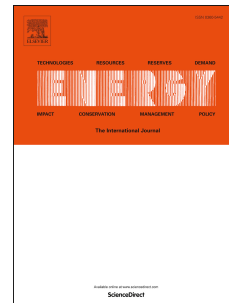


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PII: S0360-5442(26)02575-2

DOI: <https://doi.org/10.1016/j.energy.2026.142468>

Reference: EGY 142468

To appear in: *Energy*

Received Date: 11 January 2025

Revised Date: 10 August 2026

Accepted Date: 16 September 2026

Please cite this article as: Song J, He Y, Cipollone R, Fatigati F, Markides CN, Comparative techno-economic-environmental investigation of hybrid renewable energy systems for combined cooling, heating and power provision to hotel buildings in hot desert climate, *Energy*, <https://doi.org/10.1016/j.energy.2026.142468>.

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Comparative techno-economic-environmental investigation of hybrid renewable energy systems for combined cooling, heating and power provision to hotel buildings in hot desert climate

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Abstract

Hybrid renewable energy systems (HRESs) are suitable for addressing the intermittency of separate, individual renewable resources, and for more reliable and flexible energy provision. They are thus expected to play a vital role in promoting the wider use of renewable energy technologies, which are a core element of energy transition pathways. In this study, various combinations of renewable energy technologies and product options are investigated within selected HRES configurations. These include photovoltaic (PV) panels, solar thermal collectors (STCs), PV-thermal (PV-T) collectors, wind turbines (WTs) and biomass boilers (BBs), representing a range of technical performance and cost levels. Detailed techno-economic-environmental assessments of these HRESs are performed for a case study of a hotel in Fayoum, Egypt, given the growing importance of the local tourism sector. Sensitivity analysis of solar field area and number of WTs are performed, along with optimisation based on net present cost (NPC) to determine optimal systems for power, heating and cooling provision to the selected hotel. The results show that PV panels, especially the low-cost product options, enable the HRESs to deliver favourable economic performance, with a lowest NPC of \$195.7k, along with a corresponding levelised cost of energy (LCOE) of 0.060 \$/kWh, a payback period (PBP) of 6.3 years and annual carbon emissions (ACE) of 22.1 ton/year. The PV-T-based systems are also promising, as they achieve the highest levels of self-sufficiency ratio (up to ~40%), while having a significant potential for further technical improvements as well as cost reductions are expected in the future. From an environmental perspective, the PV- and PV-T-based systems are similar, delivering significant emissions reductions (>50%). A modified HRES layout that splits the heat provision into hot water and space heating satisfied by renewables (solar and biomass) and the hotel's existing air-conditioning system is also proposed. A decrease of 10% in NPC relative to the original PV-based HRES is achieved, while the LCOE decreases from 0.060 to 0.054 \$/kWh and the PBP from 6.3 to 3.4 years. The modified HRES layout benefits from a smaller boiler, lower biomass consumption and less electricity fed/sold to the grid. The results and conclusions from this study can provide valuable guidance for the design and establishment of HRESs in practical applications, especially for the selection of available renewable energy technologies and product options, thus facilitating the wider deployment of such promising systems.

Keywords: hybrid renewable energy systems; techno-economic-environmental assessment; renewable technologies; system configurations

Nomenclature**Energy and power terms**

E_{cov}	Electricity demand covered by HRES generation (kWh)
E_{de}	Electricity demand of electrical appliances (kWh)
E_{exc}	Excess electricity exported to the grid (kWh)
E_{gen}	Annual electricity generation (kWh)
E_{grid}	Electricity imported from the grid (kWh)
Q_c	Space cooling demand (kWh)
Q_{gen}	Annual thermal energy generation (kWh)
Q_h	Space heating demand (kWh)
Q_{HW}	Hot water thermal energy demand (kWh)
Q_s	Solar thermal energy generation (kWh)

Performance indicators

COP	Coefficient of performance
SSR	Self-sufficiency ratio
η_{EH}	Efficiency of electric heater
η_{PV}	PV panel efficiency
η_{STC}	Solar thermal collector efficiency
η_{el}	Electrical efficiency of PV-T collector
η_{th}	Thermal efficiency of PV-T collector

Economic parameters

C_0	Initial capital investment cost (\$)
C_{bio}	Biomass fuel cost (\$)
$C_{O\&M}$	Operation and maintenance cost (\$)
C_s	Annual cost savings (\$)
d	Discount rate
i_F	Inflation rate
LCOE	Levelised cost of energy (\$/kWh)
NPC	Net present cost (\$)
NPC_0	Net present cost of benchmark system (\$)
NPV	Net present value (\$)
$p_{E,buy}$	Electricity purchase price (\$/kWh)
$p_{E,sell}$	Electricity selling price (\$/kWh)
PBP	Payback period (year)

Environmental parameters

ACE	Annual carbon emissions (ACE)
M_{bio}	Biomass fuel consumption (kg)
δ_{bio}	Biomass emissions factor (kgCO ₂ /kWh)
δ_{grid}	Grid electricity emissions factor (kgCO ₂ /kWh)

1. Introduction

Energy resource security and environmental deterioration are crucial issues that the developing world is facing. To tackle these challenges, there is an on-going transition of energy systems towards less carbon-intensive and more sustainable systems via the utilisation of renewables for electricity, heating and cooling provision. In the “Net Zero Emissions by 2050” scenario, renewables are placed at the centre of energy transition to enable decarbonisation. The utilisation of renewable sources has been promoted significantly in recent years, thanks to the technical development, policy support and cost reduction of renewable technologies, in particular solar photovoltaic (PV) and wind power systems, of which the levelised cost of energy (LCOE) has decreased by 84% and 50% in the last decade, respectively, and are now cost-competitive with conventional coal and gas-fired power plants [1]. Renewables accounted for a share of 30% in the global electricity generation in 2023, and their deployment is expected to further increase to meet the Net Zero Emissions Scenario, with a fraction of overall electricity generation predicted to exceed 60% by 2030 [2].

Renewable energy technologies, especially those utilising solar, wind and biomass resources, have been widely investigated and developed as alternatives to fossil fuels [3-5]. However, the utilisation of renewables is commonly criticised due to their nature of intermittent availability, which further leads to operation uncertainties. The unpredictability and dependence on locations and climate conditions of renewables also hamper the reliability and stability of energy supply. Energy storage technologies have been proposed to address these issues and also to balance the mismatch between energy supply and demand [6,7]. On the other hand, hybridisation of multiple renewable sources in so-called hybrid renewable energy systems (HRESs) arises as another promising solution, as this combines a variety of renewable energy technologies (or sometimes both renewable and conventional resources [8,9]) with complementary provision characteristics to cover the downtimes of individual technologies [10,11]. Such HRESs have the capability of suppressing the change in energy supply from a single source [12]. For example, researchers from the National Renewable Energy Laboratory (NREL) [13] have originally reported complementary electricity generation profiles of PV panels and wind turbines (WTs) based on actual meteorological data. Therefore, HRESs are acknowledged as a more reliable and less costly solution to the utilisation of renewables, specifically compared to solutions relying on any single renewable resource as well as those integrated with energy storage units [14,15].

The earliest studies on HRESs dated back to the 1980s [13,16], and an acceleration of interest in this research field has been experienced recently, with studies concerned with system sizing, optimisation and performance assessments, along with effective control and management strategies for optimal operation [11,17].

Sizing of HRESs is a critical step in the design processes, and the associated difficulties include estimate of actual demand and determination of step time to accurately capture the fluctuations in renewable energy resources [18]. A list of software such as HOMER (Hybrid Optimisation Model for Electric Renewable), INSEL (Integrated Simulation Environment Language) and HOGA (Hybrid Optimization by Genetic Algorithm) [19], and analytical methods, e.g., probabilistic, iterative and artificial intelligence approaches [20], have been used for research on sizing of HRESs. Researchers have also assessed HRESs’ performance at different scales to address the key parameters for system design. Yang et al. [21] investigated the influence of a list of parameters including the

number of PV panels, number of WTs, and size of battery storage on the performance of HRESs. A case study considering a remote island along the south-east coast of China was conducted, and the results showed that good complementary generation between solar and wind energy resources was achieved and the match between the electricity generation and demand was facilitated. Ma et al. [22] further assessed the influence of size/capacity on an HRES's performance to explore the potential to replace the diesel generator on a remote island for electricity generation. The authors reported an LCOE of 0.595 \$/kWh, indicating that HRESs were cost-effective for practical applications. A study focusing on the sizing of an HRES conducted by Anoune et al. [23] also revealed that HRESs were economically comparable with conventional systems.

Research on optimisation and performance assessments of HRESs is also extensive, and various configurations have been proposed and investigated. Ahmed et al. [24] performed a study on an HRES consisting of PV panels, WTs and biomass units to meet the energy demands in Kallar Kahar, Pakistan, of which the power capacity was 50 MW and an LCOE of 0.060 \$/kWh was obtained. Baruah et al. [25] explored the techno-economic feasibility of HRESs for electricity provision to an academic township in the east district of Sikkim, India. A total of 31 possible combinations and design schemes of solar energy, wind energy and biogas were analysed, and the optimal option provided an LCOE of 0.095 \$/kWh. Das et al. [26] investigated the performance of HRESs for electricity and thermal energy provision to a remote community, which consisted of PV panels, WTs, batteries, thermal load controllers, and gas boilers. The results showed that potential cost reduction and environmental benefits could be attained by the optimised hybrid system. Khan et al. [27] analysed the performance of PV-wind HRESs for residential applications to address the techno-economic and socio-environmental benefits. The LCOE and net present cost (NPC) of the optimised HRES were 0.180 \$/kWh and \$31.4k, respectively.

Effective control and management allow HRESs to meet energy demands, while maximising the use of renewables and reducing operational costs. Distributed control [28] and hybrid control [29] are commonly used in HRESs, as they minimise system failures and offer various operational strategies. Management of HRESs ensures high system efficiency and reliability throughout the entire operating periods and enables extended lifetime of components and equipment. Typical management categories include technical and economic strategies, within which technical and economic parameters are taken into account. More precisely, technical strategies focus on parameters such as temperature, pressure and flowrate, advancing system operation to cover energy demand, increase equipment performance and lifetime, and obtain higher stability [30,31]; while economic strategies represent the influence of local economic parameters, aiming at reducing system costs and achieving better economic benefits [32].

Previous research on HRESs has mainly covered system sizing, optimisation and performance assessments, as well as control and management. However, techno-economic-environmental comparisons of HRESs with different types of technologies and product options, and performance across different sizes/capacities are still lacking. Given the broad range of renewable technology options (i.e., different types of technologies and products with trade-offs between technical performance and capital cost), along with the complexities in local renewable resources and end-user demand profiles, such comparisons are crucial for a proper determination of the optimal configurations of HRESs based on specific performance indicators. In this present study, a comprehensive techno-economic-environmental assessment of selected HRES configurations based on a wide

range of renewable technologies and product options available on the market is performed, for a case study of a hotel in Fayoum, Egypt. It should be stated that in the wake of land reclamation effort by the Egyptian government for agricultural use, there have been increasing interests in renewable energy utilisation and HRESs in various sectors in Egypt [33,34]. Fayoum, located in north-east Egypt, is characterised by a hot desert climate with high solar irradiance levels and moderate wind resources, making it a promising location for renewable energy deployment. The region has experienced growing interest in renewable energy in recent years, driven by increasing electricity demand, tourism development and national decarbonisation initiatives.

Compared to previous studies focusing mainly on single-technology optimisation or limited configuration comparisons, this study provides a comprehensive system-level comparison across multiple renewable technologies and real market product options, combined with optimisation and practical system layout modification. PV panels, solar thermal collectors (STCs), and hybrid PV-thermal (PV-T) collectors are considered for solar energy utilisation, while WTs are used for electricity generation from wind, and biomass boilers (BBs) are adopted for thermal energy (hot water and space heating) provision. Based on the above research gaps, this study aims to: (1) compare the techno-economic-environmental performance of HRES configurations based on various renewable technologies under site-specific resource and price conditions; (2) identify optimal system sizing and technology selection considering real market component options; and (3) evaluate technical, economic and environmental performance of a modified HRES layout. The holistic assessments of the proposed HRESs are expected to provide valuable guidance for technology and component selection as well as optimal design of such systems.

2. Methodology

In this section, we present the proposed HRES configurations consisting of different renewable technologies and product options, along with an introduction of the developed models and the performance indicators.

2.1 System configurations

A schematic diagram of the proposed HRESs is shown in Figure 1. These systems consist of a solar field for the installation of PV panels, STCs or PV-T collectors, plus WTs and a BB as renewable technologies for electricity and heating provision, while the cooling demand is satisfied by the hotel's existing air-conditioning system. PV panels, STCs and PV-T collectors are considered for solar energy conversion to electricity and/or thermal energy, and the thermal energy from STCs and PV-T collectors is stored in a water tank to satisfy the heating demand of the hotel. A BB is installed to act as a backup option for heating the water up to the required temperature for hot water use and space heating; this replaces the existing electrical heaters in the hotel. Small WTs are installed to generate additional complementary electricity to that from PV panels and PV-T collectors. The combined electricity generated from solar and wind energy resources is used to cover the hotel's electricity demand, as well as the self-consumption of the system (e.g., the circulation pump); any surplus is fed/sold to the grid using the net metering option (black dashed lines in Figure 1), while electricity will be bought/extracted from the grid when the electricity demand cannot be fully covered by the HRES generation (green dashed lines in Figure 1).

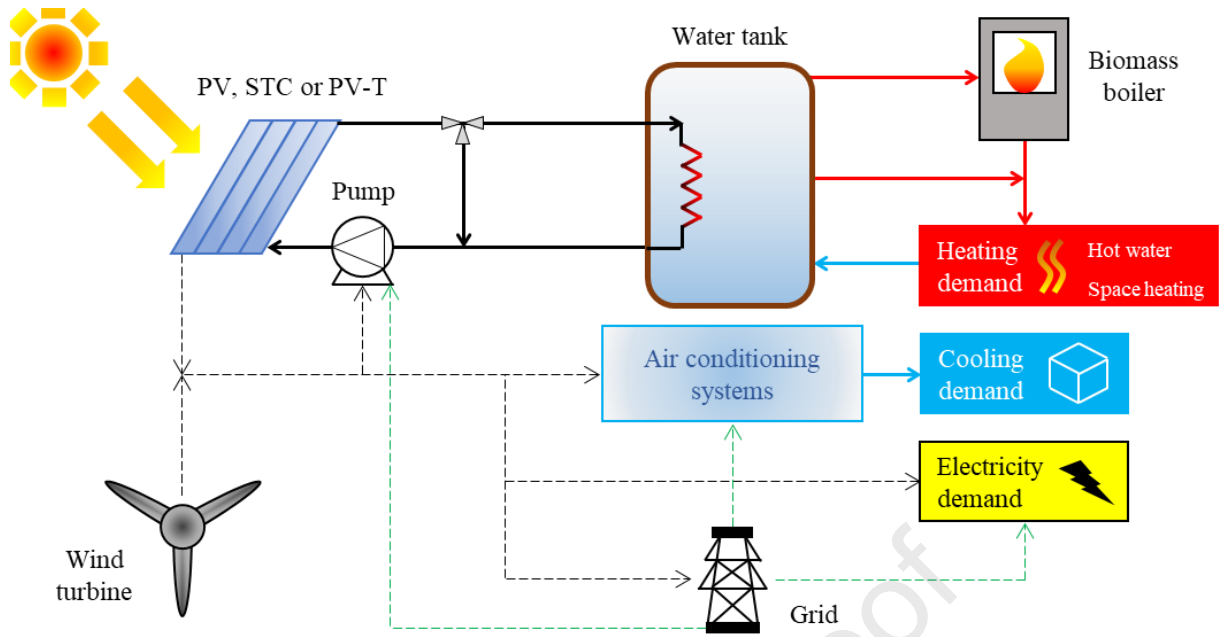


Figure 1. Schematic diagram of HRESs investigated in this study. The solar field comprises PV panels, STCs or PV-T collectors, WTs are installed for complementary electricity generation and a BB for heating purposes.

2.2 Renewable technologies and product options

Technical development of renewable technologies plays a vital role in promoting the utilisation of renewable energy. A broad range of solar and wind energy technologies and product options are available on the market. Based on a comprehensive market investigation and pre-screening of suitable technologies, this study aims at addressing the influence of components' technical parameters and costs on the techno-economic-environmental performance of HRESs, so as to obtain the optimal configuration considering actual weather conditions, demand profiles and availability of renewable energy sources.

A list of renewable technologies and product options considered for the proposed HRESs, along with their detailed technical and economic parameters, are summarised in Table 1. High-performance and low-performance PV panels, STCs and PV-T collectors, which normally associated with high and low costs respectively, are selected for comparison, as this is expected to reveal the trade-offs between technical and economic performance. Ten types of small WTs are considered for additional power generation, with rated power ranging from 0.085 to 11 kW as typical options available on the market.

Table 1. Detailed parameters of HRES components considered in this study.

PV panels	Electrical efficiency	Temperature coefficient	Rated Power (W)	Size (m ²)	Type	Price (\$/panel)
285 Wp Mono [35]	0.175	-0.40	285	1.63	Monocrystalline	180
370 Wp Cello NeON R [36]	0.214	-0.30	370	1.73	Monocrystalline	415
275 Wp REC Peak Energy Module [35]	0.167	-0.40	275	1.65	Polycrystalline	160
355 Wp REC Peak2s Energy Module [35]	0.177	-0.36	355	2.01	Polycrystalline	235
STCs	Gross area (m ²)	Absorber area (m ²)	Performance coefficient			Price (\$/collector)
Junkers FCC-2S [37]	2.09	1.92	c_0	c_1	c_2	530
RemaSol C 250 H [38]	2.51	2.35	0.77	3.45	0.008	805
Eurotherm-Solar 20R [39]	3.10	1.88	0.39	0.88	0.012	510
Solarbayer CPC 14 Nero Brutto [37]	3.26	2.84	0.63	0.93	0.004	1535
PV-T collectors	Electrical efficiency	Temperature coefficient	Thermal efficiency	Performance coefficient		Price (\$/collector)
Ecomesh polycarbonate flat-box PV-T [40]	0.147	0.45	0.73	c_1	c_2	365
Ecomesh covered sheet-and-tube PV-T [40]	0.160	0.47	0.51	4.93	0.021	600
WTs	Rated power (kW)	Cut-in speed (m/s)	Cut-out speed (m/s)	Nominal wind speed (m/s)		Price (\$/turbine)
LE-300 [41]	0.085	2.0	18	8		1.45k
LE-450 [41]	0.105	3.0	20	8		1.29k
LE-600 [41]	0.16	3.0	18	8		2.03k
Skystream 3.7 [42]	2.1	3.2	15	11		6.12k
WES5-Tulipo [42]	2.5	3.0	20	9		12.90k
Evance-R9000 [42]	5	3.0	/	12		38.06k
Eoltec Scirocco [43]	6	2.7	/	11.5		34.82k
Evoco-10 [44]	9.55	2.5	/	11		58.05k
Aricon 10S [42]	10	3.5	25	11		80.30k
Gaia 133 [42]	11	4.0	25	9		70.82k
Water storage tank	Size				Price (\$)	
Ref. [45]	50 L per unit area of collectors				$0.944 \cdot V_{\text{tank}} (L) + 825$	
Biomass boiler	Rated power (kW)		Efficiency		Price (\$/kW)	
Ref. [46]	70		0.9		500	

2.3 System modelling and performance indicators

A model has been developed in MATLAB to simulate the performance of the proposed HRES configurations. The model takes weather data (solar irradiance, ambient temperature and wind speed) and building demand profiles (electricity, heating and cooling) as inputs, and integrates sub-models for the main system components, as summarised below. The detailed modelling approaches for the solar technologies (PV, STC and PV-T) are based on the authors' previously validated models reported in Refs. [4748]:

(1) PV:

$$\eta_{PV} = \eta_{ref} \cdot [1 - \beta \cdot (T_c - T_{ref})], \quad (1)$$

where η_{ref} is the reference PV efficiency at standard test conditions, β is the temperature coefficient, T_c is PV cell temperature and T_{ref} is reference temperature.

(2) STC:

$$\eta_{\text{STC}} = \eta_0 - c_1 \cdot \frac{T_m - T_a}{G} - c_2 \cdot \frac{(T_m - T_a)^2}{G}, \quad (2)$$

where η_0 is the optical efficiency of the collector, c_1 is the first-order heat loss coefficient, c_2 is the second-order heat loss coefficient, G is solar irradiance, T_m is the mean collector temperature, and T_a is ambient temperature.

(3) PV-T:

$$\eta_{\text{el}} = \eta_{\text{ref}} \cdot [1 - \beta \cdot (T_c - T_{\text{ref}})], \quad (3)$$

$$\eta_{\text{th}} = \eta_{0,\text{th}} - c_1 \cdot \frac{T_m - T_a}{G} - c_2 \cdot \frac{(T_m - T_a)^2}{G}, \quad (4)$$

where η_{el} and η_{th} are electrical and thermal efficiency of PV-T collector.

(4) WT:

WT performance is modelled using manufacturer power curves. Figure 2 shows the power output of each individual WT as a function of wind speed, based on datasheets obtained from manufacturers. It can be seen that WTs with a higher rated power generally cover a wider range of wind speed, which is also associated with a higher cost according to the economic parameters listed in Table 1.

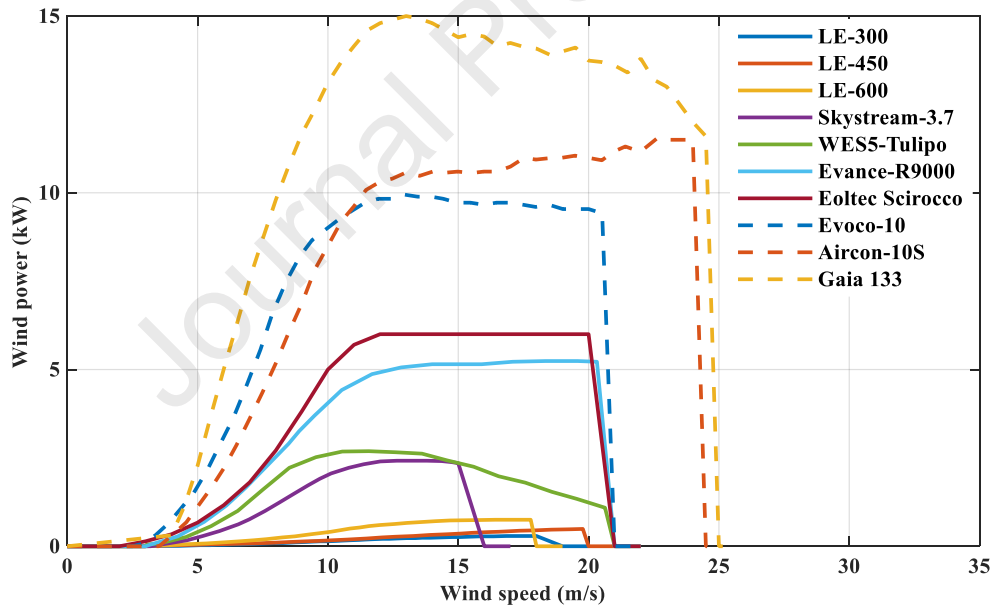


Figure 2. Power curves of considered WTs in this study. The data is obtained from manufacturers and the key technical and economic parameters are listed in Table 1.

In this study, the modelling framework is used primarily for system-level performance assessment and optimal sizing of different HRES configurations. A selection of indicators is used to quantify and compare the techno-economic-environmental performance of the HRES configurations.

2.3.1. Technical indicator

Self-sufficiency ratio (SSR) is selected as a technical indicator in this study, which is defined as the ratio of energy demand covered by self-generation of HRESs to the total demand, and can be expressed as:

$$SSR = \frac{\sum E_{cov} + \sum \frac{Q_s}{\eta_{EH}}}{\sum \left(E_{de} + \frac{Q_{HW} + Q_h}{\eta_{EH}} + \frac{Q_c}{COP_c} \right)}, \quad (5)$$

where E_{cov} refers to the electricity coverage by HRES generation (PV panels or PV-T collectors, and WTs), Q_s is the thermal energy generated from solar (STCs or PV-T collectors), E_{de} is the electricity demand required by electrical appliances (air-conditioning system excluded), Q_{HW} is the thermal energy demand for hot water (HW), Q_h is the thermal energy demand for space heating, Q_c is the demand for space cooling, COP_c is the coefficient of performance (COP) of the existing air-conditioning system, and η_{EH} is the efficiency of existing electric heaters for hot water provision. It should be stated that as the hotel currently operates under an electrified energy supply scenario (i.e., using electricity to satisfy all energy demands), SSR here is based on the total equivalent electrical energy accounting for the direct electricity generation and the electricity required to deliver the same amount of thermal energy output.

2.3.2. Economic indicators

(1) Net present cost:

The net present cost (NPC) is defined as the discounted present value of all costs throughout a system's life cycle, including total investment cost and annual operation and maintenance cost:

$$NPC = C_0 + \sum_{i=1}^n C_{O\&M} (1 + i_F)^{i-1} (1 + d)^{1-i}, \quad (6)$$

where C_0 is the total investment cost, and $C_{O\&M}$ is the operation and maintenance cost. The inflation rate i_F is taken as 2.9% [49], the discount rate d is taken as 4%, and the system lifetime is taken as 25 years in this study.

(2) Net present value:

The net present value (NPV) is the value of all future cash flows over a system's life cycle, which refers to the NPC difference from the benchmark case:

$$NPV = NPC - NPC_0, \quad (7)$$

where NPC_0 is the NPC of the benchmark case, and in this study, it refers to the existing grid-dependent system.

(3) Levelised cost of energy:

The levelised cost of energy (LCOE) can be calculated by dividing NPC by a system's life-cycle discounted energy generation:

$$LCOE = \frac{C_0 + \sum_{i=1}^n C_{O\&M} (1 + i_F)^{i-1} (1 + d)^{1-i}}{\sum_{i=1}^n (E_{gen} + Q_{gen}) (1 + d)^{-i}}, \quad (8)$$

where E_{gen} and Q_{gen} is the net annual electricity and thermal energy generation, respectively.

(4) Payback period:

The payback period (PBP) is also selected as another important indicator for evaluating economic performance, considering the investment cost, operation and maintenance cost, and cost savings associated with the reduced electricity consumption and revenues from electricity excess fed back to the grid:

$$PBP = \frac{\ln\left[\frac{C_0 \cdot (i_F - d)}{C_S} + 1\right]}{\ln\left(\frac{1+i_F}{1+d}\right)}, \quad (9)$$

where C_S is the annual cost savings related to the reduced electricity consumption, income of selling electricity to the grid, additional cost for biomass fuels and system operation and maintenance cost:

$$C_S = (E_{cov} + E_{HW} + E_h) \cdot p_{E, buy} + E_{exc} \cdot p_{E, sell} - C_{O\&M} - C_{bio}, \quad (10)$$

where E_{HW} and E_h refer to the electricity consumption for hot water and space heating in the electrification scenario that is completely covered by solar and biomass in the proposed HRESs, E_{exc} refers to the electricity excess that is fed/sold to the grid when the generated amount is higher than the demand, $p_{E, buy}$ and $p_{E, sell}$ are the prices of buying and selling electricity from/to the grid, and C_{bio} is the annual cost for biomass fuel consumption. The electricity buying and selling prices are based on local data. The buying tariff represents the cost of electricity imported from the grid, while the selling tariff represents the revenue obtained from excess electricity exported to the grid.

The economic assessment considers capital investment cost, operation and maintenance cost, biomass fuel cost, and electricity import/export costs, while building retrofit costs and distribution infrastructure costs are not included.

2.3.3. Environmental indicator

Annual carbon emissions (ACE) index is used to evaluate the HRESs' environmental performance, including equivalent carbon emissions of grid imported electricity and direct carbon emissions due to biomass consumption:

$$ACE = \delta_{grid} \sum E_{grid} + \delta_{bio} \sum M_{bio}, \quad (11)$$

where δ_{grid} is the carbon emissions factor of the utility grid, taken as 0.215 kgCO₂/kWh, E_{grid} is the electricity extracted from the grid, δ_{bio} is the carbon emissions factor of biomass fuels, taken as 0.065 kgCO₂/kWh in the present study [2,50], and M_{bio} is the mass of biomass fuel consumption. Biomass-related emissions depend on fuel origin, supply chain and combustion conditions. Biogenic CO₂ from biomass combustion is often reported separately, while non-CO₂ species also contribute relevant and depend on technology and operating conditions. It should be stated that the grid emission factor used in this study represents an average value, reflecting the overall emissions intensity of electricity supply, while the biomass emission factor is based on standard literature values for biomass combustion.

The teaching-learning-based optimisation (TLBO) algorithm is applied to optimise the sizes of HRESs. A flow chart of the optimisation algorithm integrated with the optimisation model is shown in Figure 3. Regarding the control parameters of TLBO, the teaching factor is randomly taken as 1 or 2, the number of populations is set to 50, and the maximum iteration is 50. Multiple runs are performed to ensure solution robustness, and the best solution is selected. System constraints, including limits on solar field area and number of WTs, are handled within the optimisation framework to ensure feasible solutions.

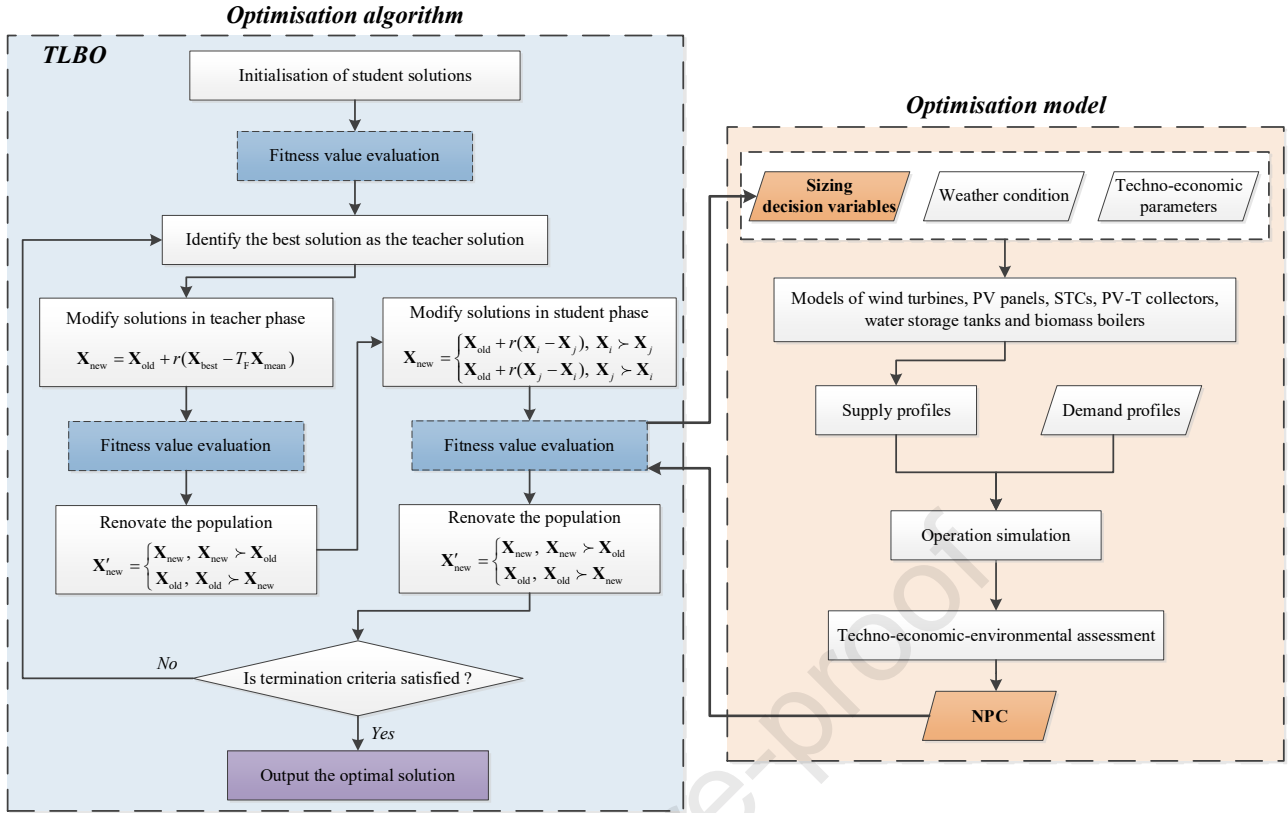


Figure 3. Flow chart of optimisation algorithm and optimisation model used in the present study.

In this study, NPC is selected as the primary optimisation objective, as it accounts for the total life-cycle cost of the system, including capital investment and operation and maintenance costs. NPC is widely used for the design and sizing of hybrid energy systems and enables direct comparison between different configurations. In addition, LCOE and PBP are used to provide complementary economic insights, while carbon emissions are considered to evaluate environmental performance. This set of indicators enables a comprehensive techno-economic-environmental assessment of the proposed HRES configurations.

3. Case study definition

This study proposes HRESs for a hotel in Fayoum to address the potential of utilising renewables for electricity, heating and cooling provision, in accordance with the local policy introduced by the government. Weather data, demand profiles and component technical parameters used in this study are obtained from measured data, manufacturer datasheets and published literature as referenced in the present article.

3.1 Weather conditions

Fayoum is a city in north-east Egypt that is classified as having a hot desert climate with relatively high average temperature and minimal rainfall. The location has an average annual solar irradiance of around 7 kWh/m²/day, and an average wind speed of 6.0-7.0 m/s at the height of 30 m (reference height). The local average daily temperature, wind speed and solar irradiance are shown in Figure 4.

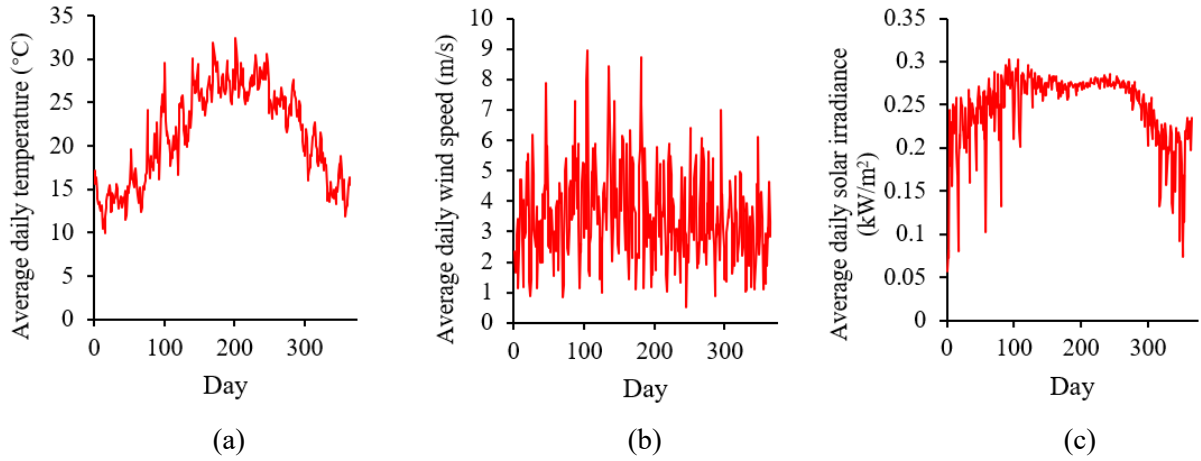


Figure 4. Weather conditions in Fayoum city: (a) average daily temperature, (b) average daily wind speed at the height of 30 m, and (c) average daily solar irradiance.

3.2 Energy demands

The selected hotel has an annual electricity consumption of 100.6 MWh, and the annual demands for hot water, space heating and cooling are 50.8 MWh, 43.7 MWh and 138.7 MWh, respectively. Electrical heaters and an air-conditioning system are currently used to meet the corresponding heating and cooling demands. Therefore, the hotel operates under a fully electrified energy supply scenario. Monthly demands for electricity, hot water, space heating and cooling are shown in Figure 5, which are directly measured by the hotel throughout a year. It is noted that the electricity demand is characteristically stable, with slight monthly variations, while heating demands are much more seasonally dependent, showing lower values for hot water and no demand for space heating during the summer period.

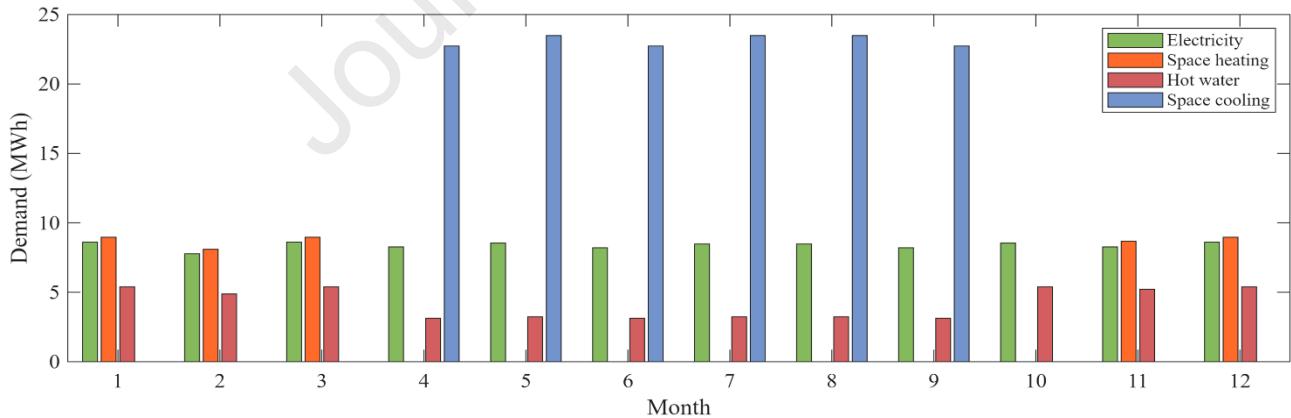


Figure 5. Monthly demands for electricity, heating and cooling of the selected hotel in Fayoum.

As the cooling demand is directly satisfied by the air-conditioning system, it can be shifted to electrical energy using performance curves of air-conditioning systems (derived from data of a wide range of air-conditioning systems collected by the Clean Energy Processes (CEP) Laboratory, Imperial College London; see Figure 6) and added to the electricity demand (electrical appliances), which is shown in Figure 7. Therefore, the proposed HRESs in this study are expected to meet the demands for electricity (electrical appliances and air-conditioning system) and heating (hot water and space heating) of the hotel.

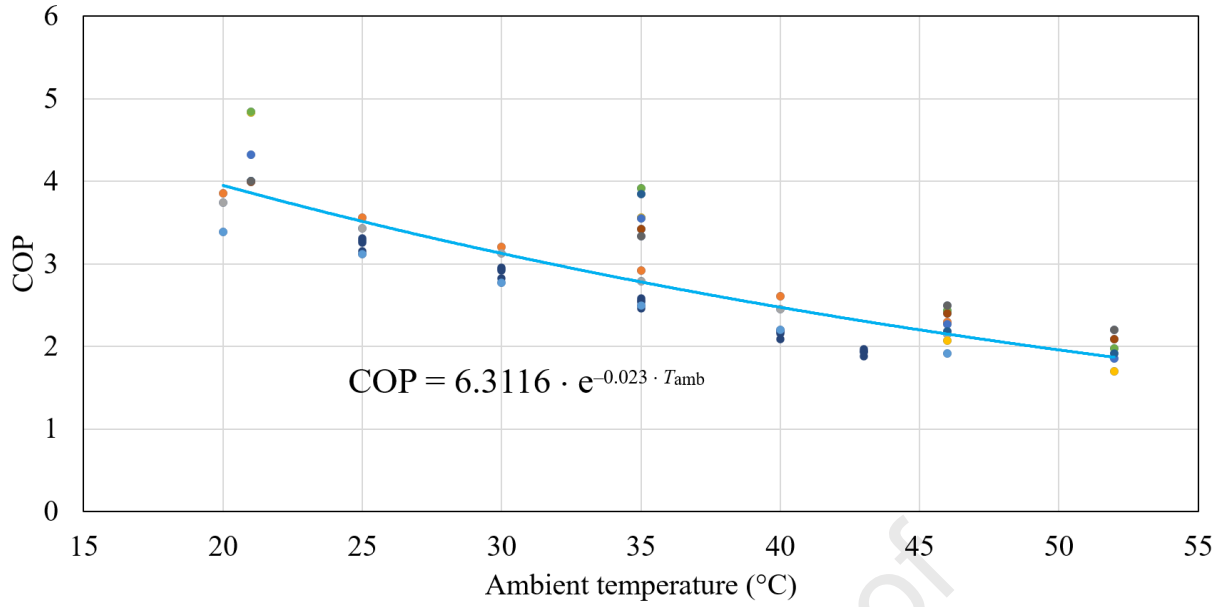


Figure 6. Performance curves of air-conditioning systems (air outlet temperature of 18 °C for space cooling, derived from a wide range of air-conditioning systems collected by the CEP Laboratory [51]).

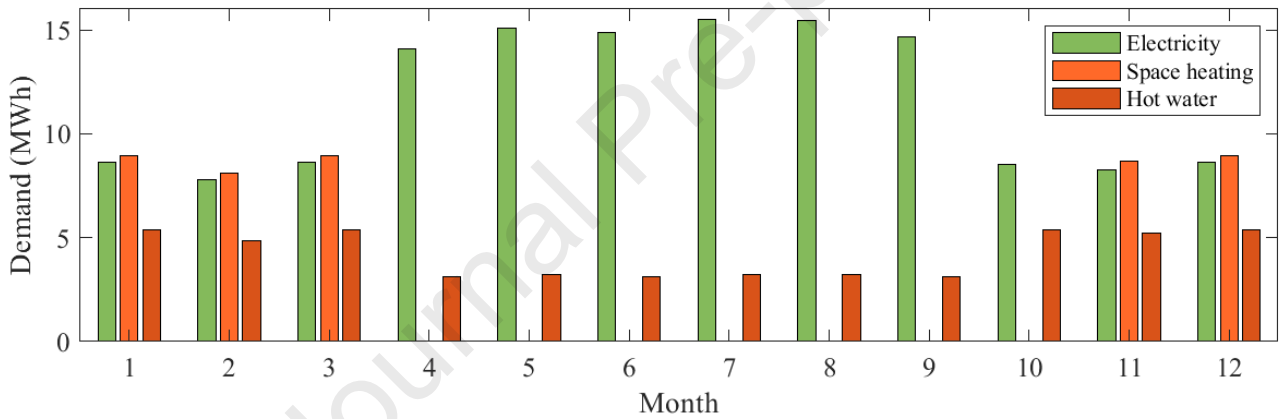


Figure 7. Modified monthly demands for electricity and heating of the selected hotel in Fayoum.

The hotel with a fully electrified energy supply scenario is considered as the benchmark case in this study. The proposed HRES configurations are evaluated relative to this baseline to quantify the benefits of integrating onsite renewable energy generation in terms of electricity demand reduction, cost savings and carbon emissions reduction.

3.3 Conditions and assumptions

The main conditions and assumptions considered in the present study are listed below:

- (1) The maximum area for the solar field is 150 m² and the maximum number of WTs is 12 considering the available space/area of the hotel building for renewable technology installation.
- (2) The buying and selling prices of electricity are 0.062 \$/kWh and 0.056 \$/kWh, respectively, based on the local data in Fayoum.
- (3) The efficiency of existing electrical heaters is assumed to be 0.98.
- (4) The required temperatures for hot water and space heating are set to 55 °C and 35 °C, respectively.

- (5) Cotton stalk is used as biomass fuel, with a heating value of 17.1 MJ/kg and a price of 19.5 \$/ton, based on local data gathered in Fayoum.
- (6) Half-hourly demand profiles are measured and given as inputs for the models, along with local weather conditions (solar irradiance, wind speed and ambient temperature).

4. Results and discussion

Sensitivity analysis of solar field area and number of WTs are performed, along with optimisation based on NPC to determine the optimal sizing of the proposed HRESs with different renewable technologies and product options ~~are performed in this section~~. A modified system layout is also proposed for further performance improvements, within which the hotel's demands for hot water and space heating are split and satisfied respectively by renewables (solar and biomass) and the hotel's existing air-conditioning system.

4.1 Wind turbine selection

Ten different types of WT are considered for complementary power generation with solar technologies (PV panels and PV-T collectors) in the proposed HRESs. Detailed information on the power output of each individual WT as a function of wind speed, based on datasheets obtained from manufacturers is provided in Section 2.2.

As WTs operate individually from solar power generation, the selection of the optimal type can be determined based on techno-economic performance, rated power curves shown in Figure 2, wind speed profiles and WT costs. Figure 8 shows that Skystream-3.7 delivers the lowest LCOE at 0.30 \$/kWh across all the considered options thanks to its lowest capital cost per kW. Therefore, this type of WT is selected for all the proposed HRESs, while the number of installed WTs needs to be optimised depending on the specifics of the case study.

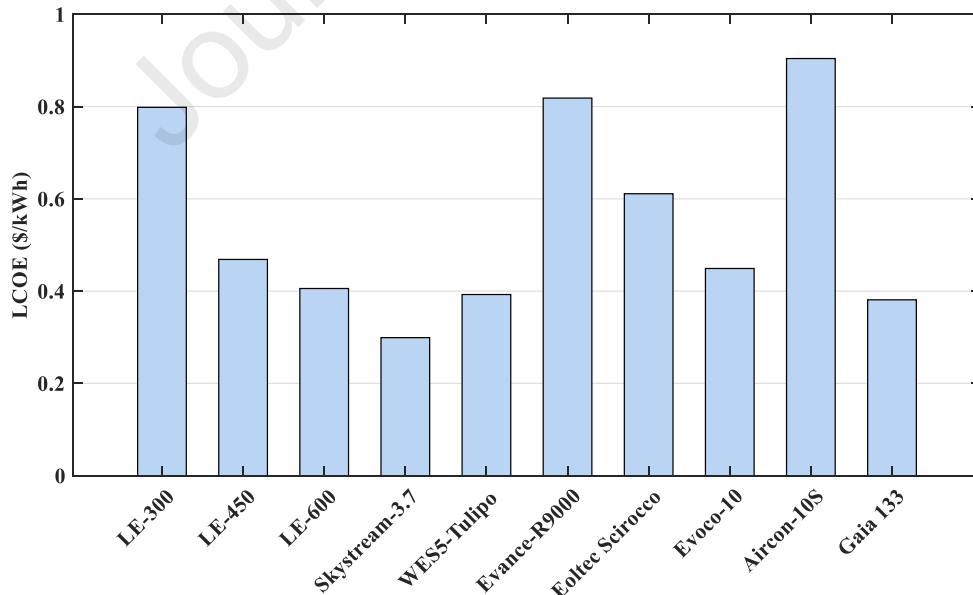


Figure 8. LCOE of considered WTs listed in Table 1, based on power curves, wind speed profiles and WT costs.

4.2 Solar technology selection and system sizing

PV panels, STCs and PV-T collectors are selected for solar energy utilisation (generating electricity and/or thermal energy) in the proposed HRESs, and various product options for each solar technology are also considered for comparison purposes. Along with Skystream-3.7 already selected as the WT option and a BB to ensure that the heating demand can be satisfied by renewables (solar and biomass), three types of HRES configurations are proposed in this study: (1) PV+WT+BB, (2) STC+WT+BB, and (3) PV-T+WT+BB systems. This section focuses on the selection of solar energy technologies and product options, along with optimal sizing of different HRES configurations. The solar field area to install solar panels/collectors and the number of Skystream-3.7 WTs are varied to address the HRES performance at different sizes. Such analysis allows comparisons at a technology level (i.e., comparison of performance of HRESs with PV panels, STCs or PV-T collectors to indicate which solar technology is preferable given the weather conditions and demand profiles of the considered case study) and also at a component level (i.e., which product option under different solar technology categories is preferable to enable the corresponding HRES to deliver the optimal performance).

4.2.1 PV+WT+BB systems

Four types of solar PV panels (see Table 1), 285 Wp Mono, 370 Wp Cello NeON R, 275 Wp REC Peak Energy Module, and 355 Wp REC Peak2s Energy Module, are considered for PV+WT+BB systems. Taking the systems with 285 Wp Mono PV panels, i.e., the low-cost monocrystalline type, as an example (with Skystream-3.7 being the optimal WT type as mentioned above), Figure 9 presents the performance maps of SSR, NPC, NPV, LCOE, PBP, and carbon emissions.

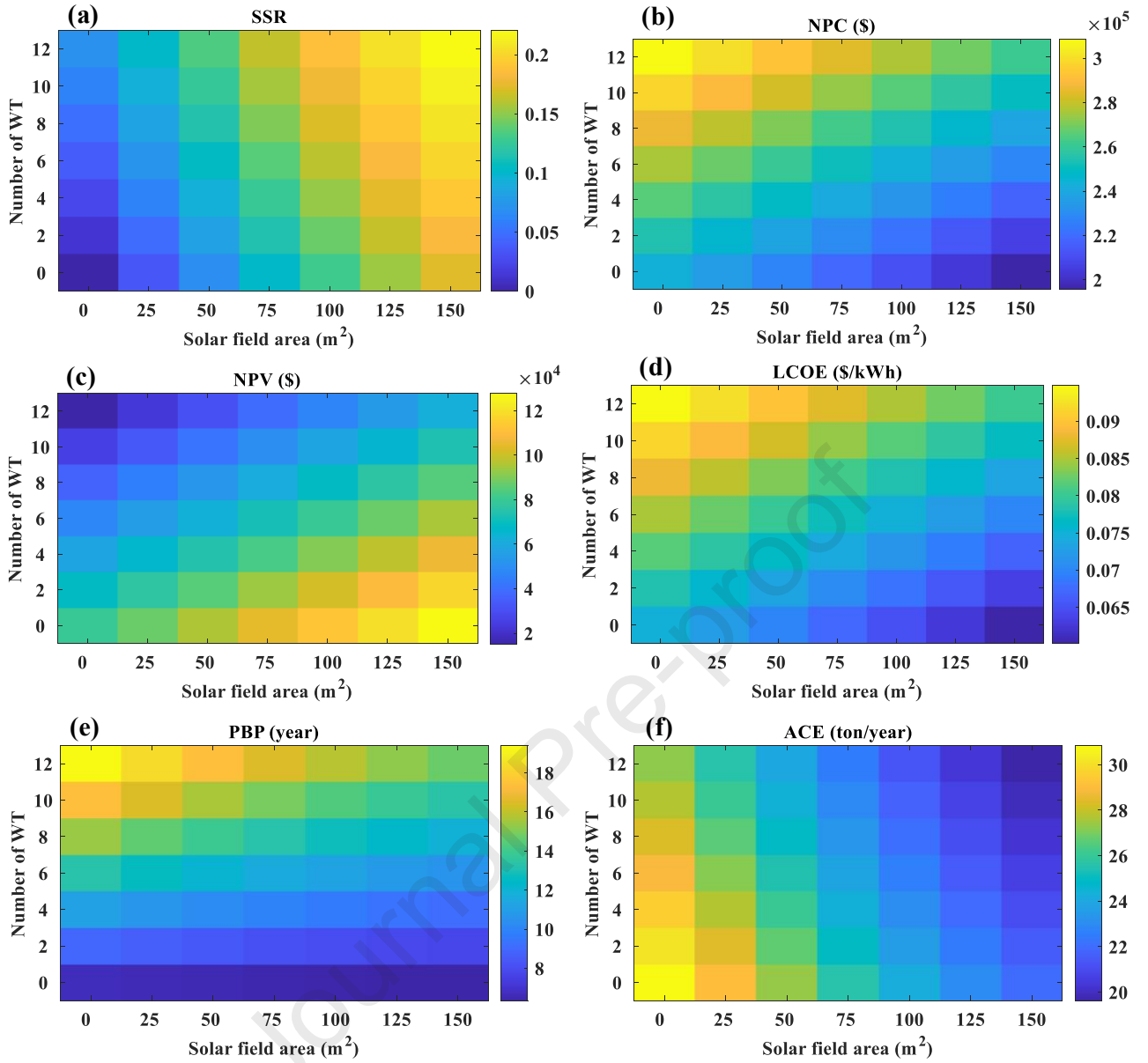


Figure 9. Performance maps of PV+WT+BB systems with 285 Wp Mono as solar PV panels, Skystream-3.7 WTs and a BB: (a) SSR, (b) NPC, (c) NPV, (d) LCOE, (e) PBP, and (f) ACE, considering various solar field areas and numbers of WTs.

As shown in Figure 9(a), increasing the installation of PV panels and WTs can increase SSR, and the highest value reaches 0.22 when the maximum area (150 m²) is utilised for solar PV and the maximum number (12) of WTs is selected. Figures 9(b) shows that NPC of the systems decreases with the solar field area while increases with the number of WTs, indicating that the utilisation of solar energy for electricity generation is more economically attractive than wind energy in Fayoum. The lowest NPC of \$195.7k is achieved when no WTs are installed, and the entire available area is installed with 285 Wp Mono solar PV panels, and the corresponding NPV is \$127.8k (see Figure 9(c)). It can be seen from Figure 9(d) that the LCOE shows the same variation trend with NPC, which further confirms that solar power generation is more preferable from the economic perspective. The lowest LCOE is 0.060 \$/kWh, which is lower/comparable to the local electricity buying price (0.062 \$/kWh) in Fayoum. This indicates that such HRESs are promising to be employed for the hotel and will be more

favourable if solar PV technologies are expected to witness a further cost reduction. As for PBP of the systems, Figure 9(e) shows that increasing the solar field area and decreasing the number of WTs allow a shorter payback. Again, the lowest PBP of 6.3 years can be obtained for an HRES with 150 m² of 280 Wp Mono PV panels and no WTs installed. For the environmental performance, Figure 9(f) shows that the system with the largest size/capacity (150 m² solar field and 12 WTs) yields ACE of 19.6 ton/year.

Similar variations in the performance indicators shown in Figure 9 are obtained for all the product options of PV panels listed in Table 1, while there is difference in the values, which is affected by the electrical efficiency and capital costs. In the interest of space and the length of the article, similar results for the HRESs with other product options of solar panels are presented in the Appendix (see Figures A1, A2 and A3).

Taking NPC as the optimisation objective, optimal sizing of PV+WT+BB systems with different types of solar PV panels is performed, with results shown in Table 2. It should be stated that the size of each system is optimised to achieve the lowest NPC, while the other performance indicators are calculated based on the same system size.

Table 2. Optimisation results and techno-economic-environmental performance indicators of PV+WT+BB systems with different types of solar PV panels. The size of each system is optimised to achieve the lowest NPC, while the other performance indicators are calculated based on the same system size.

Type of PV panels	285 Wp	370 Wp Cello	275 Wp REC Peak	355 Wp REC Peak2s
	Mono	NeON R	Energy Module	Energy Module
Solar field area (m ²)	150	150	150	150
Number of WTs	0	0	0	0
SSR	0.17	0.19	0.17	0.17
NPC (\$)	195.7k	203.3k	196.7k	195.9k
NPC reduction	40%	37%	39%	40%
NPV (\$)	127.8k	120.3k	126.8k	127.6k
LCOE (\$/kWh)	0.060	0.062	0.060	0.060
PBP (year)	6.3	8.2	6.2	6.4
ACE (ton/year)	22.1	21.1	22.3	22.0
ACE reduction	57%	58%	56%	57%

It can be seen that for all considered PV panels, the use of solar field area needs to be maximised as solar energy utilisation is economically attractive, while no WTs are to be installed. Therefore, all systems turn out to be PV+BB configurations. The system with 150 m² of 285 Wp Mono PV panels (the low-cost monocrystalline type) delivers the lowest NPC of \$195.7k, along with the highest NPC reduction of 40% relative to the hotel's current electrification scenario. Moreover, the highest NPV of \$127.8k, and the lowest LCOE of 0.060 \$/kWh are also obtained. Switching to the performance indicator of PBP, the system with 150 m² of 275 Wp REC Peak Energy Module PV panels (the low-cost polycrystalline type) outperforms across all the candidates, with the lowest PBP of 6.2 years. The system with of 370 Wp Cello NeON R PV panels (the high-cost monocrystalline type) provides the highest SSR of 0.19, and the lowest ACE of 21.1 ton/year, thanks to the highest electrical efficiency. A summary of the performance indicators corresponding to systems with the lowest NPC is shown in Figure 10, which

indicates that the selection of PV types, i.e., with different electrical performance/efficiency and cost, has a significant influence on the system performance.

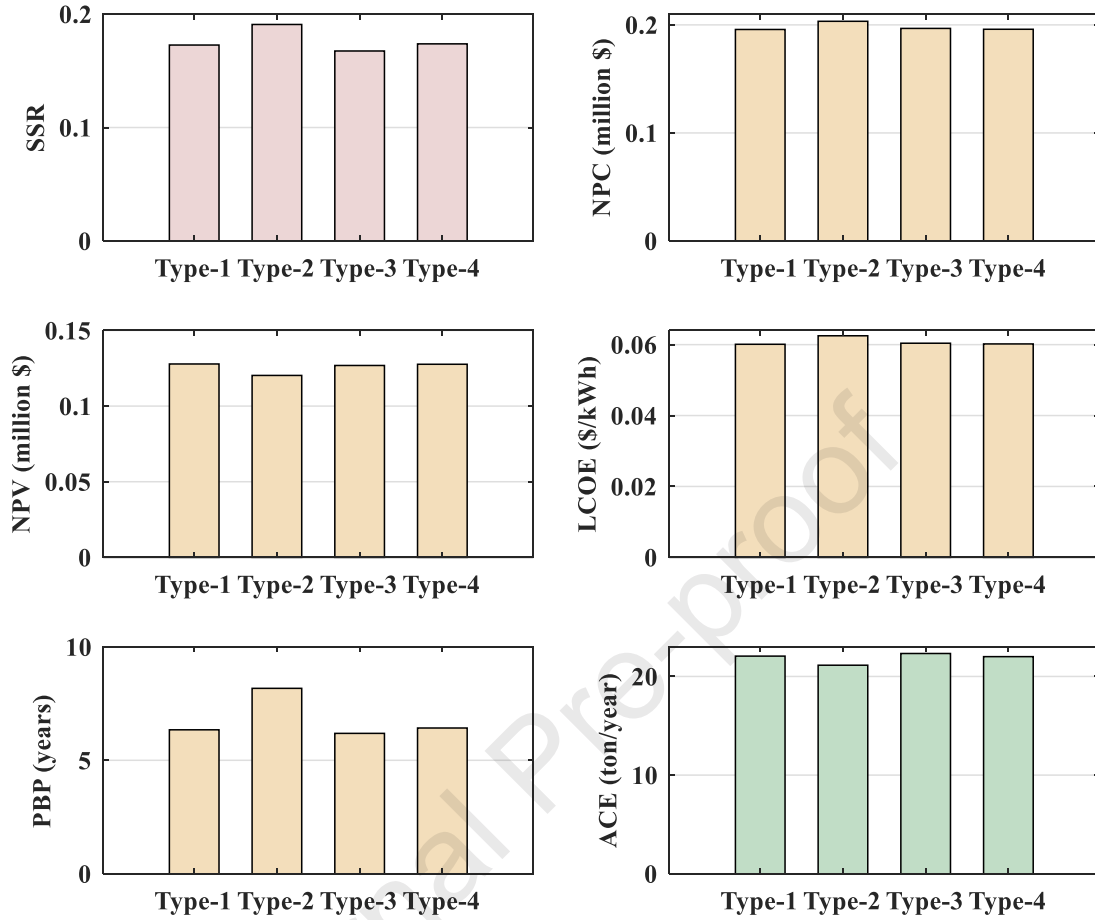


Figure 10. Techno-economic-environmental performance indicators of WT+PV+BB systems with different types of solar PV panels. The HRES size is optimised to achieve the lowest NPC for systems with each type of the PV panels, while the other indicators are calculated correspondingly. Type-1: 285 Wp Mono, Type-2: 370 Wp Cello NeON R, Type-3: 275 Wp REC Peak Energy Module, and Type-4: 355 Wp REC Peak2s Energy Module.

4.2.2 STC+WT+BB systems

Figure 11 shows STC+WT+BB system performance maps, in which Junker FCC-2S (the low-cost flat plate collector (FPC) type in Table 1) is selected as an example to show the variations in performance indicators across different system sizes. Interestingly, the highest SSR of 0.23 is achieved, which is slightly higher than that of the PV-based systems (see Figure 9(a)). This is because SSR in the present study is on an electricity basis, and the amount (absolute values) of thermal energy generated by STCs is typically higher than the electricity generated by PV panels.

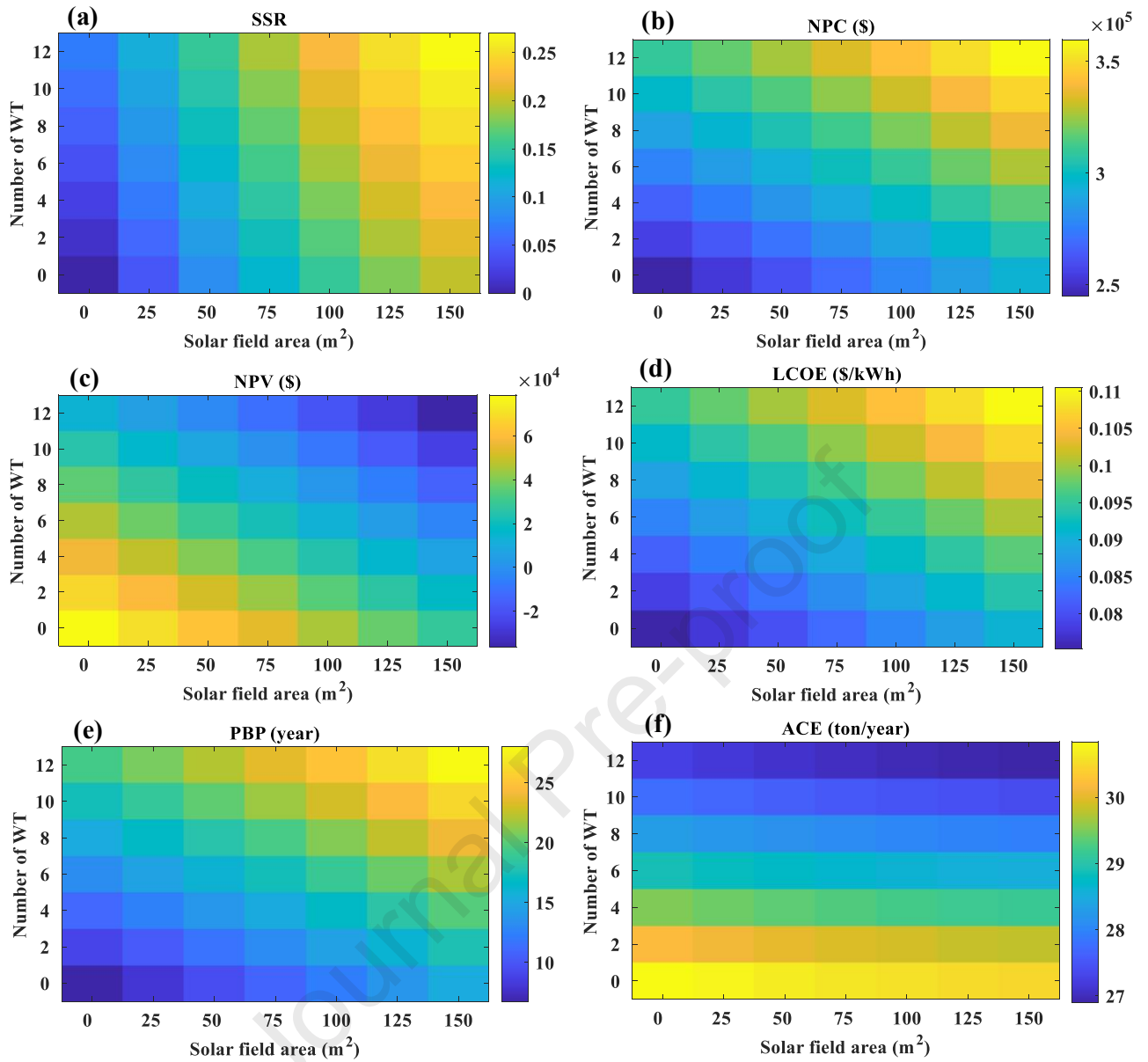


Figure 11. Performance maps of STC+WT+BB systems with Junkers FCC-2S as STCs, Skystream-3.7 WTs and a BB: (a) SSR, (b) NPC, (c) NPV, (d) LCOE, (e) PBP, and (f) ACE, considering various solar field areas and numbers of WTs.

In terms of all the economic indicators (NPC, NPV, LCOE and PBP, see Figures 11(b) to 11(e)), installing more STCs and WTs is not beneficial, which indicates that the STC+WT+BB systems are not economically promising and may not be considered for the hotel. As for the heating demand, it is more attractive to use biomass with a relatively low price (via the BB) rather than solar thermal energy (via STCs) in Fayoum. Figure 10(f) shows that the system with the largest size yields ACE of 27.0 ton/year, which is significantly higher than the PV+WT+BB systems (see Figure 9(f)). Although biomass fuel consumption is lower as the heating demand is partially satisfied by the thermal energy generated by STCs, while in these systems only WTs are utilised to generate electricity, more electricity needs to be purchased from the grid and this acts as a dominant factor in carbon emissions. Performance maps of alternative HRESs using other types of STCs are given, for comparison purposes, in the Appendix (see Figures A4, A5 and A6).

NPC is again taken as the key indicator and, thus, optimisation objective, to size the STC+WT+BB systems with different types of STCs, with results shown in Table 3. As expected from the performance maps, the best results are obtained by a configuration with only a BB (i.e., no STCs and WTs are installed). This is because of the low prices of electricity (compared to WTs for power generation) and biomass fuels (compared to STCs for thermal energy generation) in Fayoum, and therefore, extracting electricity from the grid and using biomass fuels are more economically attractive. The lowest NPC of \$245.0k is obtained for such BB systems, and the corresponding NPC reduction is 24%. The NPV is \$78.6k and the LCOE is 0.075 \$/kWh, while the PBP is 6.8 years, thanks to the system simplicity as only one BB needs to be installed. The ACE is 30.8 ton/year, which results in a reduction of 39% relative to the current state of the hotel.

Table 3. Optimisation results and techno-economic-environmental performance indicators of STC+WT+BB systems with different types of STCs. The size of each system is optimised to achieve the lowest NPC, while the other performance indicators are calculated based on the same system size.

Type of STC	Junkers FCC-2S / RemaSol C 250 H / Eurotherm-Solar 20R / Solarbayer CPC 14 Nero Brutto
Solar field area (m ²)	0
Number of WTs	0
SSR	0
NPC (\$)	245.0k
NPC reduction	24%
NPV (\$)	78.6k
LCOE (\$/kWh)	0.075
PBP (year)	6.8
ACE (ton/year)	30.8
ACE reduction	39%

4.2.3 PV-T+WT+BB systems

PV-T collectors can generate both electricity and useful thermal energy from the same aperture area as PV panels and can deliver much higher overall (electrical + thermal) efficiencies than separate standalone systems and have been considered in a variety of applications [52-55]. PV-T Ecomesh polycarbonate flat-box PV-T collectors (the low-cost type in Table 1) are taken as a representative of the PV-T+WT+BB systems, with performance maps shown in Figure 12. PV-T collectors generate electricity and thermal energy simultaneously, and therefore a higher SSR can be achieved by PV-T+WT+BB systems relative to PV- and STC-based systems. With the maximum solar field area utilised and maximum number of WTs installed, the highest SSR reaches 0.44. Similar to the PV-based systems, solar energy utilisation by PV-T collectors is more economically favourable than wind energy utilisation using WTs, evidenced by the results shown in Figures 12(b) to 12(d). The NPC decreases, the NPV increases, and the LCOE decreases when more PV-T collectors and fewer WTs are installed. Figure 12(e) shows that the PBP increases when the system size is enlarged, which is due to the high capital costs of PV-T collectors and WTs (comparing to the low prices of electricity and biomass fuels in Fayoum). The economic benefits of employing PV-T collectors in the proposed HRESs are not significant at the current stage relative to the PV-based systems due to the high cost, while the environmental performance

of the PV-T-based systems is slightly better thanks to the hybrid electricity and thermal energy generation. HRES performance maps with other PV-T collectors are given in the Appendix (see Figure A7).

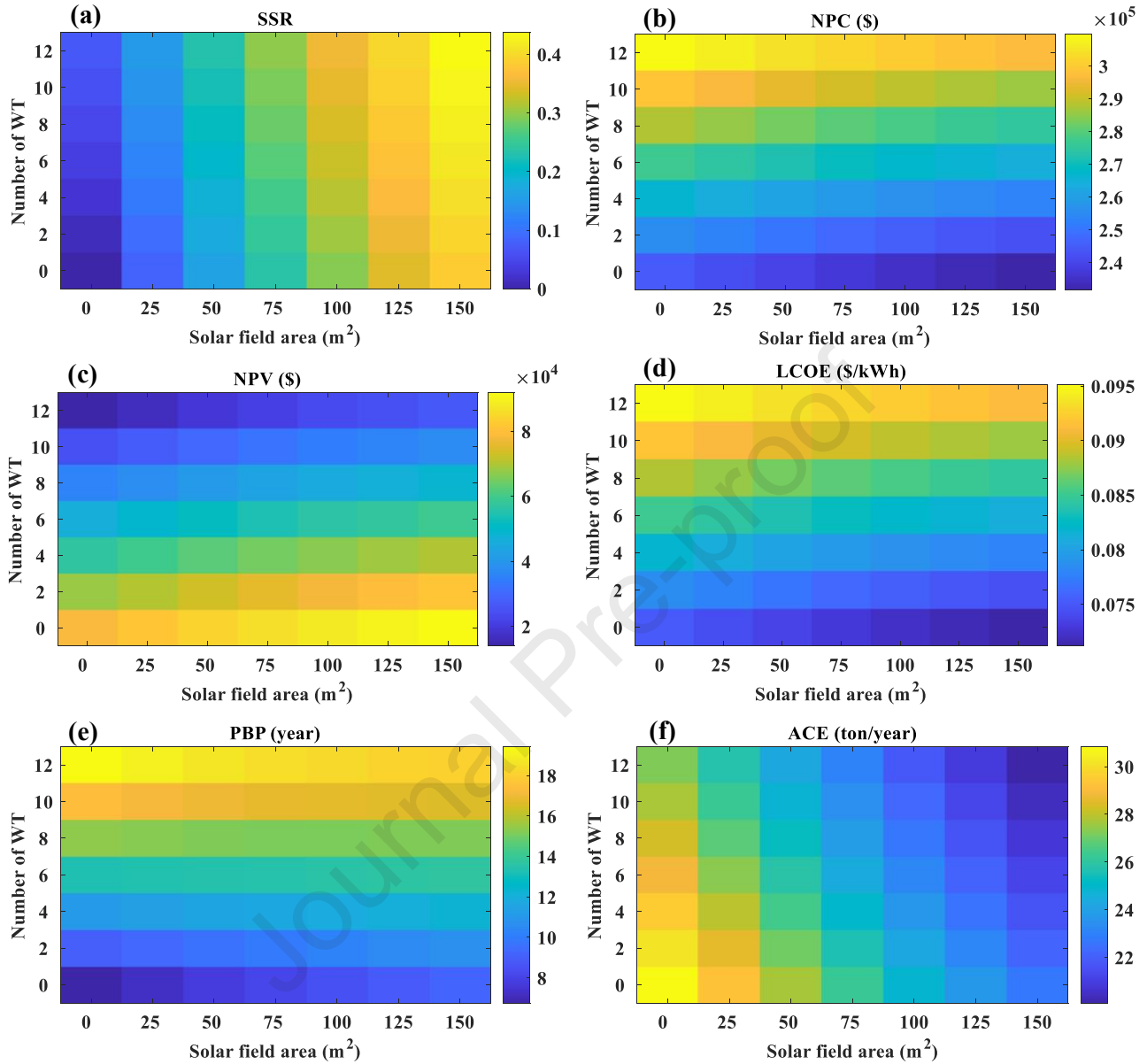


Figure 12. Performance maps of PV-T+WT+BB systems with Ecomesh polycarbonate flat-box PV-T collectors, Skystream-3.7 WTs and a BB: (a) SSR, (b) NPC, (c) NPV, (d) LCOE, (e) PBP, and (f) ACE, considering various solar field areas and numbers of WTs.

Similar to the analysis above, the NPC is considered as the optimisation objective to determine the optimal system size. The results in Table 3 show that WTs are still not recommended for the systems with PV-T collectors. Comparing the two types of PV-T collectors, the optimal sizing of system with Ecomesh covered flat-box type (the low-cost option) requires the total available solar array area to be utilised, while the high cost of Ecomesh covered sheet-and tube PV-T collectors hinders their application in the present case study. The HRES with Ecomesh covered flat-box PV-T collectors delivers better economic performance, evidenced by a lower NPC of \$231.7k, along with a decrease of 28% in NPC comparing to the existing system in the hotel. The NPV is \$91.9k and the LCOE is 0.071 \$/kWh, respectively. The PBP of this system is 9.2 years,

which is longer than the PV-based systems, as the price of PV-T collectors is currently higher on the market. The ACE is 22.7 ton/year, leading to a reduction of 55%.

Table 4. Optimisation results and techno-economic-environmental performance indicators of PV-T+WT+BB systems with different types of PV-T collectors. The size of each system is optimised to achieve the lowest NPC, while the other performance indicators are calculated based on the same system size.

Type of PV-T	Ecomesh covered flat-box PV-T	Ecomesh covered sheet-and-tube PV-T
Solar field area (m ²)	150	0
Number of WTs	0	0
SSR	39%	0
NPC (\$)	231.7k	245.0k
NPC reduction	28%	24%
NPV (\$)	91.9k	78.6k
LCOE (\$/kWh)	0.071	0.075
PBP (year)	9.3	6.8
ACE (ton/year)	22.7	30.8
ACE reduction	55%	39%

4.2.4 Comparative analysis

Optimal HRES configurations with different solar technologies achieving the lowest NPC can be obtained via the optimisation and analysis above. The convergence curves of different solar-based systems via TLBO, as well as the optimality verification are shown in Fig. A8 (Appendix). Since WTs are less preferable due to high capital costs, they are included in the configurations explored here. Similarly, STCs are not included as the cost of biomass fuels in Fayoum is low. Therefore, a PV+BB system with 150 m² of 285 Wp Mono PV panels, a BB system (corresponding to STC-based systems, but no STCs are considered), and a PV-T+BB system with 150 m² of Ecomesh covered flat-box PV-T collectors, are selected for comparison.

A summary of the corresponding performance indicators is provided in Table 5. WTs and STCs are less preferred, given the low prices of electricity and biomass fuels as discussed above. Between the PV- and PV-T-based systems, the latter have the highest SSR, and the former are associated with a better economic performance (including lowest NPC), mainly due to the much lower current prices of PV panels relative to those of PV-T collectors. From an environmental perspective, the PV- and PV-T-based systems are similar and deliver significant emissions reductions (56±1%), with ACE of ~22.4±0.3 kgCO₂/kWh.

It should be noted that the environmental performance of these different HRES configurations is highly context dependent; here, it is strongly affected by the relatively low ratio between the heat and power demands of the hotel considered in the case study, which is based in a geographical region where the demand for (electrified via an existing system) cooling dominates those for hot water and space heating. The relative performance of the HRES systems is influenced by local grid emissions intensity, resource availability and technology characteristics. Considering that the market readiness levels of PV-T collectors are much lower than PV panels, a significant potential for further technical improvements on PV-T collectors as well as cost reduction can be expected in the near future, which can contribute to wider applications of PV-T technologies [56-58].

Table 5. Summary of optimisation results and techno-economic-environmental performance indicators of HRESs. The size of each system is optimised to achieve the lowest NPC, while the other performance indicators are calculated based on the same system size.

System configuration	PV+BB	BB	PV-T+BB
Solar field area (m ²)	150	0	150
Number of WTs	0	0	0
SSR	0.17	0	0.38
NPC (\$)	195.7k	245.0k	231.7k
NPC reduction	40%	24%	28%
NPV (\$)	127.8k	78.6k	9.19k
LCOE (\$/kWh)	0.060	0.075	0.071
PBP (year)	6.3	6.8	9.2
ACE (ton/year)	22.1	30.8	22.7
ACE reduction	57%	39%	55%

4.3 Modified system layout

In this section, a modified system is proposed whose layout is defined in the schematic diagram in Figure 13. In this system, the hotel's demands for hot water and space heating are split and satisfied respectively by renewables (solar and biomass) and the hotel's existing air-conditioning system. In other words, the air-conditioning system is used for space heating during the winter period, and the thermal energy generated from renewables is only used for hot water provision in the hotel.

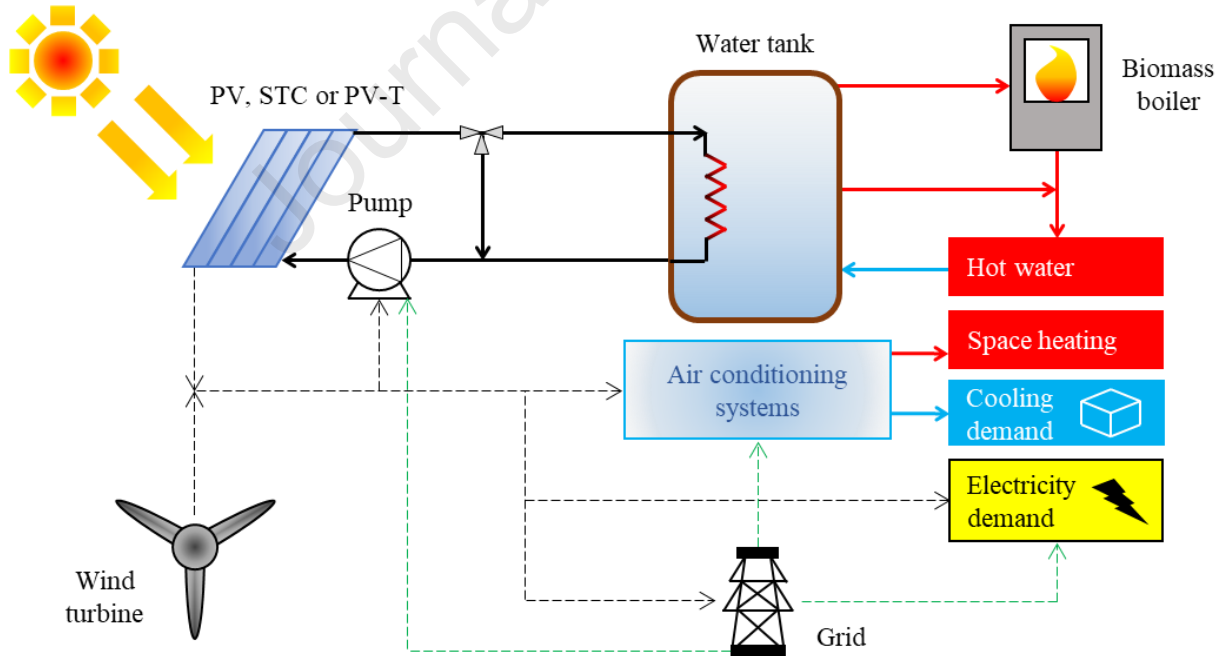


Figure 13. Schematic diagram of a modified HRES layout that splits the heating provision into hot water and space heating, which are satisfied by renewables (solar and/or biomass) and the hotel's existing air-conditioning system, respectively.

Similar to the cooling demand, the demand for space heating is also shifted to electricity and added to the demand for electrical energy, using the performance curves of air-conditioning systems for heating (see

Figure 14). In this way, the total electricity demand is increased, and therefore, less electricity will be fed/sold to the grid when the generation from the HRESs is higher than the demand. Another benefit arises from the BB, as: (1) the biomass fuel consumption will be reduced, and (2) the rated power/capacity of the boiler can also be reduced to save the capital cost. Moreover, the retrofit costs will also decrease as only the sub-system and pipelines for hot water supply need to be changed, instead of changing the space heating system as well (this is out of the scope of the present study, and the potent cost reduction is not considered here).

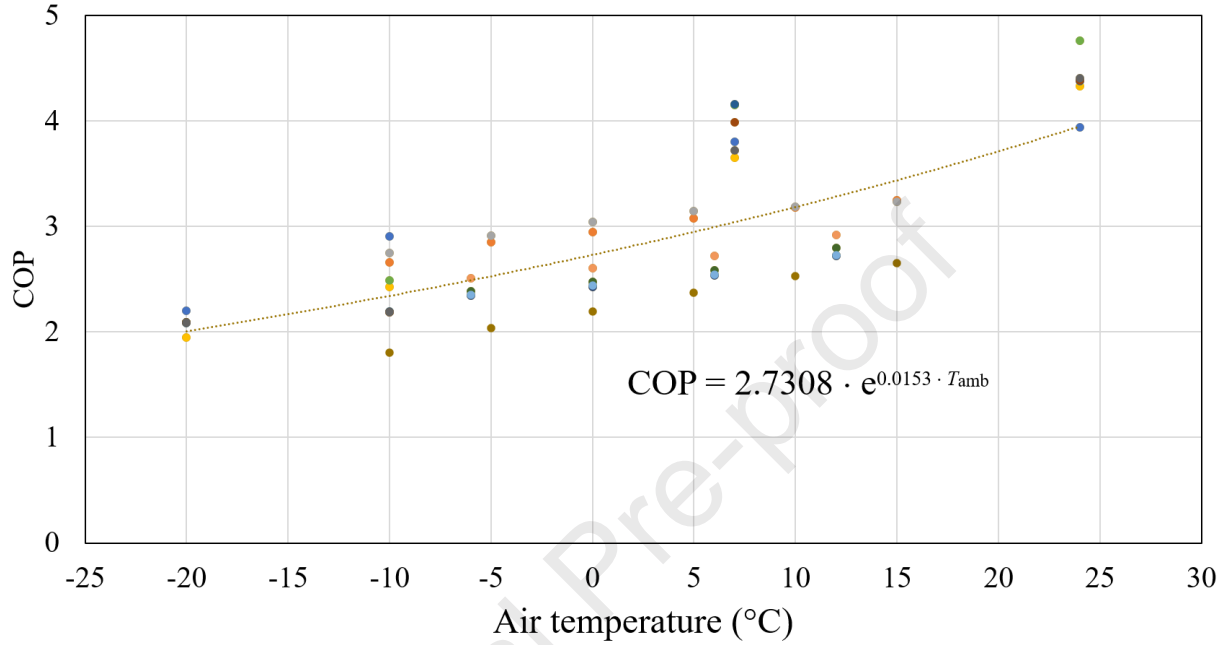


Figure 14. Performance curves of air-conditioning systems (air outlet temperature of 27 °C for space heating, derived from a wide range of air conditioning systems collected by the CEP Laboratory [51]).

Optimal sizing of the modified systems is also performed to achieve the lowest NPC, using the same analytical approaches above for the original ones. The results are summarised in Table 6 as well as shown in Figure 15, along with the original systems (from Table 5) for comparison purposes. It can be seen that although the modification of the system layout does not change the optimal sizing of the HRESs and the selection of technologies and components, all modified systems deliver better performance than the original systems as expected. Taking the PV-based HRES as an example, the NPC of the modified system is \$176.8k, which is 10% lower than the original system, the LCOE decreases by 10% from 0.060 to 0.054 \$/kWh, and the PBP decreases by over 40% from 6.3 to 3.4 years. At the same time, SSR of this system improves slightly from 17% to 18%. From a practical implementation perspective, this modified HRES layout reduces biomass boiler capacity and fuel consumption, lowering both capital and operating costs, as well as improving energy supply security. It also simplifies retrofit implementation, as only the hot water subsystem requires integration with renewable heat sources. This improves the feasibility of deploying hybrid renewable energy systems in existing (similar and other commercial) buildings. Overall, the PV-T-based HRES attains the highest SSR (40%), the PV-based alternative achieves the best economic performance, and the environmental performance of these two remains similar although slightly higher than the original systems (by ~8%).

Table 6. Techno-economic-environmental comparison of different system configurations. The size of each system is optimised to achieve the lowest NPC, while the other performance indicators are calculated based on the same system size.

System configuration	PV+WT+BB		STC+WT+BB		PV-T+WT+BB	
	Original	Modified	Original	Modified	Original	Modified
Solar field area (m ²)	150	150	0	0	150	150
Number of WTs	0	0	0	0	0	0
SSR	0.17	0.18	0	0	0.38	0.40
NPC (\$)	195.7k	176.8k	245.0k	226.4k	231.7k	213.9k
NPC reduction	40%	45%	24%	30%	28%	34%
NPV (\$)	127.8k	146.8k	78.6k	97.2k	91.9k	109.7k
LCOE (\$/kWh)	0.060	0.054	0.075	0.070	0.071	0.066
PBP (year)	6.3	3.4	6.8	2.0	9.2	6.2
ACE (ton/year)	22.1	23.7	30.8	33.1	22.7	24.7
ACE reduction	57%	54%	39%	35%	55%	52%

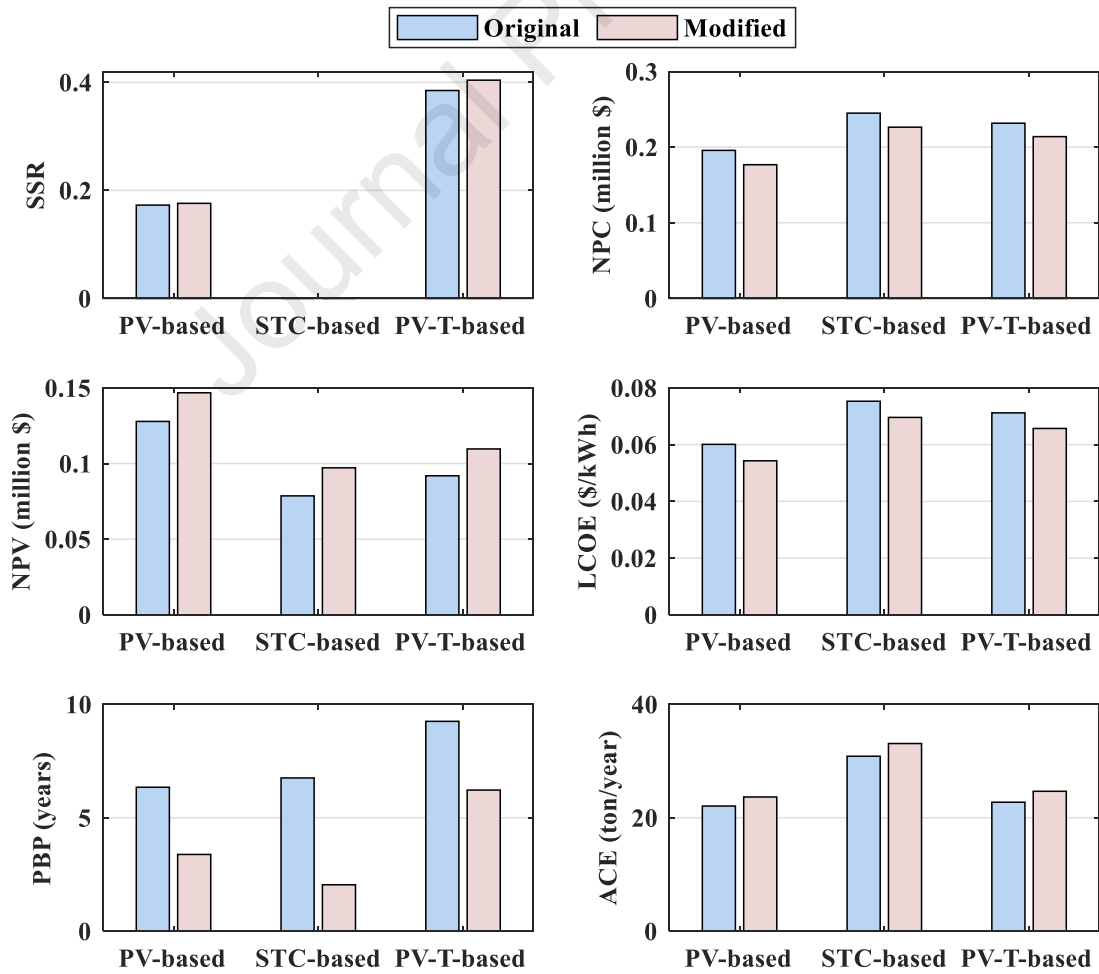


Figure 15. Key performance indicators of different system configurations. The HRES size is optimised to achieve the lowest NPC, while the other indicators are calculated correspondingly.

5. Conclusions

In this study, we propose hybrid renewable energy system (HRES) configurations based on photovoltaic (PV) panels, solar thermal collectors (STCs), PV-thermal (PV-T) collectors, wind turbines (WTs) and biomass boilers (BBs) for combined cooling, heating and power provision. Specifically: (1) PV+WT+BB, (2) STC+WT+BB, and (3) PV-T+WT+BB systems are designed as effective integrated options for the utilisation of solar, wind and biomass resources for a hotel in Fayoum, Egypt. The hotel currently operates based on an electrification scenario, and the HRESs aim to reduce the electricity consumption as well as enhance the use of renewables.

We have developed comprehensive models, with a list of renewable energy technologies and product options (i.e., with different performance and costs) available on the market as candidates for the HRESs, to address the research gap of techno-economic-environmental comparisons of HRESs with different types of technologies and product options, as well as performance across different scales (i.e., sizes/capacities).

The results show that PV panels, especially low-cost options, are preferable for inclusion in the proposed HRESs from an economic perspective, while WTs and STCs are less suitable, due to the low prices of local electricity and biomass fuels. The PV-based HRES that utilises the maximum solar field area (150 m²) delivers the optimal economic performance, evidenced by the lowest net present cost (NPC) of \$195.7k. The corresponding levelised cost of energy (LCOE) is 0.060 \$/kWh, payback period (PBP) is 6.3 years, and annual carbon emissions (ACE) is 22.1 ton/year. The optimal PV-T-based system yields higher NPC (\$231.7k), LCOE (0.071 \$/kWh) and PBP (9.2 years). From an environmental perspective, the PV- and PV-T-based systems are similar, delivering significant emissions reductions (>50%). Considering that this system achieves the highest self-sufficiency ratio (SSR) of ~40%, and that the market readiness level of PV-T collector technology is lower than that of PV panels with ongoing R&D efforts showing a significant potential for further technical improvements as well as cost reductions, this hybrid solar technology remains attractive given that even at present it outperforms HRES alternatives based on mature STCs.

A modified HRES layout that splits the heating provision into hot water and space heating satisfied by renewables (solar and biomass) and the hotel's existing air-conditioning system, is also proposed. The performance of this system is appreciably improved, with results showing that a decrease of 10% in NPC relative to the original PV-based HRES is obtained, and the LCOE decreases from 0.060 to 0.054 \$/kWh, and the PBP decreases from 6.3 to 3.4 years. The performance improvement arises from a smaller boiler, lower biomass consumption and less electricity fed/sold to the grid.

The proposed HRESs as well as the analytical approaches can provide valuable guidance for component selection and optimal design of such systems to promote the utilisation of renewables. In future research, additional hybridisation options will be considered, including solar absorption chillers and biomass tri-generation to match the cooling demand. Integration with advanced energy storage options, will also be addressed, along with advanced operation and control strategies.

Acknowledgements

This work was supported by an Institutional Links grant, ID 352350650, under the Newton-Mosharafa Fund partnership. The grant was funded by the UK Department for Business, Energy and Industrial Strategy and the Science and Technology Development Fund, and delivered by the British Council. For further information, please visit www.newtonfund.ac.uk. Data supporting this publication can be obtained on request from cep-lab@imperial.ac.uk. For the purpose of Open Access, the authors have applied a CC BY public copyright license to any Author Accepted Manuscript version arising from this submission.

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Appendix

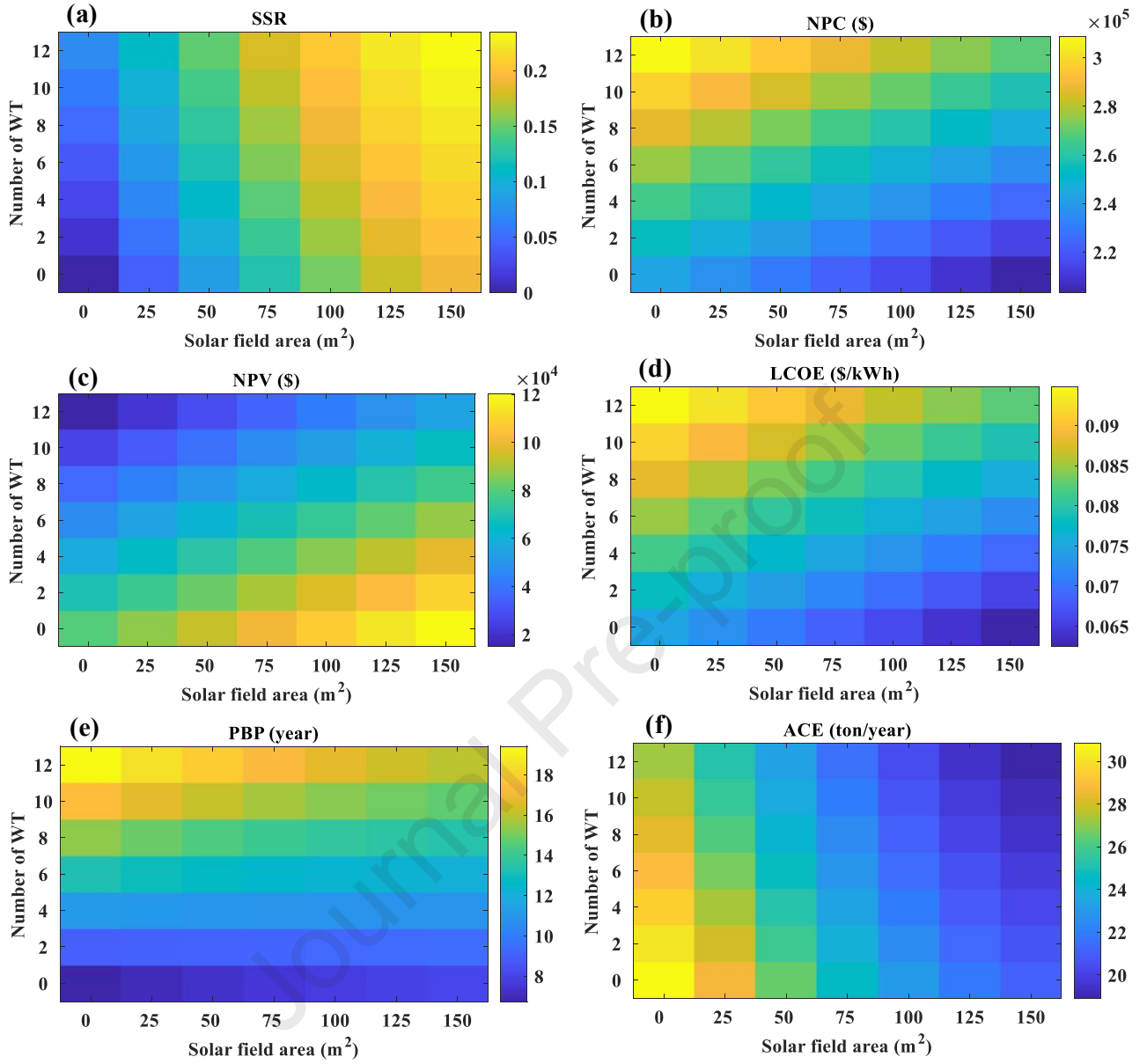


Figure A1. Performance maps of PV+WT+BB systems with 370 Wp Cello NeON R as solar PV panels, Skystream-3.7 WTs and a BB: (a) SSR, (b) NPC, (c) NPV, (d) LCOE, (e) PBP, and (f) ACE, considering various solar field areas and numbers of WTs.

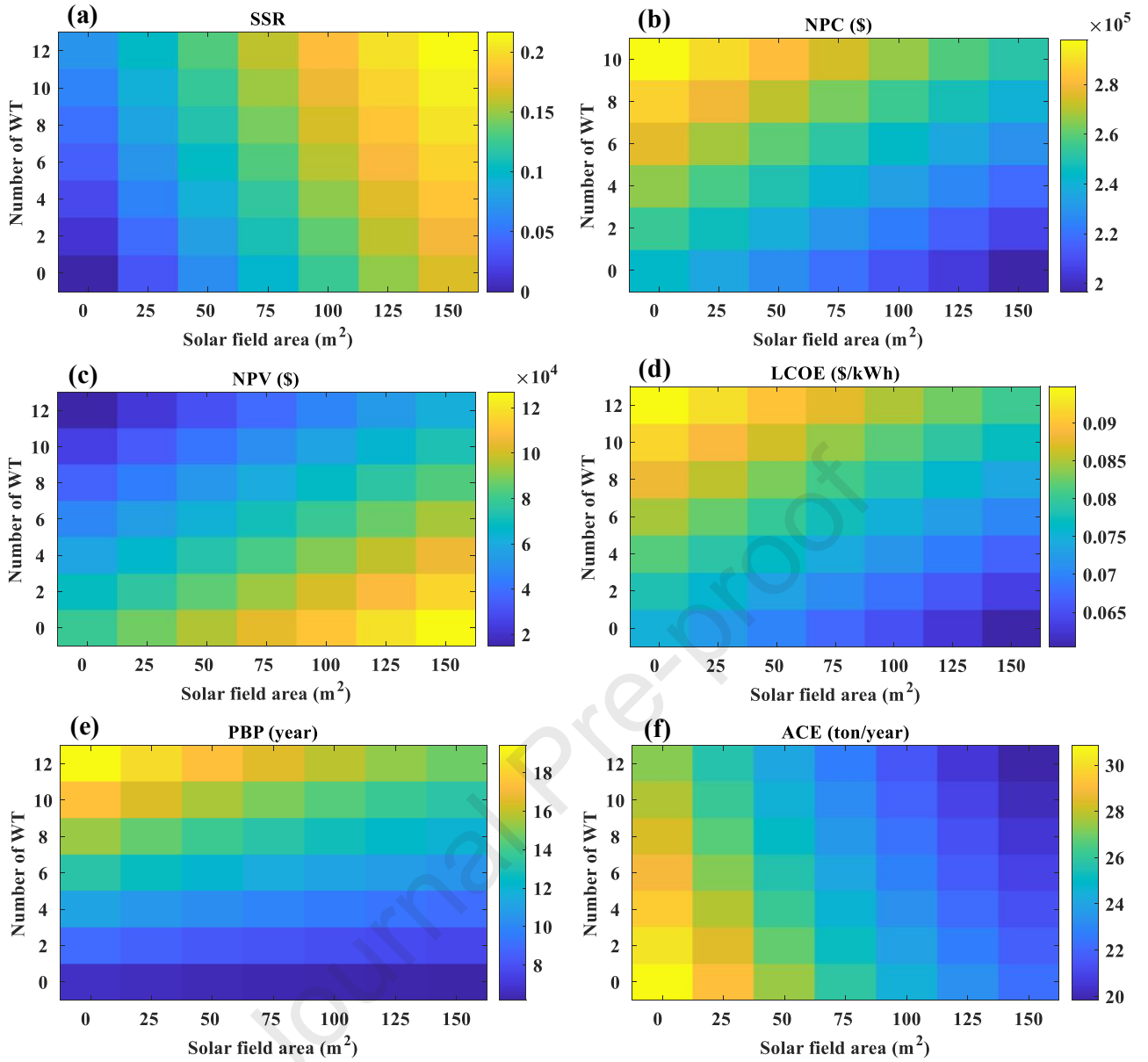


Figure A2. Performance maps of PV+WT+BB systems with 275 Wp REC Peak Energy Module as solar PV panels, Skystream-3.7 WTs and a BB: (a) SSR, (b) NPC, (c) NPV, (d) LCOE, (e) PBP, and (f) ACE, considering various solar field areas and numbers of WTs.

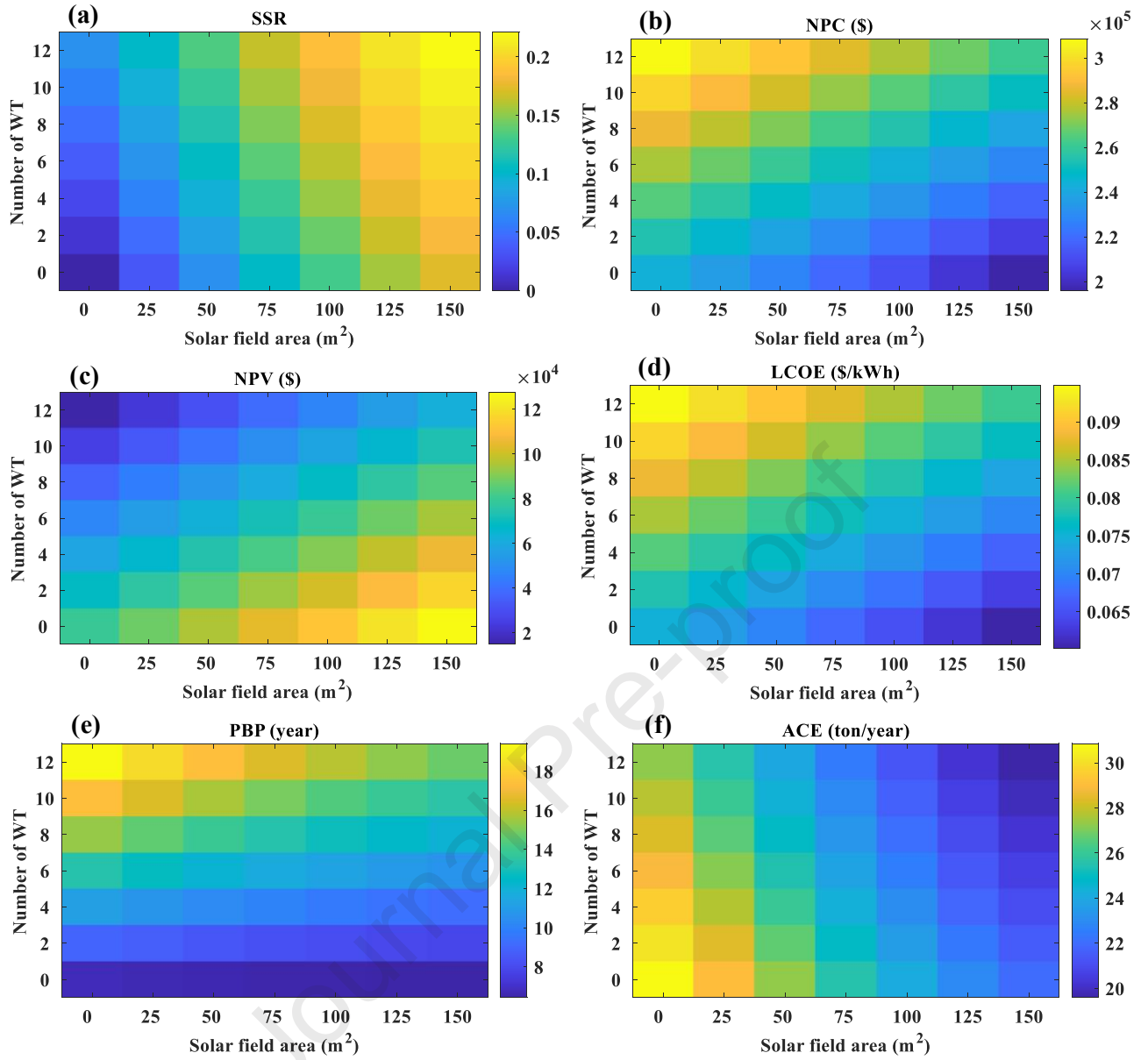


Figure A3. Performance maps of PV+WT+BB systems with 355 Wp REC Peak2s Energy Module as solar PV panels, Skystream-3.7 WTs and a BB: (a) SSR, (b) NPC, (c) NPV, (d) LCOE, (e) PBP, and (f) ACE, considering various solar field areas and numbers of WTs.

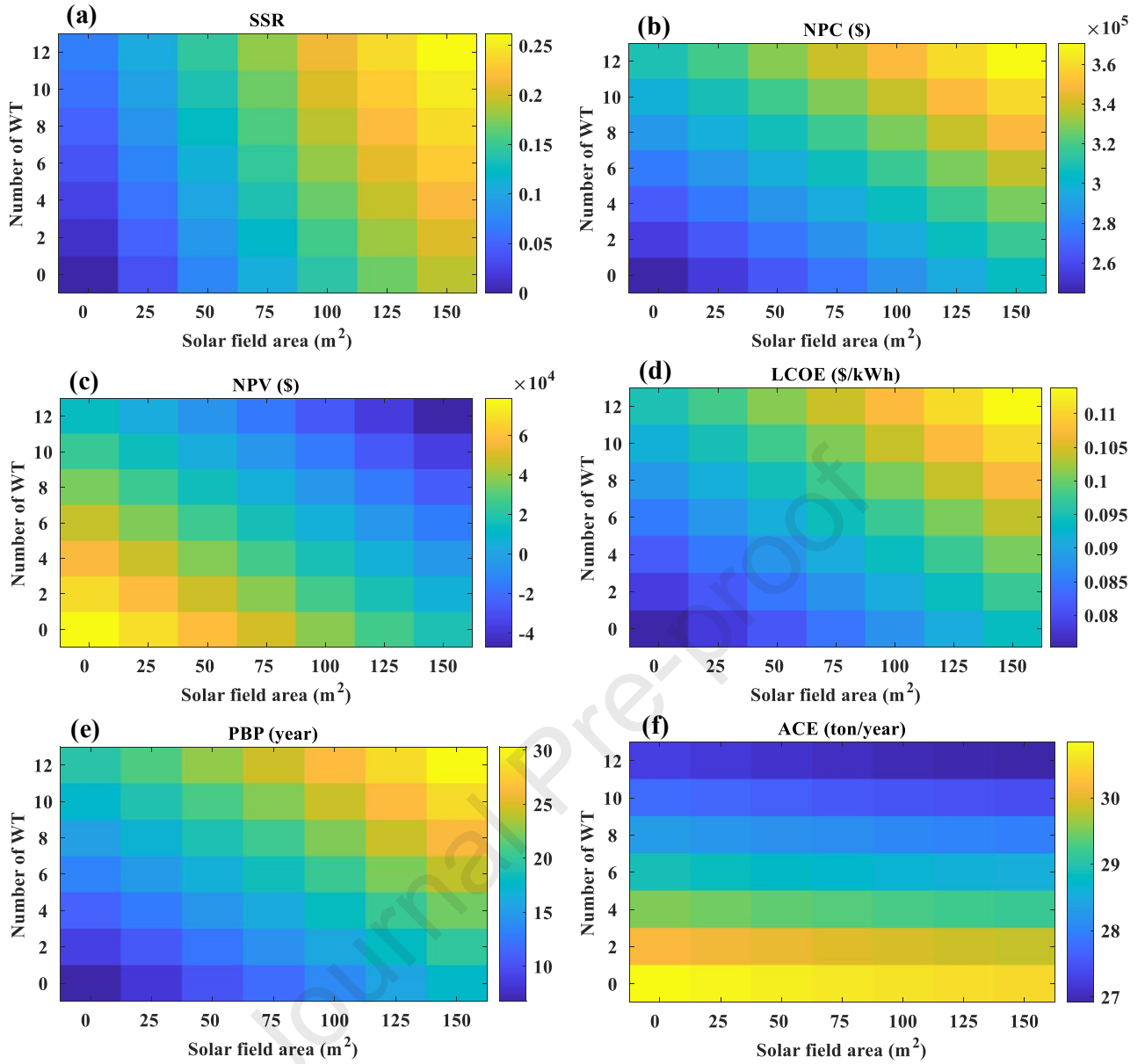


Figure A4. Performance maps of STC+WT+BB systems with RemaSol C 250 H as STCs, Skystream-3.7 WTs and a BB: (a) SSR, (b) NPC, (c) NPV, (d) LCOE, (e) PBP, and (f) ACE, considering various solar field areas and numbers of WTs.

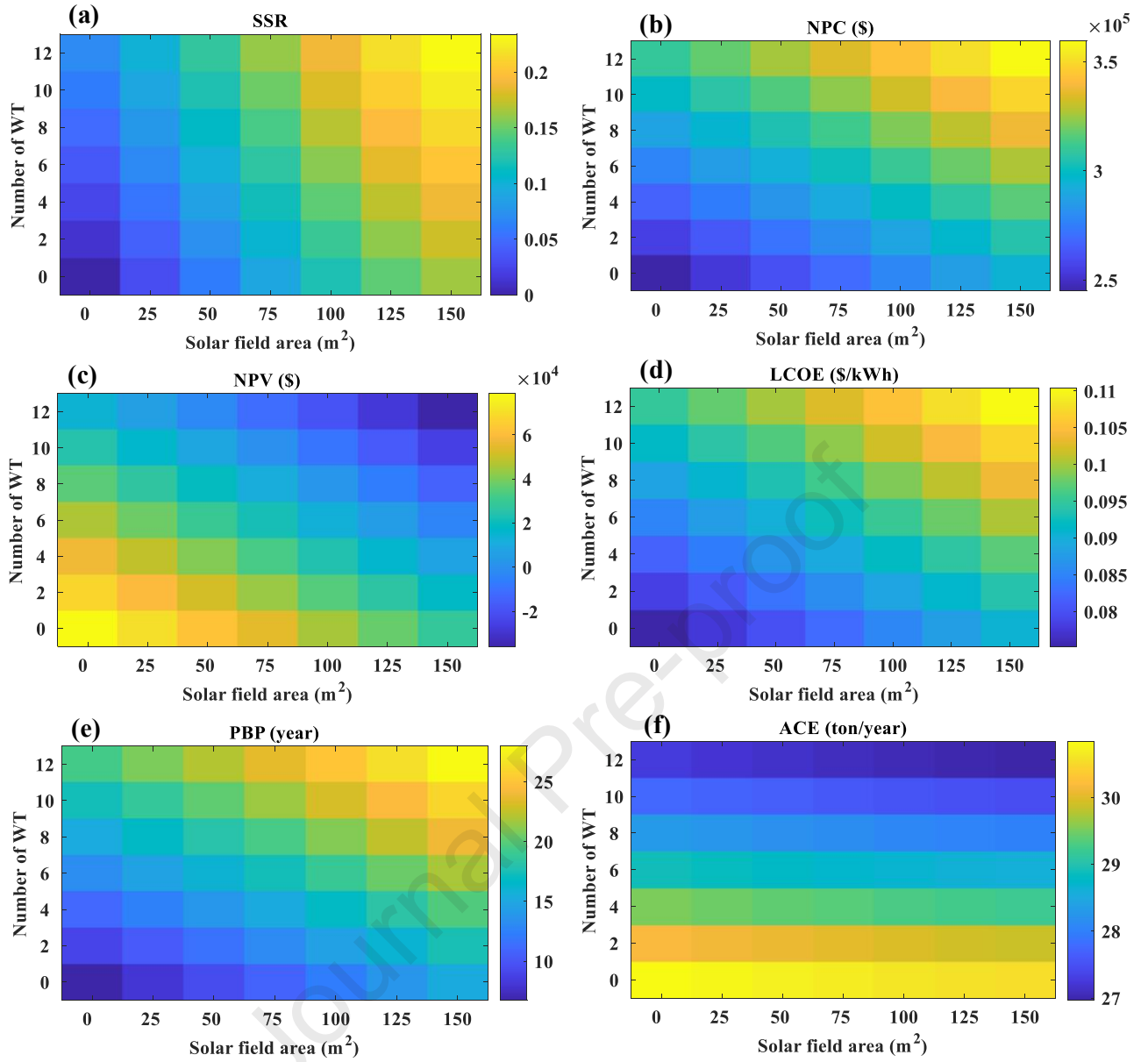


Figure A5. Performance maps of STC+WT+BB systems with Eurotherm-Solar 20R as STCs, Skystream-3.7 WTs and a BB: (a) SSR, (b) NPC, (c) NPV, (d) LCOE, (e) PBP, and (f) ACE, considering various solar field areas and numbers of WTs.

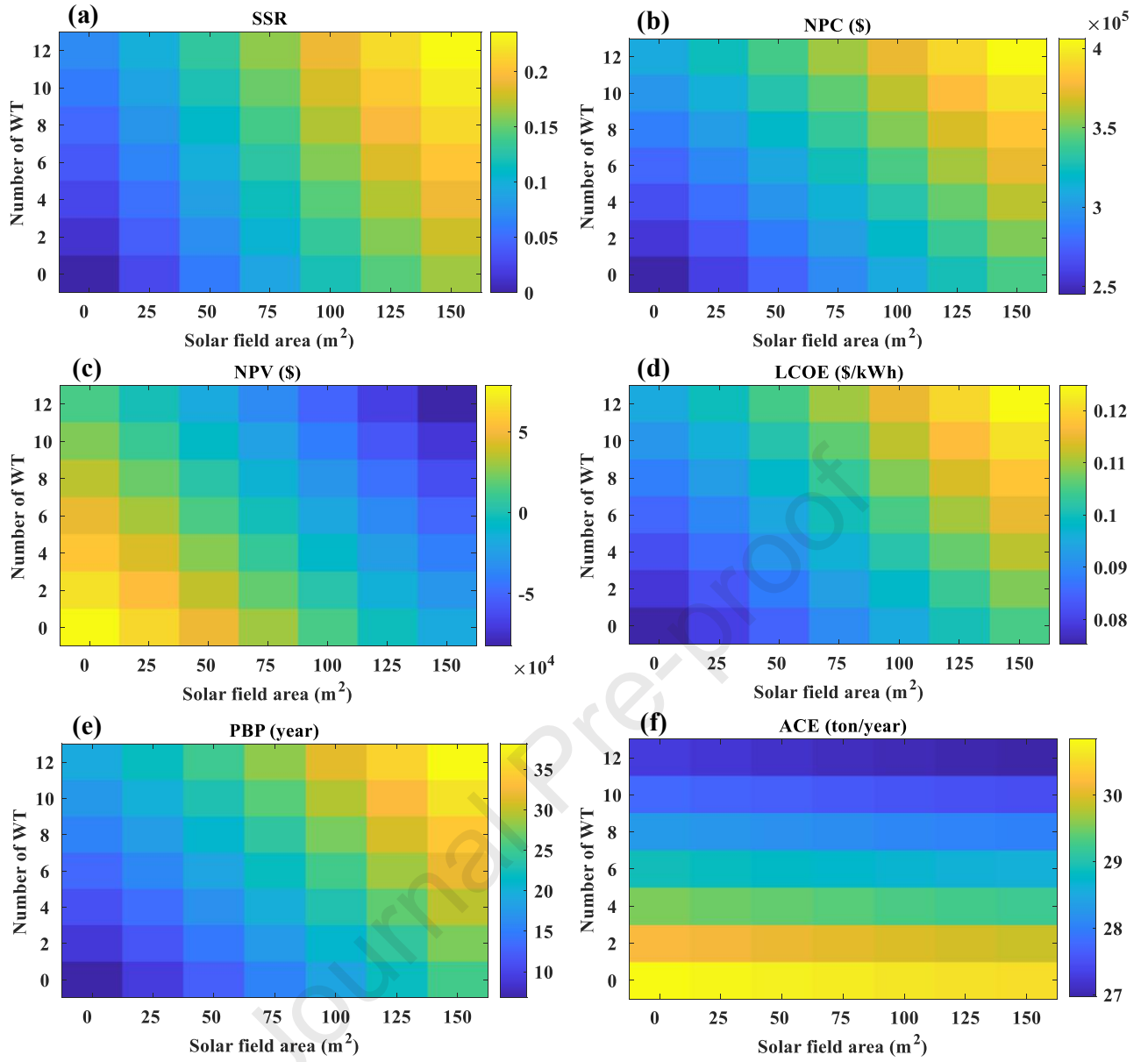


Figure A6. Performance maps of STC+WT+BB systems with Solarbayer CPC 14 Nero Brutto as STCs, Skystream-3.7 WTs and a BB: (a) SSR, (b) NPC, (c) NPV, (d) LCOE, (e) PBP, and (f) ACE, considering various solar field areas and numbers of WTs.

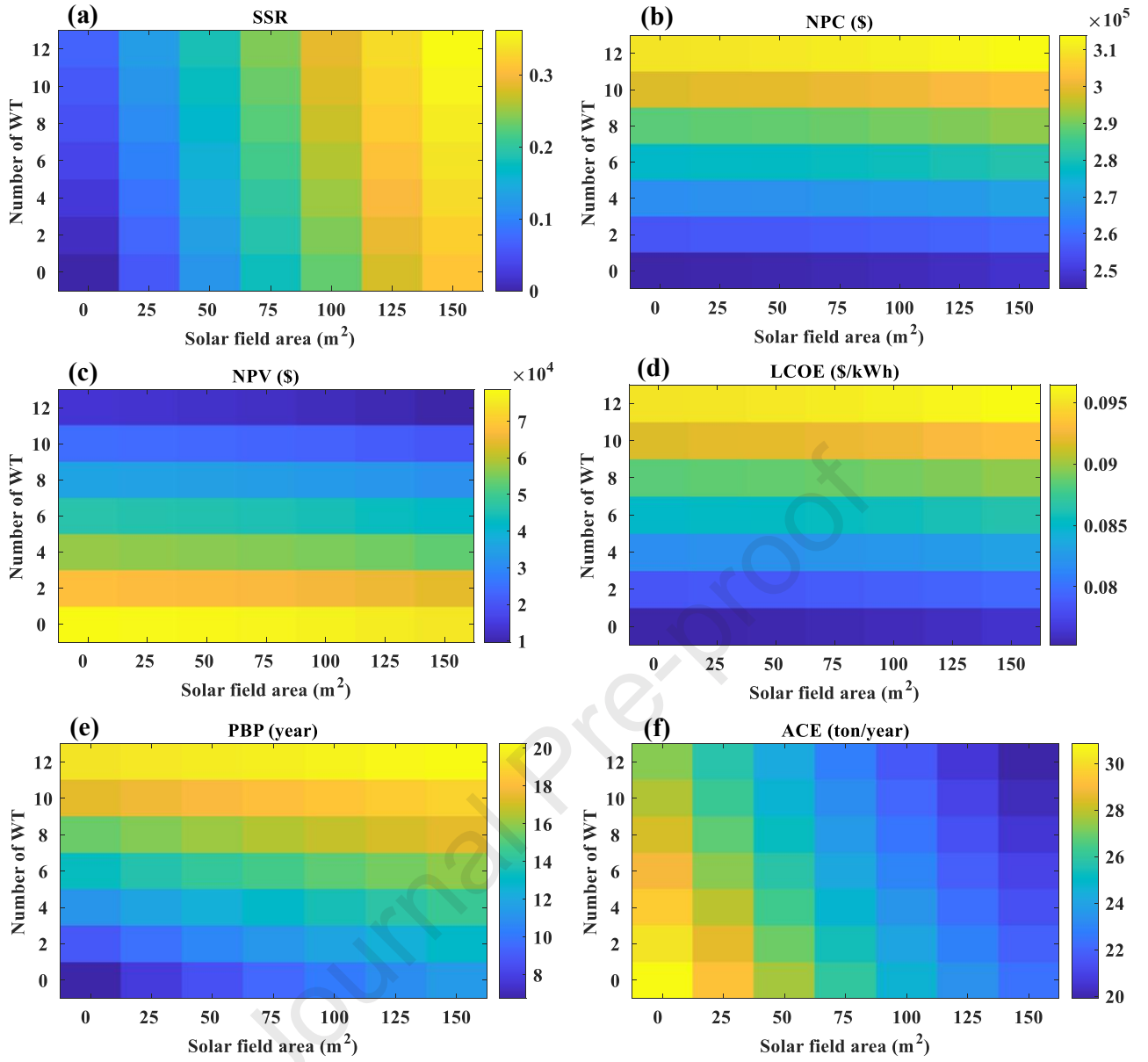


Figure A7. Performance maps of PV-T+WT+BB systems with Ecomesh covered sheet-and-tube PV-T collectors, Skystream-3.7 WTs and a BB: (a) SSR, (b) NPC, (c) NPV, (d) LCOE, (e) PBP, and (f) ACE, considering various solar field areas and numbers of WTs.

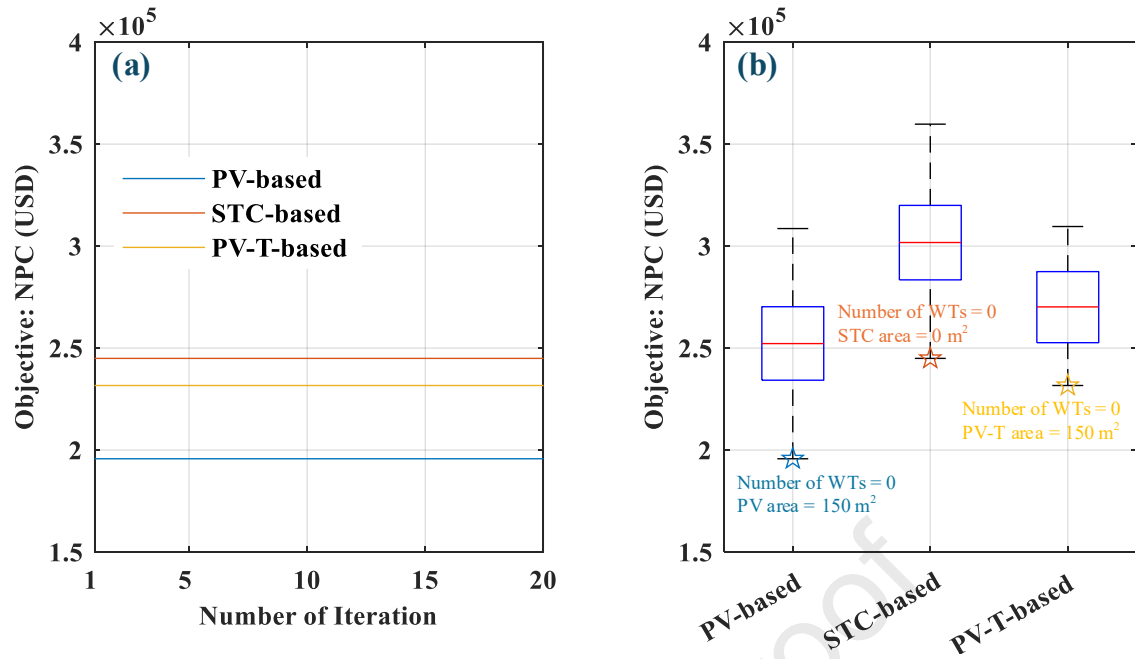


Figure A8. (a) Convergence curves of the different solar-based systems, and (b) optimality verification of the TLBO algorithm using the enumeration method. In figure A8(a), the optimization processes converge efficiently after the 1st iteration, as the optimal decision variables for different systems locate at the upper or lower bounds of the decision space, which enables them straightforward to be found. In figure A8(b), the enumeration method evaluates all integer decision variables, with the number of WTs ranging from 0 to 12, and the solar field area ranging from 0 to 150 m². The boxplots show the NPC of all possible decision variables, and the star markers denote the TLBO-derived optimal solution. This figure indicates that the optimal solutions obtained by TLBO consistently lie at the lower bound of all possible NPCs for each system, thus verifying the global optimality of the solutions.

Highlights

- HRESs with various technology and product options proposed for CCHP
- Comparative techno-economic-environmental investigation to obtain optimal design
- PV panels, especially low-cost options, enable HRESs' favourable performance
- Lowest NPC of \$195700, LCOE of 0.060 \$/kWh and payback period of 6.3 years achieved
- Modified layout benefits from lower costs and higher electricity self-consumption

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: