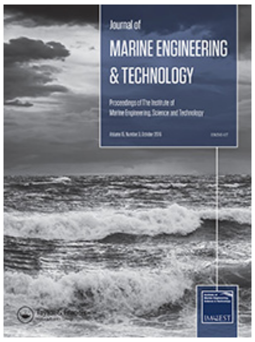

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Analysis of marine solar power trials on Blue Star Delos

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ABSTRACT

In October 2014 the high speed car and passenger ferry Blue Star Delos was fitted with a marine solar power system. This was done as part of a project to study the use of renewable energy on large ships. In May 2015 while the ship operated in the Aegean Sea, the performance of system was checked and a range of data collected. This paper is focused on the analysis of these data and the evaluation of two days of system trials.

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Introduction

Solar power is increasingly used as an alternative source of energy with land-based applications including large-scale grid connected photovoltaic (PV) power stations, home solar power systems, remote power solutions and off-grid applications. However, the use of solar power on ocean-going ships has to date been limited to just a few vessels. Notable amongst these include the Kaiyu Maru (Solar Frontier 2011), Auriga Leader (media release: world's first solar-power-assisted vessel further developed), Emerald Ace (World's First Hybrid Car Carrier Emerald Ace Completed) and MS Tûranor PlanetSolar (D'Orazio 2016). However, it is possible that in the near future more ships will utilise solar power as a means to improve energy efficiency and due to the adoption of methodologies such as the Energy Efficiency Design Index (EEDI) (EEDI). Additionally many port and maritime authorities offer financial incentives to encourage ship owners to implement measures to reduce vessel airborne emissions (*Green Ship Programme*; *Ocean-Going Vessel Emission Reduction*).

In 2014 the high speed car and passenger ferry, Blue Star Delos (Table 1), became the first ship of this type to be installed with a marine solar power system. This system was installed as part of a wider project to evaluate the use of renewable energy on merchant ships. Unlike smaller vessels fitted with solar panels such as the MS Tûranor PlanetSolar, Delos is a large commercial ship. It has the capacity to transport 2400 passengers and 430 vehicles (*Blue Star Fleet*) and typically departs daily from the Port of Piraeus, Greece, at 07:25 and returns at 23:25. The ship is a vital transport link to several islands in the Aegean Sea and often operates in harsh conditions with apparent wind speeds of over 50 knots having been observed. The ship also incorporates many innovative features including highly efficient shaft alternators for electrical power generation (Holthof 2012).

Marine solar power system overview

The photovoltaic power generating system (PV System) on Delos is designated as a marine solar power system. This designation is applied since the system elements were specifically chosen because of their suitability for use on ships. The marine-grade PV panels are designed to withstand exposure to saltwater as is all external wiring. The data logging computer system and batteries are Nippon Kaiji Kyokai (ClassNK) approved and certified for use on ships. In addition the overall system design has been accepted by ClassNK for use on classed vessels (*Media Release: Marine Solar Power Solution Receives Acceptance*). An overview of the system configuration is shown in Figure 1, Table 2 and the locations where equipment is installed on-board Delos are shown in Figure 2.

Marine solar panel array

The marine solar power array or PV array consists of 16 thin PV panels (Table 3) made using polycrystalline cells. The polycrystalline cells and a junction box are affixed to a flexible and lightweight backing material which has a thickness of 2 mm. There is a border space on each panel therefore the area covered by PV cells is 0.90 m^2 whereas the total area of each panel is 1.03 m^2.

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Table 1. Blue Star Delos vessel particulars.

Blue Star Delos - vessel particulars (Flag: Greece)			
Built	2011	Main Engines	4 × MAN B&W 18 V 32/40
Length	145 m	Main Engines Total Power	32,000 kW
Breadth	22 m	2 Shaft Alternators (Main)	1254 kW (each)
Gross Tonnage (GRT)	18,498 tonnes	3 Diesel Alternators (Aux)	1320 kW (each)
Deadweight (DWT)	2775 tonnes	Passengers	2400
Draft	5.70 m	Vehicles	430
Service Speed	26 knots	Lanemeters	600
IMO Number	9565039	Classification	Bureau Veritas

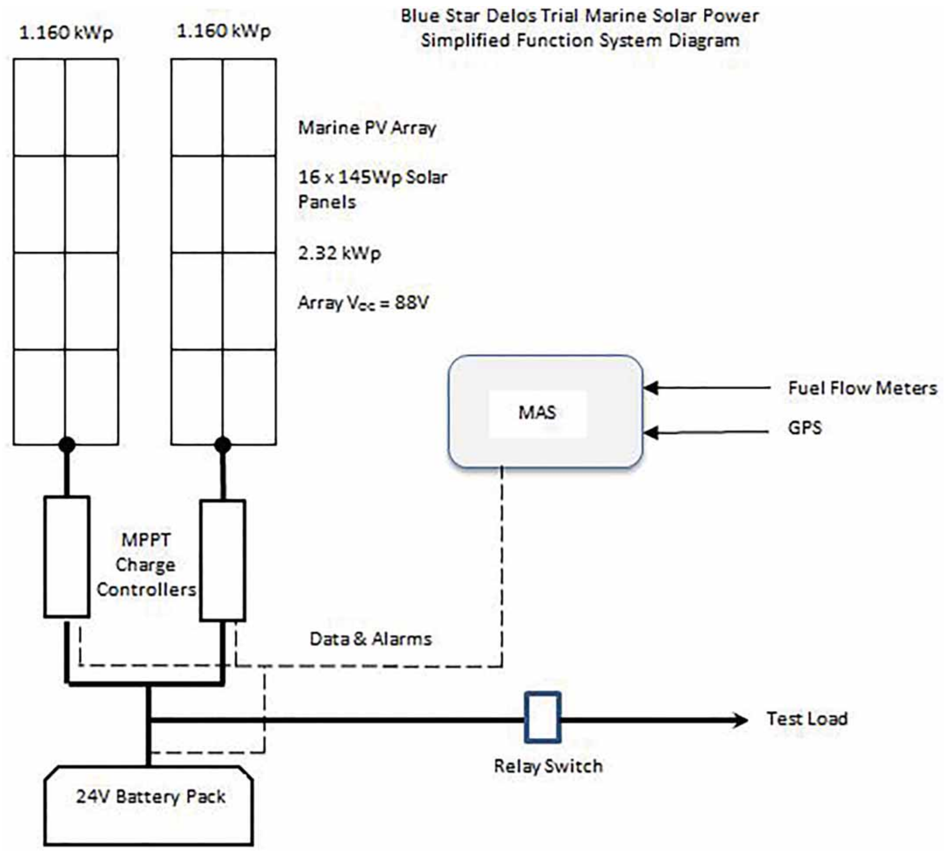


Figure 1. Simplified Blue Star Delos marine solar power system diagram during trials.

Table 2. Overview of marine solar power system configuration during trials.

Component	Details
Solar Panel Array Total: 2.32 kWp	16 × 145 Wp Marine Grade PV Panels
Energy storage	12 × VRLA 12 V Batteries. Configured as a 24 V Battery Pack. Total: 5.4 kWh
Computer system	MAS with combined CPU/AGU, ILS unit, data hubs & associated communication devices
Charge controllers	2 × 60 A MPPT Charge Controllers
Other equipment	1 × GPS antennae & receiver. Circuit breakers, relays, switches, etc.

Each panel is attached to a marine-grade aluminium tray and mounted slightly above the deck as shown in Figure 3. Electrically the panels are connected in series in four rows, with two rows then connected in parallel to a charge controller as shown in Figure 1. The key specifications for the marine solar panel array are listed in Table 4.

Energy storage

Twelve valve-regulated lead-acid (VRLA) batteries (Table 5) are installed in an equipment space (AHU Room) directly below the marine solar panel array. These were connected in a two by six configuration to form a 24 V 5.4 kWh battery pack. The batteries are protected from over discharge via a controlled relay which disconnects them from the load if the battery voltage falls to be pre-set level. During the trials this voltage was set at 23.4 V. The batteries store energy from the solar array and also stabilise the output voltage to the load. When being charged the batteries also effectively become part of the load on the PV system.

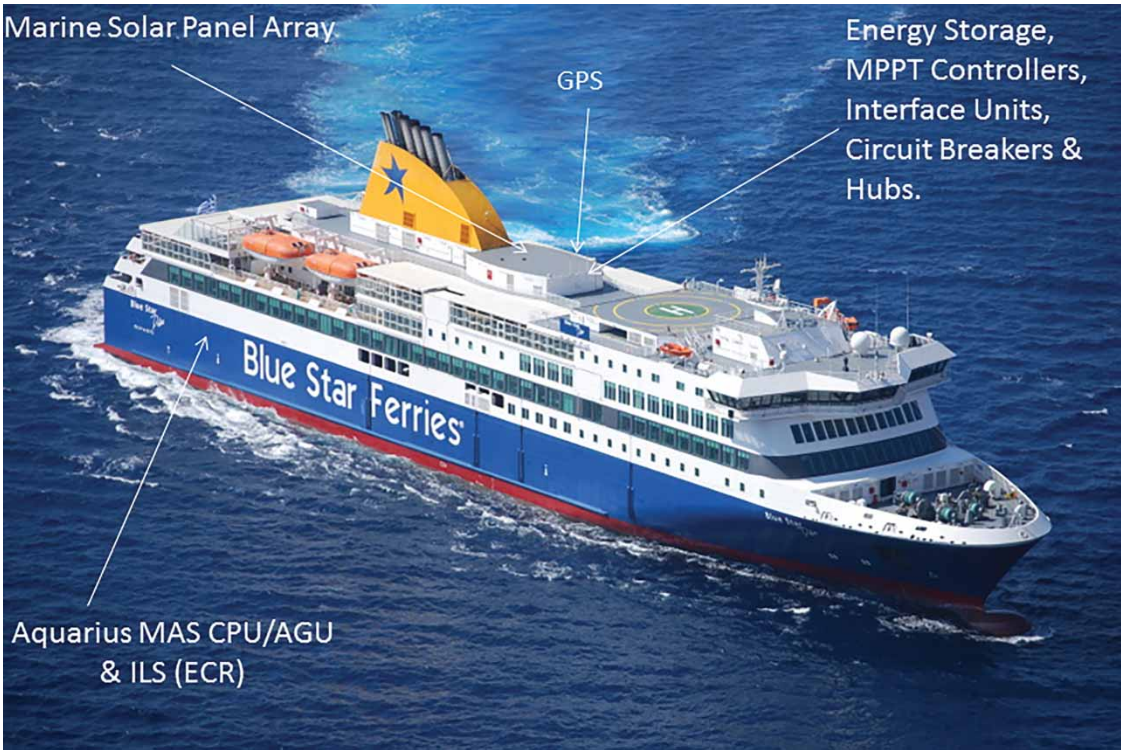


Figure 2. Marine solar power system equipment locations on Blue Star Delos. The picture of the ship is used with the permission of Blue Star Ferries.

Table 3. 145 W PV panel specifications, and image of 145 W PV panel (Solbian Energie Alternative Srl. 2016).

P_{Max} (+/−5%)	145 Wp	
Panel dimensions	1515 × 680 mm	
PV cell area	0.90 m^2	
Panel thickness	2 mm	
Panel weight	2 kg	
V_{OC}	22 V	
V_{PM}	18 V	
I_{SC}	8.7 A	
I_{PM}	8.1 A	
Panel efficiency	15%	

Computer system

As part of a larger project to evaluate the use of renewable energy on ships, a computer management, automation and data logging system (MAS) (Table 6) was also installed on-board Delos in October 2014. The MAS comprises of a combined central processor unit (CPU)/advanced graphics unit (AGU), input/output link system (ILS) unit and LCD touch-screen display that are located in the engine control room (ECR) and interface devices installed in the AHU Room. The MAS is connected to the main elements of the PV system so that key performance data can be recorded plus it also receives data from a GPS unit and fuel flow meters. System alarms and error messages are displayed on the monitor in the ECR.

Charge controllers

Two maximum power point tracking (MPPT) charge controllers are used to match the PV array voltage to the battery voltage and regulate charging. The charge controllers also dynamically optimise the PV input voltage to maximise power output and have several modes of operation. Each controller is connected to a group of eight PV panels which are in turn configured into two serially connected rows of four panels each. Data from these units are sent via interface devices to the MAS and each charge controller also retains up to 128 days of performance data.

Other equipment

A GPS antennae and receiver is connected to the MAS so that the ships position and speed can be logged. Ethernet

Figure 3. Blue Star Delos marine solar power array during trials.

Table 4. Delos marine solar power array specifications.

Rated power	2.32 kWp	Array area (Approx.)	17 m^2
Voc	88 V	Array PV cell area	14.4 m^2

hubs and protocol converters are also installed to integrate various system components to the MAS network. In the AHU room circuit breakers, a control relay and other electrical power distribution equipment are also installed.

Purpose and methodology

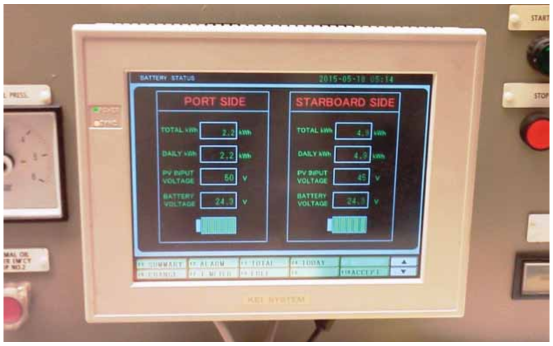
The primary purposes of the system trials were to compare the predicted energy output with measured values, evaluate the operational performance of the PV system and confirm that continuous power could be supplied to the test load. A range of data were collected and recorded between the 17th and 20th May including information stored in the MPPT charge controllers during the previous three months. Two system evaluation trials were conducted on the 17th and 19th May as the ship sailed

Table 5. FC-38-12 specifications and picture of one FC-38-12 battery on Delos.

Voltage	12 V
Capacity (20 Hr)	38 Ah
Dimensions	172(h) × 165(w) × 197(d) mm
Weight	15.5 kg
Self-discharge (at 25°C)	Less than 0.1% per day

Table 6. MAS specifications and picture of MAS display in Delos ECR.

Main unit	KEI 3240 CPU\AGU
Communications	Ethernet, RS-232c, ILS, USB
Power consumption	25 W
Display	LCD Touch-screen
Operating range (°C)	+5 to 50



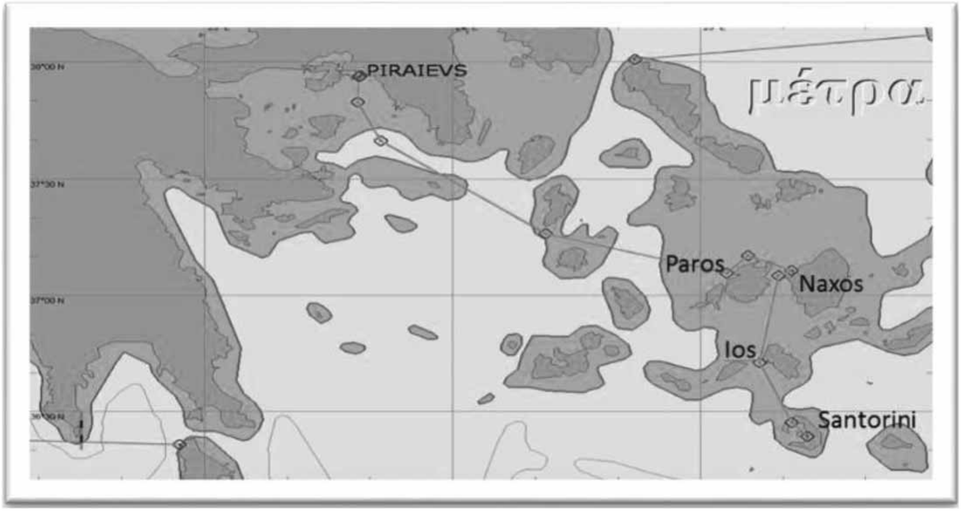


Figure 4. Blue Star Delos route map during system trials. Map used with the permission of Blue Star Ferries.

Table 7. MAS data channels as configured for the trials.

CH0301	CH0302	CH0303	CH0304	CH0306	CH0307	CH0308	CH0309
Port PV Volts MPPT	Batt Volts MPPT	Port PV kWh Total	Port Side kWh Daily	STBD PV Volts MPPT	Batt Volts MPPT	STBD PV kWh Daily	STBD PV kWh Total

Note: CH0XXX – Data channel number.
STBD – Starboard.

Figure 5. Measurement of solar radiation at Naxos & Paros (19th May).

from Piraeus to Ios, Naxos, Paros, Santorini and on the return journey to the Port of Piraeus late in the evening (Figure 4).

During the system trials, performance data as per Table 7 was logged by the MAS every minute plus the following measurements were taken each hour between 07:00 and 20:00;

(1) Solar irradiation readings using a portable solar power meter (Figure 5).
(2) Power, voltage and current readings from each charge controller.

The surface temperatures of various PV panels were also recorded but this was generally limited to when the ship was in or near a port due to safety reasons. Several readings were obtained at the same time when using hand-held devices to avoid errors that might occur if they were not used or positioned correctly.

The estimated electrical production of the PV system was calculated based on the Photovoltaic Geographical

Table 8. Incident global irradiation for Athens (Joint Research Centre (JRC) European Commission 2001–2002b).

Incident global irradiation for Athens Month	Hh
April	5990
May	7130
June	8070

Note: Hh: Irradiation on horizontal plane (Wh/m2/day).

Table 9. Estimated system losses.

	PVGIS Estimate (Joint Research Centre (JRC) European Commission. 2001–2002a)	Trial System Estimate	Notes
Total system losses	27.7%	23.7%	Estimated losses for trial system reduced by 4% since no inverter was required for DC output

Table 10. Estimated electrical production per day for trial PV system.

Month	Irradiation (I) Wh/m^2/day	Electrical production (no losses) Wh	Estimated losses (L_{SYS}) (Loss 23.4%) Wh	Estimated energy (E_P) Wh (per day)
April	5990	13,800	3228	10,572
May	7130	16,428	3844	12,584
June	8070	18,593	4350	14,243

Information System (PVGIS) (Joint Research Centre (JRC) European Commission 2015) and Incident Global Irradiation Data for Athens (Location: 37°44′30″ North, 23°49′6″ East) (Joint Research Centre (JRC) European Commission 2001–2002a) as displayed in Table 8. The PVGIS information for Athens was considered suitable even though the ship sailed away from this location since using these data would lead to a conservative estimate of the available solar irradiation.

Estimated energy losses for the system were based on PVGIS Estimates of Solar Electricity Generation (Joint Research Centre (JRC) European Commission 2001–2002a) but modified to take into account that the PV system on Delos does not include an inverter (Table 9).

To calculate the estimated energy production of the system, the following expression was used:

$$E_P = I \times A \times \eta - L_{SYS} \quad (1)$$

where

E_P = Estimated energy production of the system in Wh.
I = Solar irradiation in watts per m^2 (Table 8).
A = Total surface area of PV cells in m^2 (14.4 as per Table 5).
η = Efficiency of PV cells (16%).
L_{SYS} = System losses in Wh (Table 10).

Although the efficiency of the solar panels used for the trial is stated as being 15%, this takes into account the border area around the polycrystalline cells. The efficiency of the polycrystalline is 16% and so this figure is used for η. For the 2.32 kWp PV system on Delos, the estimated electrical production (E_p) for April, May and June were calculated and the results listed in Table 10.

Evaluation and trial results

On the day of first system trial on 17 May the solar panels had not been cleaned since installation in October 2014 and it was observed that they were unevenly covered in a light layer of dirt and salt. This was expected to impact the energy production of the PV system to some extent. Before the second evaluation voyage on the 19th May the panels were thoroughly cleaned and all surface dirt and salt removed. On both trial days the weather was warm and sunny with cloudless skies. Seas were calm and the apparent wind speeds were generally in the range of 20–25 knots when the ship was underway. The test load comprised of two 24 V 50 W LED floodlights and two sets of 24 V 216 W LED strip lights connected to the output of the 24 V battery pack. The total load provided by these LED lights was approximately 532 W.

During each day of the trials the energy produced by the PV system was similar and no degradation in

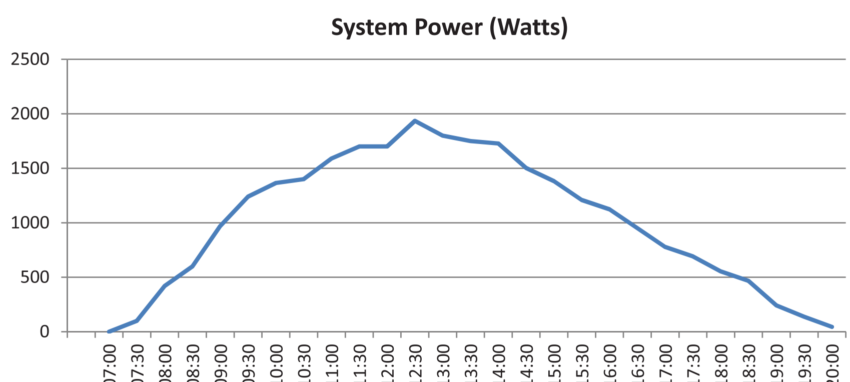


Figure 6. Averaged PV system output power during trials.

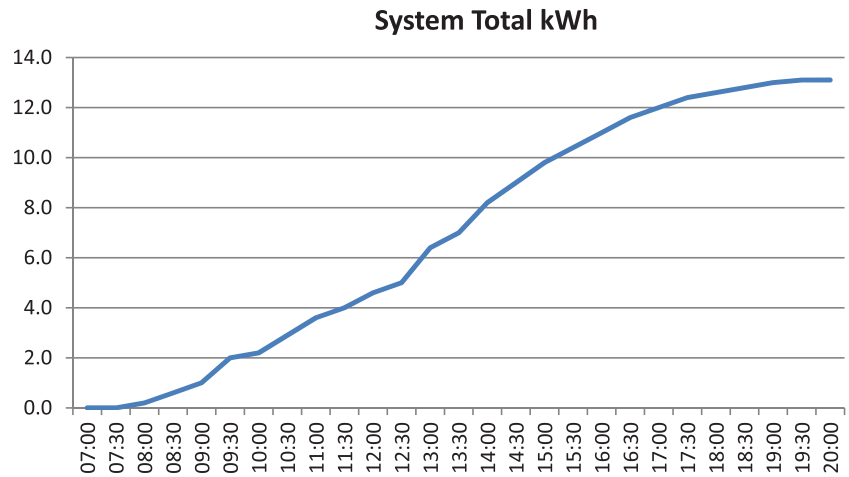


Figure 7. Averaged daily total electrical production during trials.

performance due to the solar panels being unwashed on the 17th May was apparent. System power output at 30-minute intervals based on data from the two days of trials is shown in Figure 6. The average energy produced was calculated as being approximately 13,500 Wh or 13.5 kWh (Figure 7). This is higher than the estimate for May (Table 10) but taking into account the power output tolerance of the PV panels (+/− 5%) and that the trials were conducted on two cloudless days in mid-May then this is within an acceptable margin.

The charging of the batteries commenced each day at around 07:30 and they were fully charged just before 12:00. The maximum solar radiation measured near the PV panel array was 1120 W/m^2 and the maximum temperature observed on the surface of the solar panels was 50.1°C. The PV system appeared to operate without any significant impact on performance when the surface temperatures of the panels were at or near this level.

An analysis of the logged data retained in the charge controllers from before the trials indicated that the maximum power reading recorded on a single charge controller was 941 W. Since each change controller is connected to eight PV panels (1168 Wp), this suggests that under certain conditions system losses were as low as 18.8%.

The LED lighting used as a test load remained on for 24 hours daily and the DC voltage provided by the battery pack remained within a range of 23.6–28 V. This voltage range is suitable for a wide range of low-voltage DC lighting and other equipment. Figure 8 displays the voltage range over a 24-hour period recorded by the MAS. Thus by using the batteries the output voltage could be maintained within the operating range of the LED lights during PV array power fluctuations or when it produced little or no power (Figure 9).

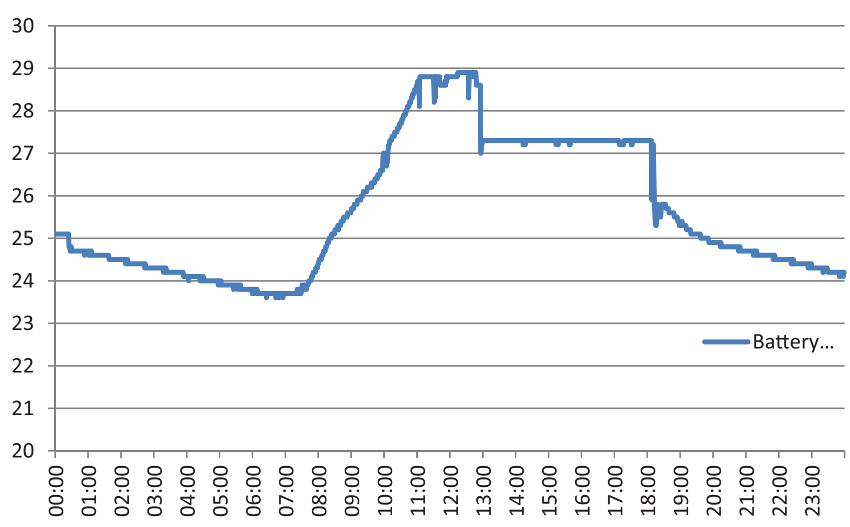


Figure 8. 24-hour battery voltage recorded by MAS (19th May).

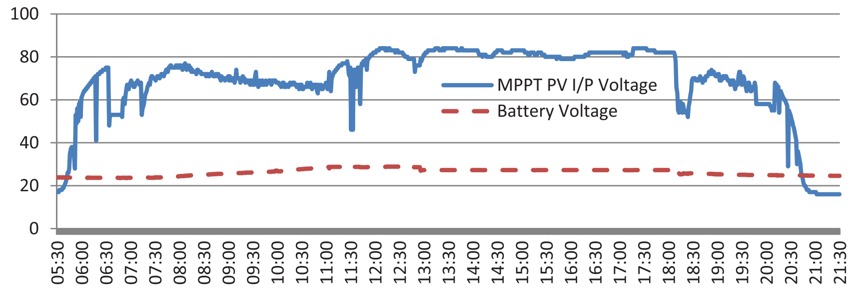


Figure 9. MPPT (1 unit) PV and battery voltages 05:30–21:30 (19th May).

The rise in the battery voltage shown in Figure 8 from approximately 07:30 until approximately 11:00 is the period during which the batteries were re-charged after discharging into the load (LED lights) during the evening. The drop in battery voltage at approximately 13:00 is due to the charge controllers switching out of their peak charging mode. The next voltage drop at approximately 18:00 is the point at which the batteries start to discharge.

In Figure 9 the MPPT PV voltage drops seen at around 11.30 were most likely caused by the shadows of personnel taking measurements near the array when the ship was near or at Paros. At around 18:00 the voltage drop was most likely caused by the shadow from the funnel when the ship was at or near the pier at Naxos.

Based on data from the 17th and 19th May, the performance ratio (PR) of the system was calculated using the following expression:

$$\mathrm{PR} = E/(I \times A \times \eta), \qquad (2)$$

where:

E = net energy output in Wh.

Thus the PR of the system was calculated as follows:

PR = 13,500 Wh/16,428 Wh = 0.82 or 82%

A PR of 0.82 equates to system losses of 18% which suggests power losses in the system were much less than estimated. However, typically the performance of a PV system is based on data taken over a longer period with 12 months being the recommended timeframe (Kurtz et al. 2013). Therefore this PR cannot be confirmed until more data are collected and analysed. In addition the performance of a PV system is influenced by the seasons and weather and during the two trials the conditions experienced were almost ideal. If for example the solar irradiation estimates for June were used as a basis for calculating the estimated energy production, then the resulting PR would be:

PR = 13,500 Wh/18,593 Wh = 0.72.

This equates to system losses of 28% and demonstrates the need to continue to evaluate the performance of the system. In addition there are various system parameters that can be adjusted some of which will alter the PR. These system parameters are currently being reviewed.

Conclusions

The trials on Blue Star Delos demonstrated that under operational conditions at sea, a low-voltage marine solar power system using thin panel PV technology and energy storage could provide a continuous stable supply of power to a DC load. The power output of the system met or exceeded design expectations and the performance of the PV panels did not appear to be significantly impacted due to the build-up of dirt and salt. However, analysis of data over a longer period needs to be undertaken and the possibility to improve the power yield by adjusting system parameters requires investigation. Additionally the impact of the marine environment on the solar panels and aluminium frames requires further study including determining how frequently the marine solar panel array should be washed and maintained.

Lastly, the utilisation a low-voltage PV system or systems together with low-voltage DC loads is a topic that requires further research. DC LED lights, for example, typically consume 1/5 of the power to deliver the equivalent level of illumination as higher voltage AC lights. Therefore it should be possible to significantly reduce the load on the ships' generators by using a combination of marine solar power and LED lighting technologies.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Nomenclature

AGU	Advanced graphics unit
CPU	Central processor unit
EEDI	Energy Efficiency Design Index
ECR	Engine control room
ILS	Input/output link system
I_{PM}	Maximum power current
I_{SC}	Short circuit current
MAS	Management and automation system
MPPT	Maximum power point tracking
LED	Light emitting diode
P_{MAX}	Maximum power
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
V_{OC}	Voltage open circuit
V_{PM}	Maximum power voltage

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