

$$P_{m3}(t) + P_{b2}(t) \leqslant Q_1, \forall t \quad (16)$$

where Q_1 denotes the allowed maximum power for grid feed-in.

E *PV constraints*

The power generated from the PV satisfies the following constraints:

$$P_{PV}(t) = \sum_{p=1}^{L} x_{1p} \cdot P_{PV,p}^{0}(t) \quad (17)$$

$$P_{PV,p}^{0}(t) \leqslant m_{1p}\ (kW) \quad (18)$$

where $P_{PV,p}^{0}(t)$ denotes the PV power generation per panel at time t.

F *Wind generation constraints*

Power generated by the WTs satisfies the following relations:

$$P_{WT}(t) = \sum_{q=1}^{M} x_{2q} \cdot P_{WT,q}^{0}(t) \quad (19)$$

$$P_{WT,q}^{0}(t) \leqslant m_{2q}\ (kW) \quad (20)$$

$$\sum_{q=1}^{M} m_{2q} \cdot x_{2q} \leqslant 10 \; (kW) \tag{21}$$

where $P^0_{WT,q}(t)$ is the power from a type q WT at time t. Eq. (21) represents that the total WT capacity installed should be less than 10 kW, which is the maximum power of any small-scale wind system allowed by the Australian government [30].

G *Water storage constraints*

Assume that variable speed drives to control the water pumps, then the water storage reservoir satisfies the following constraints in (22) – (27):

$$S_{min} \leqslant S(t) \leqslant S_{max} \tag{22}$$

$$S(t) = S(t-1) + \sum_{k=1}^{n} P_{pump,k}(t) \cdot M_k - F_0(t) - V_L(t) + R_0(t) \tag{23}$$

$$V_L(t) = \frac{(1-\delta) \cdot D \cdot A}{T} \tag{24}$$

$$P_p(t) = \sum_{k=0}^{n} P_{pump,k}(t) \tag{25}$$

$$0 \leqslant P_{pump,k}(t) \leqslant P^{rated}_{pump,k} \tag{26}$$

$$F_0(t) = \frac{D \cdot A}{T_1} \tag{27}$$

where:

- S_{min} is the minimum amount of water in the reservoir (ML);
- S_{max} is the maximum allowed water volume of the reservoir (ML);
- $S(t)$ is the amount of water volume in the reservoir at the t^{th} hour (ML);
- $P^{rated}_{pump,k}$ is the rated power of the k^{th} pump (kW);
- M_k is the average amount of water that each kW of input power at the k^{th} pump can raise from the water source (e.g. river) to the reservoir (in ML/kW). That is, this $P_{pump,k}(t) \cdot M_k$ mega litre of water will be pumped from the water source to the reservoir once the k^{th} pump is run at its rated power, and this value depends on the water head from the water source to the reservoir;
- D is the annual water demand for cotton irrigation (ML/Ha);
- A is the size of the irrigated cotton farm (m^2);
- T_1 is the total irrigation hours in a year (Hours);
- $V_L(t)$ is the loss of water from evaporation and seepage at time t, and $V_L(t)$ is calculated by Eq. (24);
- δ is the on-farm water use efficiency during the irrigation period [31]; δ=80% in this study [32];
- n is the total number of pumps; and
- $R_0(t)$ is average rainfall at the t^{th} hour (ML). As a source of supplementary water, the ratio of annual rainfall to irrigation water can be obtained from CRDC publications. For example, the rainfall in 2016 was approximately 33% of total irrigation [33].

3 Case study

A *Basic information*

In Australia, the average amount of requested water of a cotton field is 6.8×10^{-4} megalitres (ML) per square meter, and the average area of a cotton farm is 3.05×10^{6} square meters [2] in the last decades. The cotton farm considered in this case study is in the southern part of Gunnedah, New South Wales, and its irrigation area in 2016 was 3×10^{6} m^2 [34, 35]. There are three sub-bore pumps in this farm, which are powered by electricity, two with the rated power of 75 kW, and one with 37 kW [34]. The farm reservoir has a maximum water storage capacity of 1500 ML. The cotton farm parameters in this study are shown in Table 1. The water demand data are taken from the average water usage of cotton farms in the Murray-Darling Basin area in 2016, which includes the rainfall as a supplementary water source accounting for about 33% [33] of the total irrigation demand. The historical solar radiation data for the Gunnedah area in 2016 can be found in [36]. Currently, no MG is installed in the farm, and the corresponding baseline annual energy consumption and total cost of the three water pumps are shown in Table 2, where Ergon Energy small-business flat rate Tariff 20 is applied. Table 3 calculates the corresponding operational costs under a different tariff, i.e., the Ergon Energy rural TOU Tariff 65. The FIT has two different schemes: a time-varying

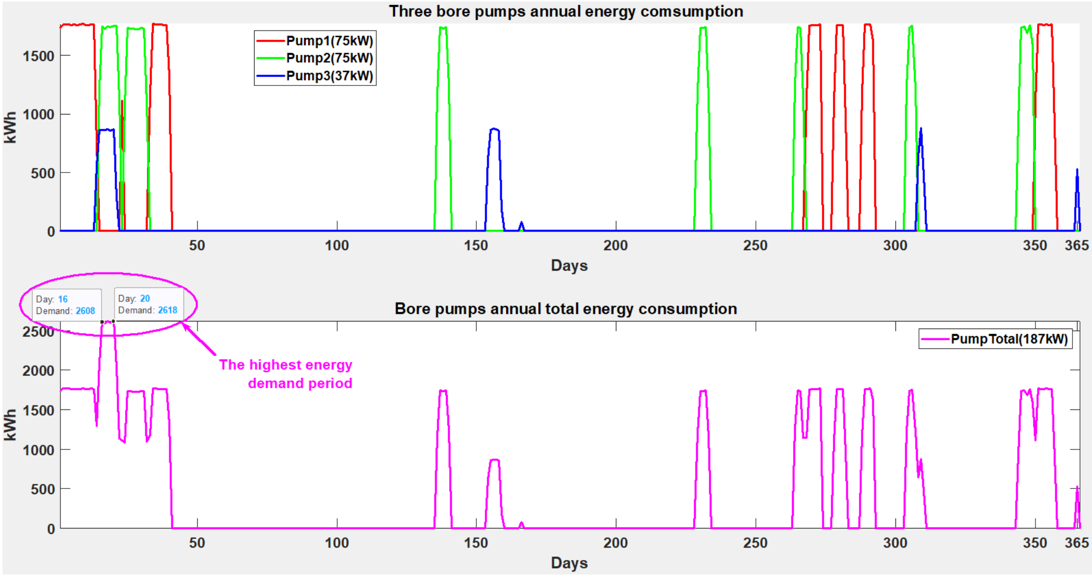

Figure 3: Load profile of the cotton farm bore pumps

and a flat one[1], see Table 4. The energy consumption of three pumps in a year is shown in Fig. 3.

Table 1: System parameters of the studied cotton farm

Pump 1 energy consumption	75,812 kWh
Pump 2 energy consumption	63,551 kWh
Pump 3 energy consumption	12,865 kWh
Farm size	3.05×10^6 m^2
Average pumping head	25 m
Average energy consumption of Lifting 1 ML water to 1-metre	4.55 kWh/(ML· m)
Average irrigation demand	6.5×10^{-4} ML/m^2
Maximum allowed water usage	1,500 ML/year
Reservoir size	1,200 ML
Rainfall	33.33%
Water-use efficiency	80%
Average wind speed at a height of 10-15m	3.42 m/s
Daily average solar irradiation in 2016	5.02 kWh/m^2

Table 2: Cost breakdown of irrigation pumps and energy consumption with a flat-rate tariff (AU$ 0.29086/kWh)

Equipment	Energy use in 2016 (kWh)	Cost (AU$)
Pump 1	75,812	22,050
Pump 2	63,551	18,484
Pump 3	12,865	3,742
Annual cost	AU$ 44,277/year	

[1]https://www.esc.vic.gov.au/electricity-and-gas/electricity-and-gas-tariffs-and-benchmarks/minimum-feed-tariff#tabs-container1

Table 3: Initial operational cost with TOU tariff (Peak Price: AU$ 0.405/kWh, Off-Peak Price: AU$ 0.223/kWh)

Equipment	Peak Cost	Off-Peak Cost	Total Cost
Pump 1	17,202	7,472	24,673
Pump 2	14,727	6,094	20,821
Pump 3	2,947	1,252	4,200
Annual cost		AU$ 49,694/year	

Table 4: FIT scheme

Name	Time	Price (AU$ /kWh)
Peak	3 pm-7 pm	0.13730
Off-peak	Remaining hours	0.05796
Flat rate	Any time	0.07842

B *Microgrid components and costs*

Table 5 shows the specifications of the PV panel considered in the case study. Table 6 lists information regarding three different sizes of WTs on the Australian market, and Fig. 4 displays the average annual energy generation of the three types of WTs. Table 7 shows popular battery storage products from Tesla® and the corresponding data [37].

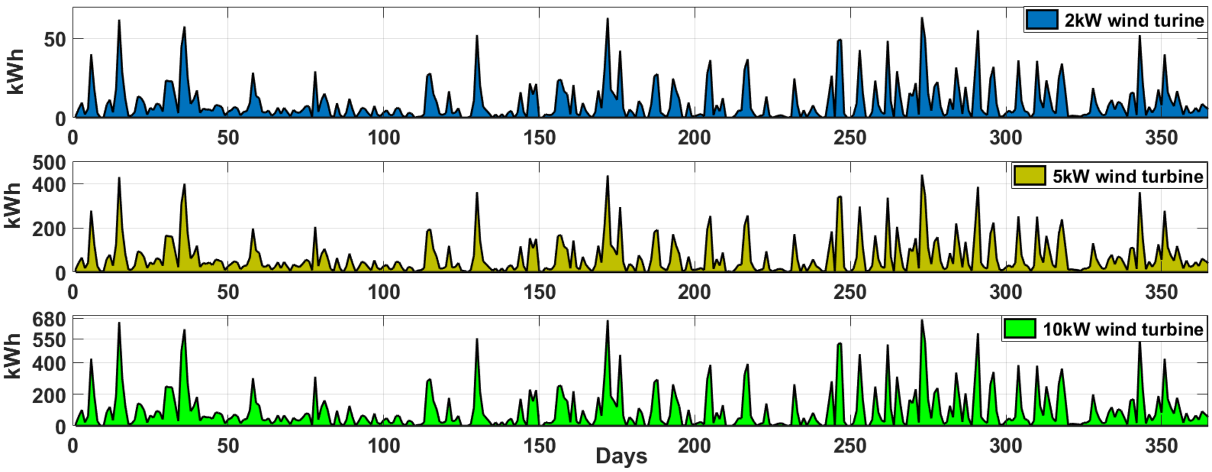

Figure 4: Daily generated energy of three types of WTs in the cotton farm in 2016

Table 5: Specifications of PV panel

Smart Panel®	60-cell SPV310-60MMJ PV
Panel power	0.253 kW
Performance ratio	0.75
Panel efficiency	18.9%
Panel dimensions	1650 × 992 × 40 mm
Maintenance cost	AU$ 5/year
Unit price	AU$ 250 (Including inverter)
Warranty	15 years

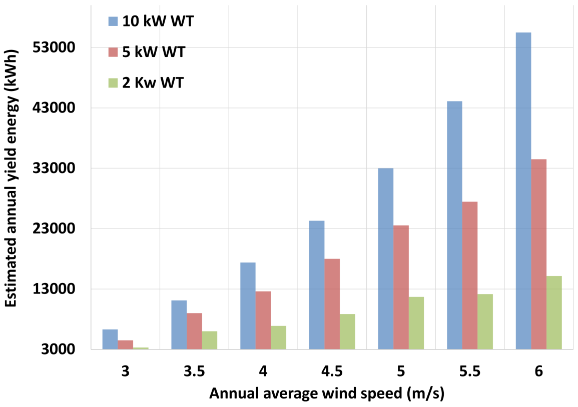

Figure 5: Annual energy yield of three types of WTs

4 Results and discussion

This case study is aimed at validating the proposed MG model. We consider deterministic algorithms for effectively leveraging historical data to optimize the configuration of RESs, utilizing the inherent advantage of high efficiency. Consequently, a deterministic algorithm is employed in this study. Note that the deterministic algorithm SQP is very sensitive when constraints are expressed as equalities. Therefore, we have modified the related constraints in the coding, replacing the equalities $(A = B)$ with inequalities $(-\varepsilon < A - B < \varepsilon)$, where ε is a near-zero positive number. The results are discussed in the next three subsections below. The multi-objective optimization model is normalized, and the Yalmip optimization solver is applied together with the MATLAB fmincon toolbox to obtain the results. Table 8 shows the Baseline Case conditions of the studied cotton farm. The historical data of the water pump energy consumption in 2016 is used in the case study as a baseline for comparison. Fig. 5 show the annual power generation of 2kW, 5kW and 10kW wind generators at the height of 10-15 meters, where the annual average wind speed is 3.4 m/s. Fig. 6 shows the energy generated by a 1kW PV panel in the Gunnedah area in 2016.

A *Optimal microgrid design solution*

Now consider the MG optimal design model in Section 3. The PV panel parameters are given in Table 5; the rated power of each PV panel is 253 W. The 2 kW, 5 kW and 10 kW WTs from Table 6 are available choices. The lithium-ion battery pack in Table 7 is used for the battery storage system, and each pack is rated as 13.5 kWh. Because the installation of the WT must comply with the Australian small renewable energy scheme, the total installed WT cannot be greater than 10 kW.

Fig. 7 shows the changes of dam water volume. This curve is drawn based on the power consumption of pumps during the watering period in the cotton farm, rainfall and water loss. The total amount of water pumped, irrigation water usage, supplementary rainfall, and water loss must meet the maximum

Table 6: WT brand and price

Rated power (kW)	2	5	10
Cut-in speed (m/s)	3	2.5	3
Cut-out speed (m/s)	25	25	25
Rated wind speed (m/s)	9	10	10
Blade diameter (meter)	3.8	6.4	8
Generator efficiency	80%	80%	85%
Design life (years)	20	20	20
Minimum Tower height (meter)	8	10	12
Maintenance cost (AU$ /Year)	800	1000	1500
Unit price (including installation cost)	AU$ 10 K/unit	AU$ 60 K/unit	AU$ 100 K/unit

Table 7: Battery storage brand and price

Tesla ® Powerwall 2 battery storage	
Usable capacity	13.5 kWh
Max charge and discharge	6.99 kW
Round trip efficiency	90%
Dimensions (L x W x H)	1150 × 755 × 155 mm
Unit price	AU$ 10,600/unit
Depth of Discharge (DOD)	100%
Cycle life	3200
Warranty	10 years

Table 8: Baseline conditions of the case study

Minimum operation cost	0 AU$/year
Minimum investment cost	0 AU$
Minimum simple payback period	0 year
Maximum operation cost	50,000 AU$/year
Maximum investment cost	300,000 AU$
Maximum simple payback period	10 year
The total energy use of 3 pumps	152,228 kWh
Operation cost @ TOU tariff	49,694 AU$/year

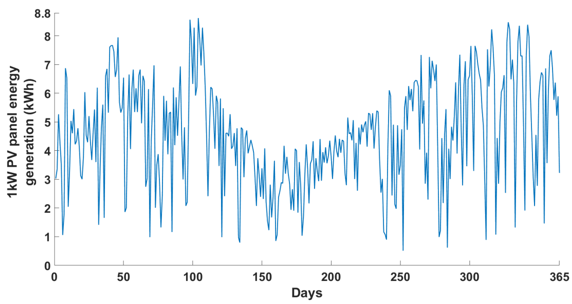

Figure 6: Daily generated energy of a 1kW PV panel at the farm location in 2016

Table 9: Baseline Case vs. Optimal Case results

Energy purchased from grid in a year	152,228 kWh	98,937 kWh
TOU operation cost	AU$ 49,694	AU$ 21,612
Installed PV size	0	61.2 kW
Installed PV Qty.	0	242
Installed WT Qty.	0	10 kW × 1
Installed battery	0	135 kWh
Installed battery Qty.	0	10
Battery charge cycles	0	288
Investment cost	0	AU$ 266,500
Feed-in energy in a year	0	89,613 kWh
Simple payback period	0	9.49 yrs

dam capacity and irrigation demand. It can be seen from Fig. 7 that when the irrigation demand is 6.5 x 10^{-4}ML/m^2, the minimum water volume is 425.6 ML during the irrigation time, the maximum water volume of the dam reaches 532.7 ML, and the remaining water after irrigation is 518.4 ML. The amount of water in the dam increases after the start of the pumps and decreases during irrigation. The total amount of water pumped plus rainfall supplementation can satisfy the total amount of water demand. Meanwhile, the total amount of pumped water is 1,338 ML, which is also within the limit of 1,500 ML for maximum water usage permission. Therefore, the irrigation and water pumping model can be verified to suit the irrigation system, and the total energy consumption of the pumps also satisfies the irrigation demand.

In this study, we define the Baseline Case as the current energy system at the cotton farm which does not have RESs, and the required energy is supplied by the power grid only. Table 9 gives the comparison result between the Baseline Case and Optimal Case in terms of the MG components, investment cost, operation cost, and simple payback period. Optimal Case (λ_1 = 0.6, λ_2 = 0.2 and λ_3 = 0.2) installed an MG and adopted TOU tariff and time-varying FIT in (4) to optimize the configuration. In addition, Optimal Case analyzes the importance of battery storage in the MG and how the battery systems store excess energy and sell it back to the grid to maximize the benefit. Fig. 8 shows that RES generates electricity to supply the water pumps, but it does not have sufficient power to meet the pump load. Consequently, grid power is supplied to meet the shortage. Meanwhile, the MG system can sell excess power to the grid during off-peak irrigation since battery storage is an essential part of this study. Battery storage can support water pumping during the irrigation period and transfer the energy back to the grid during the off-peak period of irrigation. In the Optimal Case, it can be determined that the battery undergoes 288 charge cycles this year with a 100%

DOD., the charge cycles of the battery are 288/3200 this year, which is 9% of the entire cycle life (3200) according to Table 7, the charge cycles of the battery are 288/3200 this year, which is 9% of the entire cycle life. Therefore, within the simple payback period of 9.49 years, there is no need to consider the cost of reinvesting in the battery. Furthermore, Fig. 9 shows the charging and discharging status of the battery over the year. The red bar is the excess energy charged to the battery storage from the MG. The magenta bars show that the battery storage provides energy to the pumps. During non-irrigation periods, the MG charges the battery storage and sells energy back to the grid when the PV stops generating power. Therefore, there are more benefits to choosing a time-varying FIT than using a flat-rate FIT. The brown bars in Fig. 9 show the scale of the battery selling energy to the grid during the year.

B *Sensitivity analyses*

In this section, we conduct a sensitivity analysis and discuss the impact of different factors on the designed MG system.

B.1 Sensitivity 1: Impact of weighting coefficients

Here two scenarios are considered; in the first scenario, i.e., Scenario 1, choose the weighting factors to be $\lambda_1 = 0.3$, $\lambda_2 = 0.1$ and $\lambda_3 = 0.6$. In Scenario 2, choose the weighting factors to be $\lambda_1 = 0.2$, $\lambda_2 = 0.6$ and $\lambda_3 = 0.2$. The other system parameters remain intact as in the previous Optimal Case. The obtained results are shown in Table 10. By comparing the three results, $\lambda_1 = 0.6$ in the Optimal Case has the highest preference for operation cost minimization, and the MG supplies the majority of the required energy, implying the smallest operation cost. Scenario 1 has $\lambda_3 = 0.6$, i.e., the payback period has the highest weight, thus the obtained simple payback period is shorter than the Optimal Case. In Scenario 2, the weighting factor for investment is $\lambda_2 = 0.6$; therefore, the optimization results show that the investment cost is lower, but the operation cost is higher than the Baseline Case and Scenario 1. Also, the simple payback period of Scenario 2 is the shortest in the three simulation cases. Fig. 10 illustrates the comparison of Scenario 1 and Scenario 2 with the Optimal Case. Fig. 11 shows the percentage of the MG components to meet the pumping load.

B.2 Sensitivity 2: Impact of different tariffs

Tariff selection is also a critical parameter affecting operating costs and simple payback periods. In this case, two types of tariff and two types of FIT based on the tariffs shown in Table 2, Table 3 and Table 4 are adopted to see their effect on the MG configuration and simple payback period. Table 11 uses Baseline Case as a benchmark and lists the results of four tariff combinations. The operating cost of the case without MG is AU$ 49,694 under the TOU tariff and AU$ 44,277 under the flat rate tariff. It can be found from Table 11 that the shortest simple payback period is 8.15 years, and the smallest investment is AU$ 183,300 among the four tariff options. Table 11 also illustrates that if the operating cost is higher, the investment cost will be higher, but the simple payback period is shorter. If the operating cost is lower, the investment cost is relatively minor, but the simple payback period will be longer.

B.3 Sensitivity 3: Impact of wind speed and solar irradiation on the optimization microgrid system

WTs are one of the RESs mentioned in the previous section. The power generation of WTs changes significantly with wind speed. In the previous case study, the average wind speed of the case study cotton farm in 2016 was 3.42 m/s. The wind speed is scaled up to an average speed of 5 m/s to check the sensitivity of wind speed to the results, and all the parameters are kept the same as the Optimal Case. The relevant results are listed in the first column of Table 12. Under the condition of higher wind speed, this system has higher power generation, more investment cost and just 10 years payback period. The number of solar panels is increased from 242 units to 348 units, and the number of battery storage is increased from 10 to 20 sets. In addition, the number of battery charge cycles is 311, which is 9.7% of the entire battery cycle life, and there is no need to replace the battery in this case. Thus, the total investment cost is increased by AU$ 132,500. Moreover, the annual power generation is increased by 90,446 kWh. Compared with the Optimal Case, the operating cost is reduced from AU$ 21,612/year to AU$ 9,794/year, i.e., 54.7% reduction, and the corresponding simple payback period is increased by six more months. Now consider the impact of solar insolation, and it is assumed that the daily average global exposure is increased from 5.02

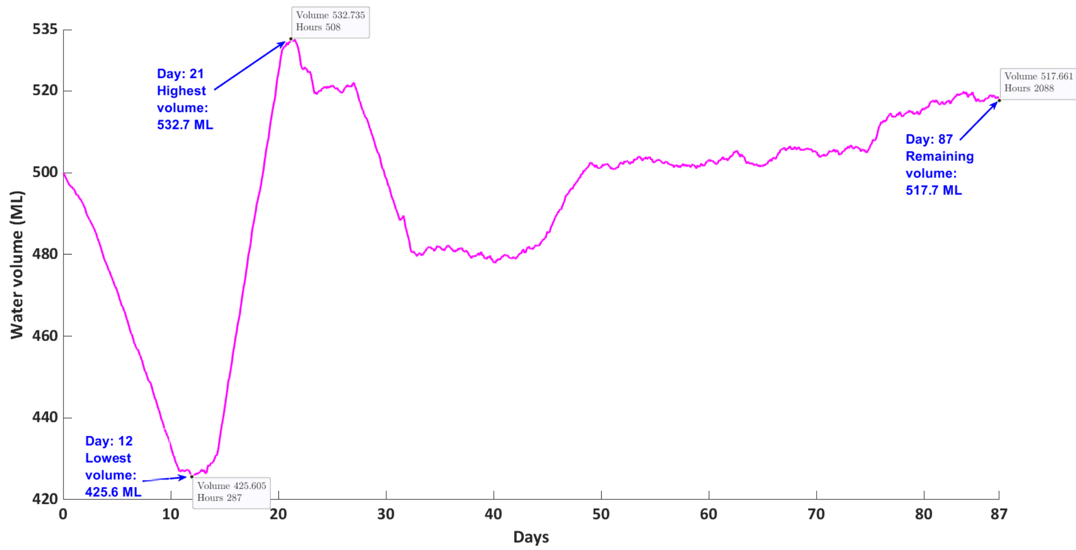

Figure 7: Water volume curve of the dam on the cotton farm

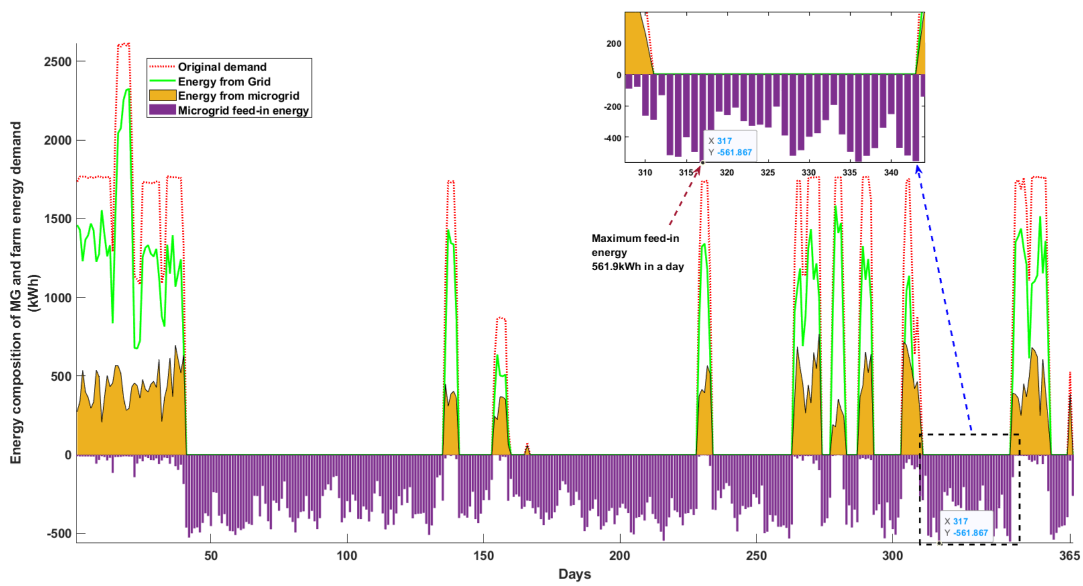

Figure 8: Microgrid energy distribution in Optimal Case

Table 10: Optimized microgrid design results of Optimal Case, Scenario 1 and Scenario 2

Item	Optimal Case	Scenario 1	Scenario 2
PV panel Qty.	242	210	206
WT 2kW Qty.	0	0	0
WT 5kW Qty.	0	0	0
WT 10kW Qty.	1	1	1
Battery pack Qty.	10	4	3
Total operational cost in the year (AU$)	21,611.8	24,284.8	27,751.4
Operation cost saving from Baseline Case	56.51%	51.13%	44.16%
Total investment (AU$)	266,500	194,900	183,300
Payback period (years)	9.49	7.7	8.35

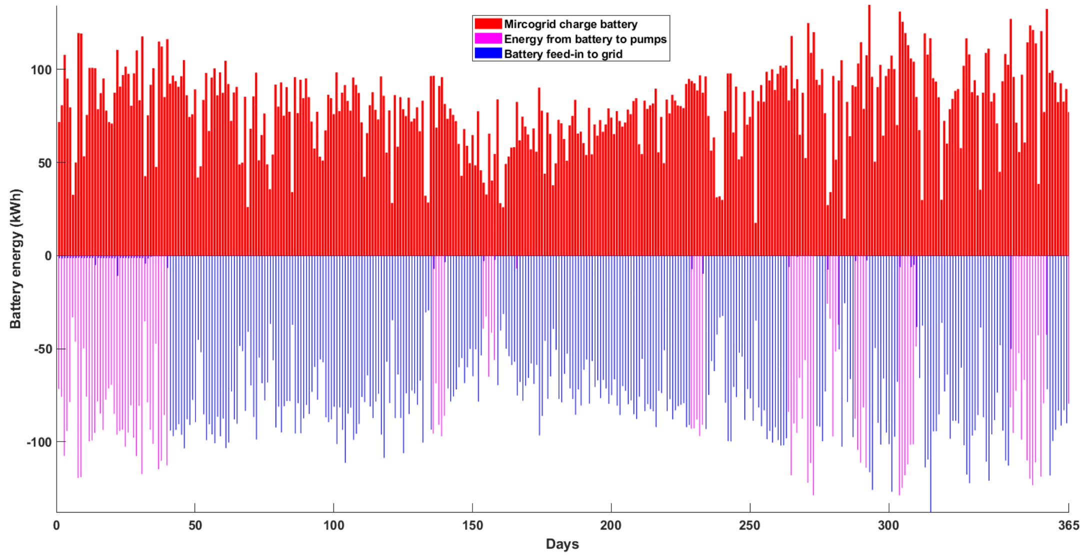

Figure 9: Battery storage charging/discharging status

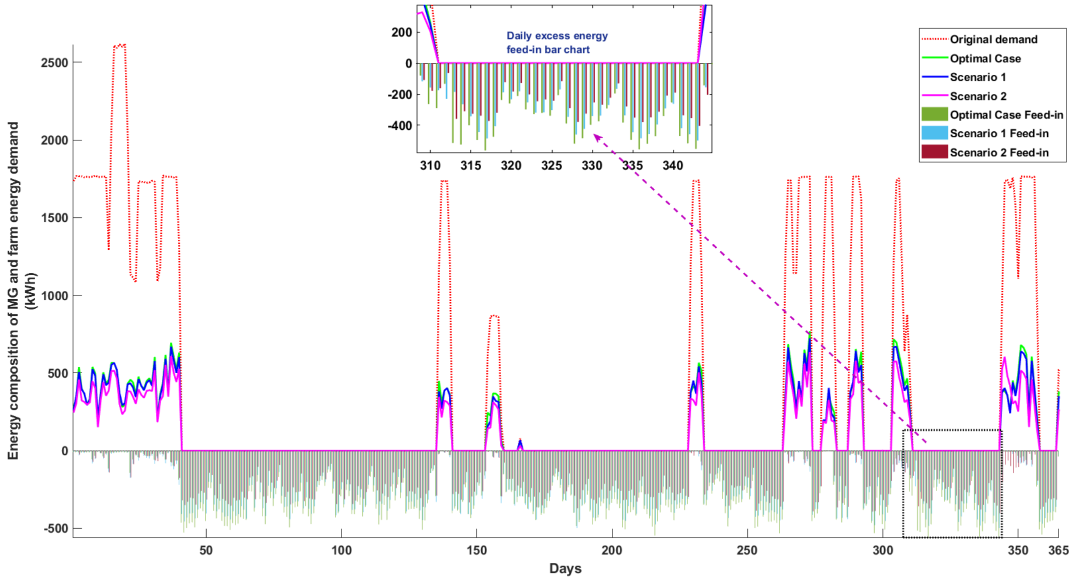

Figure 10: Microgrid power generation and the load demand

Table 11: Optimization results for different tariff combinations

	Time-varying FIT based on TOU Tariff	Flat-rate FIT based on TOU Tariff	Time-varying FIT based on Flat-rate Tariff	Flat-rate FIT based on Flat-rate Tariff
Number of PV panels	242	238	234	206
WT (kW)	1 × 10 kW	1 × 10 kW	1 × 10 kW	1 × 10 kW
Battery storage numbers	10	6	7	3
Under microgrid operating cost (AU$ /year)	21,612	22,319	20,532	24,422
Investment total (AU$)	266,500	223,100	232,700	183,300
Simple payback period (years)	9.49	8.15	9.80	9.23

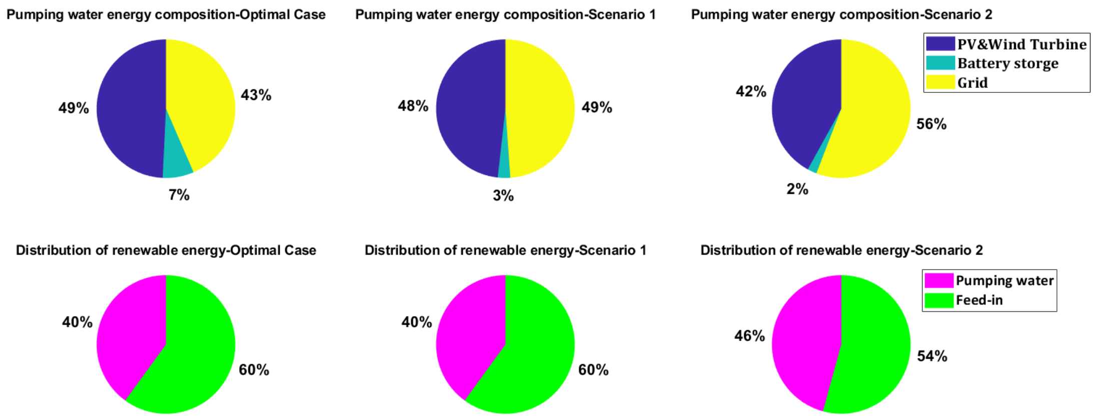

Figure 11: The energy contribution percentage of the microgrid Components

Table 12: The results with increased average wind speed and daily solar global exposure for Optimal Case

	Annual average wind speed increased to 5 m/s	Annual daily average global exposure increased to 6 kWh/m^2
PV panels number	348	245
WT configuration	1X10 kW	1X10 kW
Battery numbers	20	14
Battery charge cycles	311	273
Microgrid annual generation (kWh)	305,506.93	243,451.65
Operating cost under TOU tariff and time-varying FIT (AU$)	9,794	17,902.42
Operating cost reduction from Baseline under TOU	80.29%	63.97%
Total investment (AU$)	399,000	309,650
Simple payback period (years)	10	9.74

kWh/m^2 to 6.0 kWh/m^2 while the wind speed and all the other conditions remain the same as Optimal Case. The corresponding MG design results are listed in the second column of Table 12. Compared with the Optimal Case, the number of solar panels is increased by 3, and the number of batter units is increased by 4. Therefore, the total investment is decreased by AU$ 43,150. The annual power generation is increased by 28,390.61 kWh; thus, the operating cost is reduced by AU$ 3,709.6, and the payback period is 3 months longer. The number of battery charge cycles is 273, which is 8.5% of the entire battery cycle life; thus, no battery replacement cost is to be considered.

B.4 Sensitivity 4: Increased irrigation demand

Note that 33.33% of irrigation demand comes from rainfall from Table 1. However, the phenomenon of global warming is developing rapidly, affecting the amount of rainfall and temperature of the world every year. We use a sensitivity analysis to model the impact of a reduction in rainfall from 33.33% to 15% due to climate change. Compared with the Baseline, when the rainfall is reduced by 18.33% and other conditions remain unchanged, it is equivalent to the need for pumping an additional 363.39 ML of water. Based on the relationship between water pumping and energy usage in Table 1, an additional 41,335 kWh of energy is required, which means the total energy demand is increased by 27.15%. Therefore, the total operational cost of the Baseline is changed to AU$

Table 13: Results comparison of Increased Irrigation Demand Case between two MG configurations

	Same configuration as Optimal Case	New optimal configuration for increased water demand
Energy purchased from grid in a year	112,267 kWh	104,384 kWh
TOU operation cost	AU$ 25,544	AU$ 24,362
Installed PV size	61.2 kW	79.4 kW
Installed PV Qty.	242	314
Installed WT Qty.	10 kW × 1	0
Installed battery	135 kWh	135 kWh
Installed battery Qty.	10	9
Battery charge cycles	296	272
Investment cost	AU$ 266,500	AU$ 273,900
Feed-in energy in a year	86,496 kWh	88,530 kWh
Simple payback period	7.08	7.05 years

63,186. Table 13 shows the optimization results of the increased irrigation demand case with two different MG configurations. In the same configuration as the Optimal Case, more energy is bought from the grid, and the operational cost is increased by AU$ 3,932; 8 more battery cycles are used. However, there is AU$37,642 saving, compared with the new Baseline operational cost; hence, the simple payback period is 7.08 years. On the other hand, the proposed model is used to re-configure the MG based on the water demand changes. To compare with the Optimal Case, the PV size is increased by 18.2 kW, and the number of batteries is reduced by 1 set; the investment cost is increased by AU$ 2,034, and the simple payback period is decreased by 2.44 years.

5 Conclusion

This paper presents an MG optimal design model for Australian cotton farms. This method formulates the design as a multi-objective optimization problem, which is subject to various constraints on PV, WT, battery storage, and cotton irrigation demand. In the 3 x 10^6 m^2 cotton farm case study, a number of different MG scenarios are presented to illustrate the effectiveness of the proposed model. Sensitivity analysis is also conducted to discuss the impact of weighting factors, battery storage and tariff options on the investment, operation cost and payback period. Compared with the existing energy consumption of this cotton farm, the designed MGs can reduce the operating costs by 44.16% to 56.51%, the simple payback periods are 8.35 years for Scenario 2 and 9.49 years for the Optimal Case, respectively. The grid-connected MG can also sell excess power to the grid to speed up the payback period. Additionally, the analysis of increased irrigation water demand illustrates the advantages of MG, especially as global warming impacts operational costs for the cotton farm; for example, the simple payback period is shortened from 9.49 years to 7.05 years. This case study provides a reference for cotton industry stakeholders to consider RES investment in cotton farms.

This study focuses only on grid-tied cotton farms while there are many cotton farms that are not grid-connected. Therefore, our future work will focus on the feasibility of MG design for those cotton farms where grid power is either limited or not available. We will also consider stochastic cases and compare the results with the deterministic approach under different availabilities of historical data.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Data availability

The data supporting this study's findings are available from the first author, Yunfeng Lin, upon reasonable request.

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