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Size and Dispatch Co-Optimisation of a Grid-Connected Agrivoltaic System

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Abstract. Agrivoltaic systems that leverage the opportunity of integrating solar photovoltaic (PV) systems into land used for agriculture, have been shown to provide an effective platform for a mutually beneficial cooperation between energy and food. However, the mainstream literature has failed to investigate the systematic design and dispatch considerations that must be made to ensure the robust and profit-maximising operation of a grid-connected agrivoltaic system from an energy perspective subject to meeting onsite load demands, such as irrigation pumps, centre pivot systems, and cow shed pumps. This necessitates formulating a coordinated, system-level strategic design and dispatch problem that considers the localised energy system and its individual components. Accordingly, this paper introduces a novel agrivoltaic system energy planning optimisation method with an integrated dispatch scheduling framework. The proposed method enables the consideration of augmenting value streams, such as temporal energy arbitrage with the grid, especially regarding the presence of behind-the-meter stationary battery storage devices and electric agricultural vehicles' batteries. Furthermore, the proposed method has a general crop type-independent structure. This allows for greater adaptability of the method to different types of agrivoltaic systems. The effectiveness of the proposed method in improving the economic feasibility of grid-connected agrivoltaic systems is demonstrated based on simulation results obtained from its application to a conceptual agrivoltaic system backed by stationary and mobile battery storage systems, proposed for implementation in a rural location in Aotearoa New Zealand.

Keywords: Agrivoltaic, Microgrid, Optimisation

1. Introduction

The need for improved energy and food security is increasingly recognised. Particularly, the ever-growing population across the globe and the impacts of climate change are further stressing the need for reliable, affordable, clean energy, as well as adequate arable land to safeguard food supply chains [1]. In this light, the concept of integrating solar photovoltaic (PV) systems into agricultural lands, known as agrivoltaic systems, has received increasing attention due to the potential mutual benefits it offers for both energy and food production. The integration of these systems presents an opportunity to address the challenges of climate change, energy security, and food sustainability simultaneously [2], [3].

Various studies have highlighted the potential benefits of agrivoltaic systems, including increased land-use efficiency, reduced water requirements, and enhanced crop productivity [4]. However, the mainstream literature has largely neglected the systematic design and dispatch considerations that are crucial for the robust and profit-maximising operation of grid-connected agrivoltaic systems. Previous studies have focused primarily on the agronomic and ecological aspects of agrivoltaic systems, such as the impact of shading on crop yield and soil moisture content. In contrast, relatively little attention has been given to the energy system design and operation of agrivoltaic systems, particularly with regard to the dispatch of energy generated by the solar PV system [5]–[8]. This necessitates a coordinated and systematic approach to the design and dispatch of agrivoltaic systems that considers the local energy system and its individual components.

More specifically, several previous studies have investigated the economic feasibility of grid-connected agrivoltaic systems, including the impact of incentives, tariffs, and subsidies on the profitability of agrivoltaic systems [9]–[11]. However, few studies have focused specifically on the energy dispatch considerations of agrivoltaic systems while optimally designing such systems in the investment planning phase.

In response, this paper introduces a coordinated and systematic approach to the design and dispatch of agrivoltaic systems that improves their economic viability. More specifically, this paper proposes a novel agrivoltaic system energy planning optimisation method with an integrated dispatch scheduling framework. The proposed method enables the consideration of augmenting value streams, such as temporal energy arbitrage with the grid, especially regarding stationary and mobile battery storage for electric agricultural vehicles. Also, the crop type-independent structure of the proposed method improves its adaptability to different types of agrivoltaic systems. To test the effectiveness of the proposed method in improving the economic viability of agrivoltaic systems, it is applied to a real site in Aotearoa New Zealand, which has verified its utility in aiding the associated decision-making processes.

2. Test-case system

Figure 1 shows the schematic diagram of the test-case system used to parametrise the proposed agrivoltaic system design and dispatch co-optimisation method. Fundamentally, the proposed system forms a grid-connected micro-grid (MG) with a defined boundary, integrating elevated solar PV panels, wind turbines (WT), and battery energy storage system (BESS) serving various load demand, such as irrigation pumps, centre pivot systems, cow shed pumps, working sheds, as well as houses on site. It also provides a platform for the system integration of electric agriculture vehicles. The WTs, elevated solar PV panels, and the multi-mode inverter were modelled as in [12]. The rated capacity of WTs and PV panels were assumed to be 50 kW and 0.33 kW, respectively. The panels were assumed to be north facing with a tilt angle of 40 degrees. The generic lithium-ion (Li-ion) BESS was modelled as in [13], considering a rated capacity of 1 kWh. Also, the agriculture EVs were assumed to be two electric tractors, each with a rated battery capacity of 20 kWh [14]. For the full techno-economic specifications of the selected product models, refer to [13].

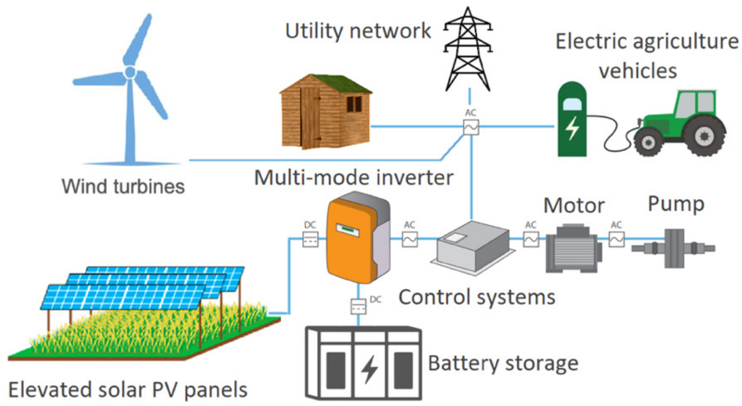

Figure 1. Conceptual battery-supported agrivoltaic system used as a test case.

3. Methodology

The objective function is defined to be the minimisation of the total system costs over the planning horizon (25 years) using the net present cost (NPC) method as [15]:

$$NPC_c = N_c \times \left(CC_c + RC_c \times SPPW + \frac{O\&M_c}{CRF(ir, PL)} - SV_c \right) \quad (1)$$

In Eq. (1), the notation N_c represents the optimal size of a component c belonging to the set $C = \{PV, WT, Bat, Inv\}$, while CC_c, RC_c, and $O\&M_c$ denote its corresponding capital cost, replacement cost, and operation and maintenance cost. In addition, $SPPW$, CRF, and SV respectively indicate the single-payment-present-worth factor, the capital recovery factor, and the salvage value, which can be determined using the following equations [15]:

$$SPPW = \sum_{n=1}^{N} \frac{1}{(1 + ir)^{CL \times n}} \quad (2)$$

$$N = \begin{cases} \left\lfloor \frac{PL}{CL} \right\rfloor - 1 & if\ PL\ mod\ CL = 0 \\ \left\lfloor \frac{PL}{CL} \right\rfloor & otherwise \end{cases} \quad (3)$$

$$CRF(ir, PL) = \frac{ir(1 + ir)^{PL}}{(1 + ir)^{PL} - 1} \quad (4)$$

$$SV = RC \times \frac{CL - (PL - CL \times \left\lfloor \frac{PL}{CL} \right\rfloor)}{CL} \quad (5)$$

where ir is the real interest rate (5%), PL is the project lifetime (25 years), and CL is the component's lifetime.

Accordingly, the objective function is formulated by adding up the NPCs (as the numerical performance criteria) of the underlying components and the costs of power exchanges with the utility grid:

$$\min OF = TNPC = \sum_{c \in C} NPC_c + NPC_{ex} + p \quad (6)$$

In Eq. (6), the variable $TNPC$ refers to the total net present cost of the project, NPC_{ex} is the NPC of power exchanges with the grid (considering a positive sign for imports and a negative sign for exports), while p is a penalty parameter that increases the value of the objective function significantly when the planning-level constraints are breached. In areas of the design space where the planning-level constraints are not breached, the value of p is zero.

The derived objective function is subject to a set of constraints on the energy management and long-term planning of the system. The operational-level constraints are enforced while conducting energy balance analyses. On the other hand, the planning-level constraints are primarily devised to reflect the inclinations of decision-makers concerning the overall system performance criteria, such as reliability and resilience, albeit to a lesser extent, to assist in preserving the balance of the analysis. For reasons of space, the reader is referred to [15] for details on the operational- and planning-level constraints.

The optimisation problem is solved using the moth-flame optimisation algorithm [16], the effectiveness of which in MG sizing applications is demonstrated in previous work [13], [15].

The flowchart in Figure 2 illustrates the dispatch strategy developed to facilitate the coordination of scheduling for distributed energy resources in the proposed agrivoltaic MG based on a set of rules. It is worth noting that the optimal strategy for charging EV batteries using stationary BESS is contingent on various factors, such as grid interconnection, charging system specifications, and renewable energy availability. These factors must be carefully considered when developing and implementing an EV charging system. The preliminary findings of this investigation indicated that it would be more cost-effective to marginally overbuild renewable energy sources rather than using the stationary BESS to charge EV batteries during periods of low solar and wind generation, which informed the devised energy scheduling strategy.

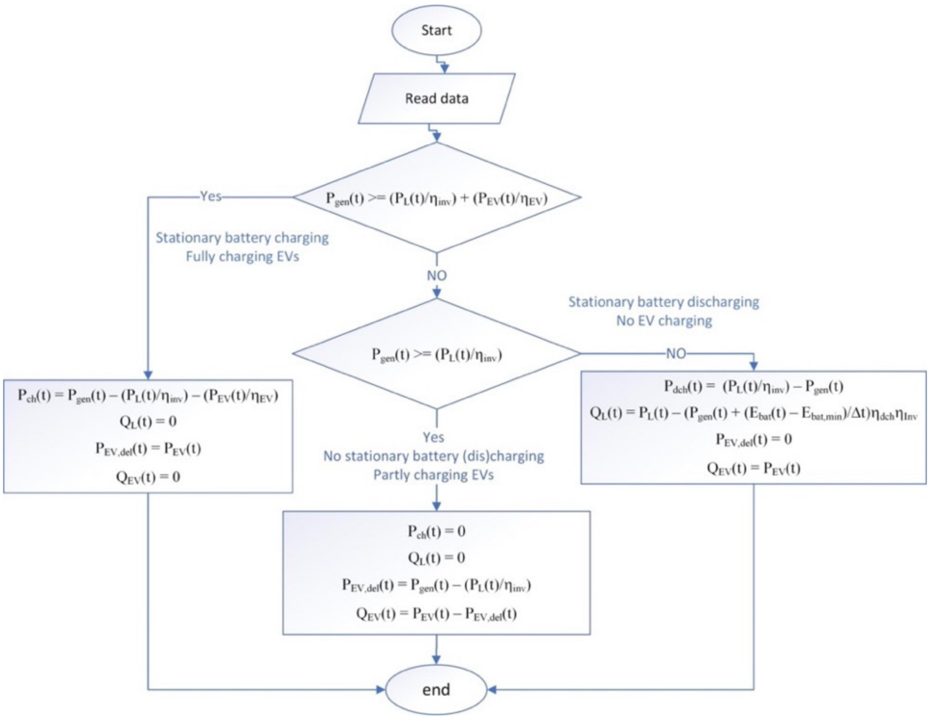

Figure 2. Flowchart of the proposed EV-addressable energy dispatch strategy.

4. Case study

4.1 Input data

To test the effectiveness of the proposed modelling framework in optimally sizing the components of an agrivoltaic MG, a case study is carried out for a dairy farm in Canterbury, Aotearoa New Zealand (coordinates: -43°45'19", 172°12'58"). Figure 3 shows the location of the site on an Aotearoa New Zealand map and a detailed map view.

Figure 3. Location and detailed map view of the site of interest.

The solar irradiance, ambient temperature, and wind speed data were obtained from the CliFlo database of New Zealand National Institute of Weather and Atmospheric Research (NIWA) [17]. To this end, a decade-long (2013 to 2022) dataset of hourly solar irradiance, temperature, and wind speed measurements were collected and averaged, providing a representative, year-round record comprising 8760 data points. Figure 4 shows the derived meteorological profiles on a monthly mean basis. Note that Aotearoa New Zealand is situated in the Southern Hemisphere.

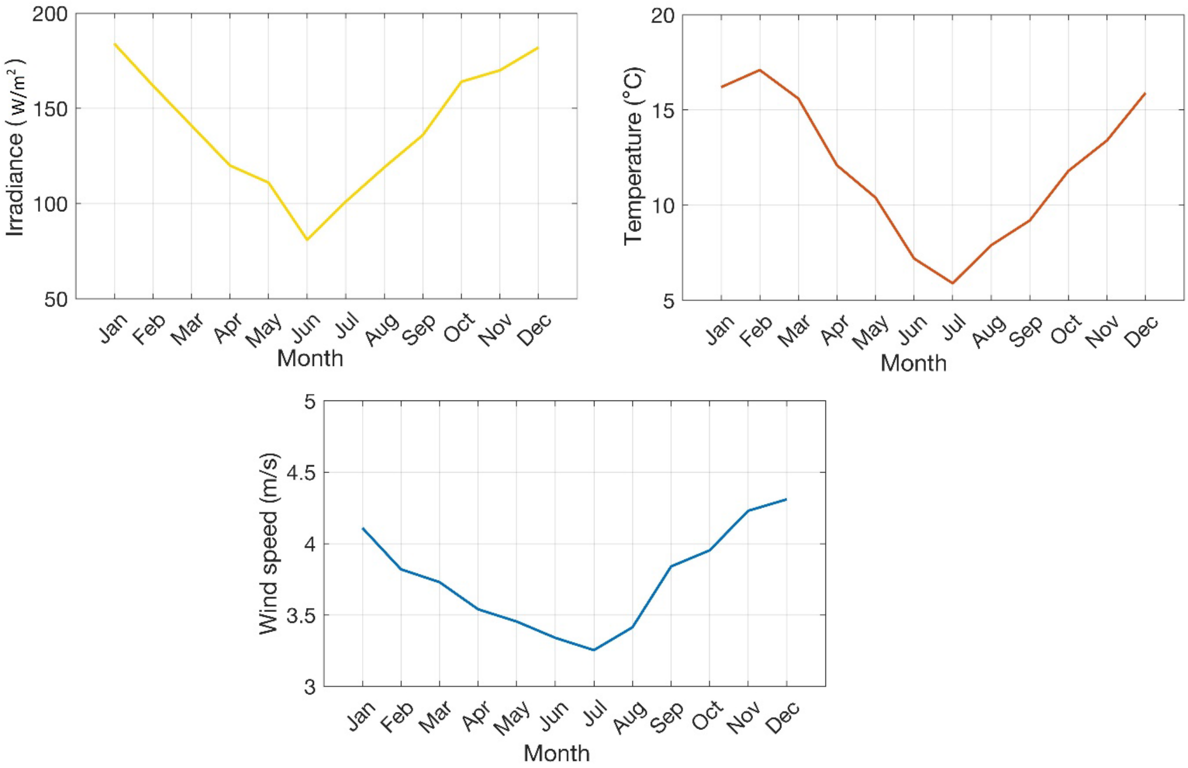

Figure 4. Monthly mean meteorological profiles for the site of interest.

The load profile excluding EVs was derived based on the site's actual electricity bill for the month of June 2022 as hourly data and further bills were not readily available. To this end, the load shape derived in [18] from 22 commercial farms in Ireland was used and the overall monthly consumption was appropriately scaled and adjusted accordingly. The fact that Aotearoa New Zealand is in the Southern Hemisphere necessitated adjustments in the seasonal load profile compared to regions in the Northern Hemisphere.

Also, the EVs' aggregate load profile was constructed under the assumption that they require a full charge every alternate day and are available for a preferential charging in the middle of the day when solar generation is plentiful.

Furthermore, wholesale electricity prices were retrieved from the New Zealand Electricity Authority's wholesale database [19] for the relevant location for the time period January 2013 to December 2022 and was processed to obtain a year-long data using the weighted rolling average method.

Figure 5 shows the derived total load profile (underlying and EVs) on the agrivoltaic MG and wholesale prices on a monthly mean basis.

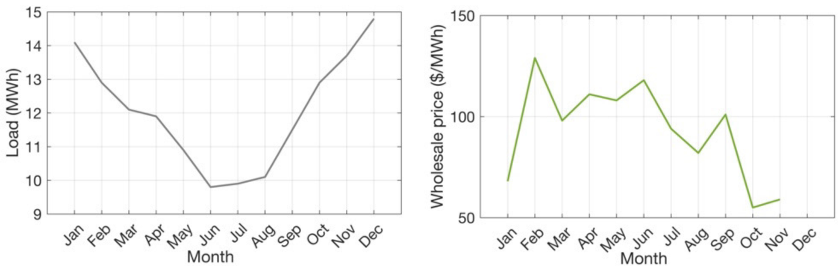

Figure 5. Monthly mean total load and wholesale prices at the site of interest.

4.2 Simulation results

Table 1 presents the summary results in the two scenarios of with and without the WT generation system in the candidate pool.

Table 1. Summary optimal sizing results with and without WTs.

Scenario	Optimal sizing results			
	Solar PV (kW)	WT (kW)	BESS (kWh)	TNPC
Solar PV/WT/battery	69	100	126	NZ$406,000
Solar PV/battery	230	N/A	266	NZ$479,000

The comparative results in Table 1 are revealing as follows:

- *The role of complementarity of solar PV and WT in reducing costs:* The results demonstrate that the scenario with the solar PV system, WT, and battery is significantly (~15%) more cost-effective than the solar PV system with only battery storage. This suggests that the complementarity of solar PV and WT in generating power can significantly reduce the overall cost of the system. Specifically, the addition of the WT system reduces the required size of the solar PV system and battery storage, which in turn, reduces the overall upfront investment required to build the system.
- *Effects on size of storage:* The results also indicate that the size of the battery storage system is affected by the presence or absence of the WT system. In the scenario with only solar PV and battery, the optimal size of the battery system is 266 kWh, whereas in the scenario with solar PV, WT, and battery, the optimal size of the battery system is 126 kWh – a ~38% reduction. This suggests that the addition of the WT system allows for a smaller battery system to be used while still meeting the energy demand. However, it implies a lower resilience to grid outages.

Additionally, the analysis of further unreported simulation results in the post-optimisation phase has revealed an important finding regarding the self-sufficiency ratio of the systems of interest. The self-sufficiency ratio represents the system's capability to fulfil its electricity demand without relying on grid imports. The self-sufficiency ratio is calculated to be 71% for the solar PV/WT/battery configuration and 60% for the solar PV/battery system. It is noteworthy that the availability of the grid and the relatively low feed-in tariff, which is set at NZ$0.08/kWh, have led the model to avoid oversizing the microgrid systems to minimise potential curtailment of local energy production and optimise cost-effectiveness.

Table 2 summarises the resulting values of the selected capital budgeting metrics for the proposed agrivoltaic MG development project with and without WTs. Collectively, the values obtained for the selected metrics – levelised cost of energy (LCOE), modified internal rate of return (MIRR), discounted profitability index (DPI), and discounted payback period (DPP) –

indicate that not only are the proposed MG projects economically viable, but they also represent high-return, low-risk investment opportunities. That is, the project proposals are found to be able to produce steady revenue streams without any subsidies for renewable energy.

Table 2. Resulting values of the capital budgeting metrics.

Scenario	Capital budgeting metrics			
	LCOE ($/kWh)	MIRR (%)	DPI	DPP (years)
Solar PV/WT/battery	0.12	16.2	2.1	8.8
Solar PV/battery	0.14	12.7	1.8	10.1

5. Conclusions and future work

This paper has presented a systematic and coordinated method for the optimal design and dispatch of grid-connected agrivoltaic systems. The proposed method effectively propagates the inner operational decisions of the system out to the objectives of the optimal design problem. A case study of a real dairy farm in Aotearoa New Zealand has shown the effectiveness of the method in determining the optimal size of the components of an agrivoltaic MG.

The results have demonstrated that the inclusion of the WT system in the candidate pool can significantly impact the overall cost and sizing of the system. Specifically, including the WT system for the case study of interest has led to a smaller system design and, in turn, reduced the system cost by a significant ~15%. This highlights the importance of the diversification of technologies in the candidate pool when designing an agrivoltaic system.

It is important to note that while the addition of a WT system in the candidate pool can result in significant cost savings and a smaller system design, it may not always be worthwhile to include it in the final design. The decision to include a WT system should be based on a careful analysis of the local wind resource and the associated costs and benefits. In some cases, the cost savings from adding a WT system may be small compared to the upfront investment required, and it may not be economically viable to include it in the final design. Moreover, it is important to consider that the sources of data used to estimate the costs and benefits of the system in this analysis may be speculative, and therefore, subject to more detailed studies. For example, the local wind resource may vary over time, the installation of a WT system might require a significant amount of groundwork, and the actual performance of the WT system may differ from the estimated values. Therefore, it is crucial to conduct a more detailed feasibility study before finalising the design of the renewable energy system.

Overall, this paper contributes to the literature by offering a novel and effective approach to optimise the design and operation of agrivoltaic systems, which can lead to improved economic feasibility and increased adoption of these systems.

Future work is planned to further advance the proposed model by formulating an uncertainty-aware multi-objective modelling framework, while leveraging the concept of land equivalent ratio to measure the combined food and energy efficiency of the agrivoltaic system on the same land, as well as self-sufficiency constraints. Accordingly, the planned agrivoltaic system co-optimisation model will enable multi-faceted quantitative decision support analyses.

Data availability statement

Data will be made available on request.

Author contributions

Soheil Mohseni: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Resources, Software, Validation, Visualization, Writing – original draft. Alan C. Brent: Supervision, Project administration, Formal analysis, Investigation, Resources, Validation, Writing – review & editing.

Competing interests

The authors declare no competing interests.

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