COST OF ENERGY IN A VESSEL: Assessing likely applications in marine transport where shift to electric will succeed without other interventions.

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ABSTRACT

Any marine technology adoption can be evaluated using economic analysis [1]. Understanding operating expenses (OPEX) is the first step with the initial focus being on the cost of energy from various sources. The primary cost drivers are fuel costs (diesel or hydrogen) and grid costs. Across various countries with a wide range of these costs, it is evident that countries with high diesel costs and low grid costs are likely to adopt electrification more quickly. The difference in energy costs (auxiliary or propulsion) is the key determinant.

The shift to electric systems is observed to be more economical for auxiliary power than for propulsion, making auxiliary systems the first to be electrified. Assessing the projected costs of hydrogen fuel in the near, medium, and long term, some countries face an easier transition, while for others, the shift seems nearly impossible. It is also evident that applications with a significant contribution from solar energy have very low OPEX. In hybrid configurations, parallel hybrids have lower cost than series hybrids. Many decisions can be made more effectively with a clear understanding of the energy costs for auxiliary power and propulsion.

Keywords: energy cost, electrification, economic analysis, solar, battery, hydrogen, diesel, hybrid

NOMENCLATURE

P_B	brake horsepower (output from engine or motor) for propulsion, kW
P_D	delivered power in kW
P_E	effective power in kW
C_G	cost of grid per kWh
C_H	cost of hydrogen per kg
C_{FO}	cost of fuel per litre
C_{EE-B}	cost of electrical energy from battery, per kWh
C_{EE-FC}	cost of electrical energy from fuel cell, per kWh
C_{EE-S}	cost of electrical energy from solar, per kWh

C_{EE-W}	cost of electrical energy from wind, per kWh
C_{EE-DG}	cost of electrical energy from generator, per kWh
C_{EE}	cost of electrical energy, per kWh
C_{PE-B}	cost of propulsion energy from battery, per kWh
C_{PE-FC}	cost of propulsion energy from fuel cell, per kWh
C_{PE-S}	cost of propulsion energy from solar, per kWh
C_{PE-W}	cost of propulsion energy from wind, per kWh
C_{PE-DG}	cost of propulsion energy from generator, per kWh
C_{PE-M}	cost of propulsion energy from motor, per kWh
C_{PE-E}	cost of propulsion energy from engine, per kWh
C_{PE}	cost of propulsion energy, per kWh
C_{M-E}	cost of engine maintenance as percentage of fuel cost
η_B	efficiency of battery
η_E	efficiency of other electrical system
η_M	efficiency of motor
η_A	efficiency of alternator
SFC_{FC}	specific fuel consumption of the fuel cell in grams per kWh
SFC_E	specific fuel consumption of engine in grams per kWh
ρ_{FO}	density of fuel in grams per cubic centimeter
E_B	% contribution of electric energy from battery
E_{FC}	% contribution of electric energy from fuel cell
E_{DG}	% contribution of electric energy from generator
E_M	% contribution of propulsion from motor
E_E	% contribution of propulsion from engine

1. INTRODUCTION

In a boat, two types of energy are required – propulsion and auxiliary. Propulsion refers to the energy needed for the movement of a vessel, typically involving the transfer of mechanical energy to propel the boat through the water. All other energy requirements within the boat are categorised as auxiliary. These auxiliary energy needs include various systems such as HVAC, lighting, controls, navigation, entertainment, public address, and other essential services. Most of these systems operate using electricity, and for the purpose of this study, it is assumed that the required energy is electrical.

Within a vessel, numerous energy sources can be identified, which can be categorised into five distinct groups: battery, fuel cell, solar, wind, and engine. This paper examines the utilisation of a battery for grid energy storage, a fuel cell driven by green hydrogen, and an engine fueled by diesel. This framework can be expanded to encompass any new types of fuels.

2. ENERGY SOURCES AND COST DRIVERS

We have identified five energy sources (battery, fuel cell, solar, wind, engine), and two types of energy used in a vessel (mechanical and electrical). We will now examine the factors driving the costs of mechanical and electrical energy for each of these sources.

2.1 Battery (grid energy)

The grid energy stored in the battery is delivered as electrical energy. The cost of electrical energy is influenced by three factors: grid cost (C_G), battery efficiency (η_B), and the efficiency of other electrical system (η_E). The cost of electrical energy (auxiliary energy) from the battery can be calculated as shown below.

$$C_{EE-B} = \frac{C_G}{\eta_B \; x \; \eta_E} \tag{1}$$

To convert this electrical energy into mechanical energy, it must be supplied to the propulsion motor with an efficiency of η_M. The cost of the resulting propulsion energy from the battery is calculated as follows:

$$C_{PE-B} = \frac{C_G}{\eta_B x \; \eta_E x \; \eta_M} \tag{2}$$

2.2 Fuel cell (H_2 energy)

A fuel cell is used to convert the chemical energy in the fuel into electrical energy. In this paper hydrogen (H_2) is considered as fuel, however it could be any type for the analysis. Three factors influence the cost: the cost of hydrogen per kilogram (C_H), the specific fuel consumption of the fuel cell (SFC_{FC}) measured in grams per kWh, and the efficiency of other electrical system (η_E). The cost of electrical energy (auxiliary energy) from the fuel cell can be calculated as follows:

$$C_{EE-FC} = \frac{C_H \; x \; SFC_{FC}}{1000 \; x \; \eta_E} \tag{3}$$

The electrical energy from the fuel cell is then converted to mechanical energy (propulsion energy) using a motor with an efficiency of η_M. The cost of propulsion energy from the fuel cell is therefore:

$$C_{PE-FC} = \frac{C_H \; x \; SFC_{FC}}{1000 \; x \; \eta_E \; x \; \eta_M} \tag{4}$$

2.3 Solar panel (solar energy)

The solar energy captured by the solar panel is free, and therefore, the cost of electrical energy for auxiliary systems and mechanical energy for propulsion is zero.

$$C_{EE-S} = 0 \tag{5}$$

$$C_{PE-S} = 0 \tag{6}$$

2.4 Wind turbine (wind energy)

The wind energy captured by wind turbines is free, so the cost of electrical energy for auxiliary systems and mechanical energy for propulsion is effectively zero. Wind, even when directly converted into thrust using sails, has zero propulsion energy cost.

$$C_{EE-W} = 0 \tag{7}$$

$$C_{PE-W} = 0 \tag{8}$$

2.5 Engine (diesel energy)

The engine converts the chemical energy from diesel into mechanical energy, which can be directly used to drive the propulsion system. The factors influencing the cost of mechanical energy include the fuel cost (C_{FO}), the engine's specific fuel consumption (SFC_E), fuel density (ρ_{FO}), and the engine maintenance cost as a percentage of the fuel cost (C_{M-E}). The cost of propulsion energy from an engine can be calculated as follows:

$$C_{PE-E} = \frac{C_{FO}\ x\ SFC_E\ x\ (1+C_{M-E})}{1000\ x\ \rho_{FO}} \qquad (9)$$

Alternatively, the engine can be connected to an alternator, forming a diesel generator (DG). The additional factors affecting the cost include the alternator efficiency (η_A) and efficiency of other electrical system (η_E). The cost of electrical energy from generator is:

$$C_{EE-DG} = \frac{C_{FO}\ x\ SFC_E\ x\ (1+C_{M-E})}{1000\ x\ \rho_{FO}\ x\ \eta_A\ x\ \eta_E} \qquad (10)$$

This electrical energy can then be converted to mechanical energy using a motor with an efficiency of η_M, and the cost of this propulsion energy is:

$$C_{PE-DG} = \frac{C_{FO}\ x\ SFC_E\ x\ (1+C_{M-E})}{1000\ x\ \rho_{FO}\ x\ \eta_A\ x\ \eta_E x\ \eta_M} \qquad (11)$$

This scenario represents a series hybrid system, where the engine drives the alternator, which is connected to a motor that drives the propulsion system.

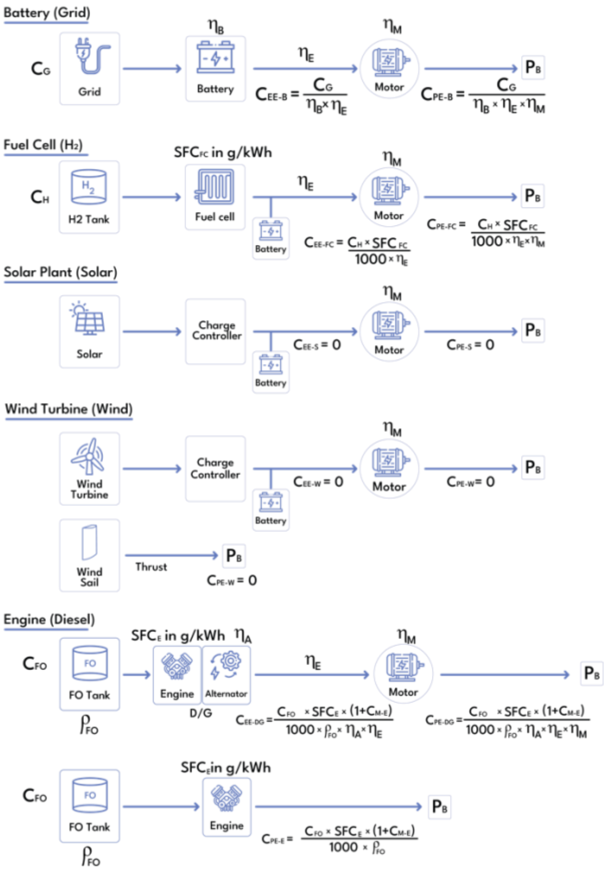

Figure 1: Cost of energy calculation for each energy source

3. COST OF FUEL AND GRID ACROSS COUNTRIES AND IMPLICATION

When comparing energy costs (fuel and grid) across countries, we observe a significant range. Diesel costs vary from 0.4 US cents per liter in Venezuela to 290 US cents per liter in Hong Kong. Grid costs also display a wide range, from 1 US cent per kWh in Libya to 58 US cents per kWh in Israel.

As discussed in an earlier section, the cost of energy from a battery is directly proportional to grid costs, while the cost of energy from an engine is proportional to fuel costs. In transport systems, the onboard energy cost (mechanical for propulsion and electrical for auxiliary) constitutes a major portion of operating expenses (OPEX). This means that the OPEX of a diesel engine boat increases in line with fuel costs, while the OPEX of an electric boat rises in accordance with grid costs.

Since the capital expenditure (CAPEX) of an electric boat is higher than that of a diesel boat, the shift to electric propulsion becomes viable only if the OPEX of the electric boat is lower. The difference in OPEX between a diesel boat and an electric boat is driven by the spread between diesel costs and grid costs. Table 6 presents a list of 133 countries ranked by the decreasing spread between propulsion energy costs. Let's take four countries from this list (ranked in brackets) and analyze their data: Norway (4), India (41), Saudi Arabia (114), and the US – California (130).

Rank	Country	C_{FO} (US Cents/l)	C_G (US Cents/ kWh)
4	Norway	201	12
41	India	125	9
114	Saudi Arabia	31	7
130	US - California	104	35

Table 1: Cost of diesel and grid

3.1 Cost of energy from battery

Using Equation 1, we can compute the cost of electrical energy from the battery. Assuming the battery efficiency (η_B) is 90% and the efficiency of other systems (η_E) is 90%, we substitute these values into Equation (1). For Norway, with a grid cost (CG) of 12 US cents/kWh, the cost of electrical energy (auxiliary energy) from the battery is:

$$C_{EE-B} = \frac{12}{90\% \; x \; 90\%} = 15 \; US \; Cents/kWh$$

Next, assuming the propulsion motor efficiency (η_M) is 90% and using Equation 2 to calculate the cost of mechanical energy from the battery (propulsion energy), we get:

$$C_{PE-B} = \frac{12}{90\% \; x \; 90\% \; x \; 90\%}$$

$$= 17 \; US \; Cents/kWh$$

We can apply the same calculations to the other three countries, and the results are as follows:

		Auxiliary	Propulsion
Country	C_G (US Cents/ kWh)	C_{EE-B} (US Cents/kWh)	C_{PE-B} (US Cents/kWh)
Norway	12	15	17
India	9	11	12
Saudi Arabia	7	9	10
US - California	35	43	48

Table 2: Cost of energy from battery

3.2 Cost of energy from engine

Using Equation 9, we can compute the energy cost from an engine. Although the specific fuel consumption (SFC_E) of small engines in ideal conditions is between 200 and 225 grams per kWh, it is typically closer to 250 grams per kWh. The density of the fuel (ρ_{FO}) is 0.85 kg per liter, and the engine maintenance cost as a percentage of the fuel cost (C_{M-E}) is taken as 10%. Substituting these values into Equation 9, and considering the diesel cost in Norway of 201 US cents per liter, we calculate the cost of mechanical energy from the engine as:

$$C_{PE-E} = \frac{201\ x\ 250\ x\ (1 + 10\%)}{1000\ x\ 0.85}$$

$$= 65\ US\ Cents/kWh$$

Assuming the alternator efficiency (η_A) is 90% and the other electrical system efficiency (η_E) is also 90%, we can use Equation 10 to calculate the cost of electrical energy from the engine in Norway:

$$C_{EE-DG} = \frac{201\ x\ 250\ x\ (1 + 10\%)}{1000\ x\ 0.85\ x\ 90\%\ x\ 90\%}$$

$$= 80\ US\ Cents/kWh$$

We can perform the same calculations for the other three countries, yielding the following results:

		Auxiliary	Propulsion
Country	C_{FO} (US Cents/l)	C_{EE-DG} (US Cents/ kWh)	C_{PE-E} (US Cents/ kWh)
Norway	201	80	65
India	125	50	40
Saudi Arabia	31	12	10
US - California	104	42	34

Table 3: Cost of energy from engine

3.3 Comparing costs of energy

After doing a comparative analysis of the propulsion and auxiliary energy costs derived from the two sources, some noteworthy observations can be made.

	Auxiliary		Propulsion	
Country	C_{EE-B} (US Cents/ kWh)	C_{EE-DG} (US Cents/ kWh)	C_{PE-B} (US Cents/ kWh)	C_{PE-E} (US Cents/ kWh)
Norway	15	80	17	65
India	11	50	12	40
Saudi Arabia	9	12	10	10
US - California	43	42	48	34

Table 4: Auxiliary and propulsion costs

If the difference between the energy costs from the engine and battery is significant, it indicates a greater difference in OPEX, since energy costs are a dominant factor in OPEX. Looking at propulsion costs: in Norway, the difference between the engine and battery costs per kWh is 48 cents. Adopting battery technology results in a cost reduction of 48 cents per unit of propulsion energy required. The reduction is 28 cents in India, 0 cents in Saudi Arabia, and there is a 14 cent increase in the US – California.

The ratio of energy costs also provides insights into the potential impact on OPEX. For propulsion energy, in Norway, the cost from the engine is 3.8 times that from the battery (65/17). In India, the ratio is 3.3. In Saudi Arabia, the ratio is 1, and in the US – California, it is 0.7.

From both the difference and the ratio, it is clear that the shift to electric (battery) significantly reduces OPEX in Norway and moderately reduces it in India. In Saudi Arabia, there is no change in OPEX, so shifting to electric provides no benefit. In the US – California, the shift to electric is more expensive. **Thus, countries with high diesel costs and low grid costs are more likely to adopt electric propulsion (battery) without requiring additional incentives.**

Examining auxiliary energy costs yields similar conclusions. However, another important observation arises when comparing the costs between propulsion and auxiliary energy for each energy source. The energy cost increases when moving from propulsion to auxiliary in the case of diesel, whereas it decreases in the case of batteries. This is because diesel engines initially produce mechanical energy, which is then converted to electrical energy with some losses. In contrast, batteries initially provide electrical energy, which is converted to mechanical energy with some losses. As a result, both the spread and the ratio of energy costs between the engine and battery are higher for auxiliary energy compared to propulsion energy.

To summarise, the spread for auxiliary energy is 65 cents in Norway, 39 cents in India, 3 cents in Saudi Arabia, and -1 cent in the US – California. Similarly, the ratio is 5.3 in Norway, 4.5 in India, 1.3 in Saudi Arabia, and 0.98 in the US – California. These values are all higher than those for propulsion energy. Given that OPEX reductions are greater when the spread and ratio between engine and battery energy costs are higher, we can conclude that shifting to electric is more economical for auxiliary energy than for propulsion energy when considering OPEX.

Interestingly, the increase in CAPEX for auxiliary energy is lower compared to propulsion energy when shifting from engine to battery, as propulsion systems approval tend to be more complex. This further reinforces the point that the shift to electric is more economical for auxiliary energy than for propulsion in any country. **Therefore, we can conclude that for any country, the shift to electric (battery) is more economical for auxiliary energy, and it should be prioritized before focusing on propulsion.**

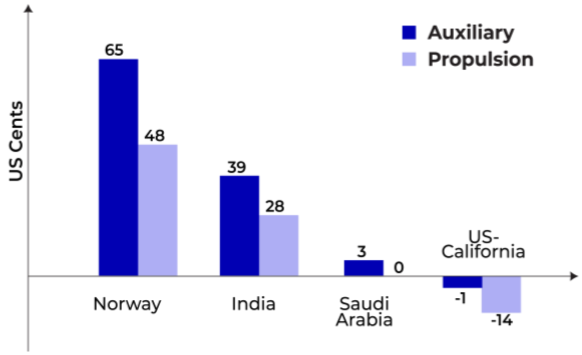

Figure 2: Spread between auxiliary and propulsion

3.4 Cost of energy from fuel cell (H_2)

The cost of energy from a fuel cell depends on the cost of green hydrogen (C_H). As this is still an emerging fuel, we can consider three different price points: 500 US cents per kg in the near term, 300 US cents in the medium term, and 200 US cents in the long term. Using Equation (3), and assuming the green hydrogen cost (C_H) is 500 US cents per kg, the specific fuel consumption of the fuel cell (SFC_{FC}) is 78 grams per kWh, and the other electrical system efficiency (η_E) is 90%, we can calculate the cost of electrical energy as:

$$C_{EE-FC} = \frac{500\ x\ 78}{1000\ x\ 90\%}$$

$$= 43\ US\ Cents/kWh$$

For green hydrogen costs of 300 and 200 US cents per kg, the cost of electrical energy decreases to 26 and 17 US cents per kWh, respectively.

To compute the propulsion energy cost using Equation (4), assuming the propulsion motor efficiency (η_M) is 90%, we get:

$$C_{PE-FC} = \frac{500\ x\ 78}{1000\ x\ 90\%\ x\ 90\%}$$

$$= 48\ US\ Cents/kWh$$

For green hydrogen costs of 300 and 200 US cents per kg, the cost of propulsion energy is 29 and 19 US cents per kWh, respectively. These results can be summarized as follows:

Auxiliary			Propulsion		
500 US C	300 US C	200 US C	500 US C	300 US C	200 US C
43	26	17	48	29	19

Table 5: Cost of auxiliary and propulsion energy from H_2

Similar to battery systems, the cost of auxiliary energy from an H_2 fuel cell is lower than that of propulsion energy, resulting in a wider cost difference compared to diesel. **Therefore, just as with battery-powered systems, the shift to H_2 fuel cells should first target auxiliary energy before transitioning to propulsion.**

Comparing the results in Table 4 and Table 5 yields some interesting insights. In the near term, with a green hydrogen cost of 500 US cents per kg and an auxiliary energy cost of 43 US cents per kWh, Norway presents a highly attractive case for shifting from diesel (80 US cents). India is marginally attractive (50 US cents), whereas the shift in the US – California is slightly unattractive (42 US cents) and extremely unattractive in Saudi Arabia (12 US cents). However, in cases where battery energy can meet the demands (for low-speed and short-range applications), the much lower cost of battery energy compared to H_2 makes H_2 adoption uneconomical at these high costs.

In the medium term, with green hydrogen at 300 US cents per kg, and in the long term at 200 US cents per kg, Norway, India, and the US – California become attractive markets for H_2 fuel cells. However, Saudi Arabia will likely remain unattractive for H_2 adoption due to the significantly lower cost of energy from both battery and diesel sources.

Looking at Tables 5 and 6, at a green hydrogen price of 500 US cents per kg, producing an auxiliary energy cost of 43 US cents per kWh, 84 countries find this cheaper than diesel for auxiliary energy. When the hydrogen price drops to 300 US cents per kg (C_{EE-FC} = 26 US cents/kWh), the number of countries increases to 116, and at 200 US cents per kg ($C_{EE\text{-}FC}$ = 17 US cents/kWh), it rises to 125 out of 133 countries. For propulsion, the number of countries is 36, 102, and 120. Therefore, in the long term, green hydrogen is likely to become an attractive energy option for most countries.

4. SOURCES AND NEEDS IN A VESSEL

Now, let's examine how various energy sources and needs are organized within a vessel. In a traditional fuel-powered vessel, the propulsion engine drives the propellers (or water jets), while the engine powers an alternator to generate electrical energy used for all auxiliary needs.

When there is a shift to electric power, in addition to the alternator generating electricity, there can be four other energy sources: battery, fuel cell, solar, and wind (see Figure 3). These can function individually or in combination. The electrical energy generated is used to power auxiliary loads.

Apart from auxiliary loads, the electricity generated can also be supplied to motors that drive the propellers (or water jets) for propulsion. In parallel hybrid systems, the engine may also directly contribute to propulsion by sharing part of the load.

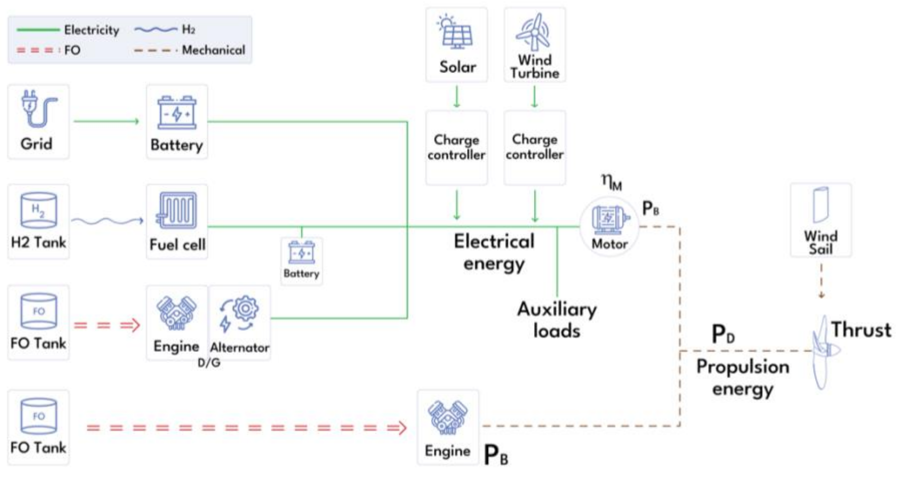

Figure 3: Energy type and sources

4.1 Cost of energy in combination

When there are multiple energy sources available among the five options, the cost of auxiliary and propulsion energy can be calculated by weighting the contribution and cost of each type. This process is illustrated in Figure 3. In scenarios where multiple energy sources are used, the percentage contribution and the cost of each energy source are combined to determine the total energy cost.

The cost of electrical energy (C_{EE}) is determined by the weighted average cost of battery, fuel cell, generator, solar, and wind. Using this, we can calculate the cost of propulsion energy from a motor ($C_{PE\text{-}M}$). By taking the weighted average of $C_{PE\text{-}M}$ and $C_{PE\text{-}E}$, the overall cost of propulsion energy (C_{PE}) can be determined.

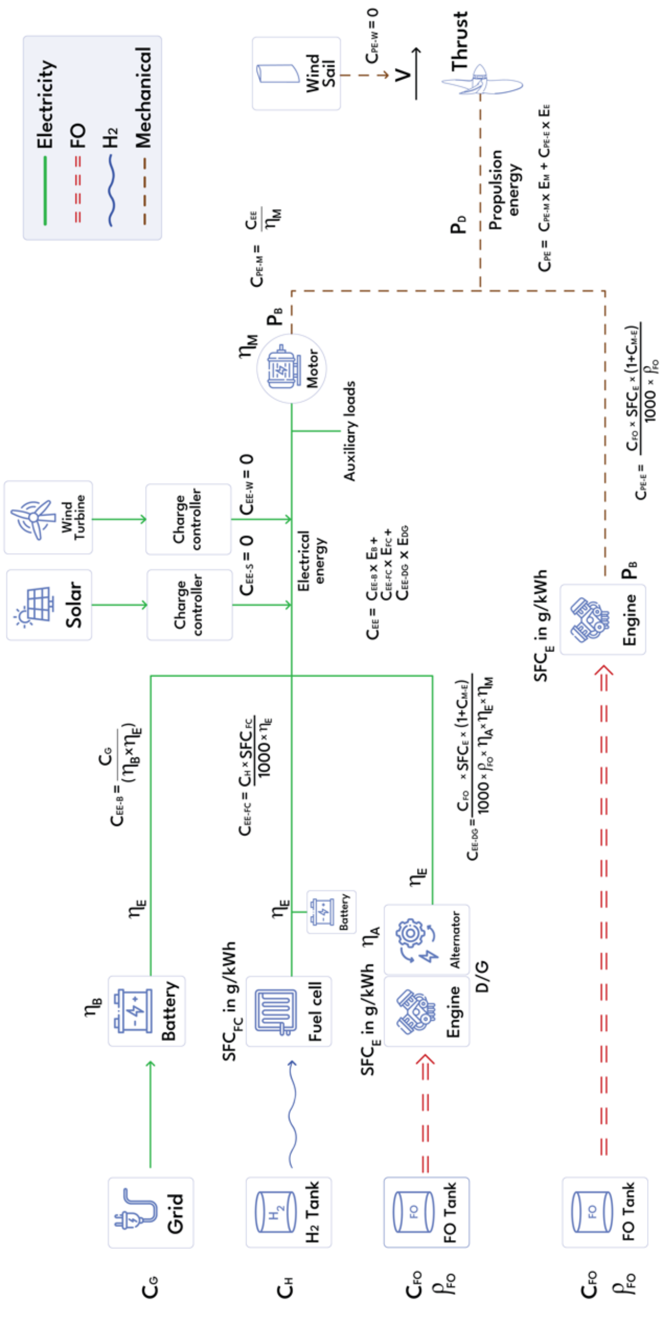

Figure 4: Cost of energy

4.2 How solar significantly reduces OPEX

We saw in Table 4 that in India the cost of propulsion energy from an engine (C_{PE-E}) is 40 US cents, while that from a battery (C_{PE-B}) is 12 US cents. Let's take the example of a slow-speed inland solar ferry, ADITYA, with a speed of 6 knots and a contribution of 67% energy from solar[2]. The contribution from solar comes at zero cost, reducing the cost of propulsion energy to just 4 US cents (see Fig 5). Therefore, shifting from a diesel ferry to an electric ferry results in a 3.3-fold reduction in OPEX, while shifting to a solar ferry result in a 10-fold reduction.

In applications where solar energy can contribute significantly (such as slow-speed passenger transport), solar ferries have lower costs than electric ferries and significantly lower costs than diesel ferries.

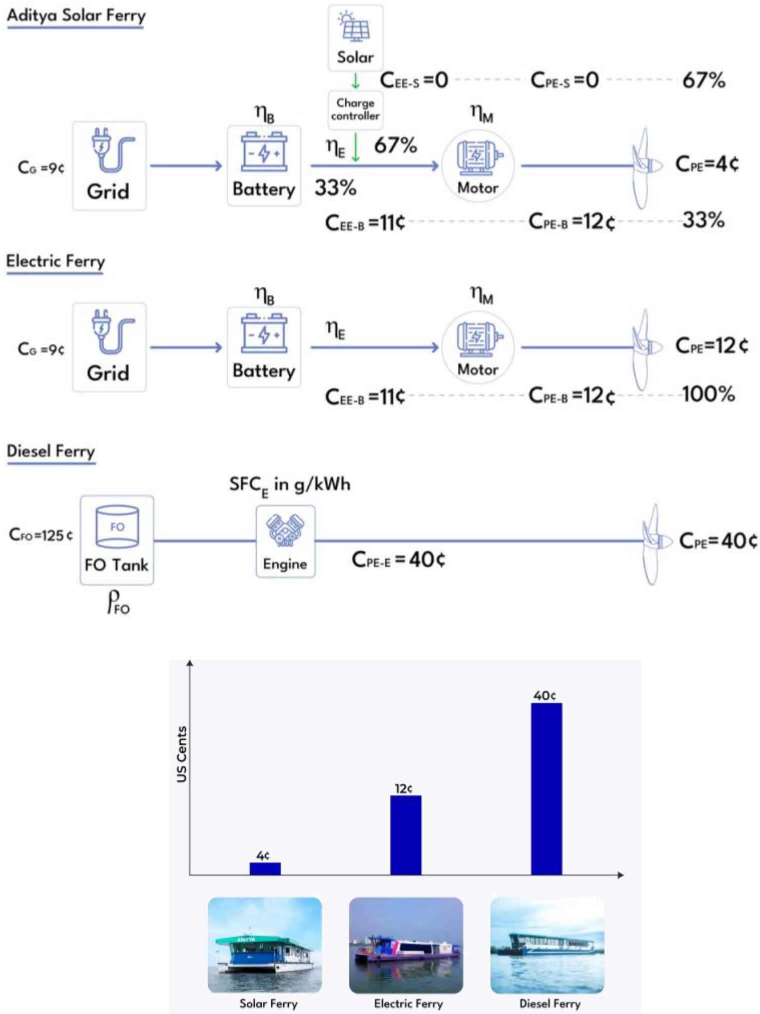

Figure 5: Solar electric, electric and diesel cost comparison

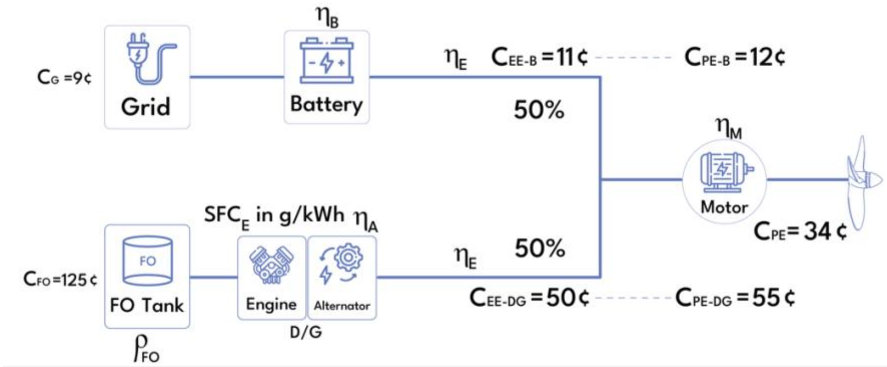

Figure 6: Series hybrid (50% propulsion energy from battery; India prices)

4.3 Parallel versus series hybrid

In many applications where a complete shift to electric using battery, solar, wind, or fuel cell is not feasible due to technical or economic reasons, a partial shift to a hybrid system is economically viable. In such scenarios, two options emerge: series hybrid and parallel hybrid [3]. In a series hybrid, both the battery and the engine generate electrical energy, which is then connected to a motor that generates propulsion energy. In a parallel hybrid, the engine directly delivers propulsion energy, while the battery drives a motor that generates propulsion energy to support the engine.

When we input the costs, using India as an example, we see that the cost of propulsion energy (C_{PE}) in a series hybrid configuration is 34 US cents, whereas in a parallel configuration it is 26 US cents. In all cases, the parallel hybrid has a lower OPEX than the series hybrid. This is because, in a series hybrid, the mechanical energy from the engine is converted to electrical energy and then back to mechanical energy, instead of directly driving the propulsion, which increases the cost. Additionally, the CAPEX is higher in a series hybrid, as the motor size and system complexity increase compared to the parallel configuration. **Hence in all cases where parallel hybrid works, it is cheaper to go for it compared to series hybrid.**

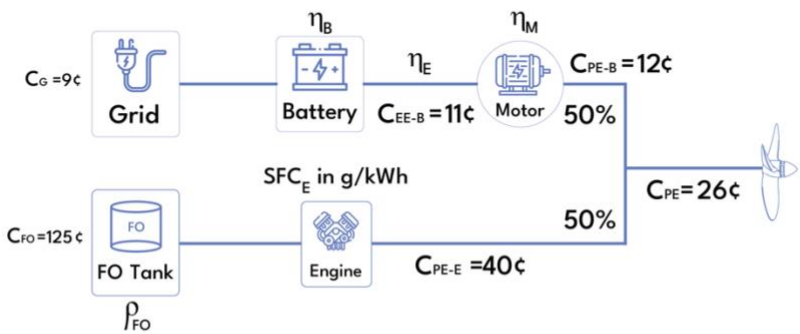

Figure 7: Parallel hybrid (50% propulsion energy from battery; India prices)

5. RESULTS AND DISCUSSION

For each of the 133 countries, the C_{FO} and C_G were taken [4][5] to compute the cost of energy—both electrical (auxiliary) and mechanical (propulsion)—from battery and engine, as shown in Table 6. The table is sorted in decreasing order of the difference between C_{PE-E} and C_{PE-B}, referred to as the spread. As we move down the list, the likelihood of electrification without additional financial intervention decreases.

				Auxiliary		Propulsion			
				from Battery	from Engine	from Battery	from Engine	Engine - Battery	from DG-motor
Rank	Country	Cost of Diesel CFO US Cents/l	Grid cost CG US Cents/kWh	CEE-B US Cents/kWh	CEE-DG US Cents/kWh	CPE-B US Cents/kWh	CPE-E US Cents/kWh	Spread	CPE-DG US Cents/kWh
1	Hong Kong	290	17	21	116	23	94	71	129
2	Iceland	235	13	16	94	18	76	58	104
3	Estonia	170	2	2	68	2	55	53	75
4	Norway	201	12	15	80	17	65	48	89
5	Albania	202	13	16	81	18	65	47	90
6	UK	191	11	14	76	16	62	46	85
7	Hungary	169	7	9	68	10	55	45	75
8	Denmark	195	14	17	78	19	63	44	87
9	Germany	188	12	15	75	17	61	44	83
10	Serbia	184	12	15	73	17	60	43	82
11	Portugal	172	10	12	69	13	56	43	76
12	Czech Republic	163	9	11	65	12	53	41	72
13	Ireland	190	15	19	76	21	61	40	84
14	Finland	209	21	26	83	29	68	39	93
15	Belgium	189	16	20	75	22	61	39	84
16	Switzerland	221	26	32	88	36	72	36	98
17	Kenya	132	5	6	53	7	43	36	59
18	Lesotho	118	2	2	47	2	38	36	52
19	Greece	183	18	22	73	24	59	35	81
20	Lithuania	166	14	17	66	19	54	35	74
21	Latvia	170	15	19	68	21	55	34	75
22	Italy	191	21	26	76	29	62	33	85
23	Belize	173	17	21	69	23	56	33	77
24	Spain	164	15	19	66	21	53	32	73
25	N. Macedonia	132	8	10	53	11	43	32	59
26	Bosnia & Herz.	146	11	14	58	16	47	31	65
27	Uruguay	147	12	15	59	17	48	31	65
28	Zambia	116	5	6	46	7	38	31	51
29	Cyprus	162	16	20	65	22	52	30	72
30	Bulgaria	148	13	16	59	18	48	30	66

31	Mozambique	143	11	14	57	16	46	30	63
32	Rwanda	130	9	11	52	12	42	30	58
33	Swaziland	126	8	10	50	11	41	30	56
34	Malawi	162	17	21	65	23	52	29	72
35	Cayman Islands	154	15	19	62	21	50	29	68
36	South Africa	126	9	11	50	12	41	29	56
37	Bhutan	96	2	2	38	2	31	29	43
38	Mexico	142	13	16	57	18	46	28	63
39	Uganda	137	11	14	55	16	44	28	61
40	Tanzania	128	10	12	51	13	41	28	57
41	**India**	**125**	**9**	11	50	12	40	28	55
42	Nepal	118	7	9	47	10	38	28	52
43	Burma	119	8	10	48	11	39	28	53
44	Nigeria	117	7	9	47	10	38	28	52
45	Luxembourg	164	19	23	66	26	53	27	73
46	Morocco	141	14	17	56	19	46	27	63
47	Chile	119	9	11	48	12	39	27	53
48	Sierra Leone	152	17	21	61	23	49	26	67
49	Cameroon	121	10	12	48	13	39	26	54
50	DR Congo	117	9	11	47	12	38	26	52
51	Slovenia	157	19	23	63	26	51	25	70
52	Mauritius	144	16	20	58	22	47	25	64
53	Ethiopia	141	15	19	56	21	46	25	63
54	Botswana	127	11	14	51	16	41	25	56
55	Jordan	102	6	7	41	8	33	25	45
56	Paraguay	99	5	6	40	7	32	25	44
57	Netherlands	189	27	33	75	37	61	24	84
58	South Korea	114	10	12	46	13	37	24	51
59	Japan	110	9	11	44	12	36	24	49
60	Syria	78	2	2	31	2	25	23	35
61	Liechtenstein	218	36	44	87	49	71	22	97
62	Togo	143	18	22	57	24	46	22	63
63	Uzbekistan	90	5	6	36	7	29	22	40
64	Malta	134	16	20	54	22	43	21	59
65	Costa Rica	133	16	20	53	22	43	21	59
66	Brazil	121	14	17	48	19	39	20	54
67	Singapore	189	31	38	75	42	61	19	84
68	Romania	155	23	28	62	31	50	19	69
69	Bangladesh	99	10	12	40	13	32	19	44
70	Sri Lanka	110	13	16	44	18	36	18	49
71	Argentina	89	8	10	36	11	29	18	39
72	Turkey	126	18	22	50	24	41	17	56
73	Vietnam	81	8	10	32	11	26	15	36
74	Sudan	66	4	5	26	6	21	15	29
75	Philippines	110	16	20	44	22	36	14	49

76	Pakistan	99	13	16	40	18	32	14	44
77	Gabon	97	12	15	39	17	31	14	43
78	Trinidad & Tobago	65	5	6	26	7	21	14	29
79	Canada	127	20	25	51	28	41	13	56
80	Peru	110	17	21	44	23	36	13	49
81	Barbados	165	30	37	66	41	53	12	73
82	USA	103	15	19	41	21	33	12	46
83	Maldives	95	14	17	38	19	31	12	42
84	Qatar	56	4	5	22	6	18	12	25
85	UAE - Dubai	82	11	14	33	16	27	11	36
86	China	102	17	21	41	23	33	10	45
87	Taiwan	91	14	17	36	19	29	10	40
88	UAE	82	12	15	33	17	27	10	36
89	Russia	72	10	12	29	13	23	10	32
90	Australia	123	23	28	49	31	40	9	55
91	Moldova	121	22	27	48	30	39	9	54
92	Burkina Faso	114	20	25	46	28	37	9	51
93	Thailand	87	14	17	35	19	28	9	39
94	Ecuador	46	4	5	18	6	15	9	20
95	Austria	176	36	44	70	49	57	8	78
96	Cambodia	100	18	22	40	24	32	8	44
97	El Salvador	98	18	22	39	24	32	8	43
98	Dom. Republic	101	19	23	40	26	33	7	45
99	Tunisia	72	11	14	29	16	23	7	32
100	Ghana	108	21	26	43	29	35	6	48
101	Kuwait	37	4	5	15	6	12	6	16
102	Nicaragua	118	24	30	47	33	38	5	52
103	Madagascar	106	21	26	42	29	34	5	47
104	Belarus	71	13	16	28	18	23	5	32
105	Bahrain	48	8	10	19	11	16	5	21
106	Honduras	93	19	23	37	26	30	4	41
107	Azerbaijan	47	7	9	19	10	15	5	21
108	Jamaica	131	28	35	52	39	42	3	58
109	Algeria	22	3	4	9	4	7	3	10
110	Angola	16	2	2	6	2	5	3	7
111	Panama	87	19	23	35	26	28	2	39
112	Georgia	128	29	36	51	40	41	1	57
113	Ivory Coast	120	28	35	48	39	39	0	53
114	Saudi Arabia	31	7	9	12	10	10	0	14
115	Libya	3	1	1	1	1	1	0	1
116	Guatemala	103	25	31	41	34	33	-1	46
117	Slovakia	167	41	51	67	57	54	-3	74
118	Lebanon	75	20	25	30	28	24	-4	33
119	Kazakhstan	63	18	22	25	24	20	-4	28
120	Bahamas	147	40	49	59	54	48	-6	65

121	Aruba	126	34	42	50	47	41	-6	56
122	Malaysia	47	15	19	19	21	15	-6	21
123	Iran	0.6	4	5	0	6	0	-6	0
124	Oman	67	22	27	27	30	22	-8	30
125	Cuba	105	32	40	42	44	34	-10	47
126	Colombia	62	22	27	25	30	20	-10	28
127	Ukraine	141	41	51	56	57	46	-11	63
128	Cape Verde	123	38	47	49	52	40	-12	55
129	Venezuela	0.4	10	12	0	13	0	-13	0
130	US - California	104	35	43	42	48	34	-14	46
131	Israel	196	58	72	78	80	63	-17	87
132	Egypt	27	20	25	11	28	9	-19	12
133	Poland	128	50	62	51	69	41	-28	57

Table 6: Energy cost across countries [4][5]

6. CONCLUSION

Electrification of vessels has a higher CAPEX compared to the current fuel systems. The primary reason electrification is appealing is its lower OPEX, due to the reduced cost of electrical and mechanical energy needed for the vessel. OPEX can only be lower when there is a significant difference between diesel costs and grid costs. Therefore, countries with high diesel costs and low grid costs are more likely to shift to electric (battery) systems without requiring additional incentives.

Auxiliary energy is electrical, while propulsion is mechanical. Diesel engines produce mechanical energy, which incurs additional losses when converting to electrical energy needed for auxiliary systems. Batteries provide electrical energy directly and can be used immediately for auxiliary purposes. However, for propulsion, electrical energy must be converted to mechanical energy, resulting in additional losses. Consequently, the OPEX reduction when using batteries as an auxiliary system is greater than when they are used for propulsion. Furthermore, the propulsion battery system is more complex and, therefore, more expensive than the auxiliary system. This means that the increase in CAPEX during electrification is higher for propulsion than for auxiliary systems. Hence, the shift to electric systems is more economical in auxiliary applications than in propulsion in any country. Therefore, auxiliary systems should be the first to be converted to battery (grid + renewable) from diesel before undertaking the conversion of propulsion systems.

When it comes to fuel cells, like batteries, they also generate electricity. This means the same reasoning for greater OPEX reduction in auxiliary systems applies to fuel cells as it does for batteries. The higher CAPEX for propulsion compared to auxiliary systems is also relevant here. This implies that the shift to electric systems and fuel cells is more economical in auxiliary applications than in propulsion in any country. Therefore, auxiliary systems should be prioritised for conversion to fuel cells (+

renewable sources) from diesel before undertaking the conversion of propulsion systems.

Since hydrogen as a fuel for transport applications is still emerging, and fuel prices have not yet stabilized across countries, three scenarios were assessed: 500 US cents per kg in the near term, 300 in the medium term, and 200 in the long term. When comparing the cost of electrical energy (auxiliary) from a fuel cell, the prices for these scenarios are 43, 26, and 17 US cents per kWh, respectively. Compared to the same energy generated from an engine, there are 84, 116, and 125 countries where fuel cells would be a cheaper source. For propulsion, these numbers are 36, 102, and 120. Hence, green hydrogen is likely to become an attractive option in most countries in the long term.

When multiple energy sources are used in a vessel, the cost of auxiliary and propulsion energy is calculated by assigning a weight to the amount (% contribution) and cost of each type. In comparing the shift from diesel to electric and solar-electric in a slow-speed ferry, using ADITYA as a case study, the OPEX decreases by 3.3 times when shifting from diesel to electric, and by 10 times when shifting to solar-electric. In applications where solar energy can contribute significantly (such as slow-speed passenger transport), solar ferries have lower costs than electric ferries and significantly lower costs than diesel ferries.

In applications where complete shift from diesel to electric is not possible, hybrids can be a solution. Among the two options, parallel hybrid has lower OPEX than series hybrid since cost of mechanical energy directly from engine is cheaper than through alternator and then as output of motor. The CAPEX of series hybrid with larger motor and complex system is also higher than parallel hybrid. Hence in all cases where parallel hybrid works, it is cheaper to go for it compared to series hybrid.

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