Brodogradnja/Shipbuilding Volume 65 Number 2, 2014

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ISSN 0007-215X
eISSN 1845-5859

# SOLAR ENERGY FOR RIVER NILE CRUISERS

UDC 629.5(05)
Professional paper

**Summary**

The concept of green shipping is now becoming an important issue for ship owners, shipping lines and ship builders globally. Solar energy may supply an environmentally friendly part to the total energy balance of a ship. Egypt is located in the world's solar belt and has excellent solar energy availability. Therefore, the aim of the present work is to present a case study for installing a photovoltaic solar system onboard a River Nile cruiser plying between Cairo and Aswan. Meteorological data for Cairo-Aswan navigation route is presented to calculate the output power of that system. A life cycle cost analysis is conducted and compared with the cost of generating the same amount of electricity by diesel generators to assess the economic benefits of the installed system. Stability of a River Nile cruiser, after the installation of a photovoltaic solar system, is rechecked to insure that the stability requirements of the Egyptian River Transport Authority are maintained.

*Key words:* *Photovoltaic; Solar Energy; River Nile Cruisers;*

## 1. Introduction

The trend towards using renewable and alternative energy sources on land has gathered momentum over the last decade or so as the general public and policy makers tackle the issues of pollution, energy security and climate change. However at sea, the shift towards the widespread adoption of alternative energy is only now beginning to take shape. Over recent years the shipping industry has begun to seriously look at ways to reduce fossil fuel consumption and operate in a more environmentally friendly way [1-2]. Due to the depleting nature of Egypt's limited fuel resources, the development of renewable energy technologies has proven to be essential. Therefore, renewable energy strategy was developed and incorporated as an integral element of national energy planning.

Implementation of such a strategy is an essential element of the national plans for achieving sustainable development and protection of the environment via upgrading energy efficiency and replacing conventional polluting sources by renewable sources. Recent advances in solar cells and panels design have led to solar power becoming a cost effective fuel reduction option on pleasure boats, ferries and tourist vessels. Therefore, the aim of the present work is using photovoltaic (PV) solar system to generate part of the required electricity onboard River Nile cruisers plying between Cairo and Aswan.

## 2. Route meteorological data

To predict the performance of a photovoltaic solar system on ship board, it is necessary to collect the meteorological or environmental data for the navigation route for such ship. The annual average total solar radiation over Egypt ranges from about 1950 $kWh/m^2$/year on the Mediterranean coast to more than 2600 $kWh/m^2$/year in Upper Egypt [3]. Sunshine duration ranges between 8-10 hrs/day from North to South with few cloudy days [3]. As Cairo-Aswan navigation route completely lays in the Upper Egypt, a value of 2300 $kWh/m^2$/year is used as the annual average solar radiation and the sunshine duration is taken equal to 8 hrs/day.

## 3. Characteristics of River Nile cruisers

Figure 1 shows general arrangement plans for a River Nile cruiser. The presence of locks and bridges along Cairo-Aswan waterway and shallow water nature of Nile represent several constraints on the dimensions of Nile cruisers [4]. Where,

- The breadth (B) and length over all (LOA) of River Nile ships are often dictated by the existing locks. ( LOA = 72 m and B = 14.4 m)
- The air clearance (height above water) is often dictated by the existing bridges. ( air draft = 10 m)
- The draft (T) and speed ($V_S$) of River Nile ships are often dictated by the shallow water nature of River Nile. ( T = 1.5 m and $V_S$ = 18 km/hr)

Due to the above mentioned points, River Nile cruisers are characterized by the following:

- Small draft (T),
- High superstructure (to gain maximum capacity and profit).

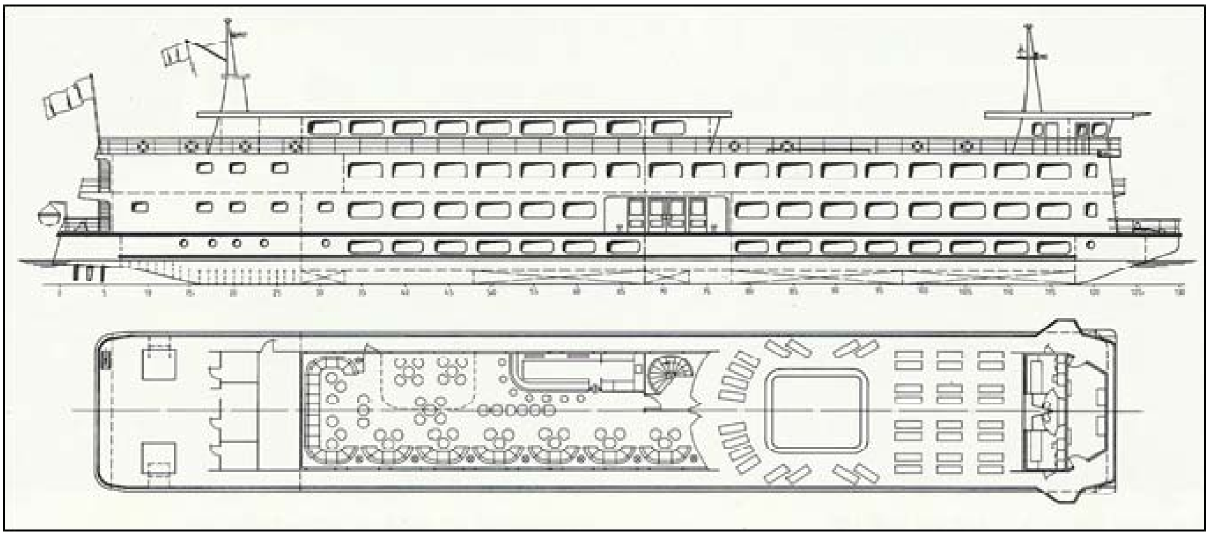

**Fig. 1** General arrangement plan for a River Nile cruiser

These led to most River Nile cruisers have a very high centre of gravity. Therefore, stability of River Nile cruisers must be considered carefully. Also, most River Nile cruisers have a large sun deck area. This will provide a suitable area to install a photovoltaic (PV) solar system onboard such ships. These will affect the centre of gravity for such ships. Therefore, the adequacy of stability of River Nile cruisers must be checked after installing a photovoltaic solar system.

## 4. Stability criteria for River Nile cruisers

The existing regulations of River Transport Authority (RTA) in Egypt, for the calculation of intact stability can be summarized as follows [5] :

1. Angle of heel, under the most unfavorable crowding of all passengers on one side, should not exceed 10°.
2. Angle of heel should not exceed 12° under the combined effect of heeling moments resulting from the following:
   - The most unfavorable crowding of all passengers on one side at the top most usable deck.
   - Beam wind of a speed of 100 km/hr applied at the center of the area subjected to wind.
   - Centrifugal force when the ship is turning with the maximum service speed (18 km/hr).
3. This combined heeling moment is to be applied statically to the vessel and the resulting angle of heel is to be calculated for the worst stability condition of the vessel.
4. Add 15% of the wind heeling moment to the combined heeling moment if there is a sunshade on the sun deck.
5. The distance between the individual waterline and the lowest opening from which water can be shipped into the vessel should at least be 5 cm.

## 5. Marine photovoltaic solar system

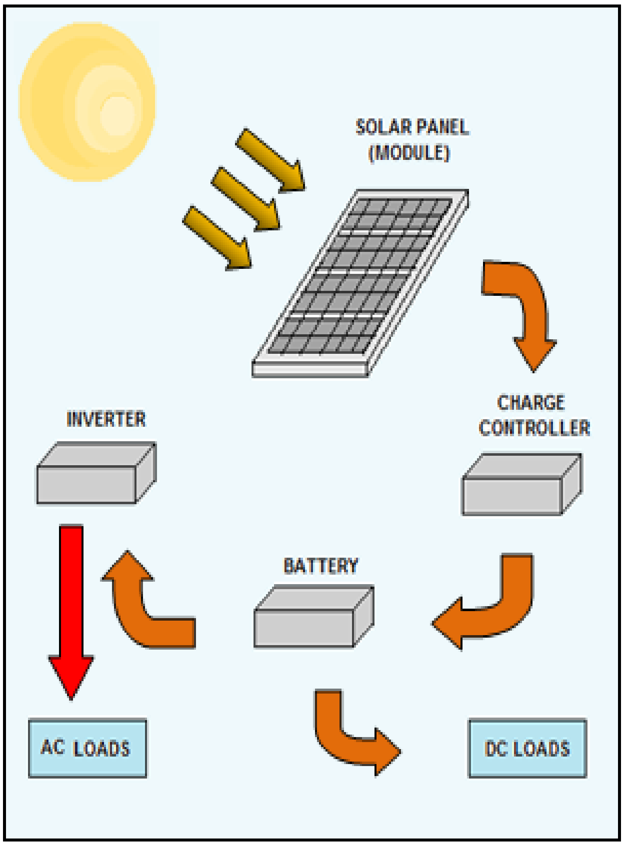


**Fig. 2** Marine solar system

Figure 2 shows the components of any marine solar system. Marine photovoltaic (PV) solar systems consist of the following components:

1. Solar panels produce the charge.
2. Charge controller or solar regulator which regulates the charge flowing into the battery and prevents overcharging.
3. Batteries which store the energy created by the solar panels.
4. Inverter which converts DC into AC.

5.1 Solar panel

Solar cells generate electrical power by converting solar radiation into direct current (DC) electricity while using semiconductors that exhibit the photovoltaic effect. Individual photovoltaic (PV) solar cells are interconnected and encapsulated between a transparent front and a backing material to form a PV solar panel. The output power of a solar panel is affected by the cell operating temperature. As temperature rises, output from the solar panel decreases [6]. The output electrical power of each solar panel (EP) may be calculated according to the following equation:

$$E_P = W_P * T_{SS} * TCF \tag{1}$$

where,

TCF = Temperature correction factor,

$T_{SS}$ = Average number of peak sunlight hours per day,

$W_P$ = The rated power for each solar panel in watt hour,

$E_P$ = The output electrical power of each panel in watt hours per day.

The PV modules represent about 60% of the total cost of the coherent system for power generation [7]. Therefore, the cost reduction in modules has a significant impact on the system investment.

5.2 Charge controller

The purpose of the charge controller or solar regulator is to regulate the current from solar panels to prevent batteries from overcharging. A charge controller senses when the batteries are fully charged and stops the current flowing to the battery and also prevents the battery from feeding back into the solar panel at night when it is dark. Most charge controllers include a low voltage disconnect feature, that senses the battery voltage and if the battery voltage drops below a pre-determined level (cut-off voltage) the charge controller will switch off the supply. Charge controllers should be capable of handling the total short circuit current of solar panels ($I_{TSC}$).

$$I_{TSC} = N_P * I_{SC} \tag{2}$$

where,

$N_P$ = Number of solar panels,

$I_{SC}$ = Short circuit current of each solar panel in amperes.

It is recommended that the selected controller is even slightly larger than the calculated total short circuit current of solar panels ($I_{TSC}$) to ensure that it is not constantly operating at 100% of its rating, particularly in regions with higher ambient temperatures.

### 5.3 Solar batteries

Solar panels should be used in conjunction with deep cycle batteries. These batteries are designed to be charged and discharged over a long period of time. Almost all of the batteries typically used in PV solar systems are lead acid. Deep cycle batteries are designed to deliver a consistent voltage while the battery is discharging. Deep cycle batteries are rated in ampere hours (Ah). This rating specifies the amount of current in Amps that the battery can supply over a period specified in hours. Size of the battery bank may be calculated according to the following steps:

1. Determine the electrical power that can be produced by the solar panels in watt hours per day (Wh/day).
2. Determine depth of discharge (DOD) of the battery. 80% should be considered the maximum for deep cycle batteries [8].
3. Divide the result of step 1 by the result of step 2. The result is the required capacity of the batteries in watt hours (Wh).
4. Find the watt hour capacity of the selected battery. Watt hours = voltage x ampere hour capacity.
5. Divide output of step 3 by the result of step 4. The result is the number of batteries required.
6. Round the number of batteries to fit system voltage.

### 5.4 Inverter

Storage batteries use and store direct current (DC) and have a low voltage output usually in the range of 12 - 24 volts. Virtually all modern appliances operate on alternating current (AC) and work on 220 volts. An inverter produces AC electricity from the DC battery to power the AC appliances, such as televisions, air conditioners, pumps, satellite communication, entertainment systems, radios and other things onboard ship.

## 6. Energy saving

Most River Nile cruisers require a high daily electrical load to cover their daily activities. Installing a solar system onboard a River Nile cruiser will produce an amount of electrical power. This amount cannot cover the required daily load on such ship but may cover a considerable percentage of that load. The output power of any solar system onboard ship represents a saving in the electrical power produced by the diesel generators on such ship. Daily output power of any solar system (EDS) may be calculated as follows:

$$E_{DS} = E_P * N_P * \eta_B * \eta_{INV} \tag{3}$$

where,

$E_{DS}$ = Daily output power of any solar system in watt hours per day,

$E_P$ = Output electrical power of each panel in watt hours per day,

$N_P$ = Number of solar panels,

$\eta_B$ = Battery efficiency, $\eta_{INV}$ = Inverter efficiency.

In this paper, the battery efficiency and inverter efficiency are taken equal to 0.85 and 0.9, respectively [7]. The amount of fuel required to generate such amount of electricity by diesel generators represents an important source for energy saving in the consumed power onboard such ship. With the instability of fuel price nowadays, reduction in fuel consumption would help reduce operating costs.

## 7. Cost of PV solar system

The Life Cycle Cost (LCC) of any system consists of the total costs of owning and operating it over its lifetime, expressed in today's money. The LCC of any PV solar system includes the sum of all the present worth's of the costs of the PV panels, storage batteries, battery chargers (charge controllers), inverters, the cost of the installation, and the maintenance and operation (M&O) cost of the system. Table1 shows the details of the used cost data for all items.

**Table1** Cost data for PV solar system

| No. | Item | Cost |
|---|---|---|
| 1 | PV Panel | $0.75/W |
| 2 | Battery | $0.9/Ah |
| 3 | Inverter | $0.12/W |
| 4 | Charge Controller | $3.12/A |
| 5 | Installation | 10% of PV Cost |
| 6 | M&O/Year | 2% of PV Cost |

The life time (N) for all items is considered to be 20 years, except that of the battery which is considered to be 10 years. Thus, another group of batteries have to be purchased after 10 years. The present worth of the second group of batteries ($C_{B2PW}$) is calculated as follows [9-10]:

$$C_{B2PW} = C_{B1PW} * (1+d)^{N-1} * (PW - i\% - N) \tag{4}$$

$$(PW - i\% - N) = 1.0/(1+i)^{N} \tag{5}$$

where,

d = Inflation rate, 5%

i = Interest rate, 10%

N = Life span in years,

PW = Single present worth factor.

$C_{B1PW}$ = Present worth of the first batteries group,

$C_{B2PW}$ = Present worth of the second batteries group.

Total present worth of maintenance & repair cost ($C_{MPW}$) may be calculated using series uniform present worth factors (SPW) as follows [9-10]:

$$C_{MPW} = 0.02 * C_{SP} * (SPW - i\% - N) \tag{6}$$

$$(SPW - i\% - N) = \frac{(1+i)^{N} - 1}{i(1+i)^{N}} \tag{7}$$

where,

CSP = Cost of solar panels, N = Life time for solar panels,

SPW = Series uniform present worth factor,

$C_{MPW}$ = Total present worth of maintenance & repair cost.

Average annual cost (AAC) of any photovoltaic (PV) solar system may be calculated as follows [9-10]:

$$AAC = LCC \; * ( CR - \; i \; \% \; - N \; ) \tag{8}$$

$$(CR - i \; \% - N) = \; 1 \; / \; (SPW - i \; \% - N) \tag{9}$$

where,

CR = Capital recovery factor, AAC = Average annual cost in $/year.

## 8. Case study

A River Nile cruiser plying between Cairo and Aswan is considered to install a photovoltaic (PV) solar system on her uppermost deck. Main particulars of such ship are shown in table 2.

**Table 2** Main particulars of River Nile cruiser

| | | | |
|---|---|---|---|
| LOA | 70.5 m | T | 1.173m |
| LBP | 64.0 m | $\Delta$ | 701.945 tons |
| LWL | 64.8 m | KG | 3.697 m |
| D | 3.50 m | $N_P$ | 100 Persons |
| B | 11.0 m | $N_{Crew}$ | 45 Crew |
| Distance between the lower edge of | | | 40 cm |

The investment costs of any solar system and availability of solar energy represent two major problems may affect the application of solar energy on ships. In our case, Cairo - Aswan navigation route has excellent solar energy availability along the year. Also, investment cost of such solar system is taken into consideration to design a photovoltaic (PV) solar system for the considered ship.

### 8.1 Number of PV solar panels

From general arrangement plans for such ship, an area of 186 $m^2$ is available on the uppermost deck. That area may be used for installing photovoltaic (PV) solar system onboard such ship. 200W mono-crystalline silicon PV solar panels are used for such system. Specifications of such panel are shown in table 3.

**Table 3** Specifications of a Mono-Crystalline Silicon PV solar panel

| | | |
|---|---|---|
| Power rating | | 200 Watt |
| Open circuit voltage (Voc) | | 36.6 Volt |
| Short circuit current (Isc) | | 7.52 Amps |
| Voltage at Pmax (Vmp) | | 29.7 Volt |
| Current at Pmax (Imp) | | 6.73 Amps |
| Size | Length | 1640 mm |
| | Width | 992 mm |
| | Height | 50 mm |
| Weight | | 19.0 kgs |
| Life span | | 20 -25 Years |

114 Mono-Crystalline Silicon PV Solar Panels (1.63 $m^2$) may be used to cover 186$m^2$. Weight and price of these panels are 2.166 tons and $17100, respectively.

8.2 Number of charge controllers

Charge controllers (solar regulators) are rated by the amount of current they can receive from the solar panels. Therefore, it has to be capable of carrying the short circuit current of the PV solar systems. A margin of safety equal to 20% may be taken to allow for growth and the fact that the solar panels may exceed their rated output. Thus, in this case, it should be chosen to handle (7.52 Amps x 114 x 1.2) 1028.7Amps. Therefore, 18 charge controllers of 60 Amps are suitable for that system. Weight and price of these charge controllers are 0.029 tons and $3370, respectively. Table 4 shows specifications of a 60 Amps charge controller.

**Table 4** Specifications of a 60Amps charge controller

| | | |
|---|---|---|
| Rated solar, load or diversion current | | 60 Amps |
| System Voltage | | 12 - 24V |
| Minimum voltage to operate | | 9 Volt |
| Maximum solar voltage (Voc) | | 125 Amps |
| Size | Height | 260 mm |
| | Width | 127 mm |
| | Depth | 71 mm |
| Weight | | 1.6 kgs |

8.3 Number of solar batteries

To calculate the required number of solar batteries for any solar system, the daily output electrical power produced by each PV solar panel ($E_P$) must be calculated. In this case, a 200 watt mono-crystalline silicon PV solar panel with sunshine duration ($T_{SS}$) equal to 8 hrs/day and temperature correction factor (TCF) equal to 0.8 [7] will produce 1.28 kwh/day. Therefore, 114 solar panels will produce 146 kwh/day. This amount may be stored in 52 deep cycle batteries each 12V 300Ah with a battery depth of discharge equal to 0.8. Weight and price of these batteries are 3.276 tons and $14040, respectively. Table 5 shows specifications of a 12V 300Ah solar storage deep cycle battery.

**Table 5** Specifications of a 12V 300Ah solar storage deep cycle battery

| | | |
|---|---|---|
| Type | | Lead-Acid Batteries |
| Size | Height | 522 mm |
| | Width | 240 mm |
| | Depth | 242 mm |
| Weight | | 63 kgs |
| Battery Life Time | | 8-12 years |

8.4 Number of power inverters

To calculate the required number of inverters for any solar system, the daily output electrical power ($E_{DS}$) produced by such system must be calculated. In this case, an amount of 112 kwh must be handled by power inverters. This amount is calculated using battery efficiency of 0.85 and inverter efficiency of 0.9. In this case, with 20% margin of safety, 27 power inverters of 5000W are suitable for such system. Weight and price of these inverters are 0.327 tons and $16200, respectively. Table 6 shows specifications of a 5000W power inverter.

**Table 6** Specifications of a 5000W power inverter

| | | |
|---|---|---|
| Type | | DC/AC inverter |
| Input voltage | | DC 12Volt |
| Output voltage | | AC 220Volt |
| Continuous output power | | 5000Watt |
| Peak power | | 10000Watt |
| Output waveform | | Pure sine wave |
| Output Frequency | | 50Hz |
| Size | Length | 544 mm |
| | Width | 199 mm |
| | Height | 146 mm |
| Weight | | 12.1 kgs |

8.5 Cost analysis

To evaluate the economical benefits of a PV solar system produces 112 kwh per day, annual cost for generating the same amount of electricity by a diesel generator will be calculated. Diesel generator of 112 kw (at maximum continues rate equal to 0.85), will consume 200 grs/kw/hr at a speed of rotation equal to 2200 rpm. Annual weight of fuel needed for diesel generator to produce 112 kwh/day is 8.176 tons. Therefore, to generate the same amount of electricity using a diesel generator will cost $10220 for the consumed fuel annually. The cost of the consumed fuel is calculated using a fuel price equal to $1250/ton. Cost details of the installed PV solar system onboard the considered River Nile cruiser are summarized as shown in table 7.

**Table 7** Cost details for PV solar system

| No. | Item | | Present Worth ($) |
|---|---|---|---|
| 1 | Solar Panels | $C_{SP}$ | 17100 |
| 2 | Charge Controllers | $C_{CPW}$ | 3370 |
| 3 | Solar Batteries | $C_{B1PW}$ | 14040 |
| 4 | | $C_{B2PW}$ | 8398 |
| 5 | Power Inverters | $C_{IPW}$ | 16200 |
| 6 | Installation | $C_{INS}$ | 1710 |
| 7 | Maintenance & Repair | $C_{MR}$ | 2912 |
| 8 | Total Cost (20 years) | LCC | 63730 |
| 9 | Average annual cost | AAC | 7486 |

From the above calculation, one can conclude that installing a PV solar system onboard the considered River Nile cruiser will save $2734 annually. This value represents 26.7% of the cost of required fuel to generate the same quantity of electricity annually.

8.6 Stability considerations

Stability calculation for the considered River Nile cruiser (before installing PV solar system) is carried out for the worst loading condition. The results show that, the considered River Nile cruiser satisfies the existing regulations of River Transport Authority (RTA).

**Table 8** Loading condition after installing PV solar system

| Item | Weight | VCG | Vertical Moment |
|---|---|---|---|
| Δ (old) | 701.945 | 3.697 | 2595.1 |
| Solar panels | 2.166 | 11.03 | 23.89 |
| Charge controllers | 0.029 | 2.0 | 0.058 |
| Batteries | 3.276 | 1.061 | 3.476 |
| Inverters | 0.327 | 2.0 | 0.654 |
| Total | 707.75 | ---- | 2623.18 |
| New Features | | | |
| Δ (tons) | 707.75 | KG | 3.706 m |
| T | 1.185 m | KB | 0.675 m |

The calculations of the ship's loading condition after installing PV solar system are given in table 8. Stability of such ship is reconsidered for the new loading condition as follows:

1. Heeling moment due to wind pressure ($M_W$) may be calculated according to the following equation [5]:

$$M_W = 0.055 * A_P * Z_W \tag{10}$$

where,

$Z_W$ = Wind heeling arm in meters,

$A_P$ = Above water lateral projected area in square meters.

By taking, $Z_W$ = 4.96 m and $A_P$ = 536.5 m$^2$, heeling moment due to wind pressure ($M_W$) equals to 146.36 tons.m.

2. Heeling moment due to crowding of all passengers on one side ($M_P$) may be calculated according to the following equation [5]:

$$M_P = 0.0375 * N_{Pass} * B \tag{11}$$

where,

$N_{Pass}$ = Number of passengers, B = Ship breadth in meters,

By taking $N_{Pass}$ = 145 and B = 11.0 m, heeling moment due to crowding of all passengers on one side ($M_P$) equals to 59.81 tons.m.

3. Heeling moment due to turning circle ($M_T$) may be calculated according to the following equation [5]:

$$M_T = 0.01 * B^3 - \frac{0.127\ \Delta}{LWL} * GM_T \tag{12}$$

where,

Δ = Ship displacement in tons, $GM_T$ = Metacentric height in meters,

LWL = Length on load water line in meters.

By taking B = 11.0 m, Δ = 708.181 tons, LWL = 64.8 m and $GM_T$ = 6.1 m, heeling moment due to turning circle ($M_T$) equals to 4.843 tons.m.

4. Heeling moment equal to 0.15 $M_W$ should be taken into consideration for the effect of sunshade [5]. This moment will be equal to 21.954 tons.m.
5. Total heeling moment due the above mentioned points could be equal to 232.95 tons.m. Therefore, total heeling arm will be equal to 0.328 m.
6. From figure 3, angle of statical balance could be equal to 3.2 degrees. At this angle, distance between the inclined waterline and the lowest opening from which water can be shipped into the vessel could be equal to10 cm.

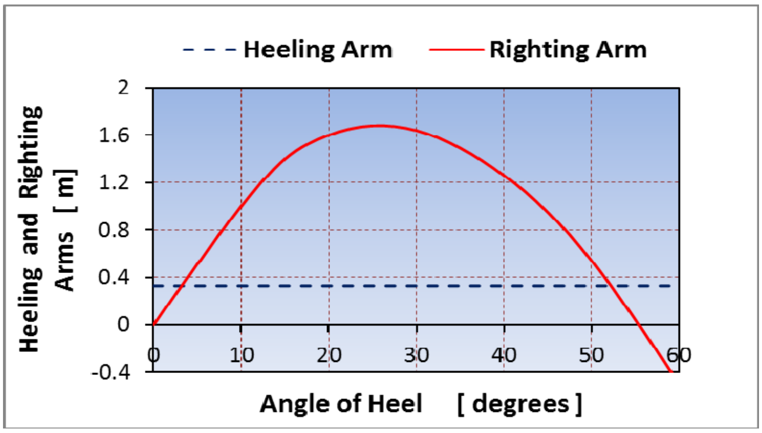


**Fig. 3** Angle of statical balance

From the above mentioned points, one can conclude that the considered ship, after installing photovoltaic (PV) solar system, still satisfying stability requirements of River Nile transport authority.

## 9. Conclusions

1. The investment costs of any solar system and availability of solar energy represent two major problems may affect the application of solar energy on ships.
2. Solar energy should be considered one of the most promising energy sources in Egypt. It represents, at the same time, a vital and economic alternative to the conventional energy generators.
3. The use of PV solar systems to supply some of the power required by instruments and lightings onboard the vessel reducing fuel consumption and thus reducing the diesel exhaust.
4. With the instability of fuel price nowadays, reduction in fuel consumption would help in saving the money and would somehow increase the income.
5. The results of the study indicate that generating electricity onboard ships using PV solar systems is beneficial and suitable for long-term investments, especially if the initial prices of the PV systems are decreased and their efficiencies are increased.
6. Installing PV solar system onboard River Nile cruisers not affect the stability of these cruisers specially, if the position of storage batteries is considered accurately.

7. The results of this study encourage the use of the photovoltaic (PV) systems to generate electricity onboard River Nile cruisers.

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Submitted: 28.09.2103.
Accepted: 13.01.2014.

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