Solar Panels-On Boat or Shore?

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Abstract

The paper expands the scope of comparing the two scenarios of solar panels on boat and shore from merely cost of grid energy to a wider TCO[1] . Three scenarios are compared-(i) maximum solar panels on boat, (ii) half the maximum solar panels and (iii) no solar panels on boat (electric boat). In all the three cases the sum of solar plant size on boat and shore as well as the functional needs are same. The case of a 75-passenger solar ferry is taken to do the comparison. It is seen that CAPEX is the lowest in the case where the solar panels are maximum on boat, since increase in solar panels on the boat decreases battery size and cost. In the case of OPEX, taking both energy cost as well as maintenance cost, all the three cases have similar values, with shore solar plant. In case of no shore solar plant, OPEX increases with decreasing solar plant size. Hence it is concluded that it is cost effective to put largest possible solar panels on the boat.

Keywords: Electric propulsion, Optimisation, Solar panels

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1. Confusion

An electric boat, defined as one with electric propulsion, has multiple sources of energy. The most popular one is stored energy of the grid in batteries. Solar energy from solar panels and energy from diesel generators are other sources. There has been lot of discussion on use of solar energy, whether it should be fixed on boat or on shore. The proponents on shore installation claim that the cost of energy from solar panels is cheaper by keeping the panels on shore and making it one single large installation rather than small plants on each boat.

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[1] Total Cost of Ownership

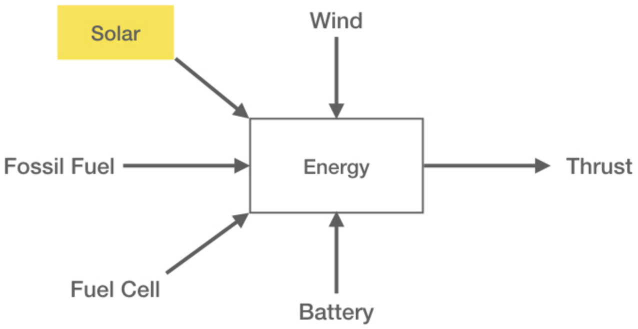

Figure 1: Energy sources

2. Introduction

One of the reason why the confusion persists is the limited scope when comparing the two scenarios-solar panels on boat or shore. In this the cost of energy from small solar plant is compared to the (cheaper) cost of energy from a large installation on shore.

However, one forgets that energy generated on shore can be used in the boat only by transferring from shore to boat through batteries or other storage medium (fuels). This increases the battery bank size and thereby the cost significantly. If the solar panels are placed on the boat, then it can generate energy as well as consume while the boat is in motion.

To make proper comparison, the total solar plant size is made same (boat + shore) and assessed.

A good way to compare, would be to compare the difference in TCO. This include both CAPEX and OPEX. While comparing one must keep the functional needs same.

Summarising the likely differences:

1. Cost differences due to different solar plant size on boat and correspondingly different battery bank size (smaller solar plant has larger battery bank).
2. Energy cost from solar plant is zero (maintenance cost is separate). Depending on energy from solar plant, both on boat and shore, grid energy consumption is different.
3. Use of generator to cover the days with lower solar irradiation differs in each case and therefore energy cost from generator is different.
4. Maintenance cost of battery bank differs by difference in size.

3. Methodology

It is attempted to generalise for any size of boats, however, to get a feel of the number, a 75-passenger solar/electric boat is chosen. The boat is a 20 meter long, 7 meter wide catamaran with slender demi-hulls with an overall displacement of 22 tonnes.

The operation pattern of ADITYA[1][2] solar ferry at Vaikom is used for reference. The boat operates from 7 AM to 7 PM and takes twenty-two trips across the backwaters for a distance of 3 km. The cruise speed is 6 knots, needing 16 kW for propulsion and 1 kW for auxiliary (ventilation fans, controls). Each trip takes 15 minutes including manoeuvring time. From the figure 2, running time is 5.5 hrs (15 mts x 22 trips) and operating time is 12 hours. Total energy is 100 kWh as sum of propulsion (16 kWh x 5.5 hrs = 88 kWh) and auxiliary loads (1 kWh x 12 hrs= 12 kWh).

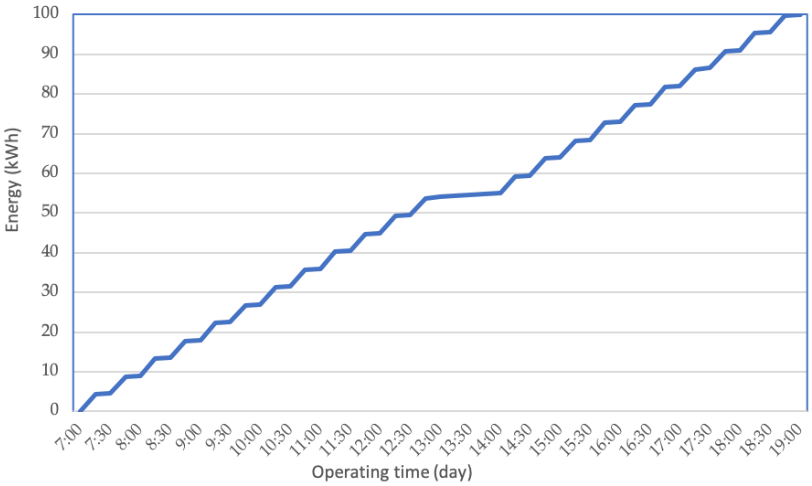

Figure 2: Cumulative motor consumption in a day

The three cases are listed:

- Case 1 All solar panels on boat. 20 kWp on the solar boat and none on shore.
- Case 2 Half solar panels on boat. 10 kWp on the solar boat and 10 kWp on shore.
- Case 3 Zero solar panels on boat. Pure electric boat and 20 kWp on shore.

For each cases, the following steps are followed:

1. Solar production-single day as well as distribution over a year
2. Battery sizing based on choice of minimum solar production
3. Generator sizing
4. Battery size optimisation based on SOC during operation
5. Energy source distribution
6. CAPEX
7. OPEX (energy cost, maintenance cost)
8. Comparison

3.1. Solar production

The solar production in different parts of the world[2] is different based on various factors. The energy production in one area also varies by each day. Hence the average irradiance for the year is used for calculation purpose.

The nature of solar production is shown in the figure 3. This curve is for location where ADITYA is operating (Vaikom), where average production for standard sun is 5.72 units. This means that for 1 kW solar panel with battery system, the energy production in a day is 3.5 kWh (61% efficiency), i.e., 5.72 x 61%. Of this 70% efficiency is for a typical solar plant with battery storage and additional loss in efficiency due to keeping the panels nearly flat on a moving system around 12.5%. Hence overall efficiency is 70% x 87.5% = 61%.

The cumulative solar production for the day is also shown in figure 3.

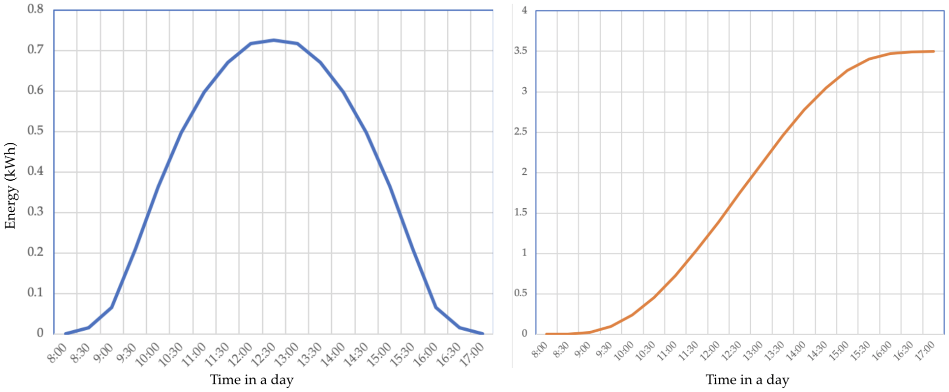

Figure 3: Daily production versus time, power (left) and energy (right)

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[2] https://www.nrel.gov/gis/solar.html

While the daily production for an average day is shown above, the production varies by each day in a year. While using the average irradiance, it is important to understand the nature of the distribution to optimise the system design.

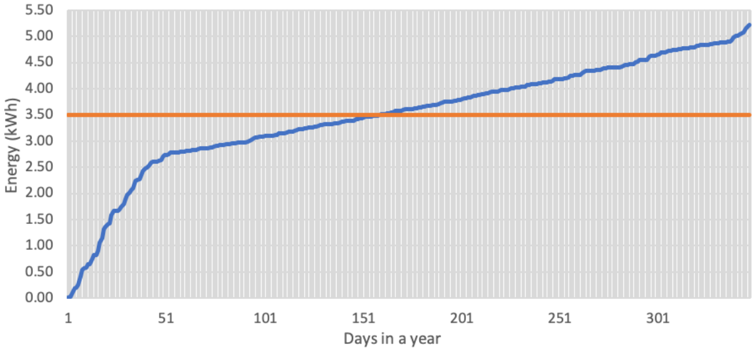

Figure 4: Data from one-year solar production of ADITYA[3] solar ferry boat (per kW)

A typical production curve is shown above. Some of the important characteristics of the curve will decide the system design. One can observe the following:

1. Only less than 12% of the days the value is half the maximum.
2. The average is 67% of the maximum.
   Based on the average for the year, which is the value we get from the irradiance maps, we observe:
3. 54% of the days have production more than the average
4. 68% of the days have production more than 90% of the average
5. 83% of the days have production more than 80% of the average
6. 92% of the days have production more than 50% of the average
7. 95% of the days have production more than 33% of the average

3.2. Battery sizing

On an electric boat without solar panels, the battery sizing is straightforward. However, with solar panels, it needs a careful deliberation.

One option is to design the boat for all scenarios of solar production, i.e. assume the worst case of solar production, which would be zero. This therefore becomes same as designing the battery size of an electric boat with no solar panels on boat (top left in figure 5). The other extreme is to size the battery assuming a bright sunny day. In this way the battery size can be significantly reduced. In reality it is something in between.

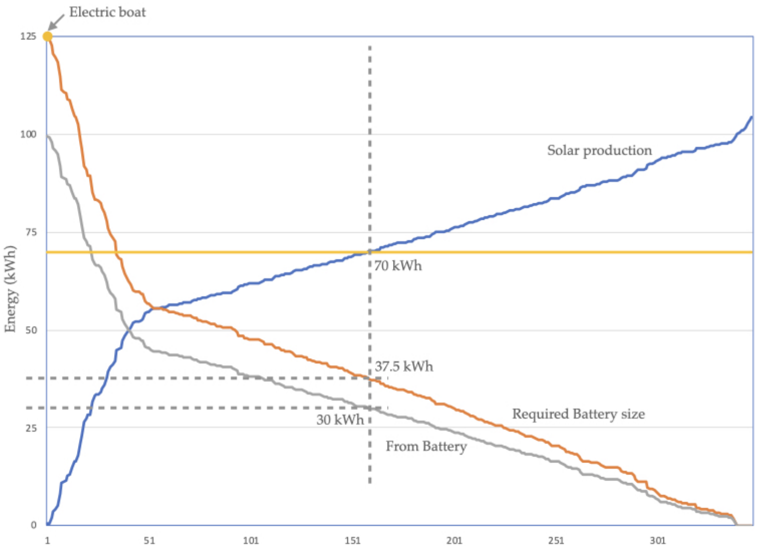

Figure 5: Battery sizing based on daily minimum solar energy to be taken

That choice represents the minimum daily solar production to be assumed. It lies in the solar energy production curve. A standard approach is to take the average solar production in that location for the whole year. In this example, it is 70 kWh energy from the sun (from 20 kWp solar panels). For this 70 kWh, the energy to be provided by the batteries is 30 kWh (since total need is 100 kWh) and therefore the battery size is 37.5 kWh (80% SOC[3] used).

For the Case 2, the average solar energy production in the location for a year is 35 kWh. Hence the remaining 65 kWh has to come from grid through batteries. The battery size must be therefore 81.25 kWh. Similary for the Case 3, 100 kWh has to come from grid through batteries. The battery size must be therefore 125 kWh.

For Case 1 and 2, during the days in which solar production is lower, one of them need to happen:

- operating time is reduced,
- charging introduced in the daytime or a combination of both.
- generator onboard will provide energy.

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[3] State of Charge

In the scenario the first two methods are not acceptable, having generator on board is the option. This also provide redundancy which the first two methods do not provide.

3.3. Generator

In this case, we assume that generator is provided onboard to provide energy. Lets see when this energy will be needed. If we plot the two energy sources (sun and grid), the gap will be provided by generator. It can be seen that generator will be needed on days where the solar production is less than average (46% of days). The generator size can be determined by the total energy need. Assuming that the battery is always full in the morning (overnight charging), the total gap in energy is 70 kWh. Since the boat operates for 12 hours, if the generator is running all the time, then a 6 kW generator can provide this energy (12 x 6 = 72 kW).

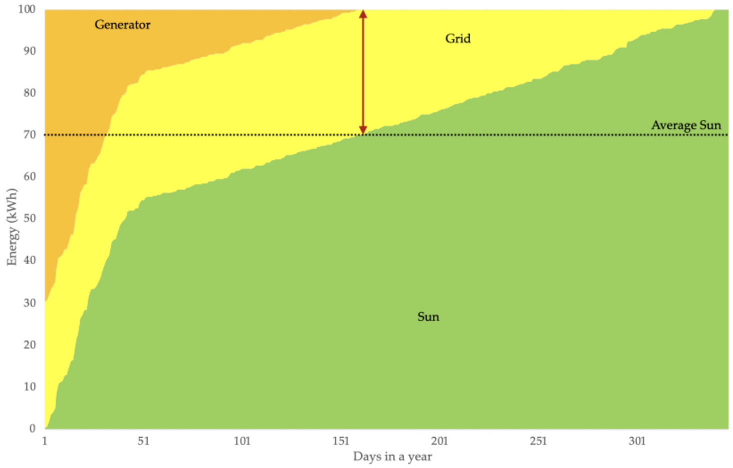

Figure 6: Energy source distribution (Case 1)

However, if we take generator to be designed for complete redundancy, then it need to be sized based on power. In this example, total load is 17 kW (16 kW propulsion, 1 kW auxiliary). Hence a 20 kW generator would be suitable to manage the worst condition. It is to be noted that a 6 kW generator can offer redundancy, but the speed of the boat will be lower (almost half), which may not be acceptable for ferry boats. Similarly in case of pure electric boat, although there is no need for generators in normal scenario, for redundancy, the same generator that can run the entire load is chosen.

Hence, in all three cases a 20 kW generator is chosen.

3.4. Solar versus electric

The above sections show how to decide the battery size and generator size once the solar panel size and minimum contribution from solar panels is assumed. From here lets assume that the minimum contribution from solar panels is the average in the location for the whole year.

To assess the cost effectiveness of solar panels on boat, as described in Sec 3 (Methodology), three cases of solar panels on boat are considered 20 kWp, 10 kWp and 0 kWp (pure electric) with rest on shore.

Comparison	**Case 1**	**Case 2**	**Case 3**
Solar on boat (kWp)	20	10	0
Solar on shore (kWp)	0	10	20

Table 1: Case comparison

3.5. Cumulative energy

Although the initial battery size is obtained by the steps described above, it has to be checked using energy plot diagram. The energy plot tracks the battery SOC during the whole operations period. From initial SOC, usually 100%, at the start, the SOC changes depending on the difference between motor consumption and solar production. If motor consumption is more, then SOC decreases, but if solar production is more, the SOC increases. It is to be noted that at this average solar production, generator is not running.

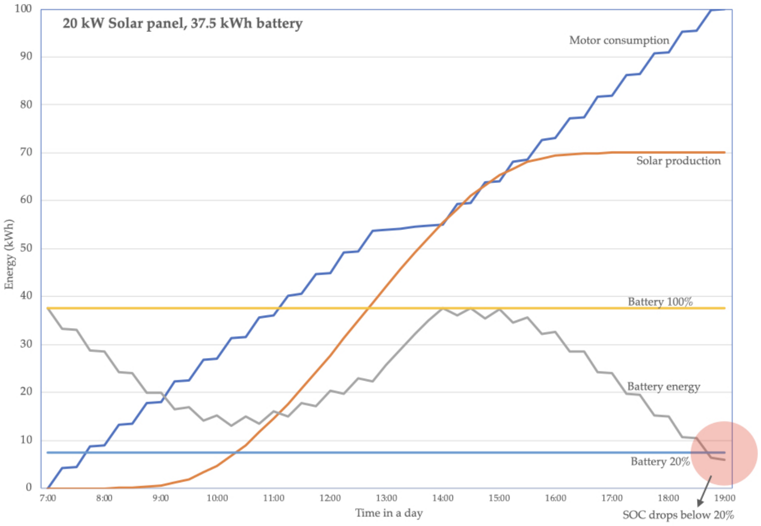

Figure 7: Energy plot before optimisation

The energy plot for the solar boat with 20 kW solar plant and 37.5 kWh battery is shown in figure 7. Although the sum of useful battery energy of 30 kWh and solar production of 70 kWh is 100 kWh, there is a period in the noon time when the solar energy cannot be absorbed because SOC is already 100%.

The final battery SOC is only 6.3 kWh (instead of 7.5 kWh). Hence, the effective solar production is only 68.8 kWh. Although this can be solved by running the generator like in days when production is lesser than average, however, for better comparison, a higher battery bank is chosen to eliminate this problem. In this case a 40 kWh battery bank is finalised (figure 8).

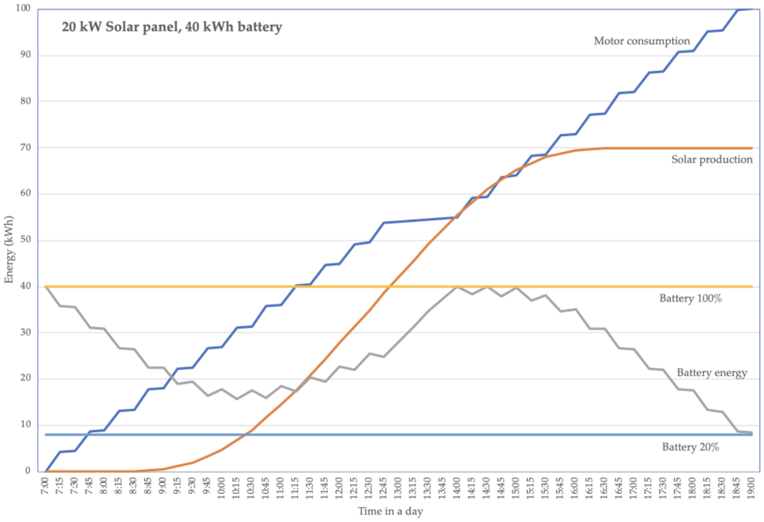

Figure 8: Energy plot after optimisation for Case 1

Similarly for Case 2 with 10 kWh solar plant, an 81.25 kWh battery bank is finalised (figure 9). For Case 3 with no solar panels, since batteries are designed for whole day operation, there is no need to plot this figure.

4. Cost Comparison

The three cases differ in the size of solar plant and battery bank kept in the boat and that is summarised in the table below.

When comparing the three cases, we should take the life cycle cost, both CAPEX and OPEX. Here, only the items where there are differences between the cases is considered.

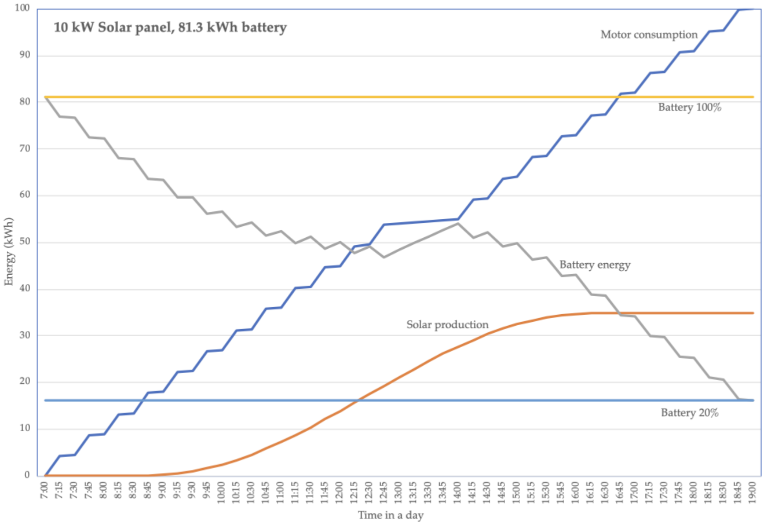

Figure 9: Energy plot after optimisation for Case 2

System	**Case 1**	**Case 2**	**Case 3**
Solar plant-Boat/Shore (kWp)	20/0	10/10	0/20
Battery bank (kWh)	40	81.25	125

Table 2: Case comparison

4.1. Weight Impact

When we compare the three cases, the difference in solar panel and battery size can have difference in weight. Solar plants weight approximately 65 kg/kWp. An additional 10% weight for charge controllers,cables, and electrical fittings yields 73 kg/kWp. For the three cases, solar plant weighs 1460kg, 730 kg, and 0 kg respectively. Battery box weights approximately 16 kg/kWh. For the three cases, battery bank weights 640 kg, 1300 kg, and 2000 kg. It can be seen that the sum of solar and battery weight in each case is nearly same, hence the small weight difference does not cause difference in powering and cost.

System	**Case 1**	**Case 2**	**Case 3**
Solar plant on boat	1,460	730	0
Battery bank	640	1,300	2,000
Total Wt.	**2,100**	**2,030**	**2,000**

Table 3: Weight comparison (kg)

4.2. Energy source

For each case, the distribution from the three sources of energy is plotted similar to the figure 6 in Section 3.3. There the 20 kW solar panels case is plotted. Each of the three areas give the respective values of total energy in a year from each source. This is summarised under Case 1 in table 3.

Similarly, the Case 2 with 10 kW solar panel can be plotted. Like earlier, during the days with lower solar energy than average, the energy has to come from generator. Here again the three areas give the respective values of total energy in a year from each source. This is summarised under Case 2 in table 2. In the Case 2, it is to be noted that another 10 kW solar panels feed energy to the grid. This is a total of 12,145 kWh (35 kWh x 347 days). Although shore solar energy is produced on days in which the boat is under maintenance, since there is no production when grid is not available, same number of days is taken.

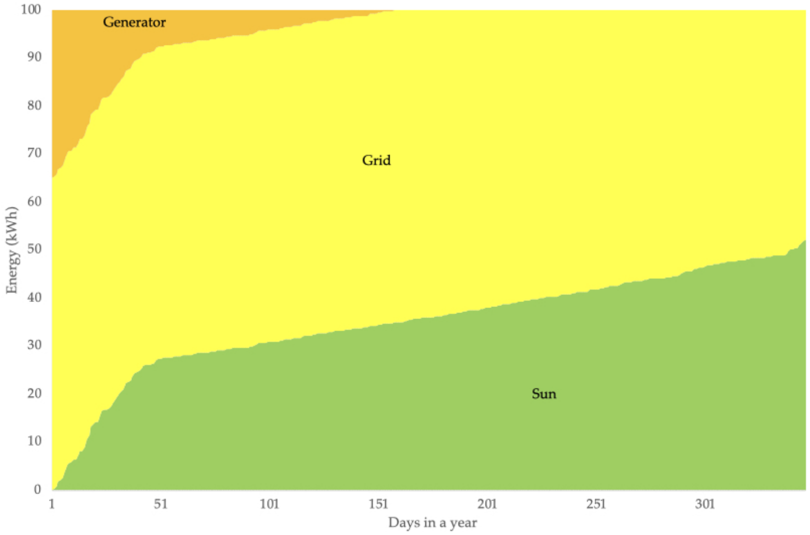

Figure 10: Energy source distribution (Case 2)

For Case 3, all the energy comes from grid stored in batteries. The total for the year is 34,700 kWh (347 days x 100 kWh). In the Case 3, the 20 kW panels on shore produces twice of Case 2, i.e., 24,290 kWh. It is to be noted that the total energy in all the three cases is 34,700 kWh.

The total energy from grid has two parts based on solar energy generated on shore and fed to the grid. The remaining is the one that is charged at grid rate ($\text{Rate}_{\text{grid}}$).

Source	**Case 1**	**Case 2**	**Case 3**
From Solar (on boat)	24,275	12,145	0
From Grid	7,935	21,159	34,700
From DG	2,490	1,396	0
Total	**34,700**	**34,700**	**34,700**

Table 4: Energy source distribution (kWh)

Source	**Case 1**	**Case 2**	**Case 3**
From Grid with $\text{Rate}_{\text{grid}}$	7,935	9,014	10,410
Solar on shore (fed to grid)	0	12,145	24,290
Total from grid	**7,935**	**21,159**	**34,700**

Table 5: Grid energy distribution (kWh)

4.3. CAPEX

In all the three cases, the total solar pant is same. Although the one on the boat is a DC system with charge controller and on the shore is a grid-tie inveter that feeds AC to the grid, the unit rate of solar plant is nearly same. The solar plant consists of solar panels, mounting structures, cables, charge controller, safety devices and other electrical fittings. For installation on boats and shore, the rate of solar plant is ₹40,000/kWp. nd Since the CAPEX is same, solar plant is not considered.

There is one system where CAPEX differ among the three cases battery bank.

A battery bank consists of LFP[4] batteries with BMS[5], system level safety devices, cell level monitoring, and controls essential to meet the standards of marine grade battery system for main propulsion[4]. The system level cost per kWh is approximately 75,000 ₹/kWh.

$$CAPEX_{battery} = BatterySize * Rate_{battery} \tag{1}$$

The system level cost for each case is calculated based on this rate and battery size.

Case 1, $\text{CAPEX}_{\text{battery}}$ = 40 x 75,000 = ₹30,00,000

Case 2, $\text{CAPEX}_{\text{battery}}$ = 81.25 x 75,000 = ₹60,93,750

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[4] Lithium Iron Phosphate

[5] Battery Management System

Case 3, $\text{CAPEX}_{\text{battery}}$ = 125 x 75,000 = ₹93,75,000

The CAPEX for each case is:

Case 1	**Case 2**	**Case 3**
30,00,000	60,93,750	93,75,000

Table 6: CAPEX (₹)

It can be observed that as we shift the solar panels from boat to shore half in second case and completely in case of third (electric boat), the CAPEX increases significantly. Hence electric boats with largest solar panels on boat (solar boats) have the lowest CAPEX.

4.4. OPEX

There are two kinds of operating expense energy cost and maintenance cost. The energy cost is direct cost incurred and maintenance is separate. The sum of two is OPEX.

$$OPEX = OPEX_{energy} + OPEX_{maint} \tag{2}$$

4.4.1. Energy Cost ($OPEX_{energy}$)

The energy cost consists of three sources solar, grid, and DG. The sum is the result.

$$OPEX_{energy} = EnergyCost_{solar} + EnergyCost_{grid} + EnergyCost_{DG} \tag{3}$$

The energy cost from solar is zero. $\text{EnergyCost}_{\text{solar}} = 0$.
The energy cost from grid is calculated using grid energy consumed, from table 4, and rate of grid power. The rate of grid power is normally ₹7.5/kWh. The part generated from solar panels on shore has zero cost.

$$EnergyCost_{grid} = Energy_{grid} * Rate_{grid} \tag{4}$$

Case 1, $\text{EnergyCost}_{\text{grid}}$ = 7,935 x 7.5 = ₹59,513
Case 2, $\text{EnergyCost}_{\text{grid}}$ = 9,014 x 7.5 = ₹67,605
Case 3, $\text{EnergyCost}_{\text{grid}}$ = 10,410 x 7.5 = ₹78,075

It can be seen that the energy cost from grid is comparable.

The energy cost from generator is calculated using energy consumed from diesel generator (DG), from table 3, and rate of DG power.

$$EnergyCost_{DG} = Energy_{DG} * Rate_{DG} \tag{5}$$

The rate can be computed using SFOC[6], density and cost of diesel.

$$Rate_{DG} = SFOC * Rate_{diesel}/(\rho * 1000) \tag{6}$$

SFOC = 250 g/kWh (slightly higher since operating at different loads)
$\rho = 0.832$ g/cm3
$\text{Rate}_{\text{diesel}}$ = ₹70/litre

Using the above values, the Rate_{DG} is calculated as ₹21/kWh. Using this rate in equation (4), for each cases $\text{EnergyCost}_{\text{DG}}$ can be calculated.
Case 1, $\text{EnergyCost}_{\text{DG}}$ = 2,490 x 21 = ₹52,290
Case 2, $\text{EnergyCost}_{\text{DG}}$ = 1,396 x 21 = ₹29,316
Case 3, $\text{EnergyCost}_{\text{DG}}$ = ₹0

Source	**Case 1**	**Case 2**	**Case 3**
From Solar	0	0	0
From Grid	59,513	67,605	78,075
From Fuel	52,290	29,316	0
Total	**1,11,803**	**96,921**	**78,075**

Table 7: Energy cost (₹)

The total energy cost ($\text{OPEX}_{\text{energy}}$) is calculated using equation (3) and adding solar, grid and fuel cost for each case.

4.4.2. Maintenance ($OPEX_{maint}$)

The maintenance cost consists of three systems solar, battery, and DG. The sum is the result.

$$OPEX_{maint} = MaintCost_{solar} + MaintCost_{battery} + MaintCost_{DG} \tag{7}$$

While making this comparison the common maintenance costs that is applicable in all the three boats are not factored.

The maintenance of solar plant is monthly cleaning to keep the surface free from dust, bird dropping and other items that will affect the performance of the solar panels. Since in all the three cases, the solar plant size is same, the maintenance cost is not considered.

For battery bank there is quarterly inspection apart from real-time monitoring using cell level monitoring. Keeping a spare for critical components is an additional cost. However, these are common for all three cases. The

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[6] Specific Fuel Oil Consumption

one aspect that differs between cases is the cells that many need to be replaced in the warranty period. Although there is no specified %, one can take 0.5% of the battery bank cost as per yearly maintenance cost.

$$MaintCost_{battery} = 0.5\% * CAPEX_{battery} \tag{8}$$

Using this data from Table 6:
Case 1, $\text{MaintCost}_{\text{battery}}$ = 0.5% x 30,00,000 = ₹15,000
Case 2, $\text{MaintCost}_{\text{battery}}$ = 0.5% x 60,93,750 = ₹30,469
Case 3, $\text{MaintCost}_{\text{battery}}$ = 0.5% x 93,75,000 = ₹46,8750

For DG, the running hours need to be calculated for Case 1 and 2. From table 3, energy from DG and taking the load as 90% maximum (18 kW), the running hours is obtained.

Source	**Case 1**	**Case 2**	**Case 3**
DG energy	2,490	1,396	0
DG running hours	138	78	0

Table 8: DG running hours (₹)

It can be seen that the running hours are very less. Hence for all the three cases, six monthly maintenance is sufficient. Hence maintenance cost of DG in all three cases is same (see Appendix A), and therefore not considered.

The maintenance cost of battery is the total maintenance cost.

Case 1	**Case 2**	**Case 3**
15,000	30,469	46,875

Table 9: Maintenance cost (₹)

Now, using equation 2, OPEX can be calculated.

	Case 1	**Case 2**	**Case 3**
Energy Cost	**1,11,803**	**96,921**	**78,075**
Maintenance Cost	**15,000**	**30,469**	**46,875**
OPEX	**1,26,803**	**1,27,390**	**1,24,950**

Table 10: OPEX (₹)

It can be seen that OPEX is similar for all the three cases. This is very interesting and it establishes that the TCO is dependent on CAPEX alone.

4.5. Impact of increasing solar plant size

The above discussion keeps the total solar plant size same by shifting them to shore. If, instead, similar size is avoided, then the comparision can give insight on impact of increaseing solar plant size on boat alone. From CAPEX (Sec. 4.3) it is clear that from Case 1 to Case 3, the increase in cost is about 30 lakhs for every 10 kWp decrease in solar plat size. If in Case 2 and 3 if solar plant is not installed on shore, then this increase in cost is about 26 lakhs (less by ₹4 lakhs/10 kWp). Similarly, instead of OPEX being same in all three cases, if there is no solar plant installed on shore, then OPEX increases from Case 1 to 2 and further to 3 as all shore charge is from 7.5 /kWh. So, larger the solar panels on the boat, the better it is for CAPEX and OPEX. See table 12.

5. Conclusion

Summarising results obtained in Section 4.3 and 4.4 in table below.

	Case 1	**Case 2**	**Case 3**
CAPEX	**38,00,000**	**60,93,750**	**93,75,000**
OPEX	**1,26,803**	**1,27,390**	**1,24,950**

Table 11: CAPEX and OPEX, with shore solar plant (₹)

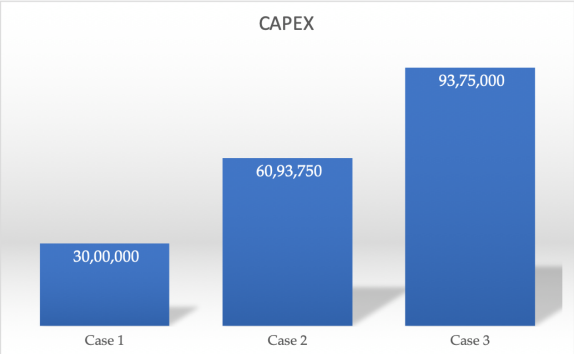

Figure 11: CAPEX (₹)

Summarising results with no solar panels on shore, obtained in Section 4.5, in table below.

	Case 1	**Case 2**	**Case 3**
CAPEX	**38,00,000**	**56,93,750**	**85,75,000**
OPEX	**1,26,803**	**1,89,162**	**307,125**

Table 12: CAPEX and OPEX, no shore solar plant (₹)

It is seen that CAPEX is the lowest in the case where the solar panels are maximum on boat, since decrease in solar panels on the boat causes increase in battery size and cost. The OPEX is nearly same in all the three cases when total solar plant is same, however OPEX is increasing with decreasing solar panels on boat when no solar panels are installed on shore. Hence it is concluded that it is cost effective to put largest possible solar panels on the boat.

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[4] Sandith Thandasherry, 'Safety of Solar and Electric Boats'

Appendix A. Maintenance Cost of DG

The maintenance cost of DG is assessed based on operating experience of a 20 kW unit.

For 6000 hours operation,
Average load = 18 kW
Time = 6,000 hrs
Energy consumed = 1,08,000 kWh
Rate_{DG} = ₹21/kWh
Energy cost = ₹22,71,635

The maintenance cost is listed below. Apart from the running hours, there is a maximum time interval for the first two. The maximum interval between two intervals is six months.

Type	**Item**	**Unit rate**	**Multiple**	**Cost**
250 hrs interval	**Lube oil**	**3,500**	**24**	**84,000**
250 hrs interval	**Filters**	**400**	**24**	**9,600**
250 hrs interval	**Manpower**	**1,500**	**24**	**36,000**
1000 hrs interval	**Belt, hose,...**	**750**	**6**	**4,500**
6000 hrs interval	**Overhaul**	**40,000**	**1**	**40,000**
	Total			**1,74,100**

Table A.13: Maintenance Cost of 20 kW genset for 6,000 hours (₹)

Maintenance cost = 7.7% of energy cost

In case the running hours is less than 500 hours, then every six months the 250 hrs interval and 1000 hours interval maintenance is to be done. The maintenance cost is independent of the running hours.