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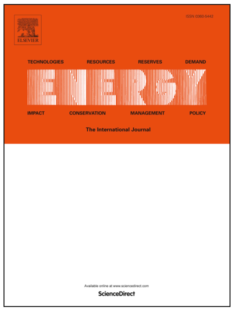

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Sustainable conversion of light to algal biomass and electricity: A net energy return analysis

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Abstract

A substantial interest is growing in the cultivation of microalgae as a source of biofuel production, considering their relatively high lipid content, fast growth rates, use of alternative water sources, and growth on non-arable land. This paper conducts an energy life cycle analysis for a novel hypothetical hybrid energy system where the electricity required for microalgae cultivation is generated from semi-transparent PV panels to energise paddle wheels and light emitting diodes installed on raceway ponds. The combined system configuration allows for a full utilisation of the solar spectrum, while enhancing the photosynthetic productivity of microalgae cultivation and reducing the evaporation from raceway ponds. The findings of study for a hypothetical system installed in Western Australia show that the amount of land use substantially decreases by 43%, the productivity of microalgae cultivation increases by 75%, while the net energy return of the system remains significantly higher than one, in comparison with a microalgae cultivation system energised by grid electricity. Among a range of variables affecting the energy performance of the proposed system, the primary energy demand for PV panels and conversion efficiency of LEDs exert the highest impact on energy life cycle of the system.

Keywords: energy life cycle, microalgae cultivation, net energy return, solar panels, light emitting diodes

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1. Introduction

The production of microalgae as a source of chemical energy has received a substantial scholarly attention, primarily due to fast growth rates and relatively high lipid content of microalgal biomass product in comparison with terrestrial crops [1-4]. Macroalgal high polysaccharides and low lignin contents also make these organisms attractive feedstocks for production of liquid biofuels via fermentation and biogas production via anaerobic digestion[5]. These properties make microalgae a potential substitute for replacing some of the fossil fuels required to meet worldwide energy demand growth in the coming decades. Despite being technically viable to produce microalgal based energy products, the commercial and environmental viability of the technology still requires improvement [6, 7]. The challenges to enhance sustainable production and utilisation of the microalgae technology include, but are not limited to, optimal selection of microalgae species type in terms of productivity and biomass composition, which in turn is significantly determined by the differences in photosynthetic efficiency, minimisation of evaporative loss, and lifecycle energy requirements of the cultivation and extraction processes [3].

Blue and red spectra are the most effective portion of light in the process of photosynthesis. In general, 48% of sunlight is in the range of photosynthetic active radiation (PAR) with only 16% in the blue and red portion. This means that a large portion of the light energy is wasted when reaching the microalgal ponds. This waste energy can negatively affect photosynthesis and cause high evaporation rate [8]. This paper conducts an energy life cycle analysis for a novel hypothetical hybrid energy system where the electricity required for microalgae cultivation is generated from semi-transparent PV panels (ST-PVs) to energise raceway ponds paddle wheels and light emitting diodes (LEDs) installed on the ponds. With such integrated system configuration, the photosynthetic productivity of microalgae is enhanced, while the evaporation from raceway ponds can be significantly reduced due to the removal of infra-red light. The energy and environmental cost (including land use) of artificial light generation and microalgae cultivation is reduced by the application of ST-PV panels. In effect, in the hybrid energy system proposed solar energy is stored in chemical form (i.e. biomass), while the productivity of microalgae cultivation is enhanced substantially via the enhanced LED light-induced photosynthesis. A comparison is made with similar system scenarios energised with grid electricity, conventional PVs, and/or operated without artificial light sources to highlight the significance of integrating the cultivation system with ST-PV panels and LEDs. The concept lends itself to operations in remote areas of temperate regions of the world with low availability of freshwater but accessibility to seawater such as the northern part of Western Australia, which is suited for large-scale microalgal biomass production [9]. Such areas normally have very limited access to grid electricity, where the transportation of liquid fuels is a costly option.

Although in the outdoor cultivation of microalgae sunlight is used as a free resource without environmental implications [10], it is well established that the natural sunlight is not optimized for algal cell growth due to the wide light spectrum including ultra-violet (UV) and infrared red (IR) rays, which can damage the cellular structure [11] and increase evaporation in ponds [8]. Photoinhibition of photosynthesis can be observed at high irradiance (above 500 μmole photons.$m^{-2}s^{-1}$) [12]. This phenomenon is observed in many areas in Australia suitable for outdoor microalgae cultivation [9]. The application of filtered lights at a particular spectrum – blue light between 420 and 470 nm and red light between 650 and 680 nm – is considered beneficial to microalgae cultivations [13]. As such, to improve the photosynthetic productivity of microalgae, an artificial light source with selective spectral exposure such as LEDs can be used. Among the current light sources, LEDs are small in size, cheap, and relatively efficient, while they generate less amount of heat with high lifetime expectancy [14]. Moreover, the spectral output of LEDs is highly matched with photosynthetic needs. Numerous studies have been conducted on the applicability of LEDs to optimal cultivation of microalgae. There has been a range of previous studies that have investigated the effect of various LEDs with different light spectra and illumination intensities on the laboratory-scale cultivation of microalgae species

[15-20].[a] Previous studies by Vadiveloo and Moheimani et. al [21] provide a review of the effect of light quality on *Nannochloropsis* sp. growth. They find that the application of LEDs (with red and/or blue spectra) provided enhancement in photosynthetic efficiencies (and/or lipid production) depending on various operating conditions and microalgae types. Blanken and Cuaresma [22]study the economics of utilising LED lighting in the production of microalgae and concluded that, unless for high-value biomass products, the elevated system costs and energy losses question the viability of using artificial light sources.

This paper builds upon an earlier proposed integrated microalgae and electricity production system by Moheimani and Parlevliet [8]. They introduce a combination of ST-PV panels for electricity generation and microalgae cultivation for biomass production so that the system makes an efficient use of available land and solar energy. ST-PV panels are used as a light filter above the microalgae culture in outdoor raceway ponds to modify the light spectrum received by microalgae culture, where the remaining part of solar irradiance is converted to electricity by the ST-PV panels. The electricity generated is used to energise LEDs installed on raceway ponds to enhance the productivity of microalgae cultivation. In contrast to conventional photovoltaic modules, ST-PV offers the twin action of using a specific light spectrum for electricity generation, while allowing the light of specific wavelength to pass through. This light filtering attribute of ST-PV can be utilised for enhancing the photosynthetic efficiency of microalgae cultivations. ST-PV can be made out of crystalline or amorphous solar cells by various fabrication steps such as larger spacing between cells or modifying the layer characteristics. These are commercially deployed in building integrated PV systems [23] and within solar greenhouses [24]. A similar technology that works towards an ideal system is Tropiglass, which transmits visible light but captures infrared [25]. Luminescent solar concentrators, that rely on fluorescent materials to concentrate the light towards the edge of a semi-transparent panel [26] are a third possible technology. Considering the low conversion efficiency, from electricity

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[a] [13] Schulze PSC, Barreira LA, Pereira HGC, Perales JA, Varela JCS. Light emitting diodes (LEDs) applied to microalgal production. Trends in Biotechnology. 2014;32(8):422-30. provide a review of relatively recent literature studying the effects of LED illumination on the cultivation of different microalgae.

supplied to LEDs to biomass, in cultivation systems with artificial lighting, the generation of electricity via ST-PV panels has the potential to reduce the energy cost of the system in terms of the primary energy demand (PED), i.e. the consumption of useful energy sources from environment that can potentially be utilised in other processes. In effect, the supply of electricity from ST-PVs may alleviate one of the disadvantages of cultivation systems with artificial lighting as concluded by Blanken, Cuaresma [22][b]. Excessive heating of the microalgae culture is the major issue with closed photobioreactors [27]. Evaporative cooling is the most economical method for keeping the PBRs internal temperature below 25 °C. The lack of freshwater availability makes PBRs unsuitable for mass algal cultivation in many places with high solar radiation. A recent study using Tropiglass technology for building plate photobioreactor indicated a significant reduction in generated heat inside of the reactor when compared to unmodified glass [28].

A cradle-to-gate energy life cycle assessment is conducted in this paper to investigate the performance of the integrated microalgae cultivation and ST-PV panels in terms of net energy return (NER), i.e. the amount of energy invested in compare to the amount of energy produced in the system. We also provide details of land use for the proposed system. The hybrid system is compared with comparable microalgae cultivation systems to evaluate the advantages or disadvantages of the system. Moreover, uncertainty and sensitivity analyses are performed to evaluate the effect of uncertainty and variation in major system design parameters.

2. Method

A cradle-to-gate energy life cycle analysis is conducted for a set of hypothetical microalgae cultivation systems as shown in Figure 1. Note that the boundary of the system is defined based on the focus of this study on the cultivation stage. As such, the analysis does not include drying, extraction, and biodiesel production stages. The analysis includes the energy content/use of

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[b] The economic feasibility of the proposed system remains the subject of a further study currently conducted by the authors.

energy and material streams supplied to the system as part of system installation and operation phases. Note that we exclude the end-of-life energy requirements of the system such as the removal, recycle, or scrapping of the disused system. We also exclude non-significant energy flows, such as the preparation of microalgae culture and CO_2 injection to maintain our focus on those parts of the system that create most significant variations in the system NER.

Table **1** lists major parameters used in the design of microalgae cultivation systems. The underlying concept for the design of proposed systems is to analyse and compare the contribution of system components and/or processes towards the energy demand and supply of each system. In three scenarios, the hypothetical configurations develop from a conventional microalgae cultivation process to an algae-PV-LED hybrid system introduced in section 01:

(1) Baseline system (Base): microalgae are cultivated in raceway ponds with paddle-wheels and make-up water pump energised by electricity from the grid. Consideration is made for PED of the raceway pond assembly lining material, nutrients for cultivation process, and the electricity supplied from the grid (see Figure 1, Panel (a)).

(2) Algae-PV system (Algae-PV): building on the Base scenario, the electricity required for paddle-wheels operation and make-up water pumping in this scenario is assumed to be supplied from conventional PV panels installed separately from the raceway ponds. All other flows and components of the system are similar to the Base scenario (see Figure 1, Panel (a)).

(3) Algae-PV-LED system (Hybrid): in comparison with the Algae-PV scenario, LEDs are installed on the raceway ponds to increase the photosynthetic productivity of microalgae. The energy required for the operation of paddle-wheels and LEDs is supplied from ST-PV panels installed on top of all raceway ponds to enhance the photosynthetic productivity of microalgae. PED of the system, including for LEDs, is also considered for this scenario (see Figure 1, Panel (b)). In this scenario, the energy system is designed to operate in breakeven point in terms of electricity generation and consumption, i.e. electricity generated by PV panels is completely consumed by LEDs and other system processes using electricity.

To investigate the comparative life-cycle energy efficiency of the proposed microalgae cultivation scenarios, NER of the systems are estimated. NER is defined as the amount of energy delivered in biomass relative to the amount of useful energy consumed for the cultivation of microalgae (which is consistent with a published definition Hall, Lavine [29]), over the total life cycle of the system:

$$NER = \frac{\sum_{L} energy\ delivered}{useful\ energy\ consumed}$$

Where useful energy consumed represents the total energy (including renewable and non-renewable sources) consumed by the system over its lifetime, L. Energy input and output streams considered for the estimation of NER in this study are those related to the cultivation process as shown by the system boundaries in Figure 1. Similar to a previous study by Jorquera et al. [30], the energy requirements for the preparation of microalgae culture, CO_2 injection, biomass separation and drying, oil extraction and biodiesel production are excluded from the analysis. The objective of this study is to make comparisons among the hypothetical microalgae cultivation systems, henceforth, this paper does not focus on the evaluation of exact NER values for the purpose of sustainability analysis.

For each microalgae cultivation scenario, two system boundaries are considered to estimate NER. The boundaries are defined based on two specific perspectives:

(1) System boundary 1 (S.B. 1): Estimating NER regardless of energy conversion efficiency for comparison with other studies with similar definition of system boundary for NER evaluation

(2) System boundary 2 (S.B. 2): Maximization of biomass production (or energy production), while accounting for PED of the system. This is used as the main approach for the comparison of the system scenarios in this study.

The second perspective factors in the PED of systems and, in effect, includes energy conversion efficiencies such as the conversion efficiency of primary energy to electricity. It is notable that some studies do not consider this conversion efficiency [30] and as a result, NER values estimated by them should be interpreted with care when making comparisons (this bias in the evaluation of NER has been previously noted [30]).[c] The first perspective for the estimation of NER, ignores the energy conversion efficiency of the system, resulting in the energy content of biomass product to be directly compared with electricity consumption and the energy cost of materials used in the system.

Based upon the definitions of system boundary, for the Base scenario, energy input streams into the system boundary S.B.1 are the electricity for paddle wheel mixing and make-up water pumping, PED for nutrients, and the embodied energy of PVC sheets for raceway ponds assembly. For S.B. 2, the PED for the electricity supply from the grid, PED for nutrients, and the embodied energy of PVC sheets are considered as the inputs into the system (as shown in Figure 1, Panel (a)). As shown in Figure 2, Panel (a), for the Algae-PV scenario, energy input streams to S.B. 1 are electricity for paddle-wheel mixing and make-up water pumping, and the PED for nutrients and PVC lining. Primary energy input streams to S.B. 2 consist of the PED for electricity from PV panels and the PED of PVC sheets for raceway ponds assembly and nutrients.

Productivity of microalgae cultivation, Y $(\mathrm{g/m^2.day})$, as a function of solar and artificial irradiance spectrum is estimated from Eq.1, based on solar irradiance at red and blue spectra,

$$Y = 6.625a[\alpha E_R + \beta(E_B + LED)] + b \tag{1}$$

where E_R and E_B $(\mathrm{MJ/m^2year})$ are total annual red and blue spectra of solar radiation, respectively. The constants used in Eq.1 are listed in Table 2.

The generalised model of microalgae growth in Eq.1 is derived from the model presented by Boruff, Moheimani and Borowitzka [9]over long-term in semi-continuous cultures, for outdoor raceway ponds in Western Australia. The irradiance-based productivity formula [6] is then adjusted based on productivity yields of microalgae under red and blue light spectra as presented in [21] to estimate the potential productivity of microalgae under different light

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[c] Note that depending on the objective of study a choice of system boundary similar to that presented by Jorquera et al. [27] can be theoretically correct.

spectra transmitted through ST-PV panels. Microalgae absorb strongly in the blue and red regions and do not respond to green light or infrared light. As such, the only portions that need to be considered in this calculation are the blue and red portions of the spectra transmitted to the culture and any additional blue light from the LEDs. Microalgae have been found to have different yields under different spectra of light[21]. These coefficients for red (α) and blue light (β) are included in the model in Eq 1. Finally, the model is adjusted to take into account that the blue and red portions of the spectra comprise only about 15% of the full spectrum.

The Hybrid scenario is run for a set of hypothetical ST-PV panels with transparency and electricity generation characteristics listed in Table 3. Different types of hypothetical ideal PV systems ranging from 0 to 100% threshold, have previously been modelled and analysed [31]. These hypothetical systems transmit varying portions of the solar spectrum to the microalgae ponds. The remainder is directed to a high-efficiency crystalline silicon solar cell. The main chlorophyll absorption peaks for Chl *a* are centred at 434nm and 662nm. The portion of the solar spectrum transmitted to the microalgae was varied by changing the threshold around these peaks. For example, full-width-half-maximum (50% threshold) meant the spectra from 400nm to 492nm and 644nm to 678nm was transmitted to the microalgae, while for a threshold of 80% only the spectra from 417nm to 458nm and 656nm to 670nm were transmitted to the microalgae. Essentially, the higher the threshold, the narrower the range of light provided to the microalgae. All energy not transmitted to the microalgae is provided to the crystalline solar cell for producing electricity. There are a number of candidate systems that can physically split the solar spectrum and generate electricity in this fashion; however, the ideal system, as described above, is not currently commercially available. Examples of similar technology include building integrated PV, transparent thin film solar modules, and luminescent solar concentrators.

The microalgae are assumed to be cultivated close to Geraldton, Western Australia, with abundance of sunshine, land area (not suitable for agriculture), sea water and existing infrastructure, while demand for liquid fuel is deemed to be buoyant [9]. Evaporation in raceway ponds is also estimated based on average annual irradiance in the region and is adjusted for the amount of sunlight filtered in ST-PV panels and additional exposure by LEDs. For simplicity, surface evaporation due to wind blowing is ignored. Nitrogen and Phosphorous nutrients used for microalgae cultivation are assumed to be Ammonium Nitrate (AN) and Triple Super Phosphate (TSP).

This paper presents an uncertainty analysis on the outcomes of the model developed based on a range of uncertain input variables. Uncertainty in input variables is represented via probability distribution functions used in Monte Carlo simulation to derive a distribution for the outcomes of the model such as NER and land use. Due to the limitations in available data, which is frequently observed in the LCA studies conducted for microalgae cultivation processes (e.g. see [32]), triangular distributions are used to represent variability and uncertainty in input variables. Although, it must be noted that the true distribution of variables may be different from a triangular distribution, in the absence of data, minimum, maximum and likely values for each input parameter are derived from literature to define the triangular distributions.

3. Results and discussion

3.1. General results

The results of the analysis based on S.B. 2 for the triple scenarios, introduced in Section 2, are summarised in Figure 2. A detailed list of results for the scenarios is also provided in Table 4. For the Base scenario, and a reference flow of 100,000 kg/year biomass production, reactor surface area required is estimated to be 15.3 ha ($land\ use = 0.15\ \mathrm{m^2/kg_{biomass}}$). The estimated water evaporation from ponds is 45,425 $\mathrm{m^3}$/year resulting to an additional 120.3 $\mathrm{GJ_e}$/year of electricity requirement for the system to make up the evaporated water. Based upon S.B. 1, NER for biomass production is estimated to be 3.55 $\mathrm{MJ_{biomass}/MJ_{Input}}$. In comparison with a study conducted using a similar raceway pond microalgae cultivation [30] (with $NER = 8.34$

$MJ_{biomass}/MJ_p$), the estimated return on energy is lower primarily due to a choice of lower calorific value for the biomass product as shown in

Table 1 and additional energy input streams considered for nutrients and evaporation make-up. Setting the system boundary to S.B. 2, however, lowers the amount of NER to 1.46 $\mathrm{MJ_{biomass}/MJ_p}$. Note that the magnitude of PED for the grid electricity depresses the NER of the system. In effect, NER is substantially affected by the conversion efficiency of grid electricity supply in the region, due to the high proportion of primary energy input to the system from the stream (84.2%).

For the same biomass production flow as assumed for the Base scenario, i.e. 100,000 kg/year, the Algae-PV scenario requires the same amount of reactor surface (0.15 $\mathrm{m^2/kg_{biomass}}$). Note that NER based on S.B. 1 system boundary is equal to the Base case, as with such definition of system boundary the efficiency of electricity supply is not considered in the estimation of the system energy return. When consideration is made for the efficiency of electricity supply (i.e. using system boundary S.B. 2), however, the system energy return is substantially improved ($NER = 7.64\ \mathrm{MJ_{biomass}/MJ_p}$) compared to the Base case. As is visually clear in Figure 2, Panels (a) and (b), the PED for electricity production from the PV panels in Algae-PV scenario (17.2% of total energy input at S.B. 2) is substantially lower than that for the grid electricity in the Base scenario. Considering the similarity in the system configurations, the results for all other system variables are similar to the Base scenario (as shown in Table 4).

For the Hybrid scenario, equipped with the ST-PV type III listed in Table 3, and with the same amount of reactor surface as in the previous system scenarios (15.3 ha), biomass yield increases substantially by approximately 75% to 174,850 $\mathrm{kg_{biomass}}$/year, as compared to the previous system scenarios.[d] This leads to a significant decrease in the amount of land use by approximately 43% to 0.09 $\mathrm{m^2/kg_{biomass}}$. The amount of water evaporated from ponds also decreases significantly to 10,937 $\mathrm{m^3}$. The input energy streams to S.B. 2 are composed of the embodied energy of raceway ponds assembly (0.03%), PV panels (78.9%), LEDs (9.2%), and nutrients (11.9%) as shown in Figure 2, Panel (c). Neglecting the energy supply conversion

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[d] ST-PV III is used in the analysis of Hybrid system in this section. As is discussed in section 3.2, this PV type provides optimal results in terms of algae productivity and land use.

efficiency, the NER of the system ($\mathrm{NER} = 0.18\ \mathrm{MJ_{biomass}/MJ_{Input}}$), based on S.B. 1, is substantially lower than Algae-PV and Base system scenarios due to the high demand for electricity consumed in LEDs. For the S.B. 2, note that the energy return of the system ($\mathrm{NER} = 1.10\ \mathrm{MJ_{biomass}/MJ_p}$), with ST-PV panel type PV III, is substantially lower than the Algae-PV scenario, where PV panels are installed to supply electricity to mixing and pumping operations.

It should be emphasized that ignoring the conversion efficiency of energy supply sources to the system scenarios may distort the interpretation of system performance in terms of energy return on primary energy invested. If no consideration is made for the energy supply conversion efficiency, the Base and Algae-PV systems show similar performance in terms of NER. However, when the PED for the energy systems is accounted for, the Algae-PV system scenario shows a significant superiority to other system configurations studied in terms of environmental energy load, i.e. primary energy requirement of the system. Although in terms of biomass yield and land use, the Hybrid scenario provides the optimal results among the systems modelled.

To highlight the contribution of electricity supply from PV panels to the overall PED of the Hybrid system, the same system was run with grid electricity to energize LEDs and other system components using electricity with the results shown in Figure 2, Panel (d). NER of the system, based on S.B. 2, decreases substantially to $0.05\ \mathrm{MJ_{biomass}/MJ_p}$ as a result of high PED for electricity supplied from the grid. In other words, the energy cost of biomass production, for the supply of electricity, is substantially large ($18.3\ \mathrm{MJ_p/MJ_{biomass}}$) if LEDs in the Hybrid system are energised by grid electricity.

3.2. Hybrid system equipped with hypothetical ST-PV panels

The Hybrid scenario is also run for the set of hypothetical ST-PVs introduced in Table 3. The results of analysis, with S.B. 2, for the four ST-PVs are summarised in Figure 3. More detailed results are also provided in Table 4. A bulk of energy input (79-85% of total energy input) is for the PED of PV panels as shown in Figure 4. A smaller fraction of input energy (8.5-12%) is due to the PED of nutrients, followed by that of LEDs (5-11%). The contribution of PVC lining embodied energy towards the energy input of systems is generally negligible. Note how the higher the proportion of total solar irradiance converted to electricity in PV panels leads to a higher amount of electric energy available to LEDs. The surplus electricity results in an increase in the number of LEDs illuminated, which in turn enhances the photosynthetic productivity of microalgae. This is, however, partially offset by the decreasing amount of sunlight transmitted through ST-PVs to microalgae as the conversion percentage to electricity in the panels increases. From the set of ST-PVs, PV III provides the highest amount of biomass production yield (31.30 $\mathrm{g/m^2.d}$) and the lowest amount of land use (0.09 $m^2/kg_{biomass}$). PV III provides the highest amount of NER (NER=1.11 $MJ_{biomass}/MJ_p$) among the set of ST-PVs. As such, from the set of hypothetical ST-PVs, PV III panels are the optimal choice in terms of the trade-off between electricity generation and the amount of sunlight transmitted to microalgae.

3.3. *Uncertainty and sensitivity analysis*

A Monte-Carlo simulation is conducted with 5,000 simulation iterations to analyse: (1) the effect of uncertainty in modelling input variables on the results, and (2) the sensitivity of results to the same uncertain input variables. A summary of uncertainty (and sensitivity) variables with associated parameters assumed is provided in Table 5. Note that for simplicity a triangular distribution is used for all uncertain input variables. The focus in the uncertainty and sensitivity analyses is on the Hybrid system scenario.

3.3.1. Uncertainty analysis

A review of the literature reveals that the amount of three input variables is significantly uncertain: (i) Power rating required for Mixing, (ii) PV panels PED, and (iii) LED lifetime. To analyse how uncertain are the results of analysis, a Monte-Carlo simulation is run based on the range of values reported in the literature for the aforementioned parameters as noted in Table 5. For other input variables, generally, a 20% variation (10% above and 10% below the most likely value) is assumed for uncertainty analysis.

A summary box plot of results for Monte-Carlo simulation is displayed in Figure 4. The mean of NERs is 0.99, 1.12, 1.15, and 0.81 $\mathrm{MJ_{biomass}/MJ_p}$ for PV I to IV scenarios, respectively. Note that the range of NER distribution from 10th to 90th percentile for different ST-PV scenarios is 0.84–1.17, 0.96–1.31, 0.99–1.35, 0.69–0.96 for PV I to IV scenarios, respectively. Note that among all system scenarios, Hybrid system with PV III has a bulk of its NER distribution on $NER > 1$ side. To put it in probabilistic terms, an inspection of NER distribution reveals that the probability of producing more energy in biomass mix than the amount invested in the growth process is 87.9%. The same probability for PV I, PV II, and PV IV equipped systems is 39.7%, 80.8%, and 5.6%, respectively. These results also confirm that the system installed with PV III provides the optimal choice in terms of system NER.

The tornado graph in Figure 5 is presented to compare and rank the effect of various uncertain input variables on systems NER for Hybrid scenario equipped with PV III.[5] The simulation iterations for uncertain input variables are grouped into a set of 10 equal-sized bins (10 percentiles in each bin), ranging from the input's lowest value to its highest. Mean values for system NER associated with simulation iteration in each bin is estimated. The length of the bar shown for each input distribution in the tornado graph is based on the lowest and highest mean NER values (annotated on the bars) estimated for all bins. Correspondingly, a longer bar in the graph represents a higher impact on output results, i.e. system NER. For instance, for the system equipped with PV III, among all uncertain variables, the PED for PV panels has the highest contribution to the variation of system NER. For the first 10 percentiles of simulated iterations

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[5] The focus of analysis in this section is narrowed on the optimal hybrid system, i.e. the system equipped with PV III. We avoid a discussion of other hybrid systems, which generally show a similar pattern in terms of the contribution of the various uncertain variables.

for PV panels PED, the average of system NER is 0.961 $\mathrm{MJ_{biomass}/MJ_p}$, which is the lowest mean NER among all other grouped bins. Similarly, the mean NER of the last 10 percentiles of iterations for PV panels PED is 1.418 $\mathrm{MJ_{biomass}/MJ_p}$.

Note that top five contributors to the variation of system NER for all ST-PV scenarios are PV panels PED, LED output power, LED lifetime, AN PED, and lipid concentration, in their order of impact. The rest of uncertain variables generally have a similar effect on the system NER. These results show that any attempt for the enhancement of system NER must be prioritised toward improvement in PV panels PED, followed by LED output power, and LED lifetime.

The results of simulation for land use are shown in Figure 6. Among the four systems with different ST-PV panels, the system equipped with PV III has the minimum amount of land use distribution range. The highest land use (and the variation in the amount of land use) is for the system with PV IV panels. Note that among the ST-PV panels considered, PV IV has the highest conversion efficiency in terms of sunlight conversion to electricity. As such, a constant variation in LED power output has a higher impact on the energy performance and land use of the system. To better understand the impact of various uncertain input variables on systems NER a tornado graph is presented with similar calculation process as explained for Figure 5 for the system equipped with PV III.

As shown in Figure 7, among the range of uncertain input variables, LED output power, paddle wheel mixing power requirement, make-up water pumping efficiency, mixing and LED illumination duration, and make-up water head required affect the amount of land use. However, the effect of LED power output and mixing power requirement is more significant when compared to the other variables. These results show that any plan to improve the performance of the system in terms of land use must be prioritised toward enhancements in LED output power, and paddle-wheel mixing power rating.

3.3.2. Sensitivity analysis

To measure the sensitivity of NER and land use parameters to the uncertain variables listed in Table 5, another Monte Carlo simulation is run. In this simulation, all uncertain input variables are varied equally by $\pm 10\%$ of their most likely value to set the minimum and maximum values required for the definition of triangular distributions. Figure 8 shows the effect of uncertain input variables on Hybrid-PV III system NER, with a legend listing the uncertain input variables in their order of contribution. Note that the top five inputs contributing to changes in NER are similar to those shown in Figure 5. Those input variables with a steeper slope indicate a more significant effect on the system NER. PV panel PED has the steepest line among the input variables in Figure 8, showing the highest impact on NER results. The more limited range of distribution in LED lifetime has slightly decreased its contribution rank (from 3rd to 5th) in comparison with the results in Figure 5.

To inspect the significance of input variables contribution toward the amount of NER and land use, a significance factor, I_s, is defined,

$$I_s = \frac{Md_{75\%} - Md}{s}$$

where Md and s are median and standard deviation for the input variable distribution, respectively. $Md_{75\%}$ is the median of input variable distribution for the simulation iterations in which the output variable, i.e. NER and land use, are greater than their 75th percentile. If the absolute value of I_s is greater than 0.5, the output is regarded significant.

Results of significance analysis are shown in Figure 9. Among the uncertain input variables, PV panel PED and LED output power are the two significant contributors to the Hybrid system NER. LED output power is the only significant contributor to the Hybrid system land use. This finding reveals that any attempt to enhance the performance of the Hybrid system in terms of energy return and land use has to be prioritised toward the decrease in the amount of PV panels PED and the efficiency of electricity to light conversion in LEDs. Among the three variables identified, however, LED output power is the common significant contributor towards NER and land use, i.e. an increase in LED energy conversion (from electricity to light) efficiency significantly increases the amount of NER and decreases the amount of land use.

The energy return analysis conducted in this study reveals that the proposed hybrid ST-PV and microalgae cultivation system can provide an opportunity for a viable electricity supply and energy storage system in terms of energy performance. The system has the potential to be used in remote areas with limited access to grid electricity and liquid fuels. The economic viability of the system, however, may only be justified with high liquid fuel prices, grid electricity costs, and transportation costs. Although the cost of energy supplied by solar photovoltaic panels is relatively high in comparison with other energy sources, the rapid growth of the technology over the past few years has substantially lowered the associated capital costs and hence the levelised cost of electricity generated [33]. PV cost reductions and future enhancement in LED efficiency may substantially improve the economic case for the proposed system. The storage of energy in the form of biomass provides an operating advantage for the system, noting that intermittency of energy supply by PV panels is a challenging problem for the electricity supply system [34]. The biofuel produced from algae biomass can be used for electricity generation when the sun is not shining through the night. In remote regions with limited access to battery storage or reserve supply, the complementary chemical storage of energy in the form of biodiesel may enhance the economic feasibility of the system.

4. Conclusion

An energy life cycle analysis was conducted for hypothetical integrated microalgae cultivation, ST-PV panels, and LEDs energy generation and storage system proposed by Moheimani and Parlevliet [8]. The proposed combined system allows for efficient utilisation of solar spectrum via filtration of light incidence by semi-transparent PV panels installed on top of outdoor raceway ponds. The photosynthetic productivity of microalgae is enhanced by transmitting blue and red spectra, which are known to be the most effective part of solar irradiance in the process of photosynthesis. The unused part of sunlight spectrum is used by ST-PVs to generate electricity. The hypothetical system was modelled for the cultivation of microalgae in Western Australia with high light irradiance. The findings of the model developed show that the cogeneration of electricity and biomass via the proposed hybrid system can substantially reduce the amount of land use, enhance the productivity of microalgae cultivation process, and reduce the amount of water evaporation from outdoor raceway ponds. The aforementioned improvements are achieved the energy return on invested (NER) remains greater than one, i.e. the proposed system may have the potential to be considered as part of a sustainable energy production and storage process. Uncertainty and sensitivity analyses of factors affecting the performance of the modelled hybrid system show that, from a range of variables, PV panels PED and the conversion efficiency in LEDs have the highest impact on the amount of NER and land use. An increase in LED energy conversion efficiency can significantly increase the amount of NER and decreases the amount of land use. The proposed system may allow for a more economic production of biofuel (or value added crops) in remote areas such as North West of Western Australia. The reliance on grid electricity or the transportation of diesel can be eliminated by concurrent production of biomass and electricity. The economic viability of the system, however, may not be justified considering the costs associated with PV panels and LEDs. Significant reductions in the cost of PV panels over the past few years, and its prospect of more cost reductions in the future, however, may change the case for investment in the system. Future studies are required to assess the economic feasibility of the system proposed considering the operational flexibility that it offers, i.e. generation of electricity and storage of energy in chemical form.

Acknowledgements

The authors are most grateful for the financial support of Murdoch University.

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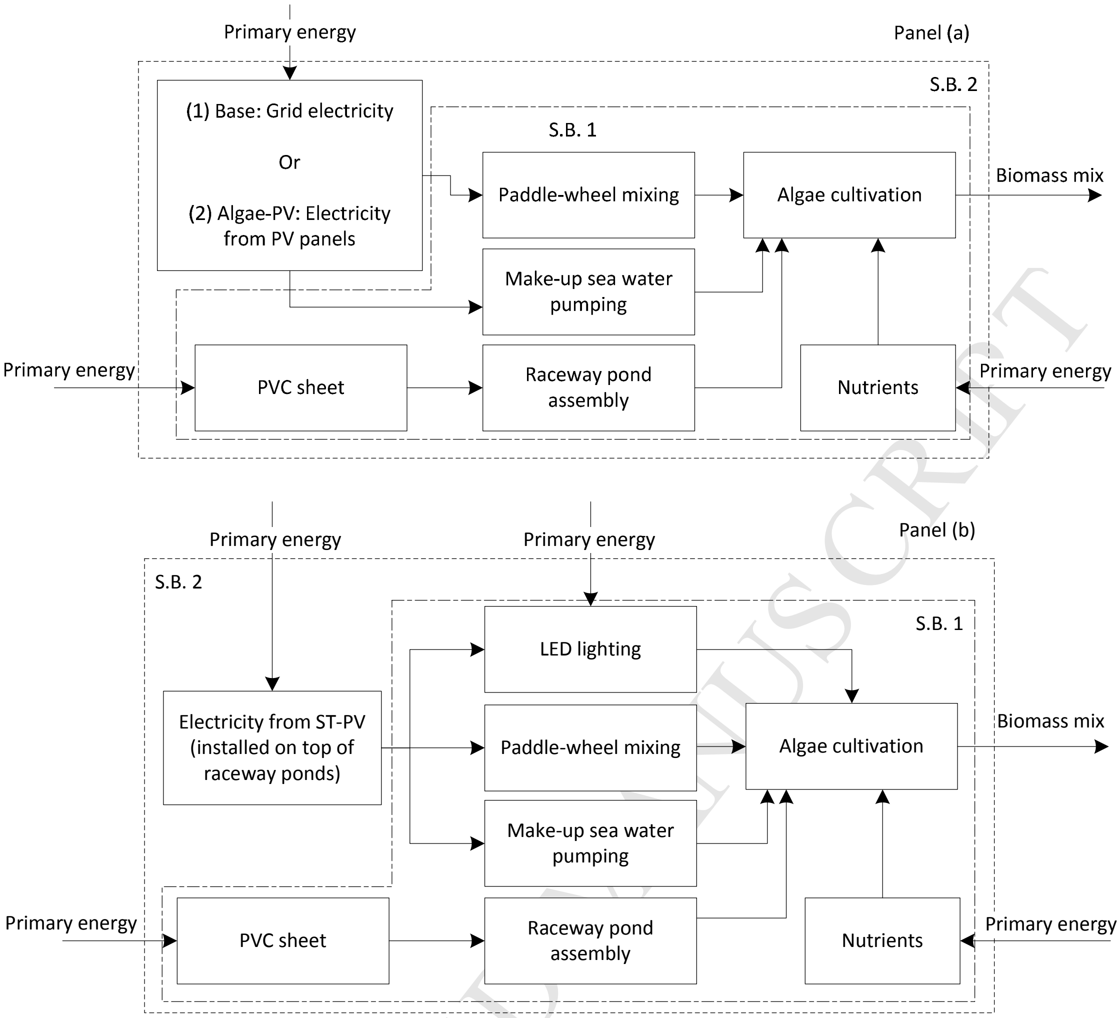

579 **Figure 1**. Hypothetical microalgae cultivation systems: Panel (a) shows the Base scenario and the Algae-PV scenario;
580 Panel (b) shows the Hybrid scenario.

Table 1. General assumptions used in the energy life cycle assessment

Parameter	Unit	Value	Note
Biomass mix			
Biomass production (used in Base scenario)	kg/year	100,000	1
Lipid concentration	%	29.6	2
Net calorific value of lipids	MJ/Kg	38.00	1
Net calorific value of proteins and carbohydrates	MJ/Kg	17.0	1
Reactor sizing			
Reactor volume to area ratio (V/A)	m	0.314	2
Paddle wheels operation			
Power rating for paddle-wheel mixing	W/m3	3.72	2
Mixing operation time	hr/day	12	1
LEDs			
Illumination hours	hr/day	12	1
LED lifetime	hr	25,000	3
Output power	W/m2	0.43	4
Input power	W	1.07	4
PED	KWh$_p$/pieace	0.41	3,5
Make-up water pumping			
Required head	m	150	1
Pumping efficiency	%	50	1
Nutrients			
Amonimum nitrate PED	MJ$_p$/kg N	40.00	6
Triple super phosphate PED	MJ$_p$/kg P	30.25	6
Nitrogen loading	g N/kg dry algae	54.0	6
Phophorus loading	g P/kg dry algae	11.0	6
Assimilation efficiency	%	90	1
PVC lining sheet			
PED for PVC used in pond lining	MJ$_p$/Kg	16.8	7
Electricity			
PED for PV panels	MJ$_p$/m2	3800	8
PED for electricity from grid	MJ$_p$/MJ$_e$)	3.33	7
Others			
System lifetime	years	20	1
Average annual solar radiation	MJ/m2.day	21	1

1. Assumption/estimation
2. Similar to/derived from [30]
3. From [35], [36], [37]
4. Based on technical specification of CREE XPeROY-L1-0000-00A01 [38]
5. The ecoinvent database [39]
6. From [40], and [41]
7. GaBi Professional Database [42]
8. From [43], and [44]

Table 2. Constants used in microalgae productivity calculation (Eq.1)

Parameter	a	b	α	β
Value	0.003254	-8.70774	0.97077	1.1107

Table 3. Hypothetical semi-transparent PV panels used in the hybrid scenario (4)

Hypothetical ST-PV type	Blue region energy intensity (MJ/m^2year)	Red region energy intensity (MJ/m^2year)	Proportion of total solar irradiance given to microalgae (%)	Proportion of total solar irradiance converted to electricity (%)
PV I	854.9	288.8	38.80%	10.42
PV II	854.9	288.8	21.24%	16.95
PV III	854.9	277.6	16.46%	19.05
PV IV	442.7	165.1	7.93%	22.60

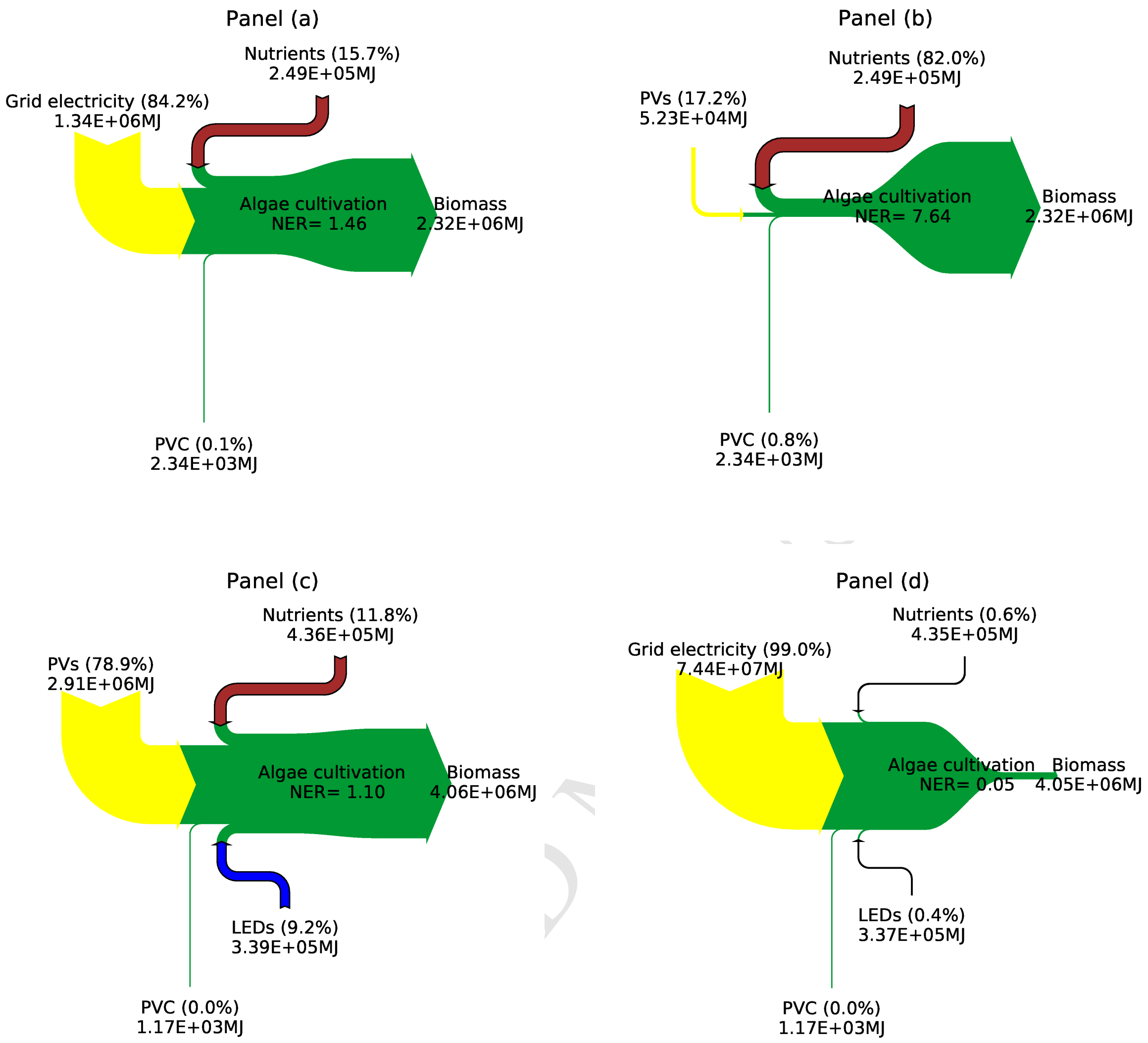

Figure 2. Primary energy requirements for the hypothetical system scenarios: Panel (a), Base scenario; Panel (b), Algae-PV scenario; Panel (c), Hybrid scenario with PV III, Panel (d) Hybrid scenario with grid electricity supply. Per cent values represent the percentage of contribution to system energy inputs.

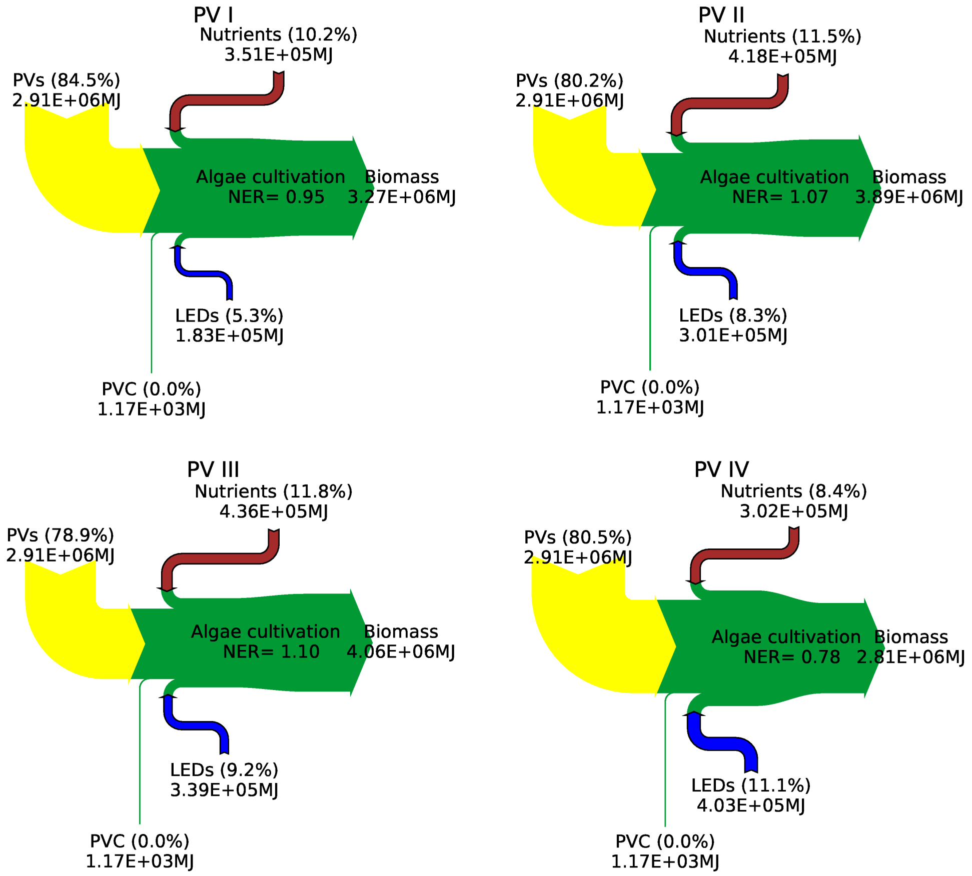

Figure 3. Hybrid system performance installed with different ST-PVs

Table 4. Summary of results for the four system scenarios

Item	**Unit**	**Base**	**Algae-PV**	**Hybrid**			
				PV I	PV II	PV III	PV IV
Biomass production							
Biomass production	kg/year	100,000	100,000	140,883	167,575	174,850	121,090
Occupied areal productivity	$g/m^2.d$	17.9	17.9	25.2	30.0	31.3	21.7
Volumetric productivity of reactor	$g/m^3.d$	57.0	57.0	80.3	95.5	99.7	69.0
Reactor volume	m^3	4,806	4,806	4,806	4,806	4,806	4,806
Reactor area	m^2	15,306	15,306	15,306	15,306	15,306	15,306
Evaporation volume	m3/year	45,425	45,425	19,465	12,675	10,937	7,648
Energy input							
Surplus electricity available to LEDs	MJ_e/year	-	-	11,895,529	19,566,414	22,036,042	26,210,357
No. of LEDs illuminated	piece	-	-	706,707	1,162,430	1,309,149	1,557,143
Makeup water pumping energy requirement	MJ_e/year	120,318	120,318	51,558	33,573	28,968	20,256
Nutrients total PED	MJ_p/year	249,275	249,275	351,186	417,723	435,858	301,848
PVC total energy input (primary energy)	MJ_p/year	2,340	2,340	1,170	1,170	1,170	1,170
PED for PVs	MJ_p/year	-	52,344	2,908,140	2,908,140	2,908,140	2,908,140
Total PED for LEDs	MJ_p/year	-	-	182,751	300,599	338,540	402,670
Total energy input @ S.B. 1	MJ/year	653,838	653,838	12,764,104	20,601,389	23,122,488	27,218,210
Total energy input @ S.B. 2	MJ_p/year	1,592,358	303,959	3,443,247	3,627,631	3,683,707	3,613,827
Energy output							
Energy produced in biomass	MJ/year	2,321,600	2,321,600	3,270,738	3,890,421	4,059,320	2,811,230
Performance indicators							
Land use	$m^2/kg_{biomass}$	0.15	0.15	0.11	0.09	0.09	0.13
NER							
NER for biomass production (S.B. 1)	$MJ_{biomass}/MJ_{input}$	3.55	3.55	0.26	0.19	0.18	0.10
NER for biomass production (S.B. 2)	$MJ_{biomass}/MJ_p$	1.46	7.64	0.95	1.07	1.10	0.78

Table 5. Uncertain variables and associated parameters used for Monte-Carlo simulation

Name	**Min**	**Most likely**	**Max**	**Note**
Lipid concentration (%)	26.64	29.6	32.56	1
LED lifetime (hr)	20000	25000	50000	2
Power rating required for Mixing (W/m^3)	0.7	3.72	26	3
(Make-up) Water head required (m)	135.0	150.0	165.0	1
Make-up water pumping efficiency (%)	0.45	0.50	0.55	1
LED output power (W/m^2)	0.38	0.43	0.47	1,2
LEDs PED (KWh_p/piece)	0.37	0.41	0.45	1,2
Mixing/LED illumination operation duration (hr/day)	10.8	12.0	13.2	1
Ammonium nitrate PED (MJ_p/kg N)	29.8	40.0	50.0	4
TSP PED (MJ_p/kg P)	27.23	30.25	33.28	4
PV panels PED (MJ_p/m^2)	2400	3800	4900	5
Nutrients assimilation efficiency (%)	81%	90%	99%	1
PVC lining PED (MJ_p/kg)	15.12	16.8	18.48	1

1. A 20% variation (10% above and below) is used for the most likely value for the parameter; See also the relevant references in
2. Table **1**.
3. See references: [35], [36], [37].
4. See references: [32], [45], [46], [47], [30]. See also the relevant literature and information sources provided by [32].
5. See references: [40], and [41].
6. See references: [43], and [44]).

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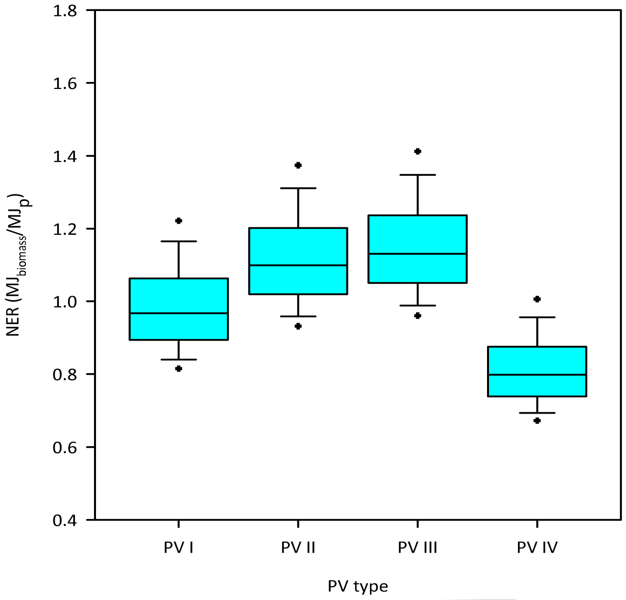

599

600 **Figure 4**. Net energy return for Hybrid system scenario equipped with different ST-PV panels. Centre lines represent
601 median values, edges of boxes represent 25th and 75th percentile, and limiting bars indicate 10th and 90th
602 percentiles. Point markers indicate 5th and 95th percentiles.

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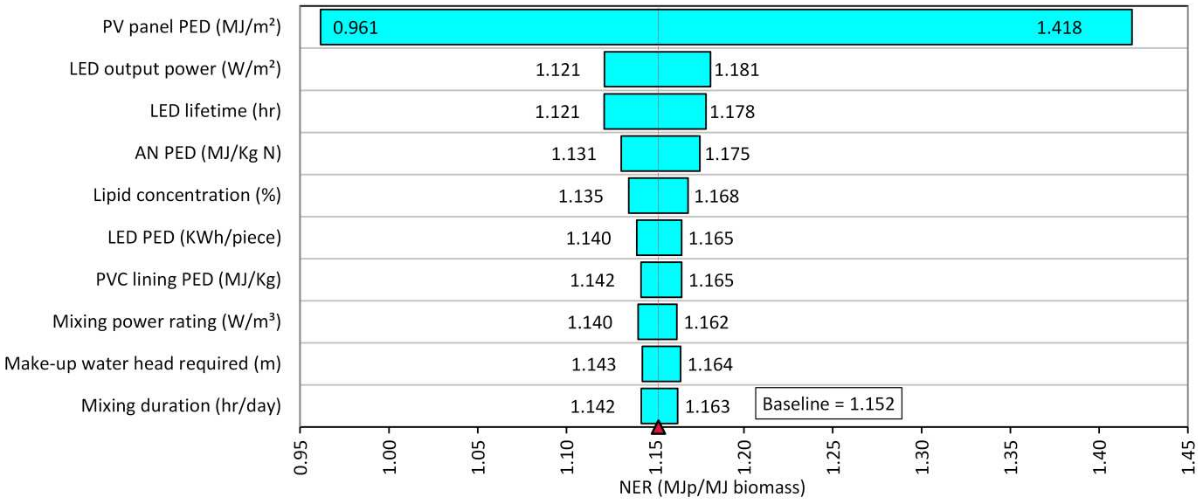

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605 **Figure 5.** The effect of various input parameters on system NER (Hybrid system equipped with PV III).

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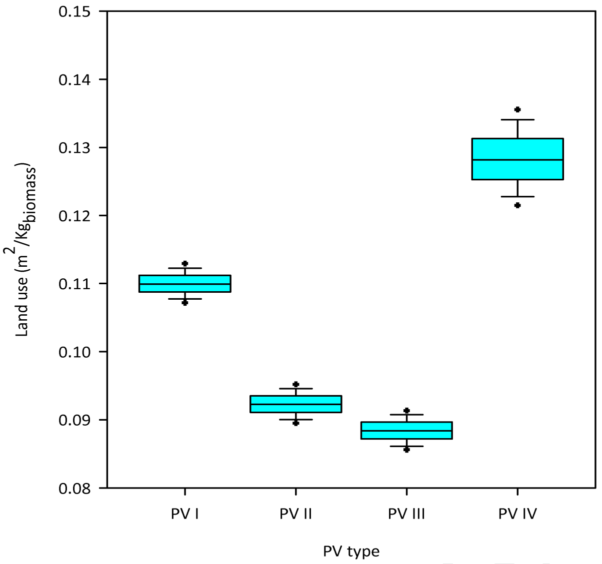


Figure 6. Microalgae cultivation land use, Hybrid system for different ST-PV panels (m2/kg biomass). Centre lines represent median values, edges of boxes represent 25th and 75th percentile, and limiting bars indicate 10th and 90th percentiles. Point markers indicate 5th and 95th percentiles.

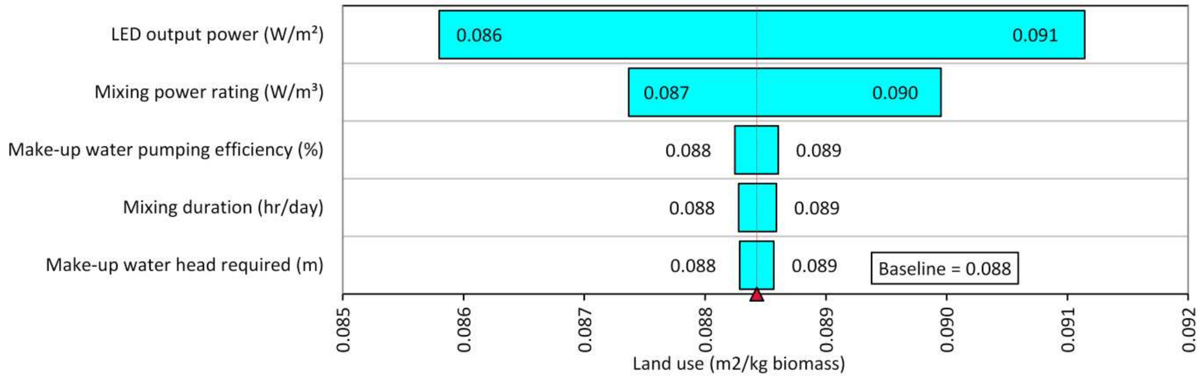
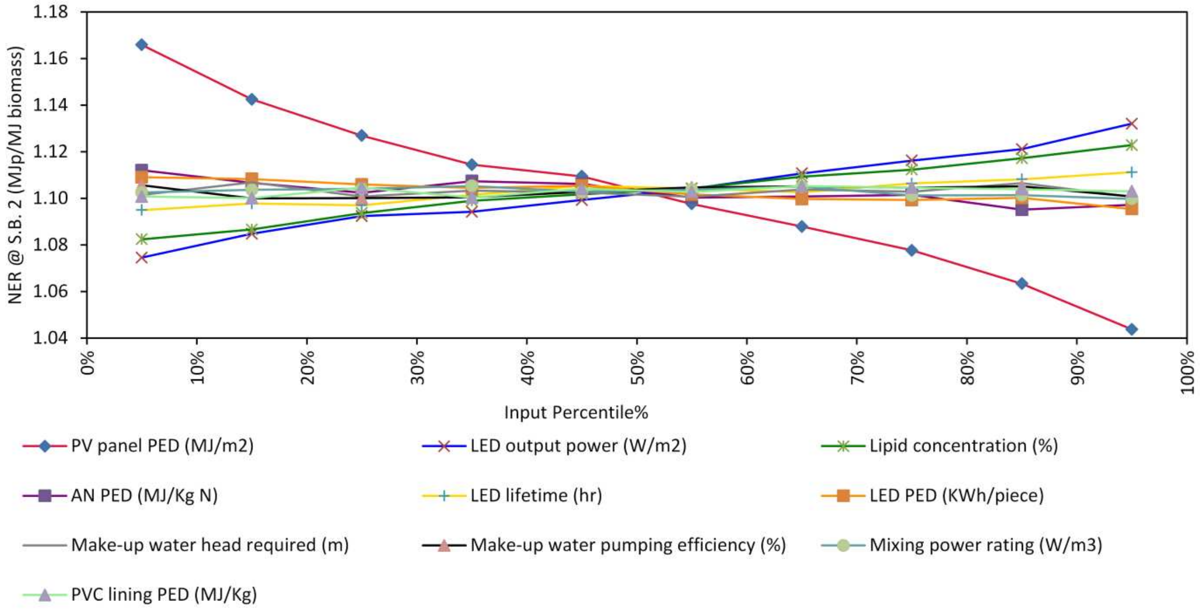


Figure 7. The effect of uncertain input variables on microalgae cultivation land use (m^2/kg biomass)



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616 **Figure 8**. A comparison and ranking of uncertain input variables on Hybrid system NER. Variables listed in the legend
617 in their order of contribution to NER (top five contributers: PV panel PED, LED output power, lipid concentration, AN
618 PED, and LED lifetime)

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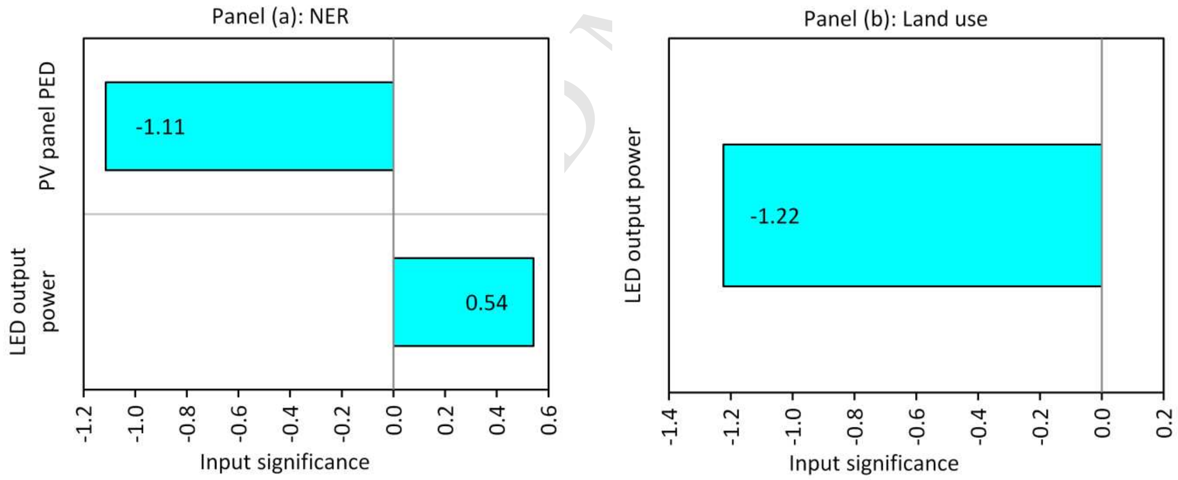

620 **Figure 9**. Major input variables significantly affecting the NER and land use of the Hybrid system. Values shown on
621 the bars indicate the significance factor, I_S.

622

Highlights

- Energy life cycle assessment is conducted for an integrated algae, PV, and LED system
- The amount of land use is substantially reduced in a hybrid algae production system
- Productivity of algae cultivation is substantially increased by using LEDs
- PV panels primary energy demand has a significant effect on system net energy return
- LEDs efficiency has a significant effect on system land use and net energy return