



ELECTRIFICATION OF MARINE TRANSPORT

Where Shift to Electric Will Succeed

Sandith Thandasherry

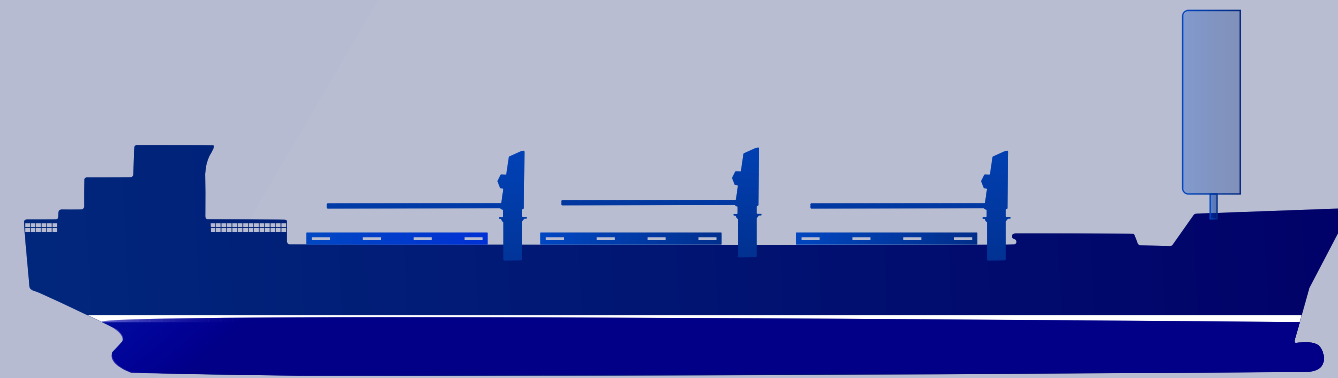


Vessels



Boats (<50 m)

Inland and Sea



Small Ships
(50-100 m)

Inland and Coastal

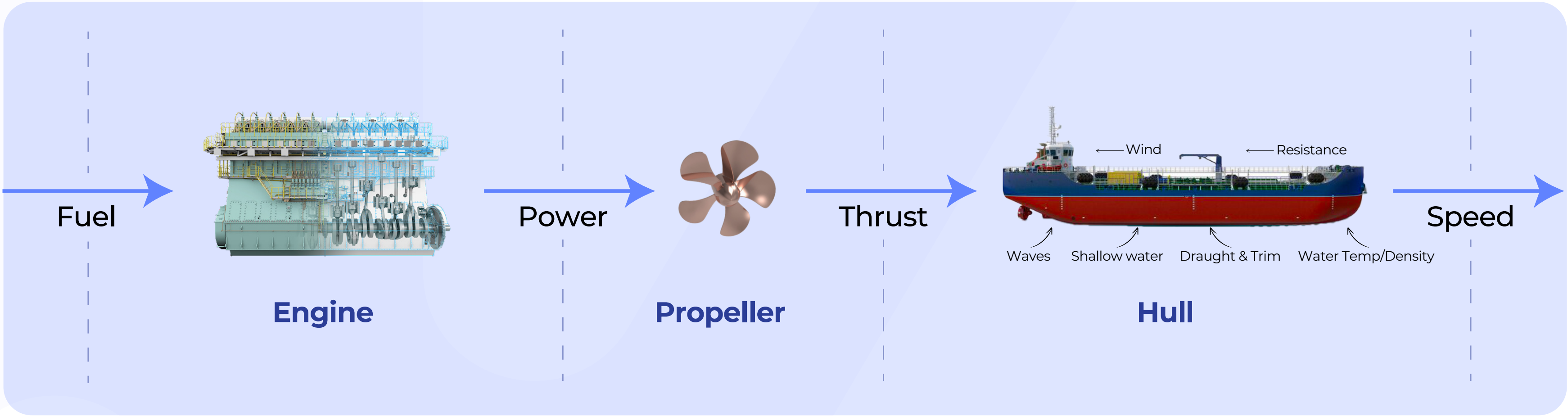


Large Ships
(> 100 m)

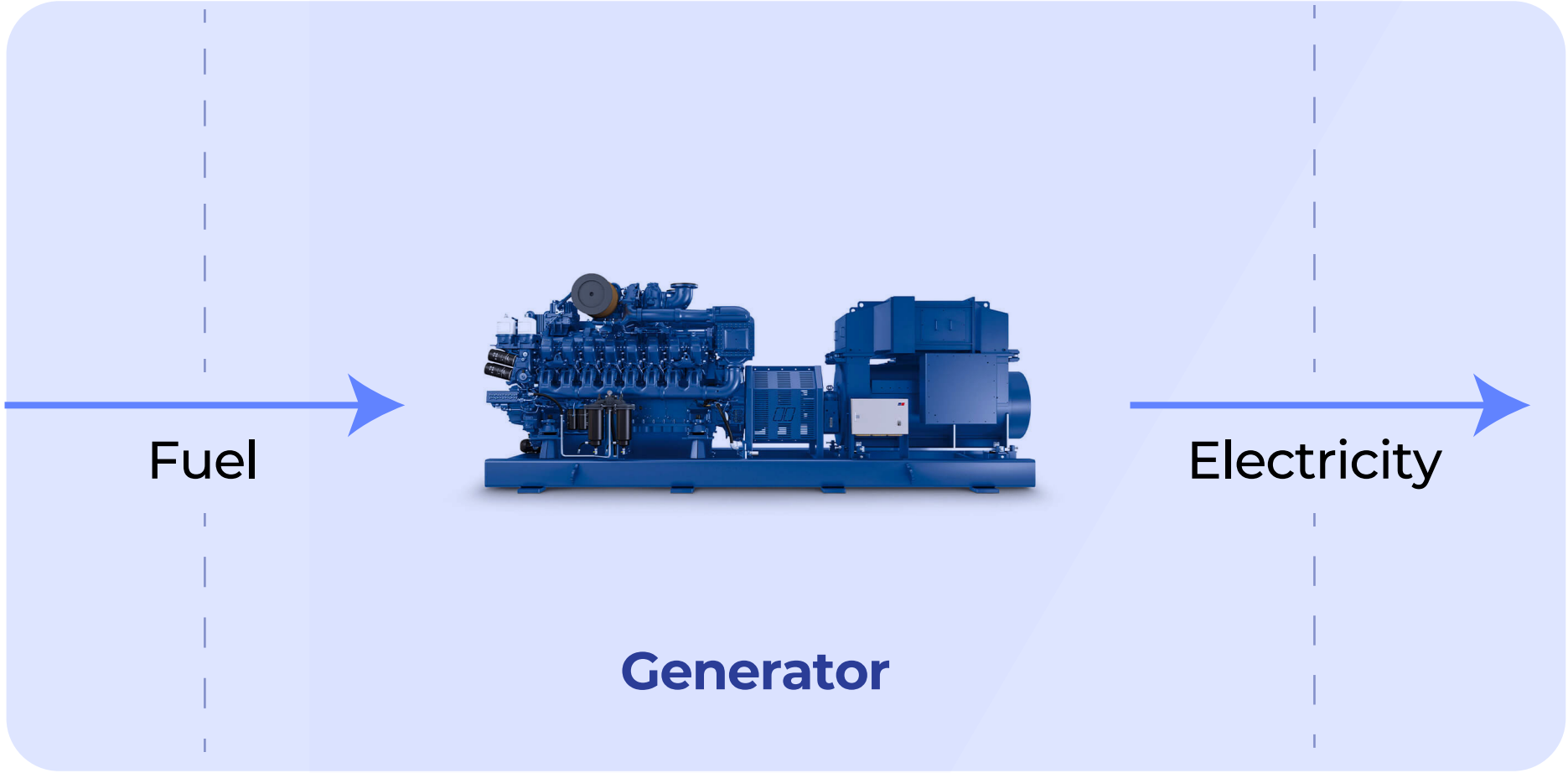
Full Sea Going

Energy need

Propulsion



Auxiliary



Types Of Energy



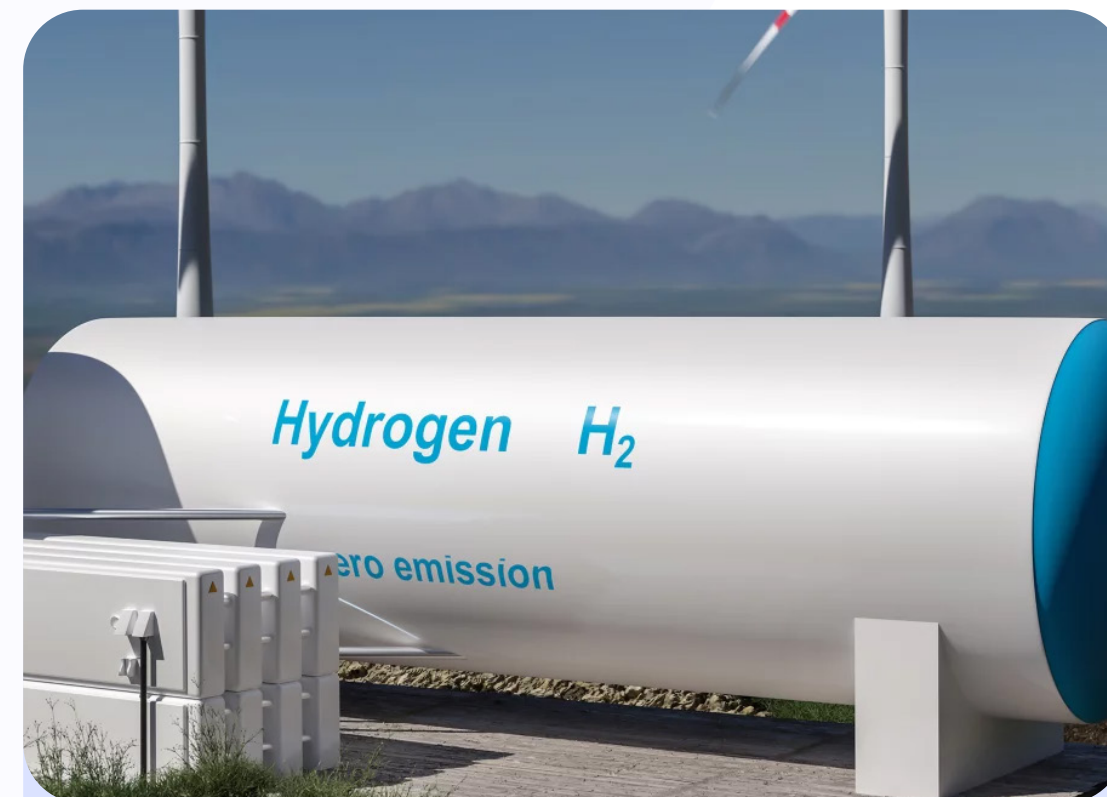
Battery
(Grid energy)



Solar panel
(Solar energy)



Wind turbine
(Wind energy)

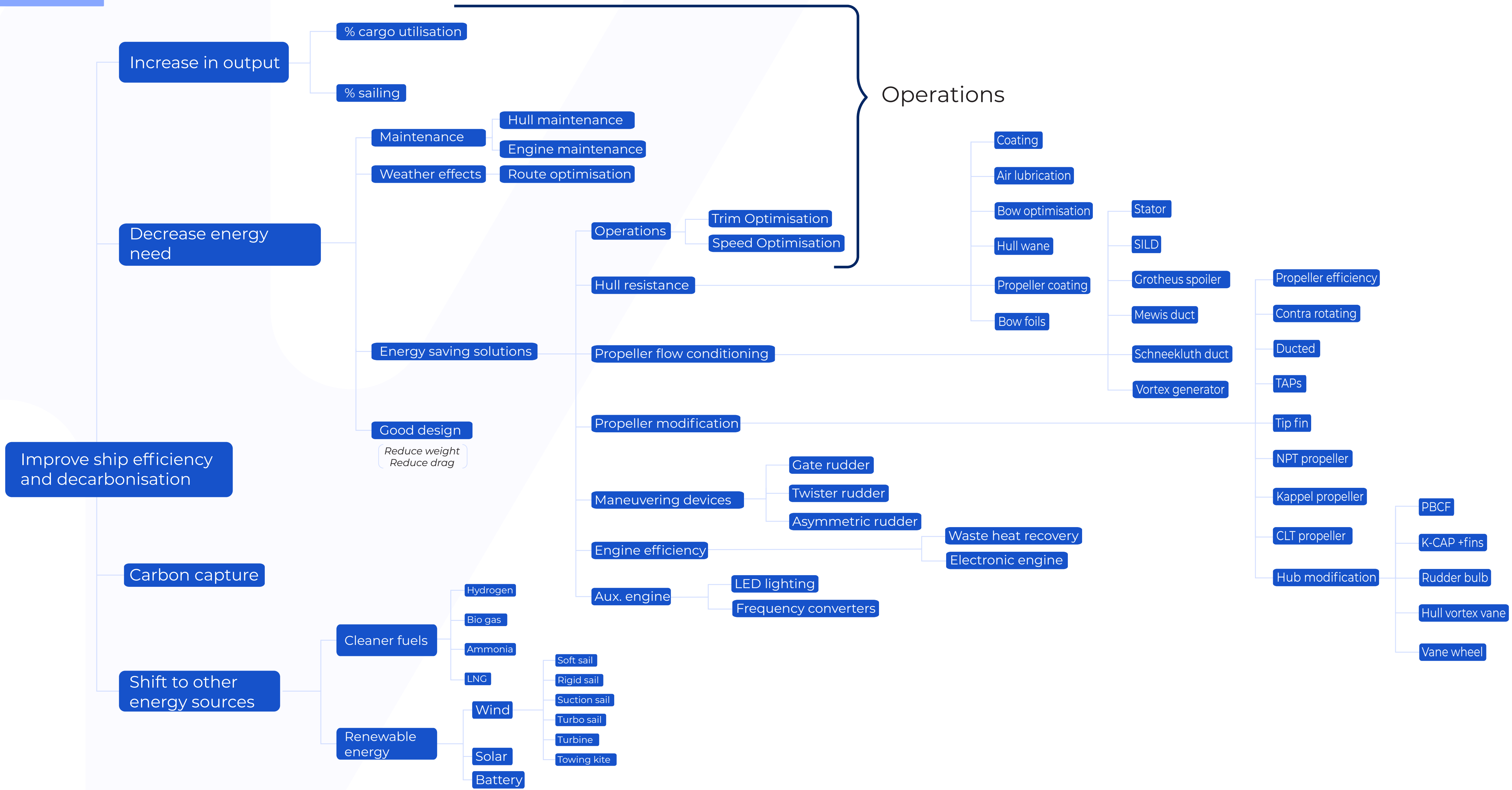


Fuel cell
(H₂ energy)



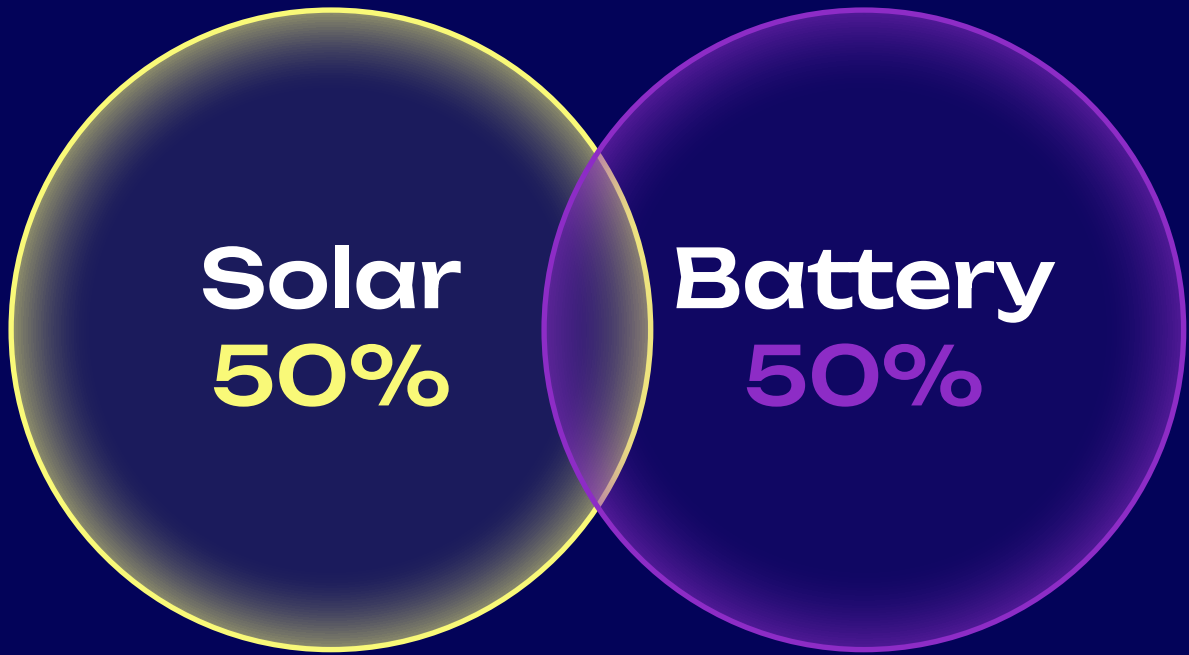
Engine
(Diesel energy)

Decarbonisation Pathway



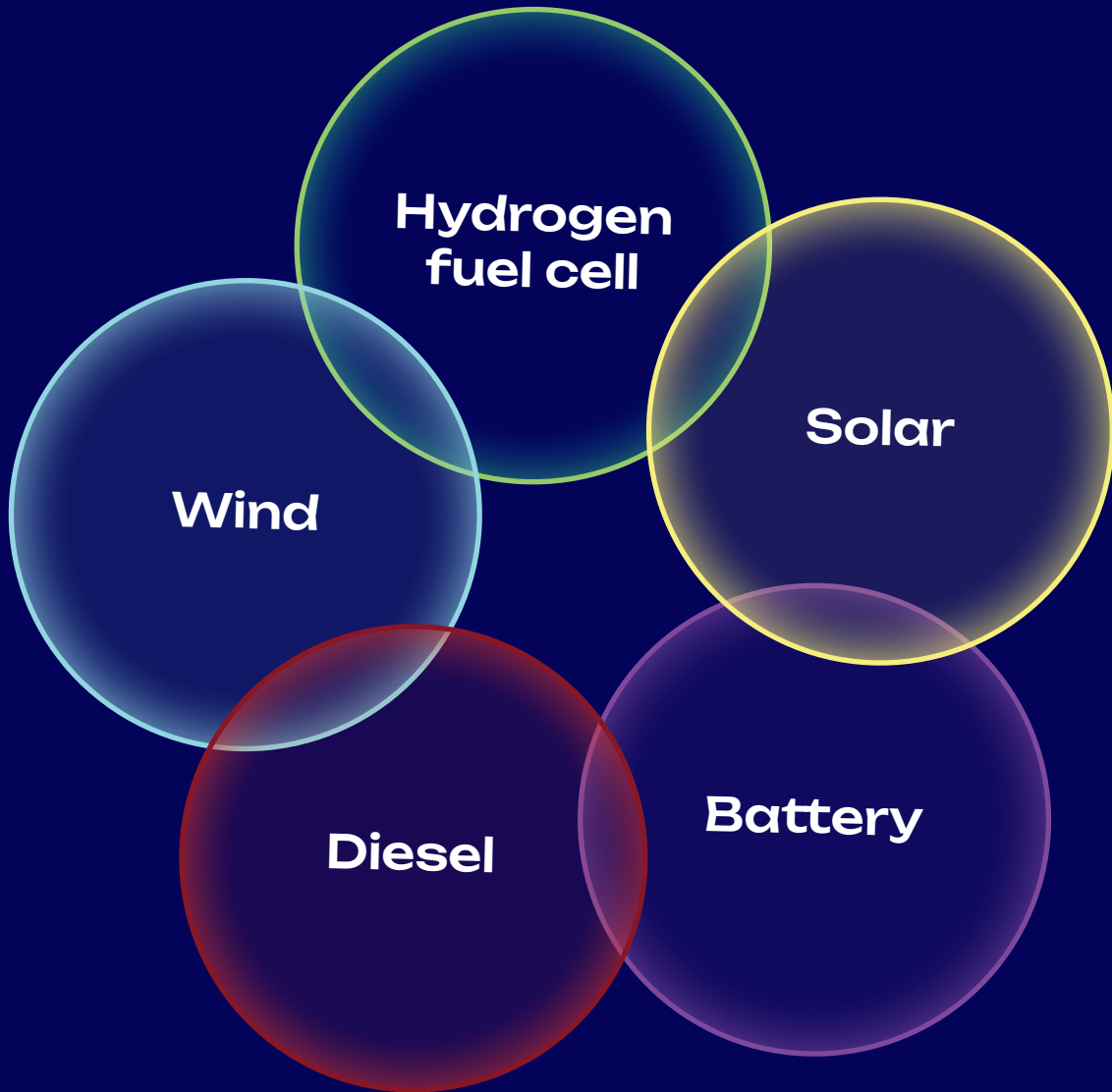
Technology Readiness

Boats (<50m)



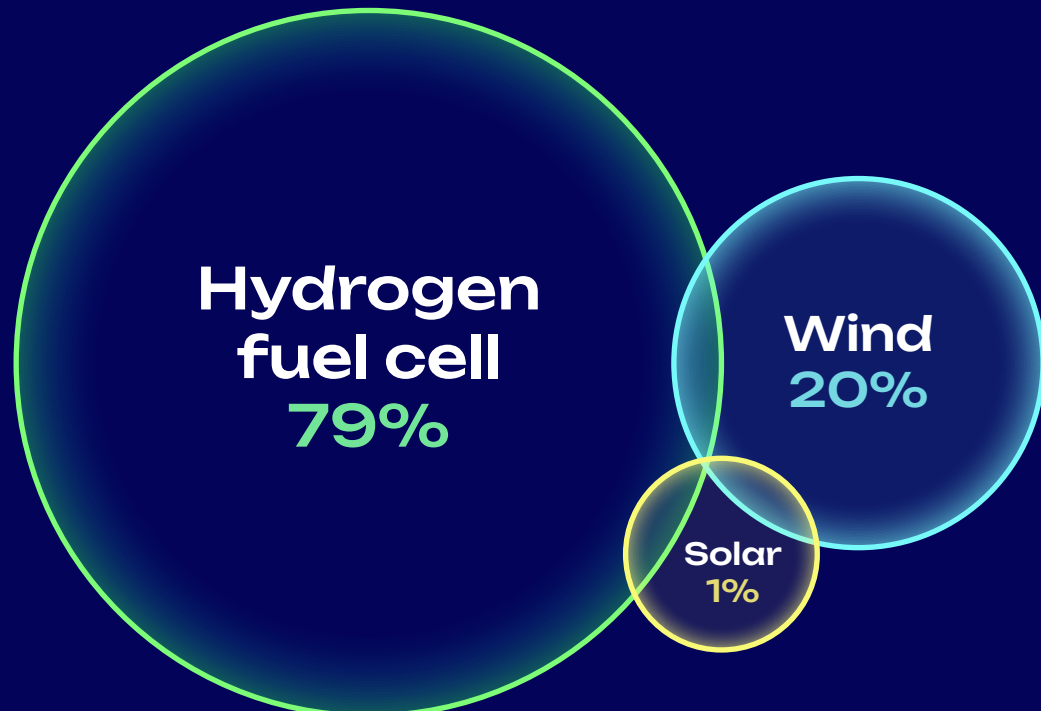
Present

Small Ships



Near term

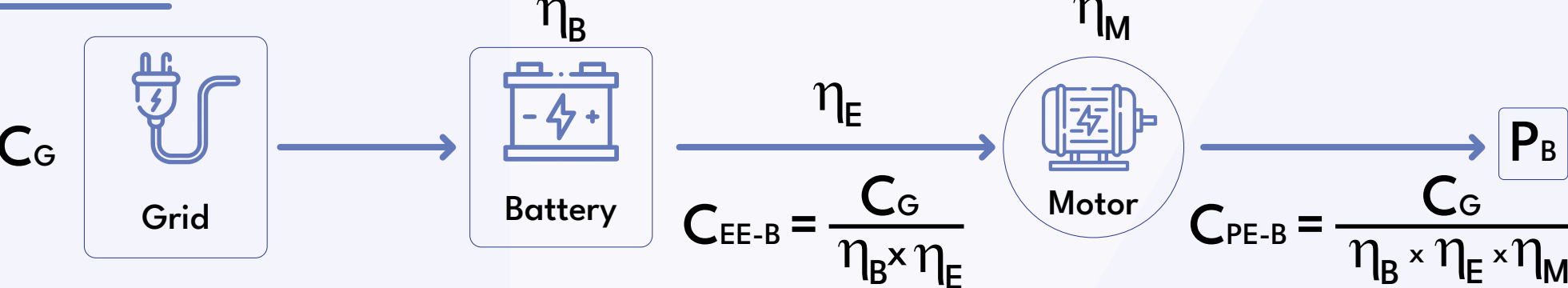
Large Ships



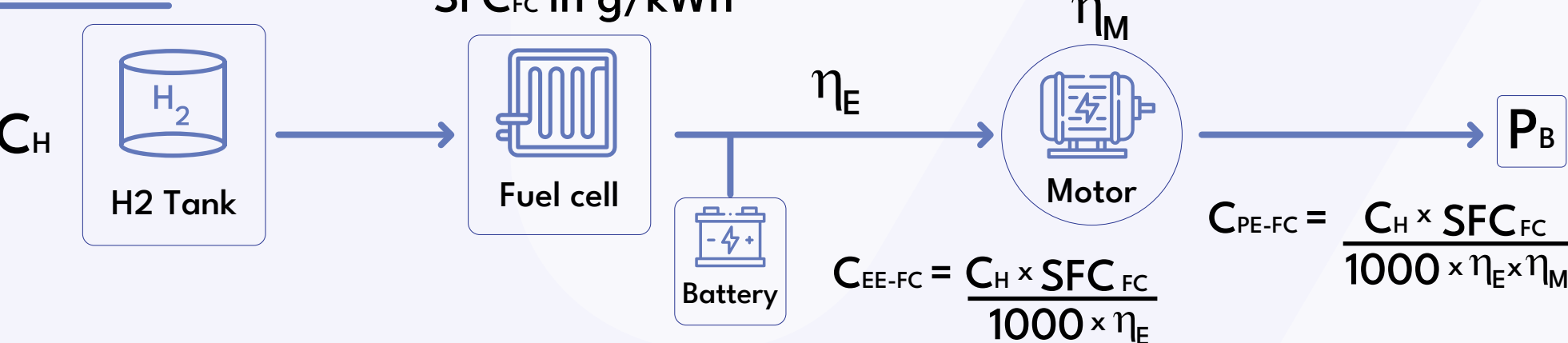
Long term

Cost of Energy

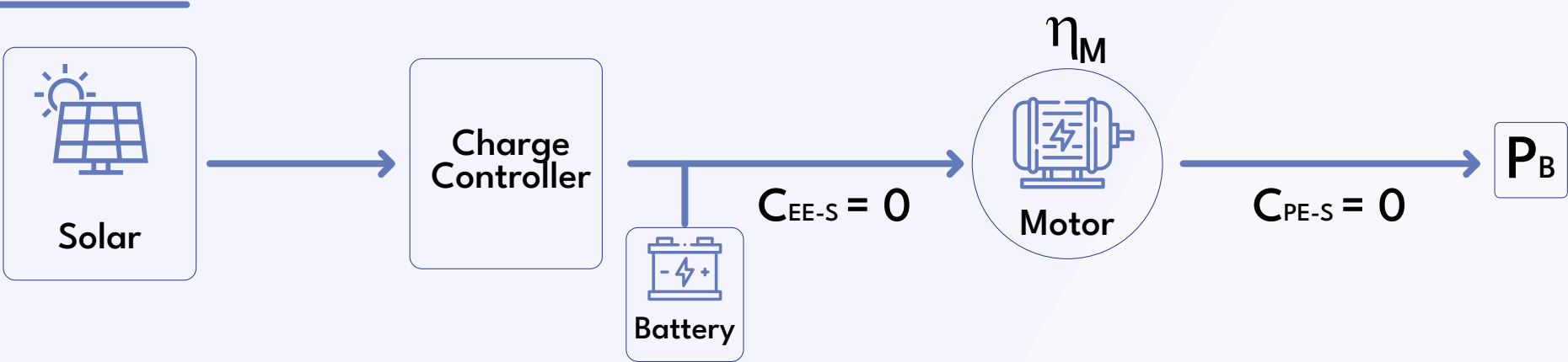
Battery (Grid)



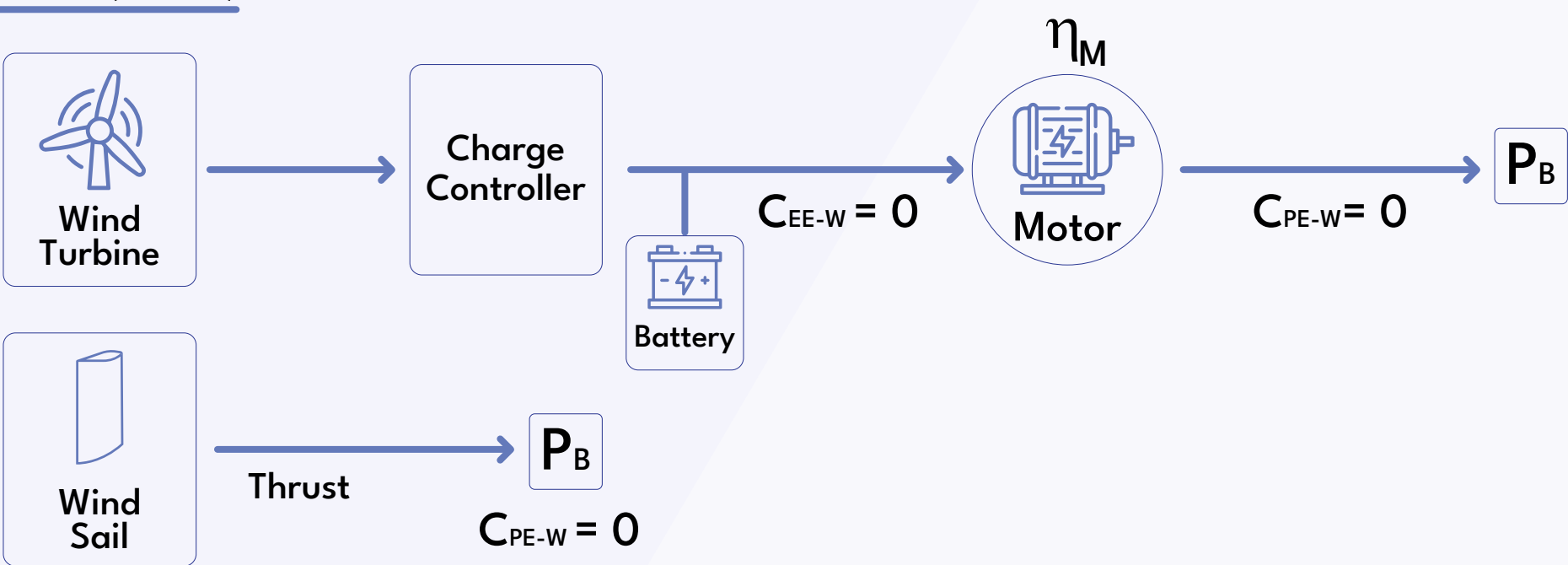
Fuel Cell (H₂)



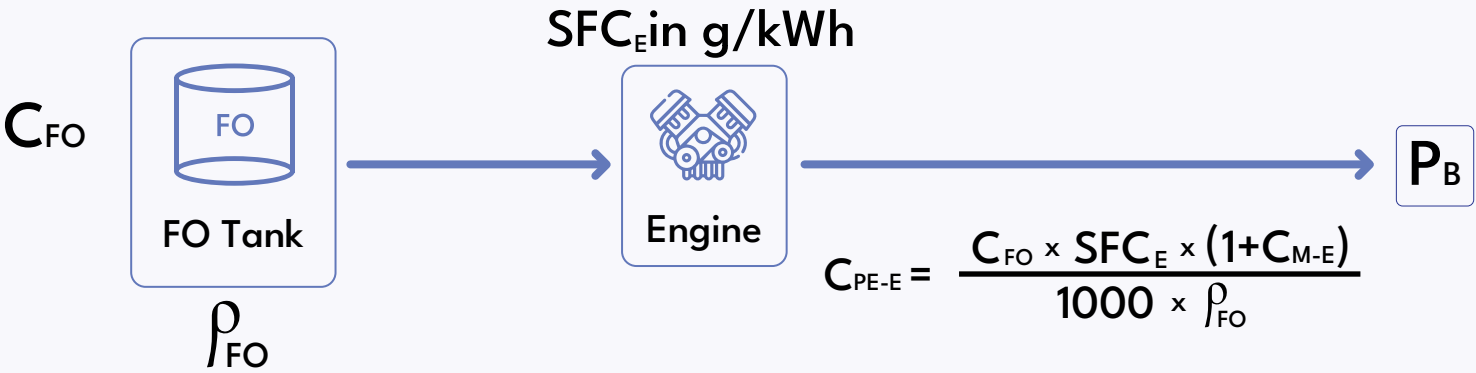
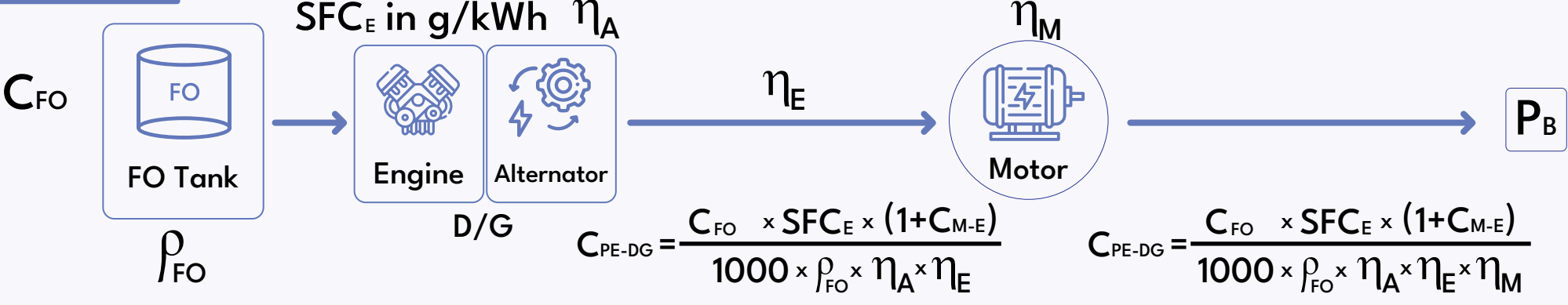
Solar Plant (Solar)



Wind Turbine (Wind)



Engine (Diesel)



Grid Cost & Fuel Cost Across The World

Rank	Country	C _{FO} (US Cents/l)	C _G (US Cents/ kWh)
1	Hong Kong	290	17
2	Iceland	235	13
3	Estonia	170	2
4	Norway	201	12
5	Albania	202	13
6	UK	191	11
7	Hungary	169	7
8	Denmark	195	14
9	Germany	188	12
10	Serbia	184	12
11	Portugal	172	10
12	Czech Republic	163	9
13	Ireland	190	15
14	Finland	209	21
15	Belgium	189	16
16	Switzerland	221	26
17	Kenya	132	5

18	Lesotho	118	2
19	Greece	183	18
20	Lithuania	166	14
21	Latvia	170	15
22	Italy	191	21
23	Belize	173	17
24	Spain	164	15
25	N. Macedonia	132	8
27	Uruguay	147	12
26	Bosnia & Herz.	146	11
28	Zambia	116	5
29	Cyprus	162	16
30	Bulgaria	148	13
31	Mozambique	143	11
32	Rwanda	130	9
33	Swaziland	126	8
34	Malawi	162	17
35	Cayman Islands	154	15
36	South Africa	126	9
37	Bhutan	96	2

Grid Cost & Fuel Cost Across The World

38	Mexico	142	13
39	Uganda	137	11
40	Tanzania	128	10
41	India	125	9
43	Burma	119	8
42	Nepal	118	7
44	Nigeria	117	7
45	Luxembourg	164	19
46	Morocco	141	14
47	Chile	119	9
48	Sierra Leone	152	17
49	Cameroon	121	10
50	DR Congo	117	9
51	Slovenia	157	19
52	Mauritius	144	16
53	Ethiopia	141	15
54	Botswana	127	11
55	Jordan	102	6
56	Paraguay	99	5
57	Netherlands	189	27
58	South Korea	114	10

59	Japan	110	9
60	Syria	78	2
61	Liechtenstein	218	36
62	Togo	143	18
63	Uzbekistan	90	5
64	Malta	134	16
65	Costa Rica	133	16
66	Brazil	121	14
67	Singapore	189	31
68	Romania	155	23
69	Bangladesh	99	10
70	Sri Lanka	110	13
71	Argentina	89	8
72	Turkey	126	18
73	Vietnam	81	8
74	Sudan	66	4
75	Philippines	110	16
76	Pakistan	99	13
77	Gabon	97	12
78	Trinidad & Tobago	65	5

Grid Cost & Fuel Cost Across The World

79	Canada	127	20
80	Peru	110	17
81	Barbados	165	30
82	USA	103	15
83	Maldives	95	14
84	Qatar	56	4
85	UAE - Dubai	82	11
86	China	102	17
87	Taiwan	91	14
88	UAE	82	12
89	Russia	72	10
90	Australia	123	23
91	Moldova	121	22
92	Burkina Faso	114	20
93	Thailand	87	14
94	Ecuador	46	4
95	Austria	176	36
96	Cambodia	100	18
97	El Salvador	98	18
98	Dom. Republic	101	19

99	Tunisia	72	11
100	Ghana	108	21
101	Kuwait	37	4
102	Nicaragua	118	24
103	Madagascar	106	21
104	Belarus	71	13
105	Bahrain	48	8
107	Azerbaijan	47	7
106	Honduras	93	19
108	Jamaica	131	28
109	Algeria	22	3
110	Angola	16	2
111	Panama	87	19
112	Georgia	128	29
113	Ivory Coast	120	28
114	Saudi Arabia	31	7
115	Libya	3	1
116	Guatemala	103	25
117	Slovakia	167	41
118	Lebanon	75	20

118	Lebanon	75	20
119	Kazakhstan	63	18
120	Bahamas	147	40
121	Aruba	126	34
122	Malaysia	47	15
123	Iran	0.6	4
124	Oman	67	22
125	Cuba	105	32
126	Colombia	62	22
127	Ukraine	141	41
128	Cape Verde	123	38
129	Venezuela	0.4	10
130	US California -	104	35
131	Israel	196	58
132	Egypt	27	20
133	Poland	128	50

Grid Cost & Fuel Cost For 4 Countries

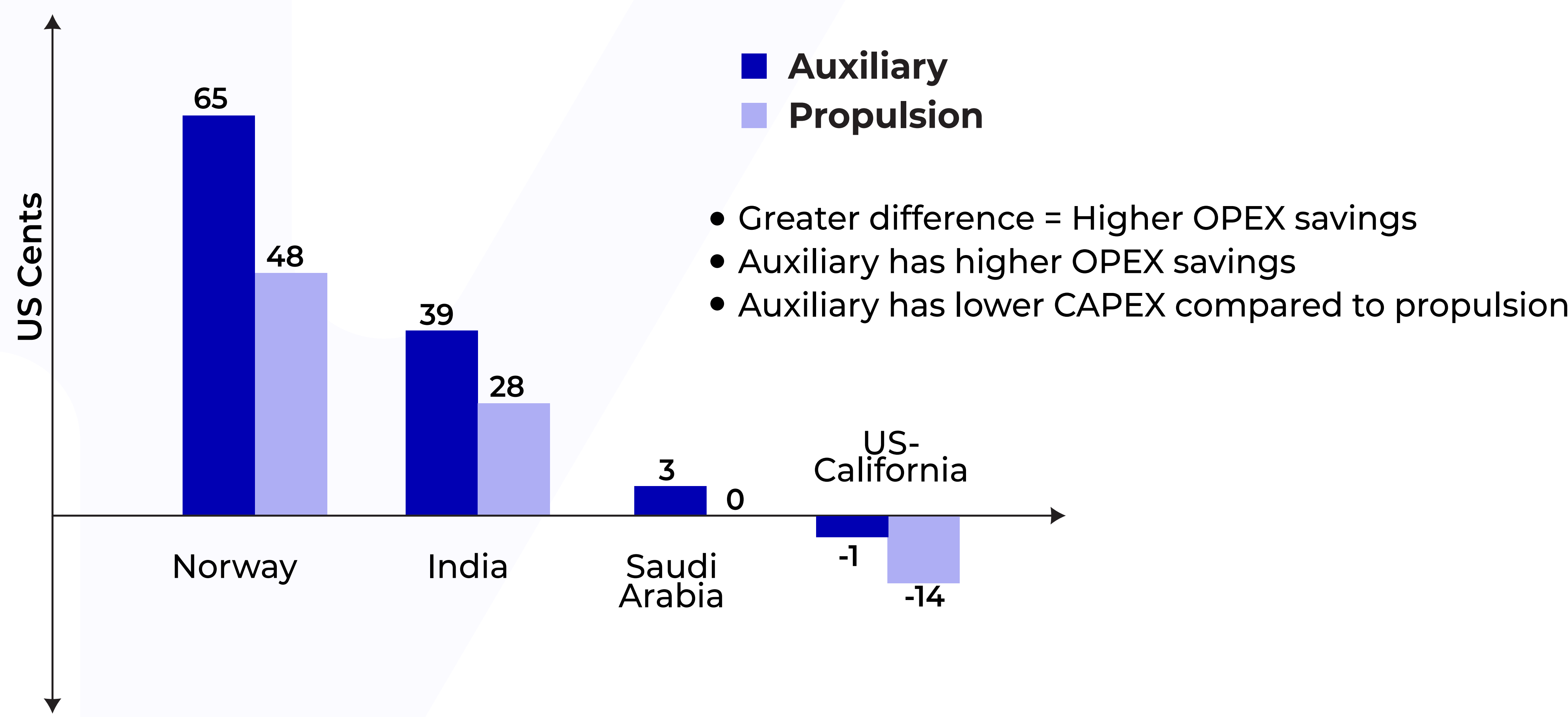
Rank	Country	C_{FO} (US Cents/L)	C_G (US Cents/ kWh)
4	Norway	201	12
41	India	125	09
114	Saudi Arabia	31	07
130	US- California	104	35

Grid Cost & Fuel Cost For 4 Countries

Rank	Country	CFO (US Cents/L)	CG (US Cents/ kWh)	C_{EE-B} (US Cents/ kWh)	C_{EE-DG} (US Cents/ kWh)	C_{PE-B} (US Cents/ kWh)	C_{PE-E} (US Cents/ kWh)
4	Norway	201	12	15	80	17	65
41	India	125	09	11	50	12	40
114	Saudi Arabia	31	07	09	12	10	10
130	US- California	104	35	43	42	48	34

 High diesel cost and low grid cost → Ease of Electrification

Auxiliary and Propulsion Energy Cost



 **Auxiliary to be converted to electric from diesel before propulsion**

Cost Of Energy From Fuel Cell (H₂)

Cost of H₂



- Higher OPEX savings in Auxiliary compared to propulsion
- Lower CAPEX in Auxiliary compared to propulsion

Cost of Energy in US Cents

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

 **Auxiliary to be converted to fuel cell from diesel before propulsion**

Cost of energy from fuel cell (H₂)

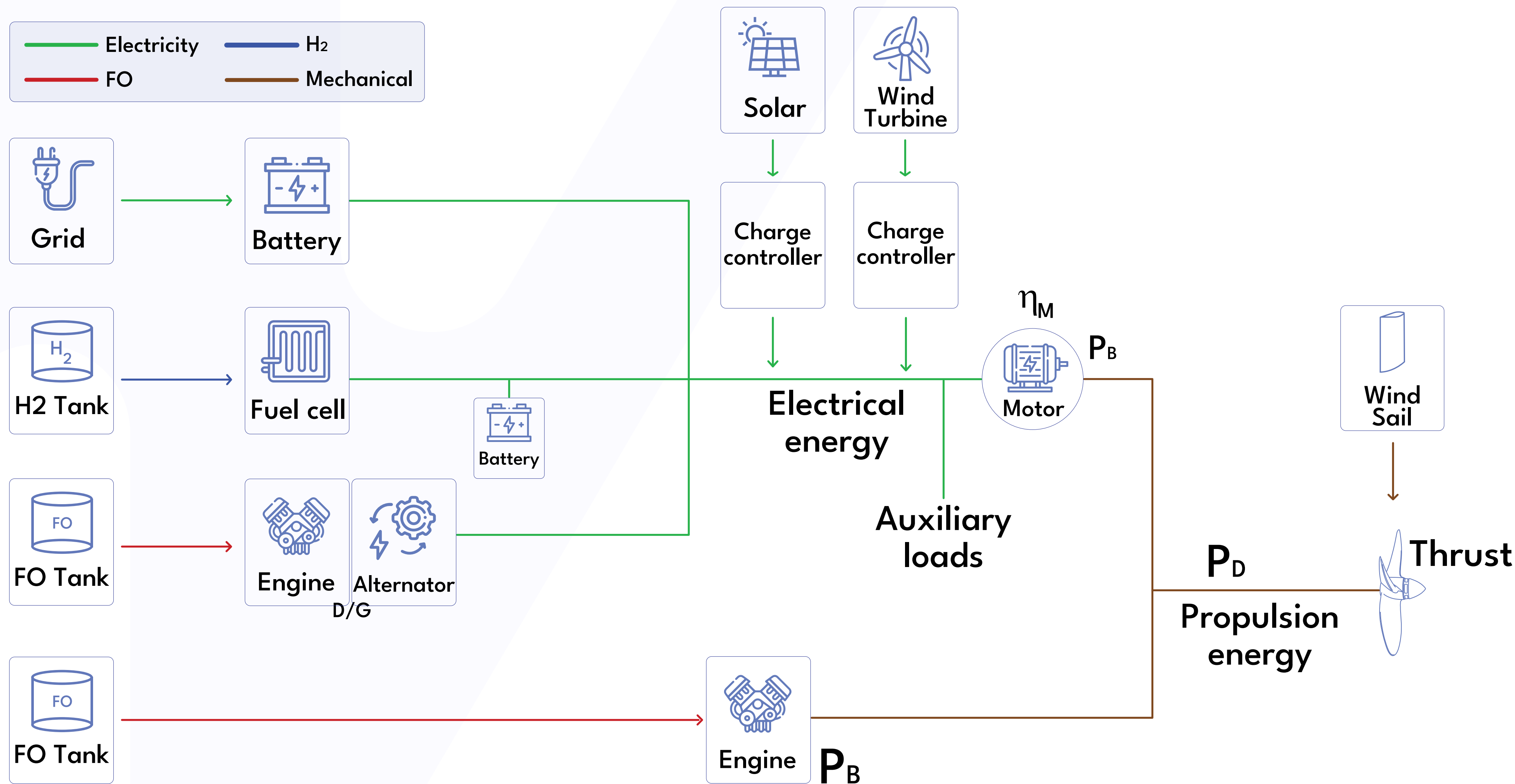
No. of countries where cost of energy from H₂ is cheaper then diesel

Auxiliary			Propulsion		
500 US C	300 US C	200 US C	500 US C	300 US C	200 US C
84	116	125	36	102	120

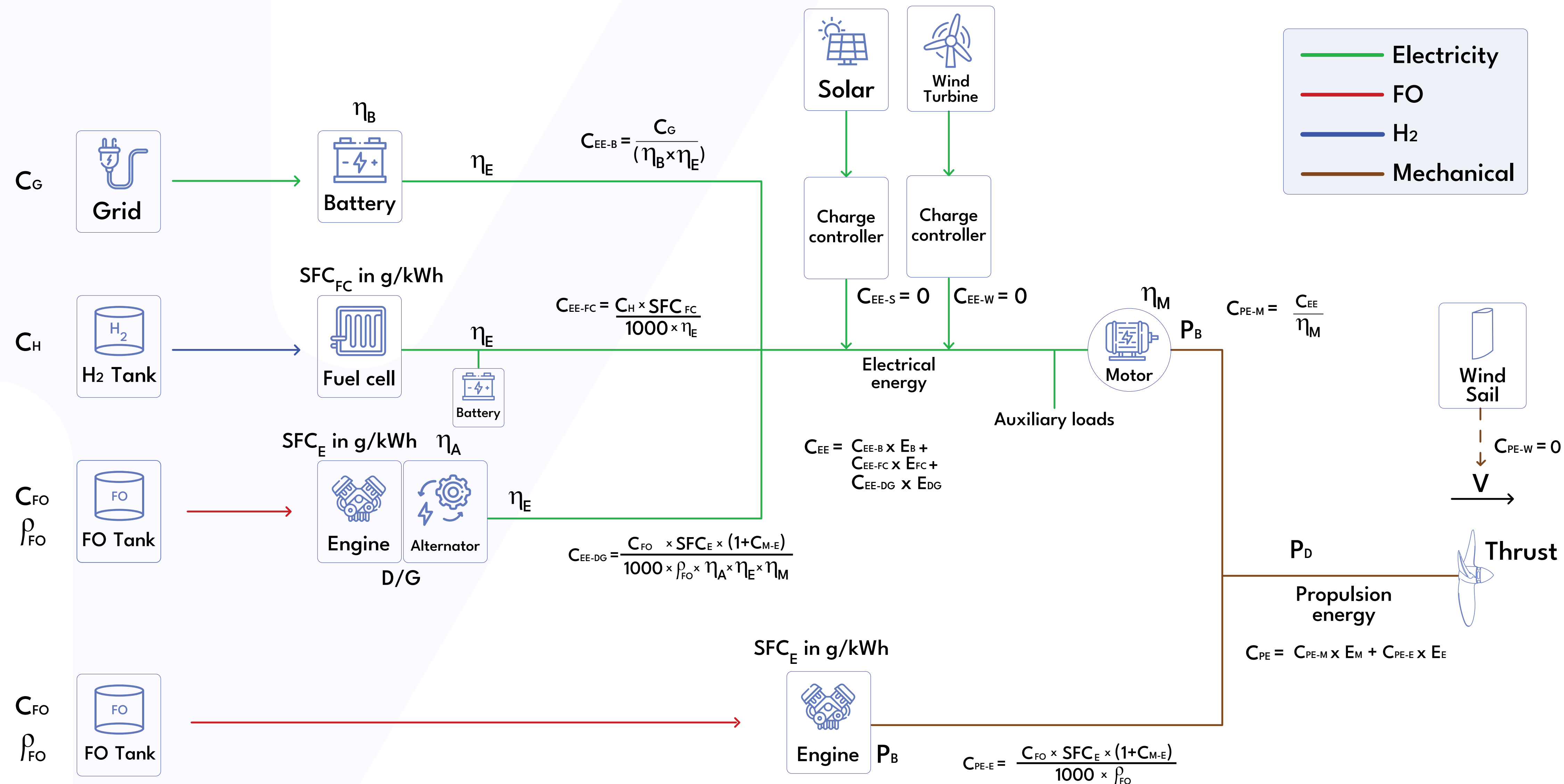
- Higher OPEX savings in Auxiliary compared to propulsion
- Auxiliary has lower CAPEX compared to propulsion

 In long term Green H₂ is likely to be attractive energy option for most countries

Combination of Energy sources

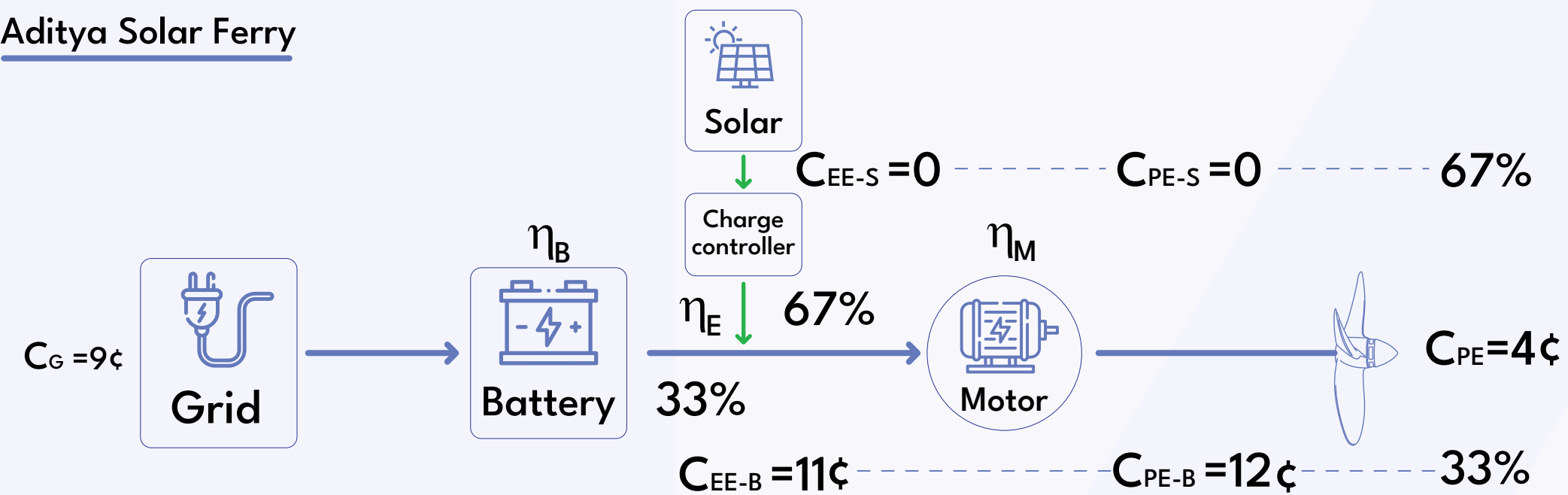


Cost of Energy from combination

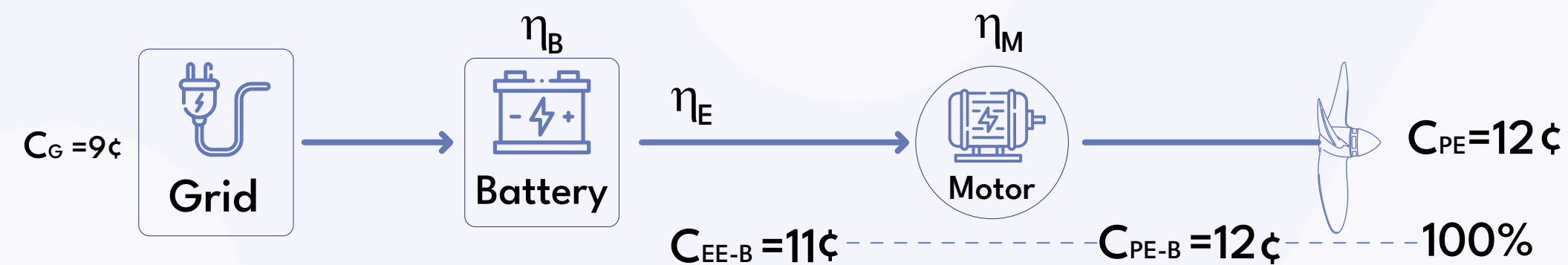


Cost of Energy from combination

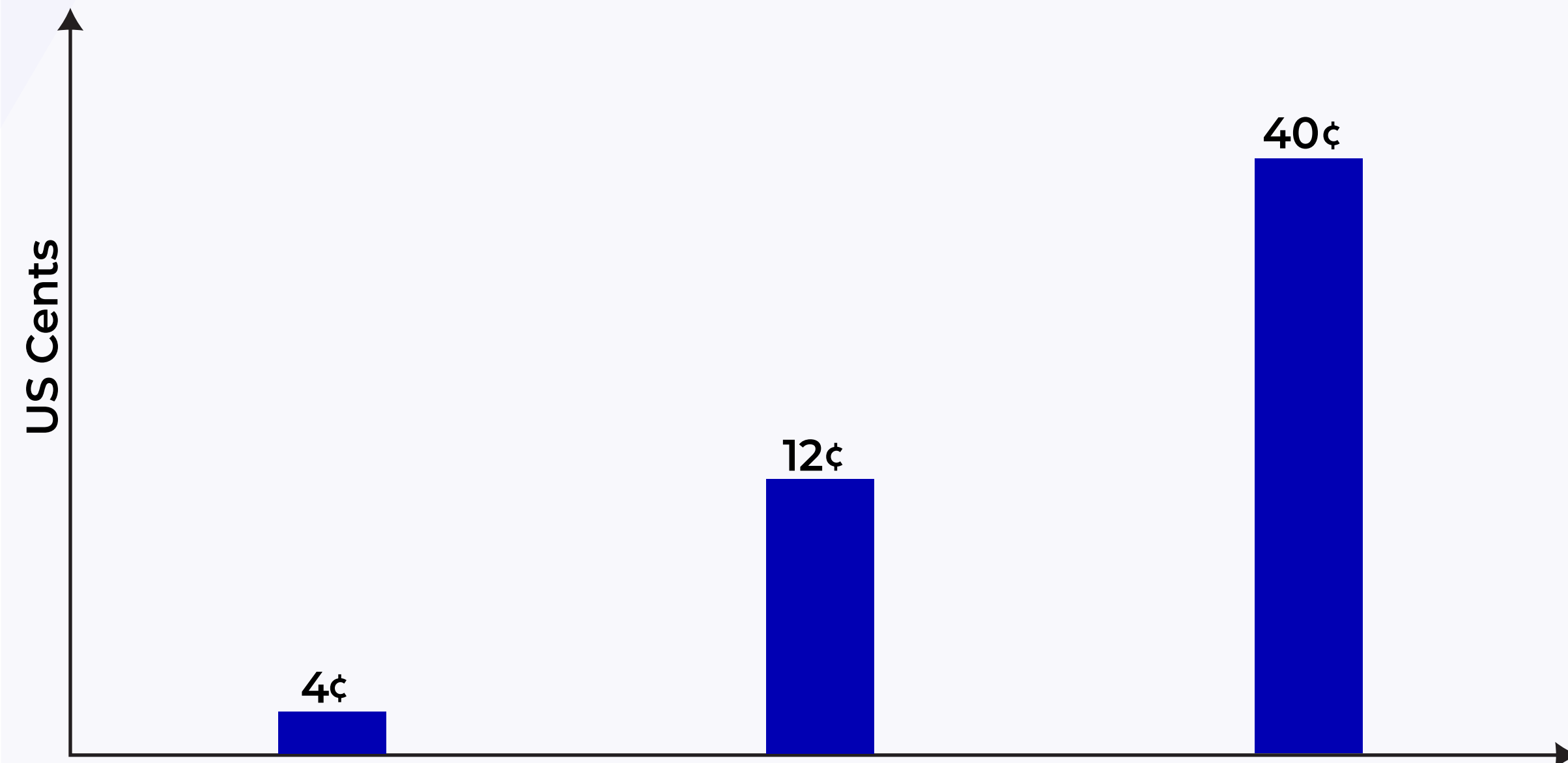
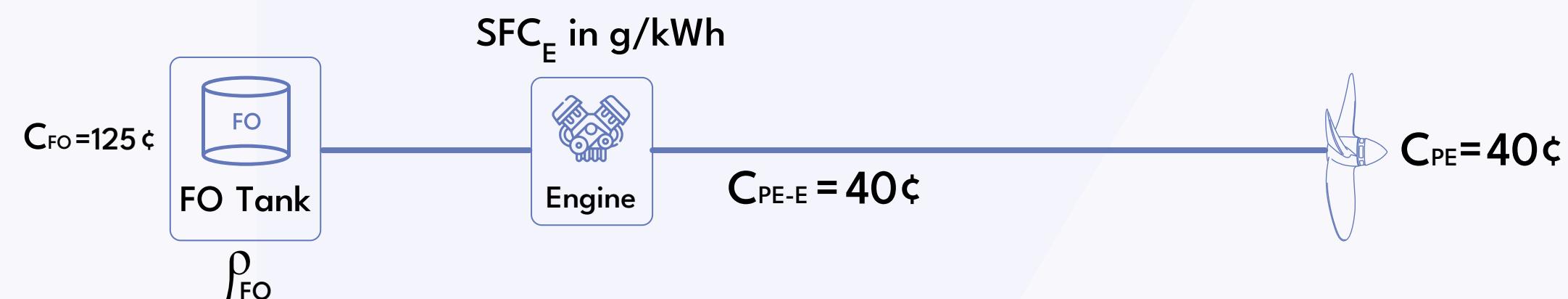
Aditya Solar Ferry



Electric Ferry



Diesel Ferry



Solar Ferry



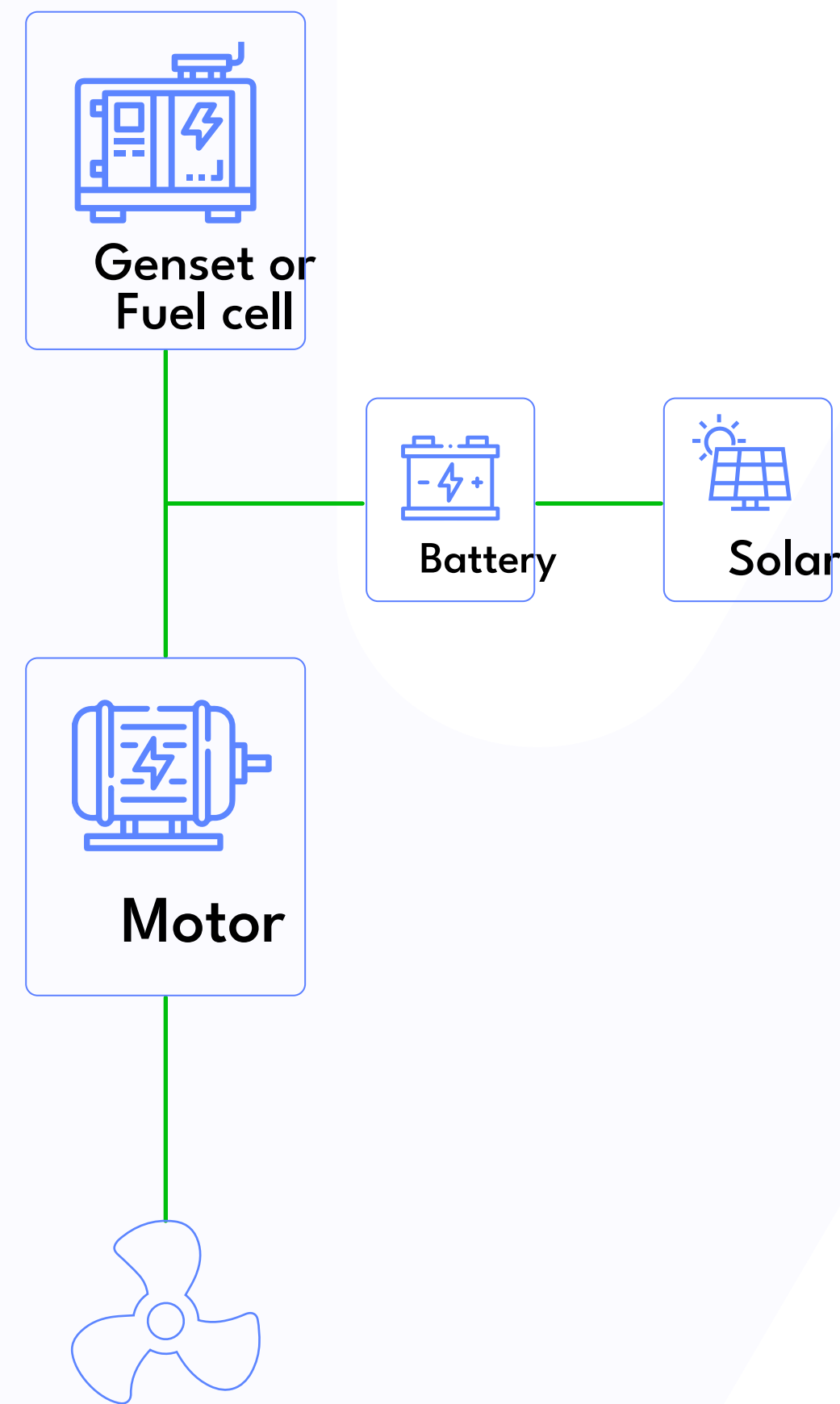
Electric Ferry



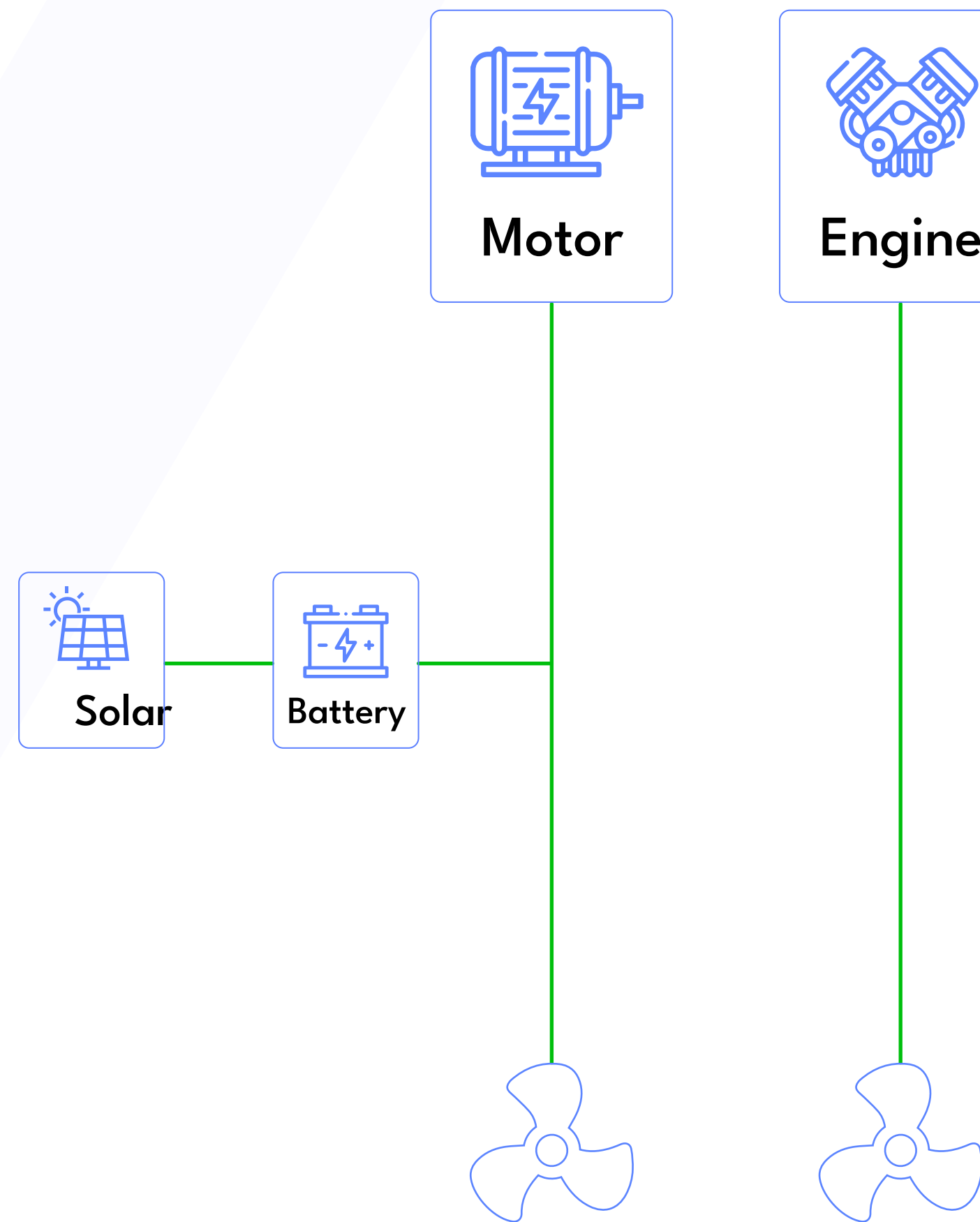
Diesel Ferry

 **Solar can significantly reduce OPEX in slow speed passenger boats**

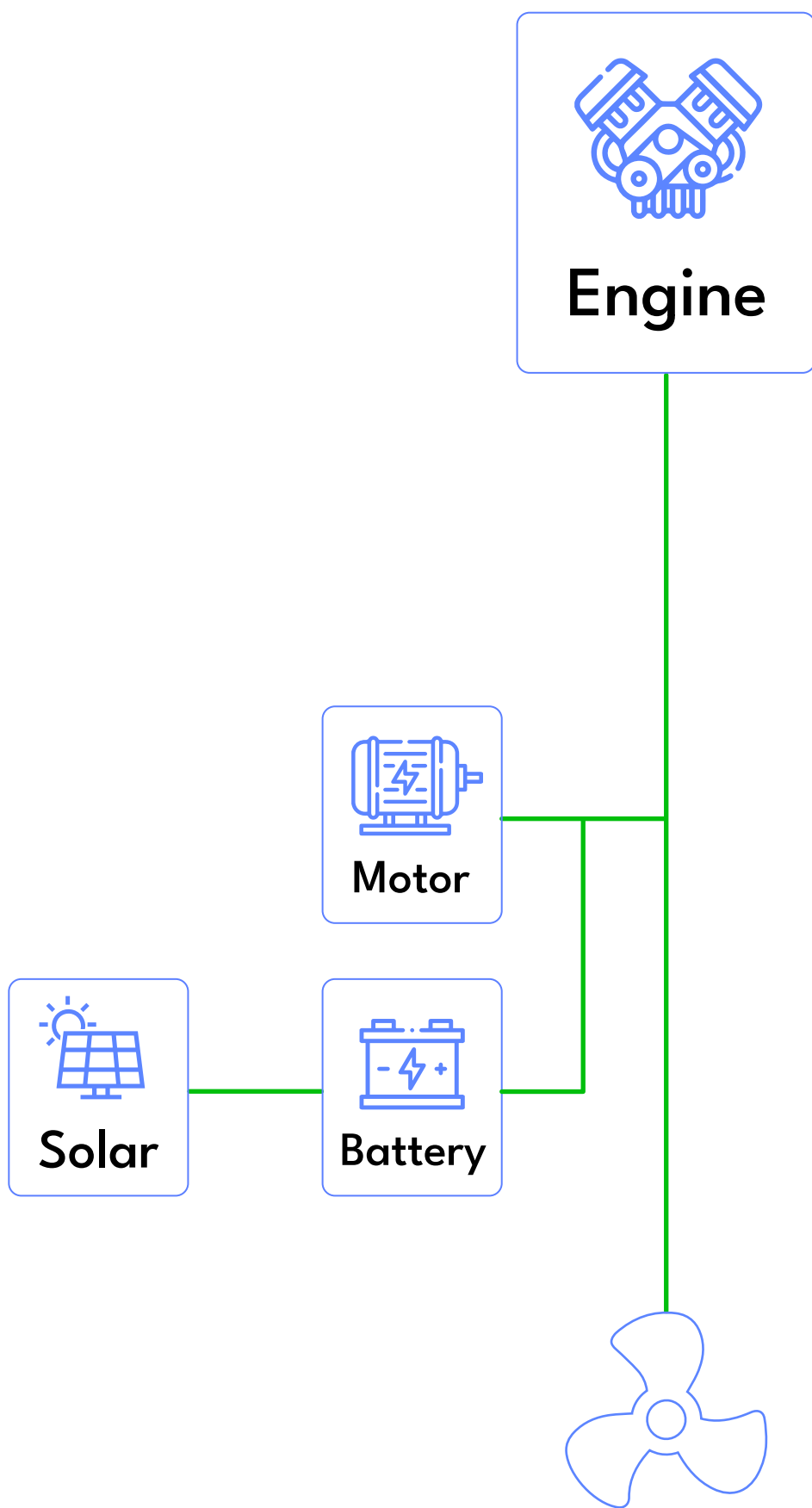
Partial shift to electric | Hybrid



Series



Independent shaft

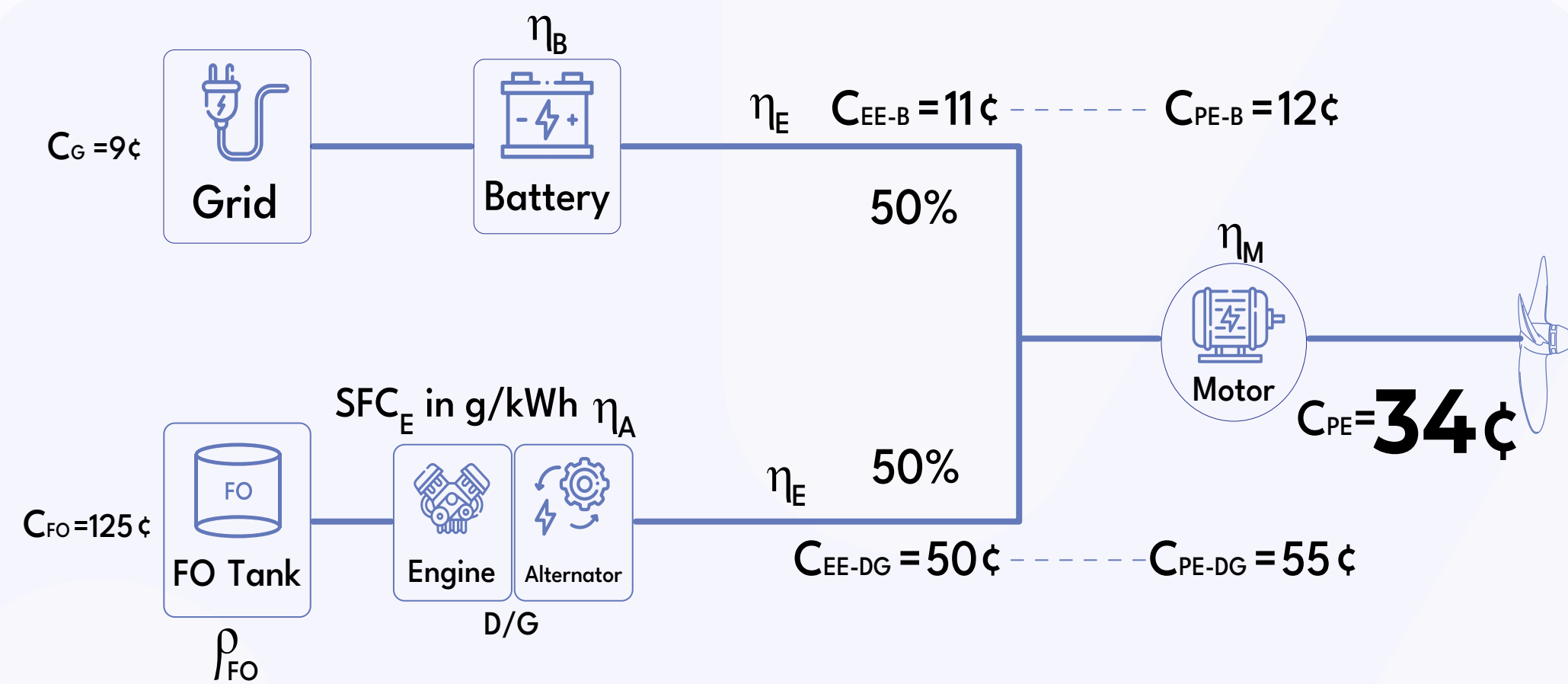


Same shaft

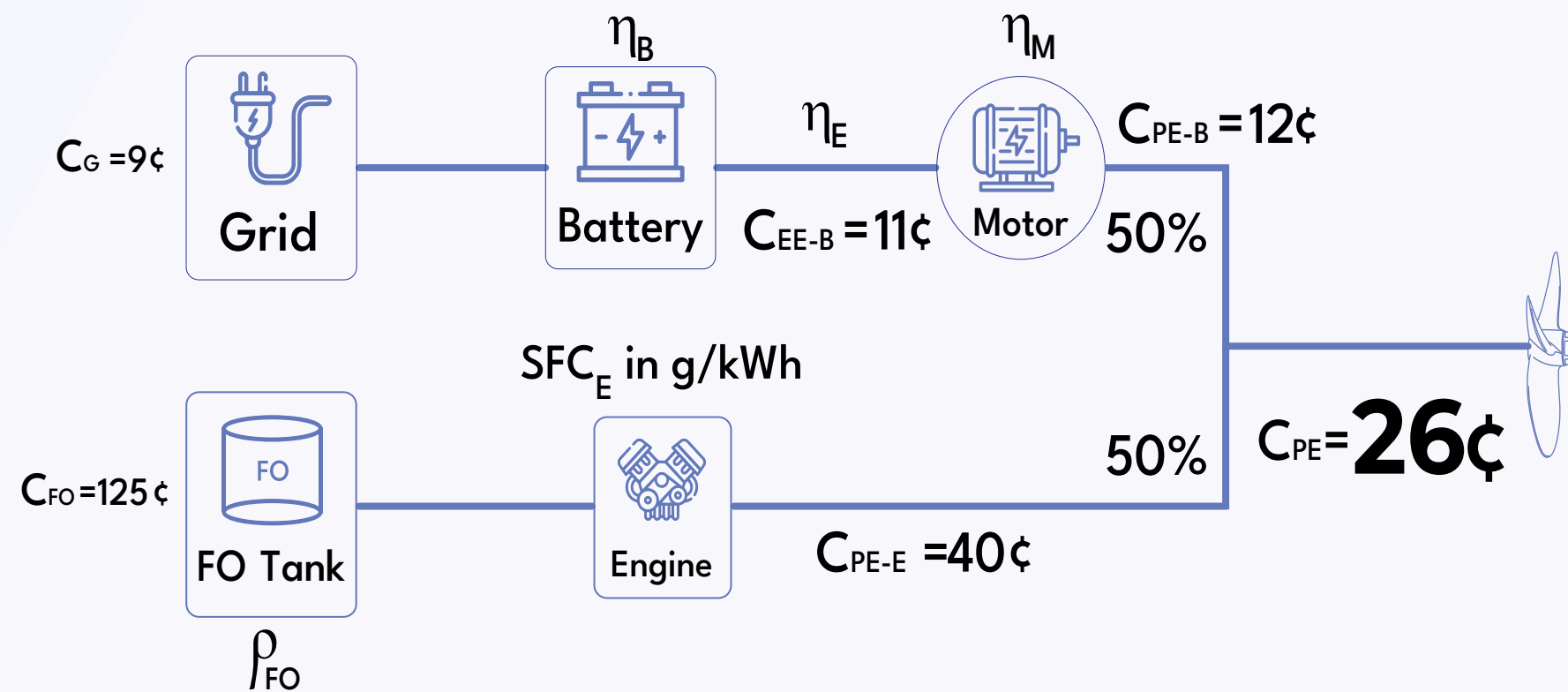
Parallel

Partial shift to electric | Hybrid

Series Hybrid



Parallel Hybrid



Pure Diesel

40¢

- Parallel hybrid has higher OPEX savings than series hybrid compared to pure diesel
- Series hybrid has higher CAPEX since motors are bigger and regulations are stringent for main propulsion.

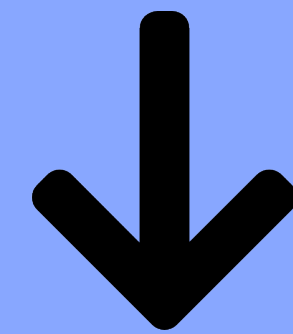
💡 In applications where it works, parallel hybrid is cheaper than series hybrid

Initial Conclusions



- 💡 High diesel cost and low grid cost → Ease of Electrification
- 💡 Auxiliary to be converted to electric from diesel before propulsion
- 💡 Auxiliary to be converted to fuel cell from diesel before propulsion
- 💡 In long term Green H₂ is likely to be attractive energy option for most countries
- 💡 Solar can significantly reduce OPEX in slow speed passenger boats
- 💡 In applications where it works, parallel hybrid is cheaper than series hybrid

$$\text{CAPEX} + \text{OPEX} = \text{TCO}$$



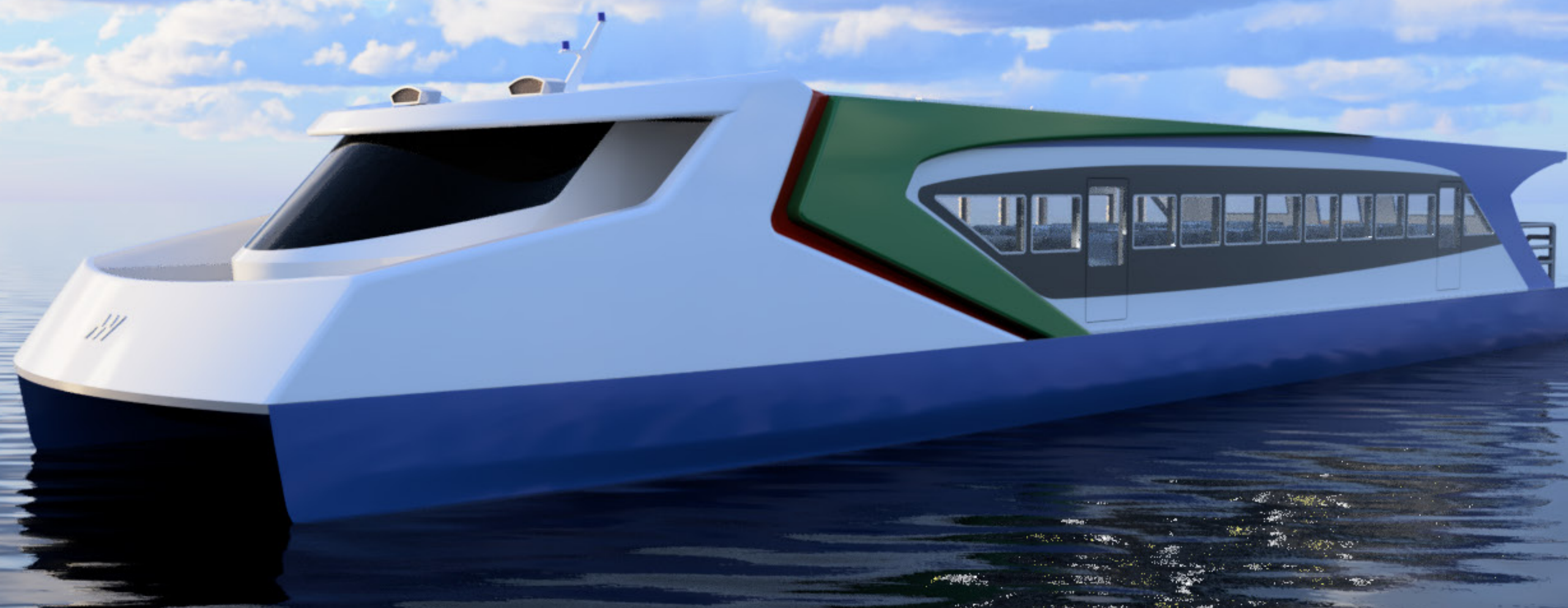
f (Cost of Energy)

Our Boats



Locations		Applications	
Canada 01	India ——— 60	Tourism ——— 34	
	Kerala ——— 41	Passenger Transport — 19	
	Uttar Pradesh — 06	Fishing ——— 06	
Turkey 01	Punjab ——— 04	Vehicle Transport ——— 02	
	Maharashtra — 03	Work Boat ——— 01	
	Madhya Pradesh - 02		
	Odisha ——— 01		
Maldives 01	West Bengal ——— 01		
	Karnataka ——— 01		
	Tamil Nadu ——— 01		

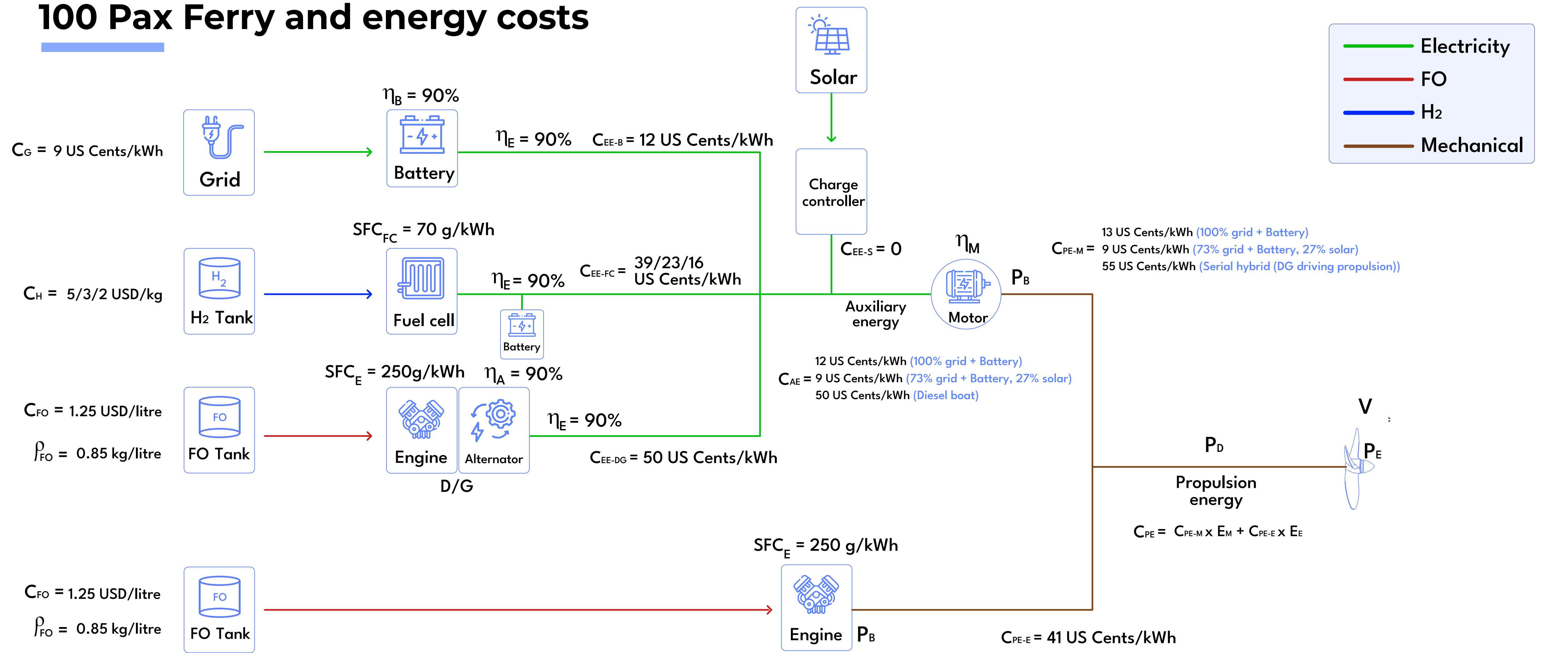
100 PAX FERRY



Speed 8-12 knots

Range 75-200 km/day

100 Pax Ferry and energy costs



C_G - Cost of grid \$/kWh	C_{EE-S} - Cost of electrical energy from solar	P_D - Power delivered to propeller	E_B - % Energy from battery	η_M - Motor efficiency
C_H - Cost of H ₂ \$/Kg	C_{PE-E} - Cost of propulsion energy from engine	P_E - Effective power	E_{FC} - % Energy from fuel cell	η_B - Battery efficiency
C_{FO} - Cost of fuel \$/l	C_{PE-M} - Cost of propulsion energy from motor	SFC_E - Specific fuel Consumption engine g/kWh	E_{DG} - % Energy from D/G	η_E - Other system efficiency
C_{EE-B} - Cost of electrical energy from battery	C_{PE} - Cost of propulsion energy	SFC_{FC} - Specific fuel consumption fuel cell g/kWh	E_S - % Energy from solar	η_A - Alternator efficiency
C_{EE-FC} - Cost of electrical energy from fuel cell	C_{AE} - Cost of auxiliary energy		E_M - % Energy from motor	ρ_{FO} - Density of fuel Kg/l
C_{EE-DG} - Cost of electrical energy from D/G	P_B - Brake horse power		E_E - % Energy from engine	ρ_{FO} - Density of fuel Kg/l
			M_E - Engine maintenance (LO, filter, overhauling) ~ 10% C_{FO}	

CAPEX, OPEX, TCO and TCO-NPV calculations

Inputs									
Platform	100 pax ferry	this decide the speed-power curve (hull and draft)			Scalability of battery		Solar plant production and degradation		
Location	Kochi	for solar production			Low voltage LFP	20 kWh	for aux. battery and sinze there are two sets of battery	Year	Energy (kWh Difference (kWh)
Speed	8 knots	decides the propulsion power required						1	30,800 0
Range per day	75 km	133 km	is 9 hrs distance		Medium voltage LFP	80 kWh	for prop. battery and sinze there are two sets of battery	2	30,515 (285)
Max charging range	15 km				Medium voltage LTO	120 kWh	for prop. battery and sinze there are two sets of battery	3	30,233 (567)
Running time	304 mts	5.1 hrs			LTO battery cooling	5 kW	for each 120 kWh scaled unit	4	29,953 (847)
Annual operations	350 days							5	29,676 (1,124)
Air con load	9 kW	for super-efficient based on the platform			Scalability of fuel cell (size)	70 kW		6	29,401 (1,399)
Air con load	12 kW	for efficient based on the platform			H2 tank scalability	7 kg		7	29,129 (1,671)
Air con load	15 kW	for traditional based on the platform						8	28,859 (1,941)
Other aux. load	1 kW	based on the platform			Efficiency of prop motor (nM)	90%		9	28,592 (2,208)
Operating time	12 hrs				Efficiency of battery (nB)	90%		10	28,327 (2,473)
Aircon running time	9.6 hrs	80% of time			Efficiency of elec system (nE)	90%		11	28,065 (2,735)
Power (supere-efficient)	40 kW	from the speed power curve			Efficiency of alternator (nA)	90%		12	27,805 (2,995)
Power (efficient)	56 kW	increase if 40%			SFC of H2 fuel cell (SFCFC)	70 g/kWh	of electrical energy	13	27,548 (3,252)
Power (traditional)	84 kW	increase is 110%			SFC of Diesel engine (SFCE)	250 g/kWh	of mechanical energy	14	27,293 (3,507)
Solar plant size	25 kW	based on platform			SFC of Diesel generator	278 g/kWh	of electrical energy	15	27,040 (3,760)
Insolation	5.5	based on location			Density of diesel (rhoFO)	0.85 kg/litre		16	26,790 (4,010)
System efficiency	0.64	3.5 kWh per kW in a day						17	26,542 (4,258)
Daily solar energy	88 kWh	Average production for whole year			USD Rate	80 Rs/USD		18	26,296 (4,504)
Solar plant degradation	0.93% every year	20% degradation in 25 years			Cost of grid (CG)	7.5 Rs	9 US Cents per kWh	19	26,053 (4,747)
					Cost of hydrogen (CH)	400 Rs	5 USD per kg	20	25,812 (4,988)
Prop solar	70.4 kWh	80% proportion for propulsion			Cost of diesel (CFO)	100 Rs	1.25 USD per litre	21	25,573
Aux. solar	17.6 kWh	20% proportion for auxiliary			Cost of LO, filters & overhaul in engine (Em	10% of CFO		22	25,336
LFP design based on	100% average production for the year							23	25,102
								24	24,870
								25	24,640
whole day	super-efficient	efficient			Cost of elec energy from battery (CEE-B)	9.3 Rs	12 US Cents per kWh		
Propulsion energy	203 kWh	283 kWh			Cost of elec energy from H2 FC (CEE-FC)	31.1 Rs	39 US Cents per kWh		
Auxiliary energy	98.4 kWh	127.2 kWh	air con load is for running time and other aux. load is for operating tin		Cost of elec energy from DG (CEE-DG)	39.9 Rs	50 US Cents per kWh	includes cost of LO, filters & overhaul	
Max Trip range	super-efficient LTO system				Cost of prop energy from battery	10.3 Rs	13 US Cents per kWh		
Trip distance	15 km				Cost of prop energy from H2 FC	34.6 Rs	43 US Cents per kWh		
Trip time	61 mts				Cost of prop energy from DG	44.3 Rs	55 US Cents per kWh		
Propulsion energy	41 kWh								
Auxiliary energy	10 kWh				Cost of prop energy from Engine (CPE-E)	32.4 Rs	41 US Cents per kWh	includes cost of LO, filters & overhaul	
CAPEX computation					Battery SOC, DOD and buffer for degradation and replacement			Currency	
Boat without propulsion and drive	2,40,00,000 INR	3,00,000 USD	GRP Boat		DoD for fast charging LTO	60%		USD	
					DoD for slow charging LFP	80%		INR	
					Degradation and additional capacity LTO	20%			
					Degradation and additional capacity LFP	20%			

CAPEX, OPEX, TCO and TCO-NPV calculations

LFP System - Propulsion battery and aux battery separate									
Propulsion energy need (mechanical)	203 kWh				Cost with drives and controls	21,67,000	Rs	27,088	USD
Propulsion energy need (electrical)	226 kWh	loss of electrical to mechanical energy							
Prop battery need	338 kWh	battery DOD is 80% and additional buddfer of 20% due to degradation replacement			Variable cost of LFP prop battery	70,000	Rs	875	USD per kWh
Prop battery size	320 kWh	Two sets of 160 kWh batteries			Replacement cost of LFP prop battery	50,000	Rs	625	USD per kWh
Aux. energy need (electrical)	98 kWh				Cost of prop battery pack	2,24,00,000	Rs	2,80,000	USD
Aux battery need	148 kWh	battery DOD is 80% and additional buddfer of 20% due to degradation replacement			Cost of replacement in 7 yrs	1,60,00,000	Rs	2,00,000	USD
Aux battery size	140 kWh	Two sets of 70 kWh batteries							
					Variable cost of LFP aux battery	40,000	Rs	500	USD per kWh
Electrical energy from grid	324 kWh				Replacement cost of LFP aux battery	30,000	Rs	375	USD per kWh
Consumptionfrom battery annually	1,13,384 kWh				Cost of aux battery pack	56,00,000	Rs	70,000	USD
OPEX energy cost	10,54,475 Rs.	13,181	USD		Cost of replacement in 7 yrs	42,00,000	Rs	52,500	USD
					System cost	25,00,000	Rs	31,250	USD
					CAPEX of boat	5,66,67,000	Rs	7,08,338	USD
LFP System - with Solar									
For sizing, total solar production	88 kWh				Cost with drives and controls	21,67,000	Rs	27,088	USD
Propulsion energy from sun (electrical)	70.4 kWh	80% of energy is for propulsion							
Propulsion enegy from battery (electrical)	155 kWh				Variable cost of LFP prop battery	70,000	Rs	875	USD per kWh
Prop battery need	233 kWh	battery DOD is 80% and additional buddfer of 20% due to degradation replacement			Replacement cost of LFP prop battery	50,000	Rs	625	USD per kWh
Prop battery size	240 kWh	Two sets of 120 kWh batteries			Cost of prop battery pack	1,68,00,000	Rs	2,10,000	USD
Aux. energy from sun	17.6 kWh				Cost of replacement in 7 yrs	1,20,00,000	Rs	1,50,000	USD
Aux. enegy from battery	80.8 kWh	remove solar from total aux. energy need (electrical)							
Aux battery need	121 kWh	battery DOD is 80% and additional buddfer of 20% due to degradation replacement			Variable cost of LFP aux battery	40,000	Rs	500	USD per kWh
Aux battery size	120 kWh	Two sets of 60 kWh batteries			Replacement cost of LFP aux battery	30,000	Rs	375	USD per kWh
					Cost of aux battery pack	48,00,000	Rs	60,000	USD
					Cost of replacement in 7 yrs	36,00,000	Rs	45,000	USD
% solar contribution	27%								
					System cost	25,00,000	Rs	31,250	USD
Electrical energy from grid	236 kWh								
Consumptionfrom battery annually	82,584 kWh				Solar plant cost	15,00,000	Rs	18,750	USD per kW
OPEX energy cost	7,68,035 Rs.	9,600	USD						
					CAPEX of boat	5,17,67,000	Rs	6,47,088	USD
LTO System - Propulsion battery and aux battery combined (Between charging)									
Propulsion energy need (mechanical)	41 kWh				Variable cost of motors (power rating)				
Propulsion energy need (electrical)	46 kWh	loss of electrical to mechanical energy				30	15,00,000	Rs	18,750 USD
Aux. energy need (electrical)	10 kWh					120	45,00,000	Rs	56,250 USD
Total energy (electrical)	56 kWh				Interpolation using above rates				
Battery size need	111 kWh	battery DOD is 60% and additional buddfer of 20% due to degradation replacement				50 kW motors			
Battery size	120 kWh				Cost with drives and controls	21,67,000	Rs	27,088	USD
Battery cooling power	5 kW	for every set of 120 kWh need 5 kW power							
Battery cooling energy	5 kWh	for the trip time			Variable cost of LTO battery	2,00,000	Rs	2,500	USD per kWh
Total battery cooling energy	60 kWh				Replacement cost of LTO battery	1,80,000	Rs	2,250	USD per kWh
Check if Total energy + battery cooling < battery size*0.8	61 < 72	TRUE			Cost of battery pack	2,40,00,000	Rs	3,00,000	USD
Final battery size (After cooling check)	120 kWh	Two sets of 60 kWh batteries			Cost of replacement in 10 yrs	2,16,00,000	Rs	2,70,000	USD
Total electrical energy	384 kWh	propulsion electrical + auxiliary electrical + battery cooling							
					System cost	4,00,00,000	Rs	5,00,000	USD
Consumptionfrom battery annually	1,34,384 kWh				CAPEX of boat	9,01,67,000	Rs	11,27,088	USD
OPEX energy cost	12,49,775 Rs.	15,622	USD						
LTO System - with Solar									
For sizing since the solar production may not be there in the max. trip time, we assume the same battery size as electric mode (can refine with exact schedule and energy plot)									
Total electrical energy	384 kWh				Solar plant cost per kW	60,000	Rs	750	USD per kW
Total solar propduction	88 kWh				Solar plant cost	15,00,000	Rs	18,750	USD per kW
Electrical energy from battery + grid	296 kWh								
Consumptionfrom battery annually	1,03,584 kWh				CAPEX of boat with solar plant	9,16,67,000	Rs	11,45,838	USD
OPEX energy cost	9,63,335 Rs.	12,042	USD						

CAPEX, OPEX, TCO and TCO-NPV calculations

	Diesel	LTD	LFP	LTD-solar	LFP-solar	H2FC + LFP + Solar	
Propulsion power	56	40	40	40	40	40	kW
Motor/Engine size	70	50	50	50	50	50	Propulsion power
Aux. engine size	16						kW
Solar for propulsion (electrical)				70	70	70	kWh
Solar for auxiliary (electrical)				18	18	18	kWh
Propulsion energy from battery		226	226	155	155		kWh
Auxiliary energy from battery		158	98	141	81		kWh
Propulsion energy from fuel cell						155	kWh
Auxiliary energy from fuel cell						81	kWh
Propulsion energy from diesel (mechanical)	283						kWh
Auxiliary energy from diesel (electrical)	127						kWh
% from battery + grid		100%	100%	77%	73%		
% from H2 FC						82%	
% from DG	100%						
% from solar				23%	27%	18%	
Cost of Auxiliary energy (CAE)	49.9	11.6	11.6	9.0	8.5	31.9	US Cents
Cost of Propulsion energy from motor (CP)	55.4	12.9	12.9	10.0	9.4	35.5	US Cents
Cost of Propulsion energy (CPE)	40.5	40.5	40.5	40.5	40.5	40.5	US Cents
% from motors		100%	100%	100%	100%	100%	
% from engine	100%						
Cost of Propulsion energy (CPE)	40.5	12.9	12.9	10.0	9.4	35.5	
Fuel consumed in propulsion engine	83						litres
Fuel consumed in DG	46						litres
Fuel consumed daily	129						litres
H2 consumed in prop and aux. daily						18	kg
Propulsion Battery size		120	320	120	240	80	kWh
Auxiliary Battery size			140		120		kWh
Annual propulsion energy from battery/FC		78,944	78,944	54,304	54,304	54,304	kWh
Annual aux. energy from battery/TC		55,440	34,440	49,280	28,280	28,280	kWh
Rate of prop. Energy from diesel /battery/l	41	13	13	13	13	43	US Cents
Rate of aux. energy from diesel /battery	50	12	12	12	12	39	US Cents
CAPEX of boat in 1000 USD	351	1127	708	1146	647	1129	
OPEX of boat in 1000 USD	62.1	15.6	13.2	12.0	9.5	32.2	
CAPEX for battery replacement in 1000 USD		770	753	770	195	50	
	3%	3%	3%	3%	3%	3%	

H2FC with LFP System and Solar					CAPEX of boat	OPEX of boat	Rs	USD	
Propulsion power (mechanical)	40 kW				Cost with drives and controls	21,67,000	Rs	27,088	USD
Propulsion power (electrical)	44 kW								
Auxiliary power (electrical)	10 kW				Variable cost of LFP prop battery	70,000	Rs	875	USD
Total electrical power need	54 kW				Replacement cost of LFP prop battery	50,000	Rs	625	USD
LFP battery size need (1C)	54 kWh				Cost of prop battery pack	56,00,000	Rs	70,000	USD
Prop and aux battery size	80 kWh	Two sets of	40 kWh batteries	If the power crosses 80 kW then next set of battery needed	Cost of replacement in 7 yrs	40,00,000	Rs	50,000	USD
Fuel cell size	70 kW								
No. of fuel cells needed	1				System cost	25,00,000	Rs	31,250	USD
Assumed no. of recharges daily	1				Battery, motors and system cost	1,02,67,000	Rs	1,28,338	USD
Propulsion energy need (mechanical)	203 kWh								
Propulsion energy need (electrical)	226 kWh	loss of electrical to mechanical energy			Cost of one 70 kW fuel cell	2,00,00,000	Rs	2,50,000	USD
Aux. energy need (electrical)	98 kWh				Cost of fuel cells for the boat	2,00,00,000	Rs	2,50,000	USD
Total electrical energy needed	324 kWh				Piping and other fuel cell system cost	150%	of fuel cell cost		
For sizing, total solar production	88 kWh				Piping and other fuel cell system cost	3,00,00,000	Rs	3,75,000	USD
Total electrical energy needed considering	236 kWh				Cost of each 7 kg cylinders	20,00,000	Rs	25,000	USD
SFC of H2 fuel cell	70 g/kWh				Cost of 7 kg cylinders	60,00,000	Rs	75,000	USD
Total H2 needed between recharges	18.4 kg	need to take the electrical system efficiency since elec energy is aux consumption							
No. of cylinders	3 sets of	7 kg	cylinders	Assuming solar	H2 system cost	5,60,00,000	Rs	7,00,000	USD
Consumption of H2 annually	6440 kg				CAPEX of boat	9,02,67,000	Rs	11,28,338	USD
OPEX energy cost	25,76,000 Rs.	32,200	USD						
Diesel engine + Generator (efficient)									
Propulsion energy (mechanical)	283 kWh				Variable cost of engines (power rating)				
SFC of Diesel engine (SFCE)	250 g/kWh	of mechanical energy			70	20,00,000	Rs	25,000	USD
Propulsion fuel consumed in engine	83 litres				240	60,00,000	Rs	75,000	USD
Auxiliary energy (electrical)	127 kWh	of electrical energy			Interpolation using above rates				
Auxiliary energy (mechanical)	141 kWh	of mechanical energy			70 kW engines				
SFC of Diesel generator	278 g/kWh	of electrical energy			Cost Engine, gearbox, tank and accessories	20,00,000	Rs	25,000	USD
Propulsion fuel consumed in generator	46 litres								
					Variable cost of generator (power rating)				
Annual fuel consumption	45,150 litres				5	10,00,000	Rs	12,500	USD
					20	25,00,000	Rs	31,250	USD
Cost of fuel annually	45,15,000 Rs.	56,438	USD		Interpolation using above rates				
Cost of LO, filter, overhaul	4,51,500 Rs.	5,644	USD		16 kW engines				
OPEX energy cost	49,66,500 Rs.	62,081	USD		Cost generator, tank and accessories	21,00,000	Rs	26,250	USD
					CAPEX of boat	2,81,00,000	Rs	3,51,250	USD

CAPEX, OPEX, TCO and TCO-NPV calculations

Currency **USD**

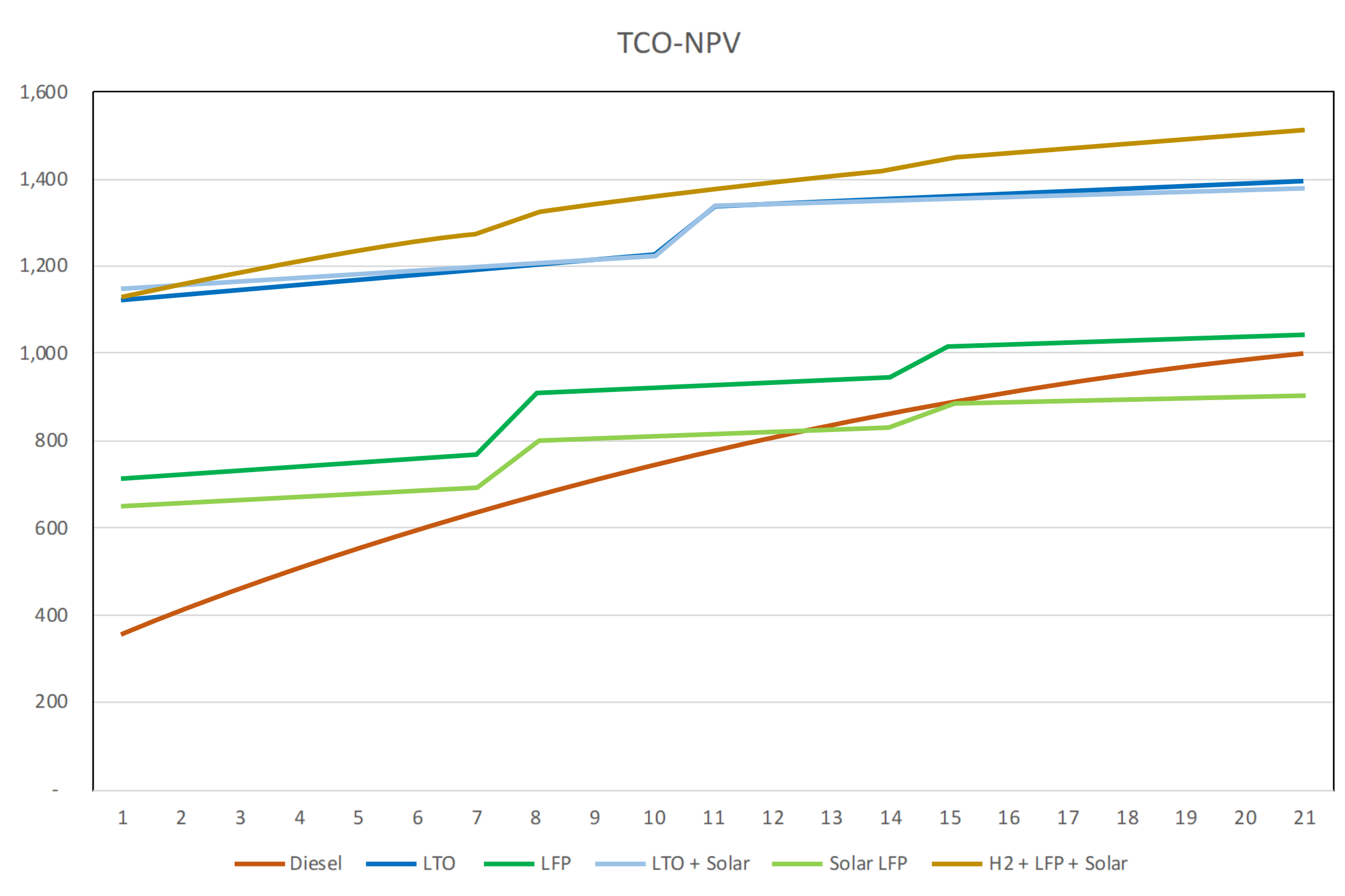
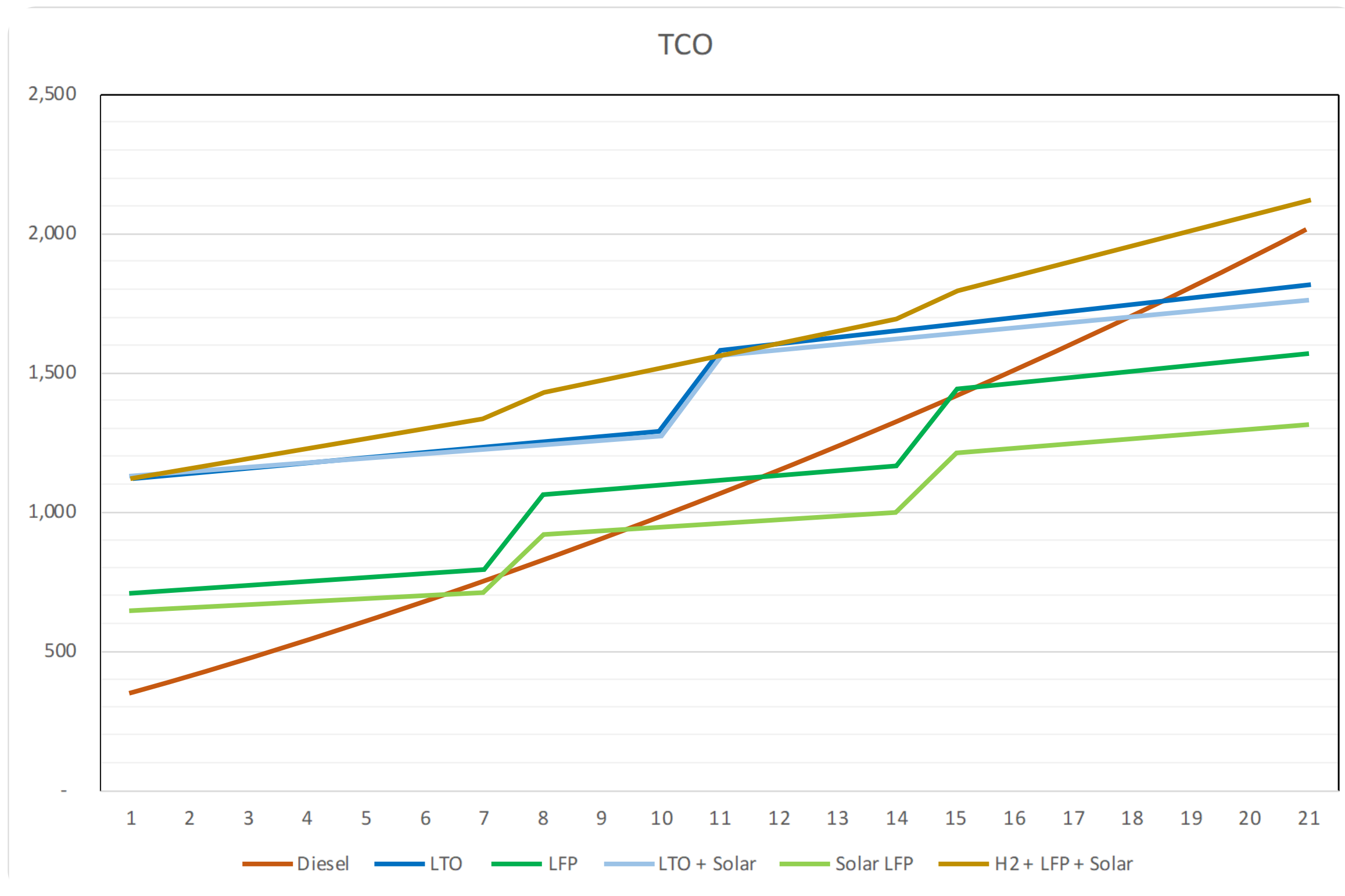
Year	Efficient				Super-efficient				Super-efficient				Super-efficient				Super-efficient				Super-efficient			
	Diesel				LTO				LFP				LTO + Solar				Solar LFP				H2 + LFP + Solar			
	CAPEX	OPEX	Total	Cumulative	CAPEX	OPEX	Total	Cumulative	CAPEX	OPEX	Total	Cumulative	CAPEX	OPEX	Total	Cumulative	CAPEX	OPEX	Total	Cumulative	CAPEX	OPEX	Total	Cumulative
Yr 0	351		351.3	351	1,127		1,127.1	1,127	708		708.3	708	1,146		1,145.8	1,146	647		647.1	647	1,128		1,128.3	1,128
Yr 1		62.1	62.1	413.3		15.6	15.6	1,143		13.2	13.2	722		12.0	12.0	1,158		9.6	9.6	657		32.2	32.2	1,161
Yr 2		63.9	63.9	477.3		16.1	16.1	1,159		13.6	13.6	735		12.8	12.8	1,171		10.2	10.2	667		33.3	33.3	1,194
Yr 3		65.9	65.9	543.1		16.6	16.6	1,175		14.0	14.0	749		13.3	13.3	1,184		10.6	10.6	678		34.4	34.4	1,228
Yr 4		67.8	67.8	611.0		17.1	17.1	1,192		14.4	14.4	763		13.7	13.7	1,198		10.9	10.9	688		35.6	35.6	1,264
Yr 5		69.9	69.9	680.8		17.6	17.6	1,210		14.8	14.8	778		14.1	14.1	1,212		11.3	11.3	700		36.7	36.7	1,301
Yr 6		72.0	72.0	752.8		18.1	18.1	1,228		15.3	15.3	794		14.6	14.6	1,226		11.7	11.7	711		38.0	38.0	1,338
Yr 7		74.1	74.1	826.9		18.7	18.7	1,247	253	15.7	268.2	1,062		15.1	15.1	1,241	195	12.1	207.1	919	50	39.2	89.2	1,428
Yr 8		76.4	76.4	903.3		19.2	19.2	1,266		16.2	16.2	1,078		15.6	15.6	1,257		12.5	12.5	931		40.5	40.5	1,468
Yr 9		78.6	78.6	981.9		19.8	19.8	1,286		16.7	16.7	1,095		16.1	16.1	1,273		12.9	12.9	944		41.9	41.9	1,510
Yr 10		81.0	81.0	1,062.9	270	20.4	290.4	1,576		17.2	17.2	1,112	270	16.6	286.6	1,560		13.3	13.3	957		43.3	43.3	1,553
Yr 11		83.4	83.4	1,146.4		21.0	21.0	1,597		17.7	17.7	1,130		17.1	17.1	1,577		13.8	13.8	971		44.7	44.7	1,598
Yr 12		85.9	85.9	1,232.3		21.6	21.6	1,619		18.2	18.2	1,148		17.7	17.7	1,595		14.2	14.2	985		46.2	46.2	1,644
Yr 13		88.5	88.5	1,320.8		22.3	22.3	1,641		18.8	18.8	1,167		18.3	18.3	1,613		14.7	14.7	1,000		47.7	47.7	1,692
Yr 14		91.2	91.2	1,412.0	-	22.9	22.9	1,664	253	19.4	271.9	1,439		18.9	18.9	1,632	195	15.2	210.2	1,210	50	49.3	99.3	1,791
Yr 15		93.9	93.9	1,505.9		23.6	23.6	1,688		19.9	19.9	1,458		19.5	19.5	1,651		15.7	15.7	1,226		50.9	50.9	1,842
Yr 16		96.7	96.7	1,602.6		24.3	24.3	1,712		20.5	20.5	1,479		20.1	20.1	1,671		16.2	16.2	1,242		52.6	52.6	1,895
Yr 17		99.6	99.6	1,702.2		25.1	25.1	1,737		21.2	21.2	1,500		20.8	20.8	1,692		16.7	16.7	1,259		54.3	54.3	1,949
Yr 18		102.6	102.6	1,804.8		25.8	25.8	1,763		21.8	21.8	1,522		21.4	21.4	1,714		17.3	17.3	1,276		56.1	56.1	2,005
Yr 19		105.7	105.7	1,910.5		26.6	26.6	1,789		22.4	22.4	1,544		22.1	22.1	1,736		17.8	17.8	1,294		58.0	58.0	2,063
Yr 20		108.9	108.9	2,019.4		27.4	27.4	1,817		23.1	23.1	1,568		22.8	22.8	1,759		18.4	18.4	1,312		59.9	59.9	2,123

Discount rate **10%**

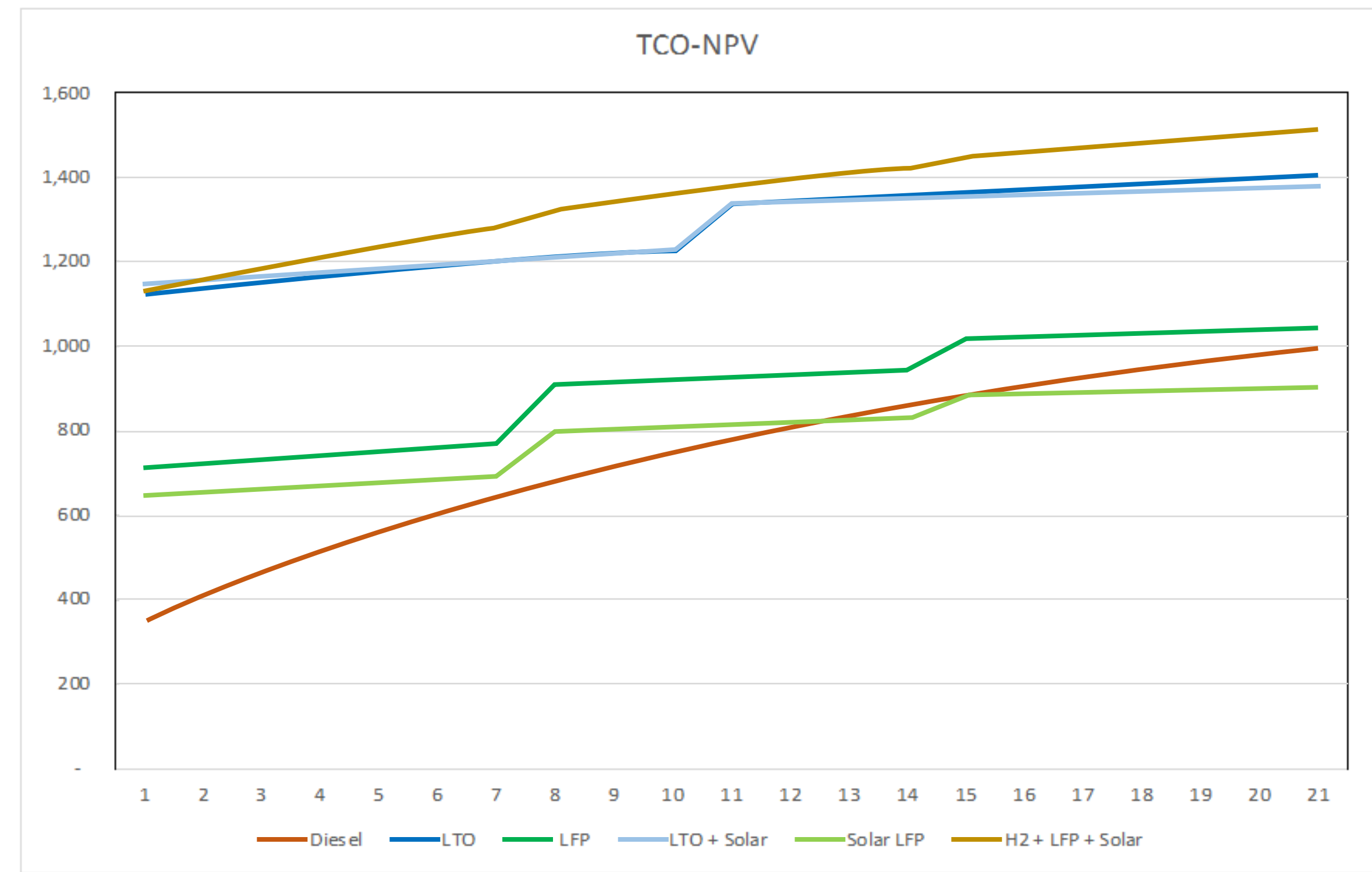
Year	Efficient				Super-efficient				Super-efficient				Super-efficient				Super-efficient				Super-efficient			
	Diesel				LTO				LFP				LTO + Solar				Solar LFP				H2 + LFP + Solar			
	CAPEX	OPEX	Total	Cumulative	CAPEX	OPEX	Total	Cumulative	CAPEX	OPEX	Total	Cumulative	CAPEX	OPEX	Total	Cumulative	CAPEX	OPEX	Total	Cumulative	CAPEX	OPEX	Total	Cumulative
Yr 0	351		351	351	1,127		1,127	1,127	708		708	708	1,146		1,146	1,146	647		647	647	1,128		1,128	1,128
Yr 1		56.4	56.4	407.7		14.2	14.2	1,141.3		12.0	12.0	720.3		10.9	10.9	1,156.8		8.7	8.7	655.8		29.3	29.3	1,157.6
Yr 2		52.8	52.8	460.5		13.3	13.3	1,154.6		11.2	11.2	731.5		10.6	10.6	1,167.4		8.5	8.5	664.3		27.5	27.5	1,185.1
Yr 3		49.5	49.5	510.0		12.5	12.5	1,167.0		10.5	10.5	742.0		10.0	10.0	1,177.4		8.0	8.0	672.2		25.8	25.8	1,211.0
Yr 4		46.3	46.3	556.4		11.7	11.7	1,178.7		9.8	9.8	751.9		9.4	9.4	1,186.7		7.5	7.5	679.7		24.3	24.3	1,235.3
Yr 5		43.4	43.4	599.7		10.9	10.9	1,189.6		9.2	9.2	761.1		8.8	8.8	1,195.5		7.0	7.0	686.7		22.8	22.8	1,258.1
Yr 6		40.6	40.6	640.4		10.2	10.2	1,199.8		8.6	8.6	769.7		8.2	8.2	1,203.7		6.6	6.6	693.3		21.4	21.4	1,279.5
Yr 7		38.0	38.0	678.4		9.6	9.6	1,209.4	130	8.1	137.6	907.4		7.7	7.7	1,211.5	100	6.2	106.3	799.6	26	20.1	45.8	1,325.3
Yr 8		35.6	35.6	714.0		9.0	9.0	1,218.4		7.6	7.6	914.9		7.3	7.3	1,218.7		5.8	5.8	805.4		18.9	18.9	1,344.2
Yr 9		33.4	33.4	747.4		8.4	8.4	1,226.8		7.1	7.1	922.0		6.8	6.8	1,225.6		5.5	5.5	810.9		17.8	17.8	1,362.0
Yr 10		31.2	31.2	778.6	104.1	7.9	112.0	1,338.7		6.6	6.6	928.6	104	6.4	110.5	1,336.1		5.1	5.1	816.0		16.7	16.7	1,378.7
Yr 11		29.2	29.2	807.8		7.4	7.4	1,346.1		6.2	6.2	934.9		6.0	6.0	1,342.1		4.8	4.8	820.8		15.7	15.7	1,394.3
Yr 12		27.4	27.4	835.2		6.9	6.9	1,353.0		5.8	5.8	940.7		5.6	5.6	1,347.7		4.5	4.5	825.4		14.7	14.7	1,409.1
Yr 13		25.6	25.6	860.9		6.5	6.5	1,359.4		5.4	5.4	946.1		5.3	5.3	1,353.0		4.3	4.3	829.6		13.8	13.8	1,422.9
Yr 14		24.0	24.0	884.9		6.0	6.0	1,365.5	66	5.1	71.6	1,017.7		5.0	5.0	1,358.0	51	4.0	55.3	885.0	13	13.0	26.2	1,449.0
Yr 15		22.5	22.5	907.4		5.7	5.7	1,371.1		4.8	4.8	1,022.5		4.7	4.7	1,362.6		3.8	3.8	888.7		12.2	12.2	1,461.2
Yr 16		21.0	21.0	928.4		5.3	5.3	1,376.4		4.5	4.5	1,026.9		4.4	4.4	1,367.0		3.5	3.5	892.2		11.5	11.5	1,472.7
Yr 17		19.7	19.7	948.1		5.0	5.0	1,381.4		4.2	4.2	1,031.1		4.1	4.1	1,371.1		3.3	3.3	895.5		10.8	10.8	1,483.4
Yr 18		18.5	18.5	966.6		4.6	4.6	1,386.0		3.9	3.9	1,035.0		3.9	3.9	1,375.0		3.1	3.1	898.6		10.1	10.1	1,493.5
Yr 19		17.3	17.3	983.8		4.3	4.3	1,390.4		3.7	3.7	1,038.7		3.6	3.6	1,378.6		2.9	2.9	901.6		9.5	9.5	1,503.0
Yr 20		16.2	16.2	1,000.0		4.1	4.1	1,394.4		3.4	3.4	1,042.1		3.4	3.4	1,382.0		2.7	2.7	904.3		8.9	8.9	1,511.9

	Diesel	LTO	LFP	LTO + Solar	LFP + Solar	H2 + LFP + Solar	
TCO	2,019	1,817	1,568	1,759	1,312	2,123	in 1000 USD
TCO NPV	1,000	1,394	1,042	1,382	904	1,512	in 1000 USD

CAPEX, OPEX, TCO and TCO-NPV calculations

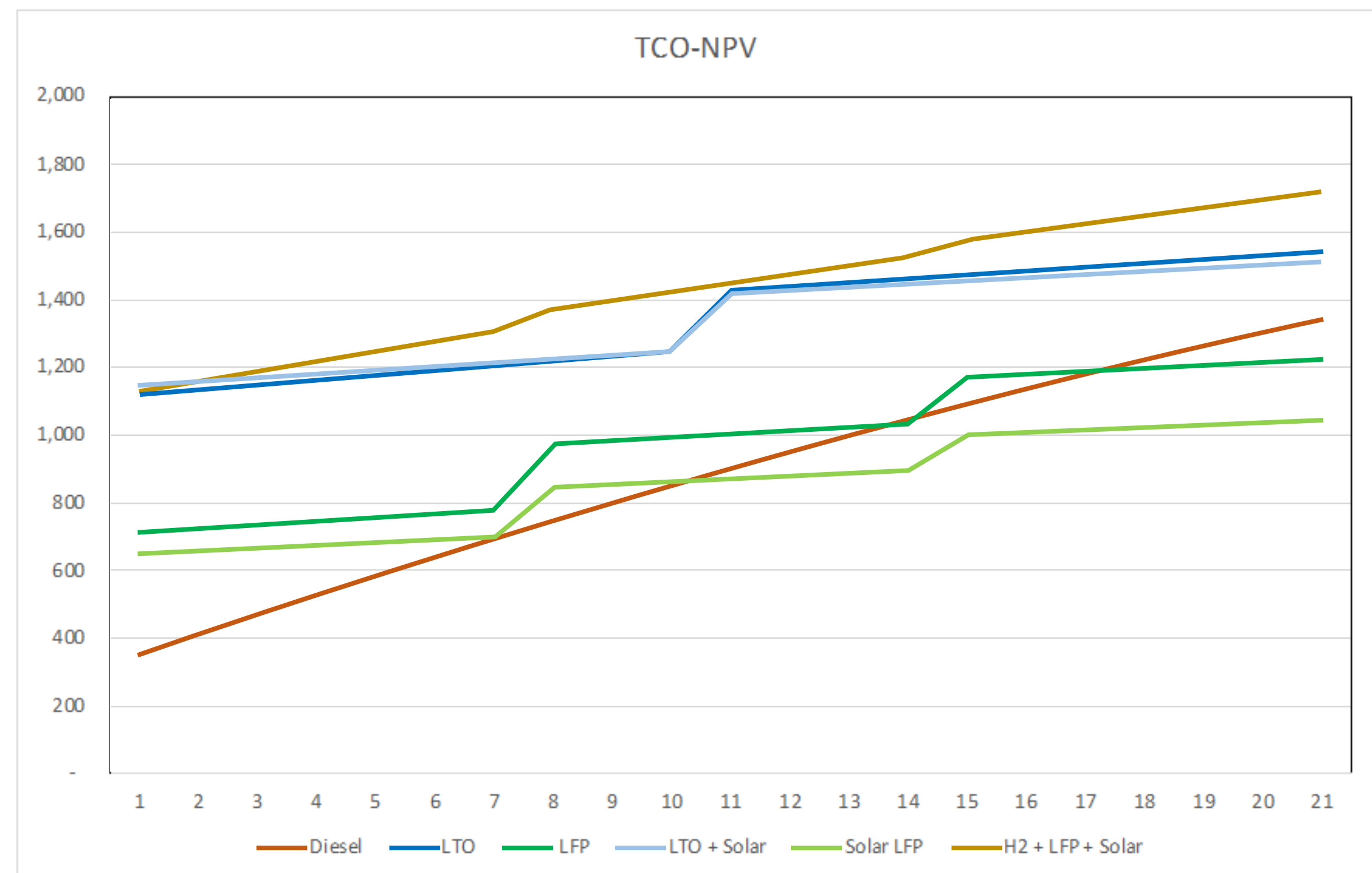


How discount rate affects TCO NPV



Speed-Range	Energy/day	Diesel	LTO	LFP	LTO + Solar	LFP + Solar	H2 + LFP + Solar
8 kn-75 km	324	1000	1394	1042	1382	904	1512

@10 % discount rate



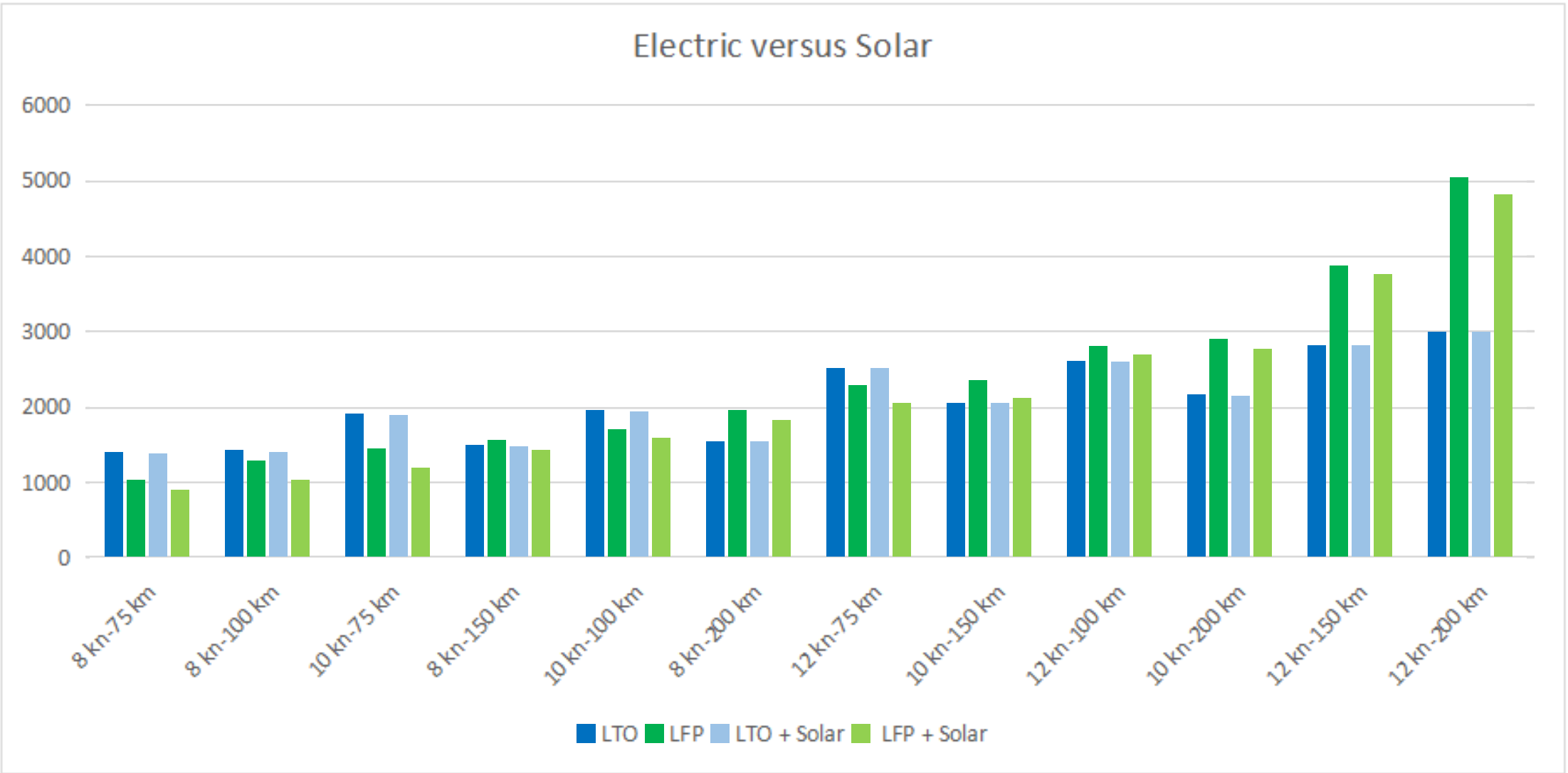
Speed-Range	Energy/day	Diesel	LTO	LFP	LTO + Solar	LFP + Solar	H2 + LFP + Solar
8 kn-75 km	324	1342	1542	1226	1514	1047	1718

@5 % discount rate

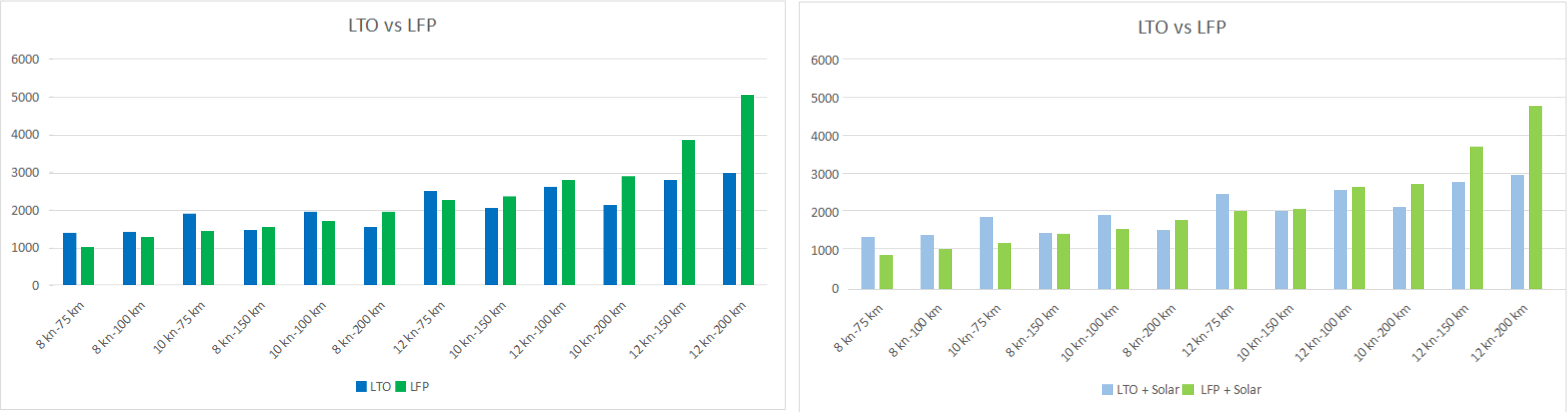
TCO NPV for various speeds (8/10/12 knots) and range (75/100/150/200 km)

Speed-Range	Energy/day	Diesel	LTO	LFP	LTO + Solar	LFP + Solar	5 USD/kg	3 USD/kg	2 USD/kg
							H2+LFP+Solar (5\$/kg)	H2+LFP+Solar (3\$/kg)	H2+LFP+Solar (2\$/kg)
8 kn-75 km	324	1000	1394	1042	1382	904	1512	1371	1308
8 kn-100 km	398	1141	1426	1291	1415	1046	1618	1433	1352
10 kn-75 km	458	1277	1902	1447	1892	1202	1858	1639	1541
8 kn-150 km	548	1422	1490	1573	1480	1438	1882	1610	1489
10 kn-100 km	578	1498	1953	1715	1945	1581	2054	1765	1636
8 kn-200 km	698	1699	1554	1963	1546	1830	2146	1786	1627
12 kn-75 km	772	1912	2517	2285	2512	2044	3254	2851	2673
10 kn-150 km	818	1946	2055	2361	2050	2121	2472	2042	1852
12 kn-100 km	998	2334	2613	2817	2611	2687	3627	3092	2855
10 kn-200 km	1058	2394	2157	2899	2155	2770	2889	2319	2067
12 kn-150 km	1448	3169	2805	3878	2808	3755	4393	3596	3243
12 kn-200 km	1898	4009	2996	5049	3005	4822	5160	4100	3631

Always LFP + Solar < LFP and LTO + Solar < LTO. Hence solar is always cheaper than electric



TCO NPV for various speeds (8/10/12 knots) and range (75/100/150/200 km)



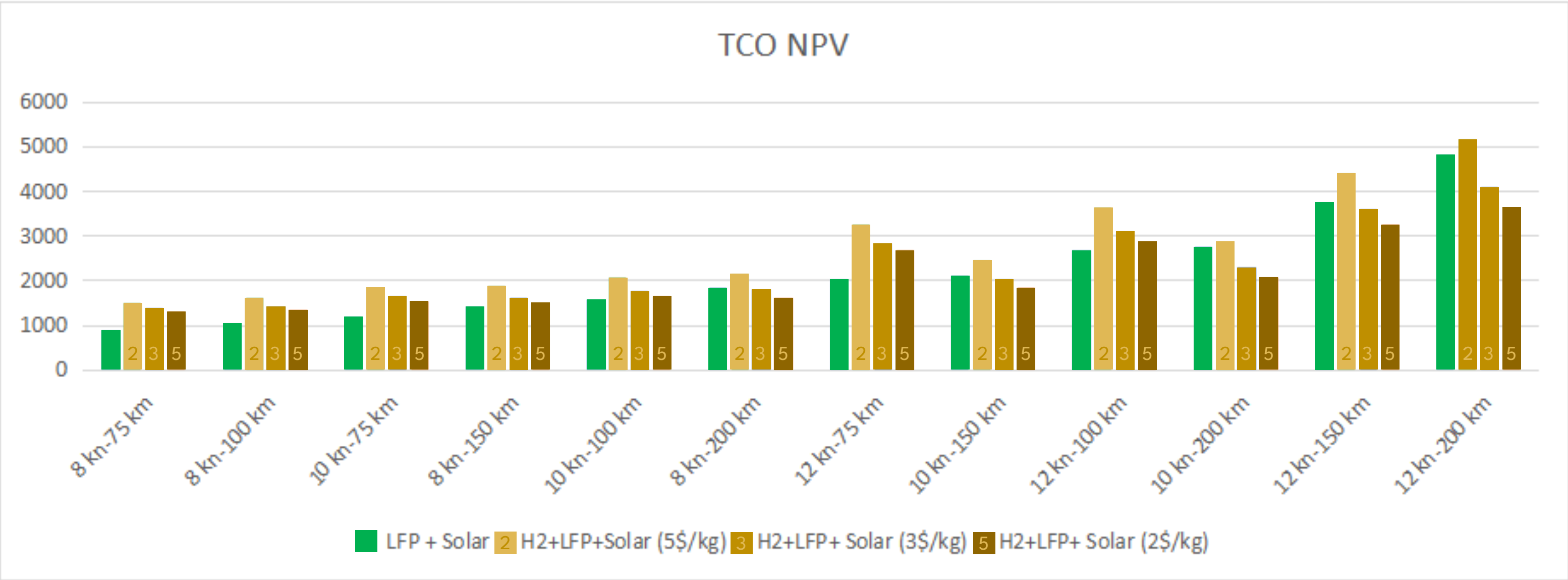
At lower speed and range LFP is cheaper than LTO. However at higher speed and range LTO is cheaper. The key is low trip range (15 km here for each charging).

When is Hydrogen effective?

8 kn-75 km	904	1308
8 kn-100 km	1046	1352
8 kn-150 km	1438	1489
8 kn-200 km	1830	1627

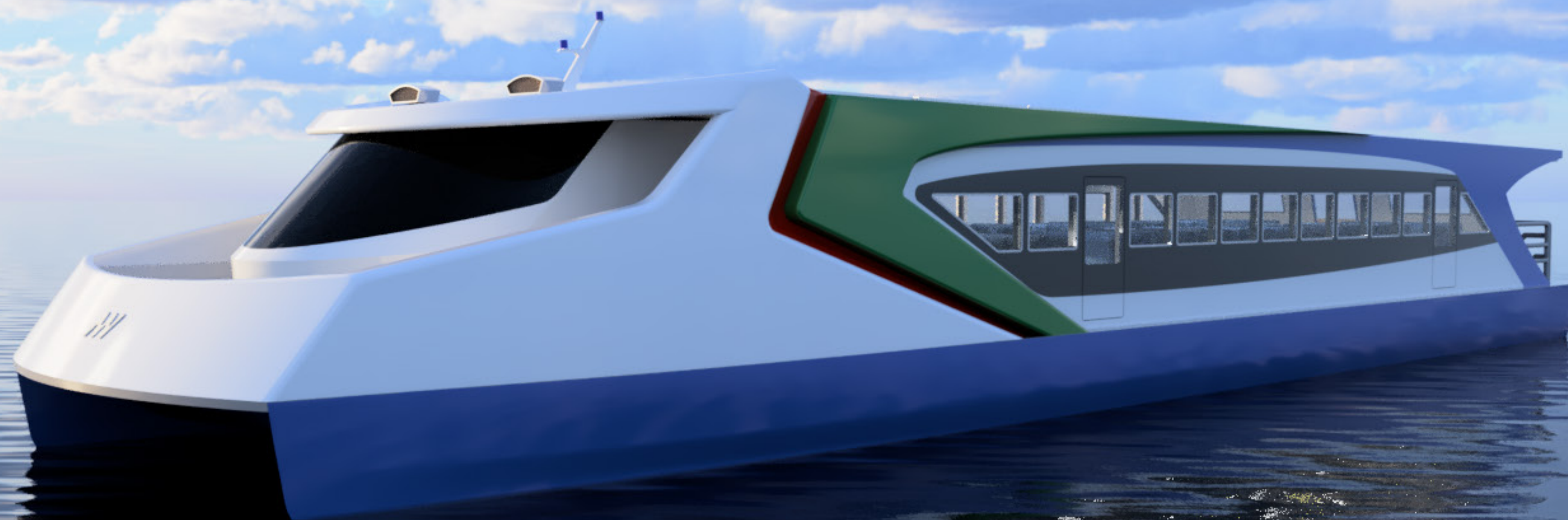
10 kn-75 km	1202	1541
10 kn-100 km	1581	1636
10 kn-150 km	2121	1852
10 kn-200 km	2770	2067

12 kn-75 km	2044	2673
12 kn-100 km	2687	2855
12 kn-150 km	3755	3243
12 kn-200 km	4822	3631



H2 @ 5 USD/kg and 3 USD/kg is more expensive than LFP + Solar. But for 2 USD/kg it is different

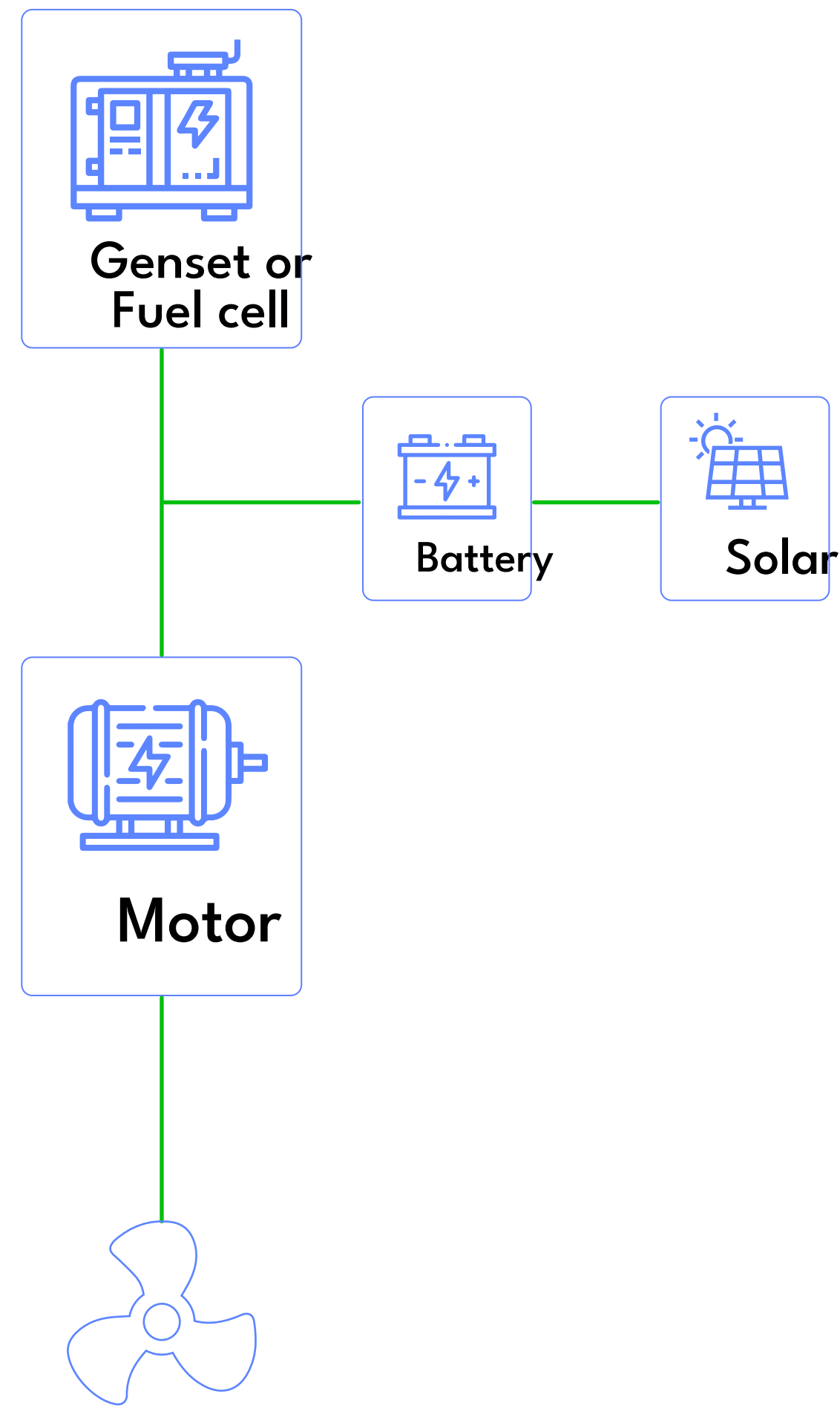
100 PAX FERRY



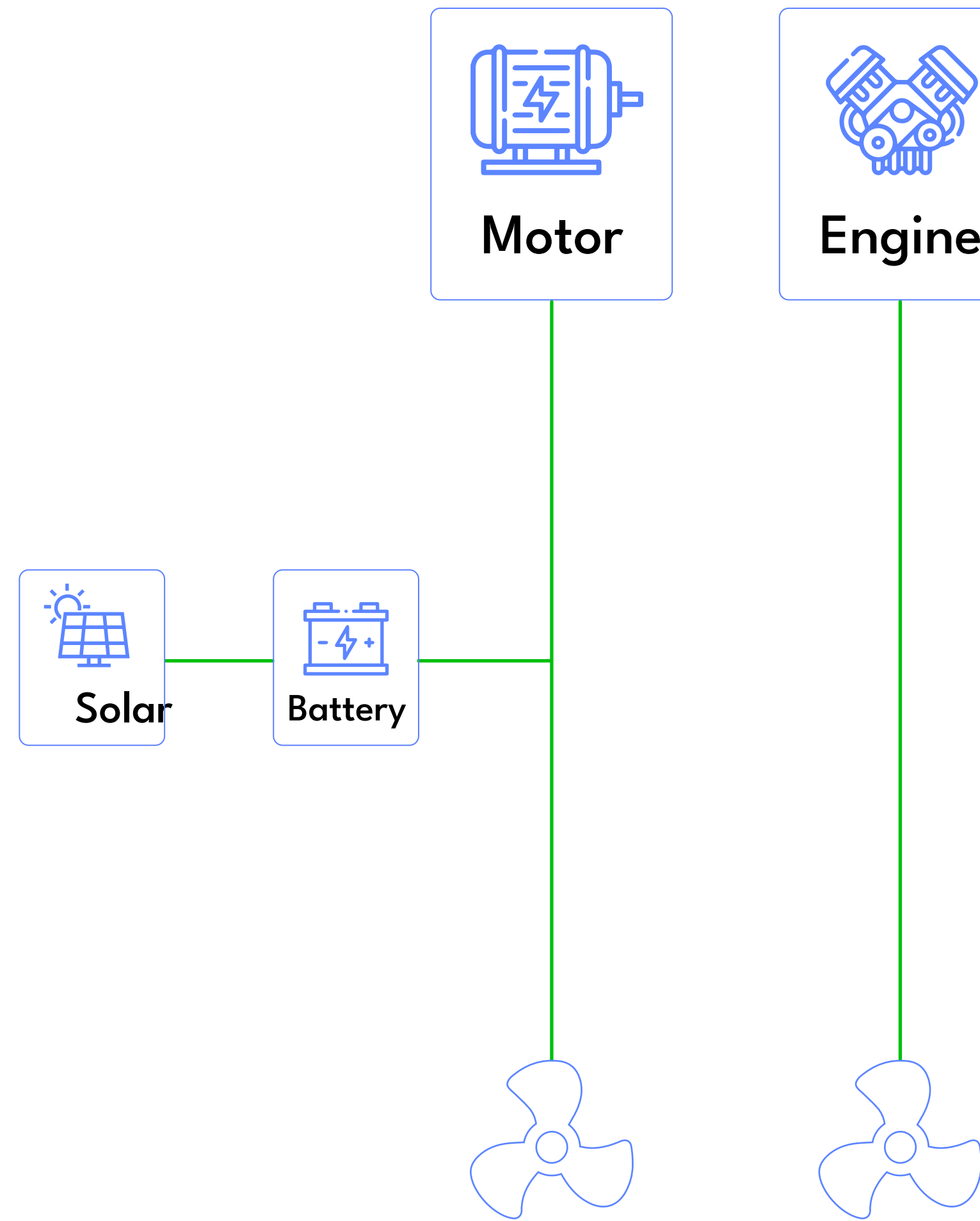
Speed 12 knots

Range 200 km/day

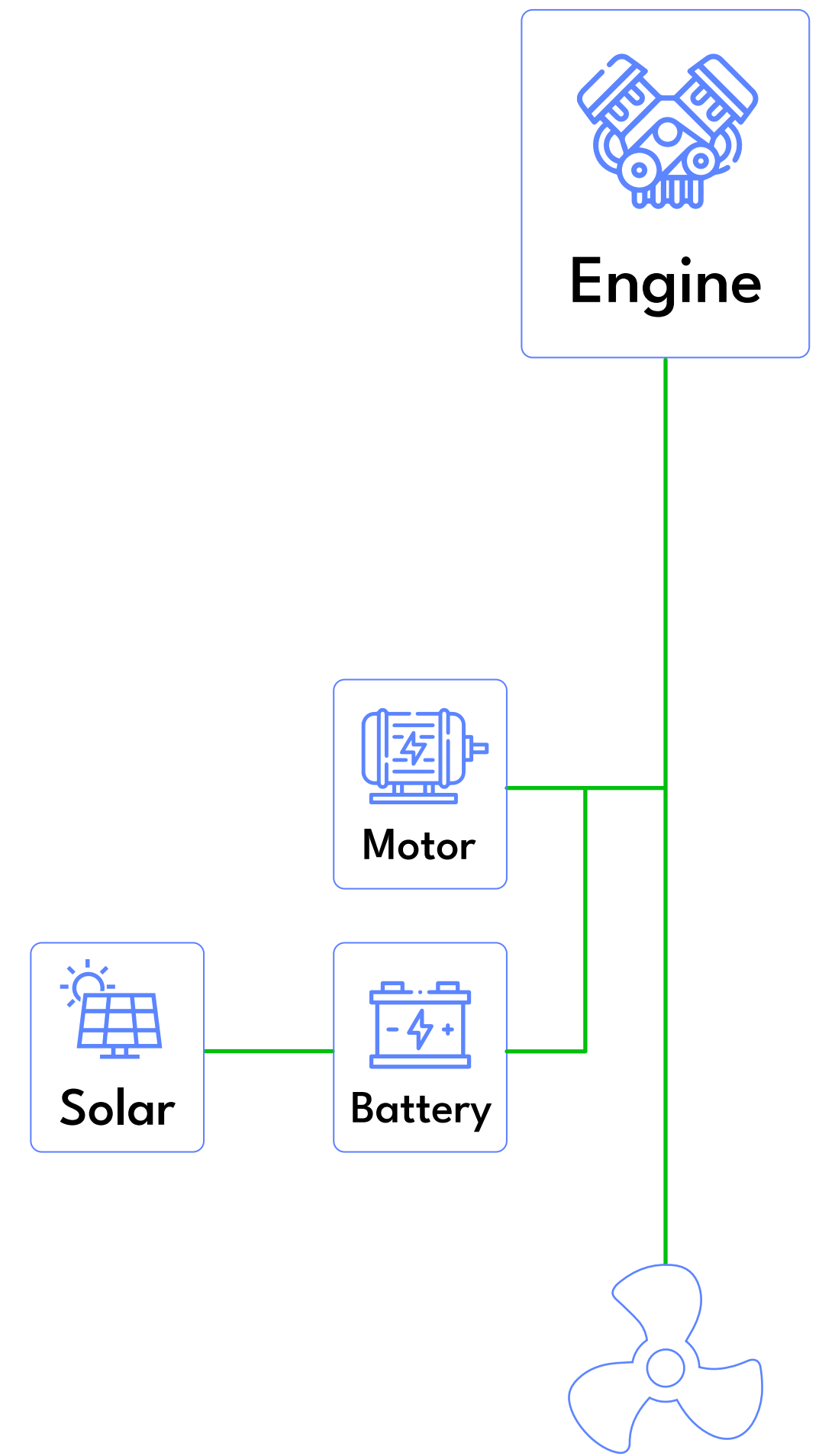
Trip range 100 km



Series



Independent shaft

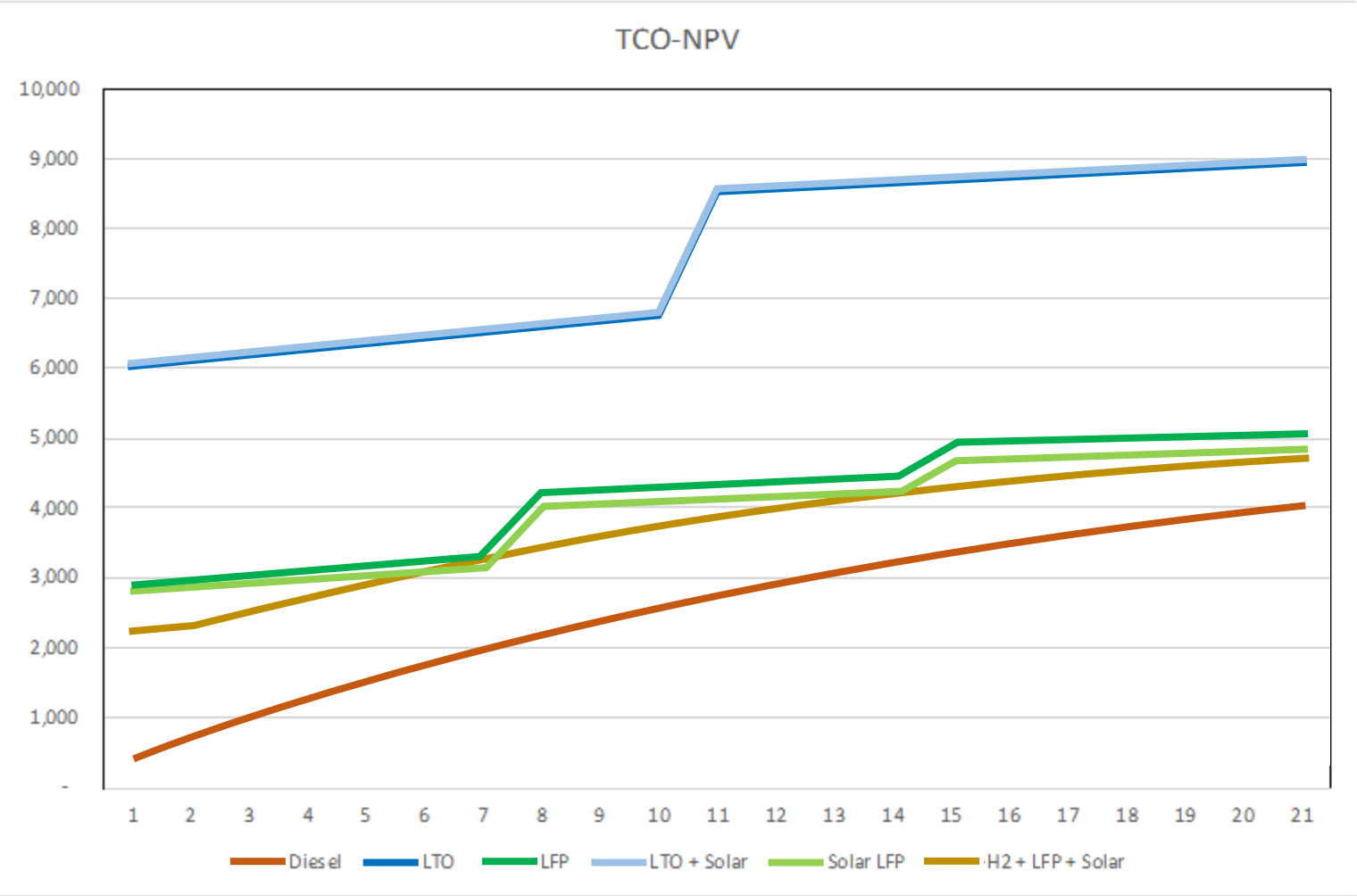


Same shaft

Parallel

What changes with high speed and high trip range?

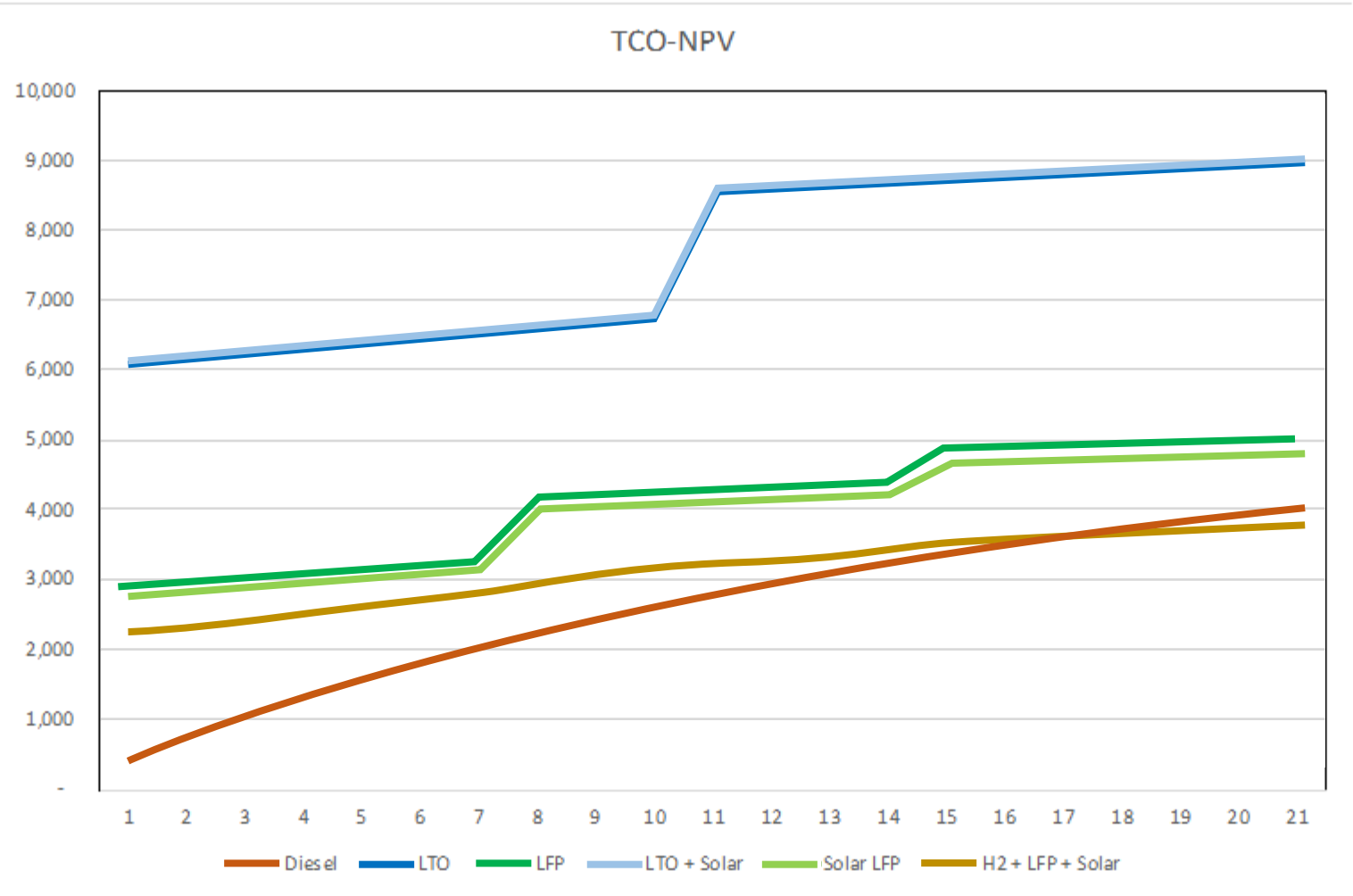
For long range - 12 knots, 200 km (with 100 km as recharge time)
for H2 FC and LTO 100 km is the recharge distance



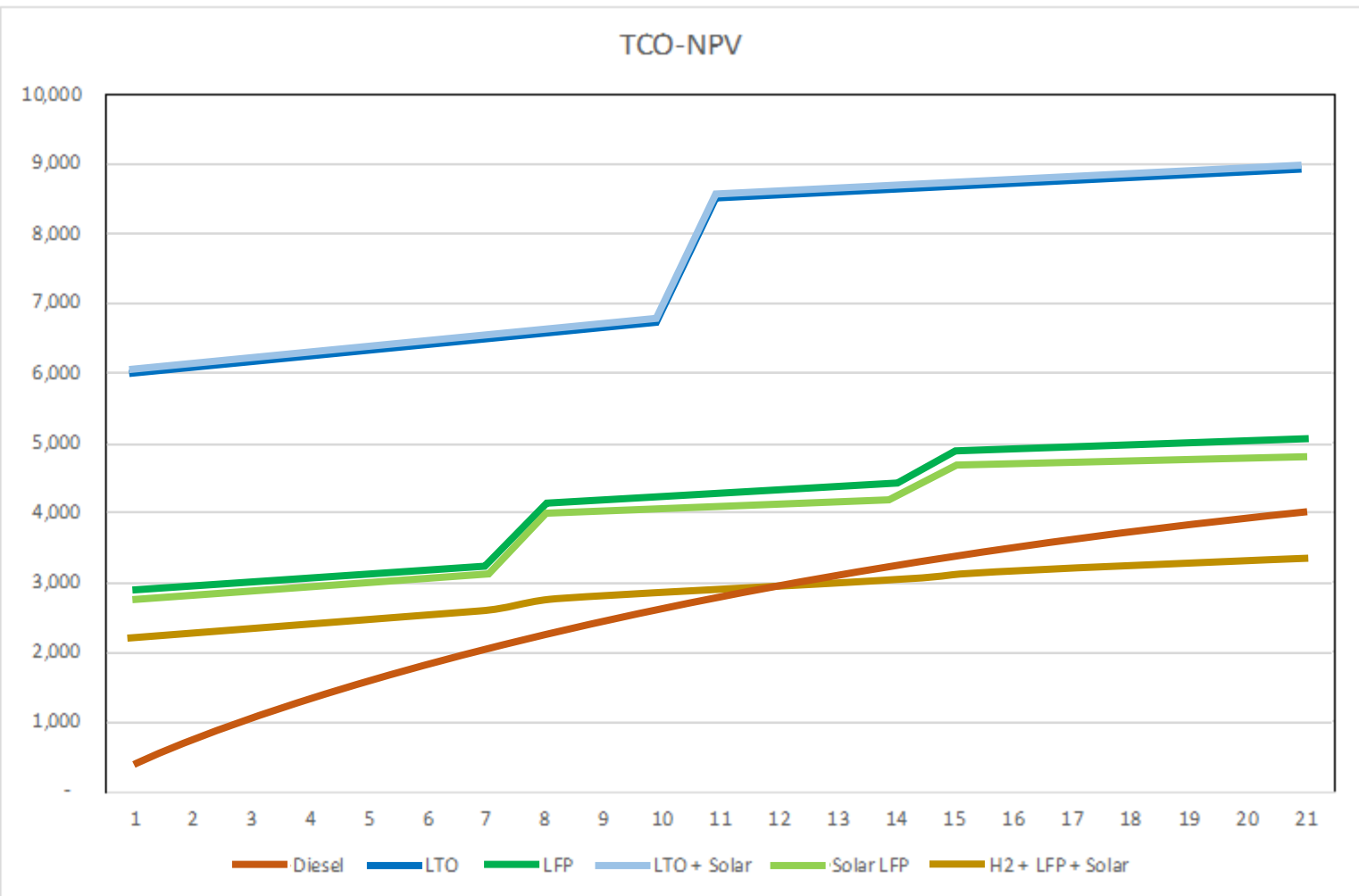
H2 @ USD/Kg

	Diesel	LTO	LFP	LTO + Solar	LFP + Solar	5 USD/kg H2 + LFP + Solar	3 USD/kg H2 + LFP + Solar	2 USD/kg H2 + LFP + Solar
TCO NPV	4,009	8,985	5,049	9,004	4,822	4,798	3,783	3,336

in 1000 USD

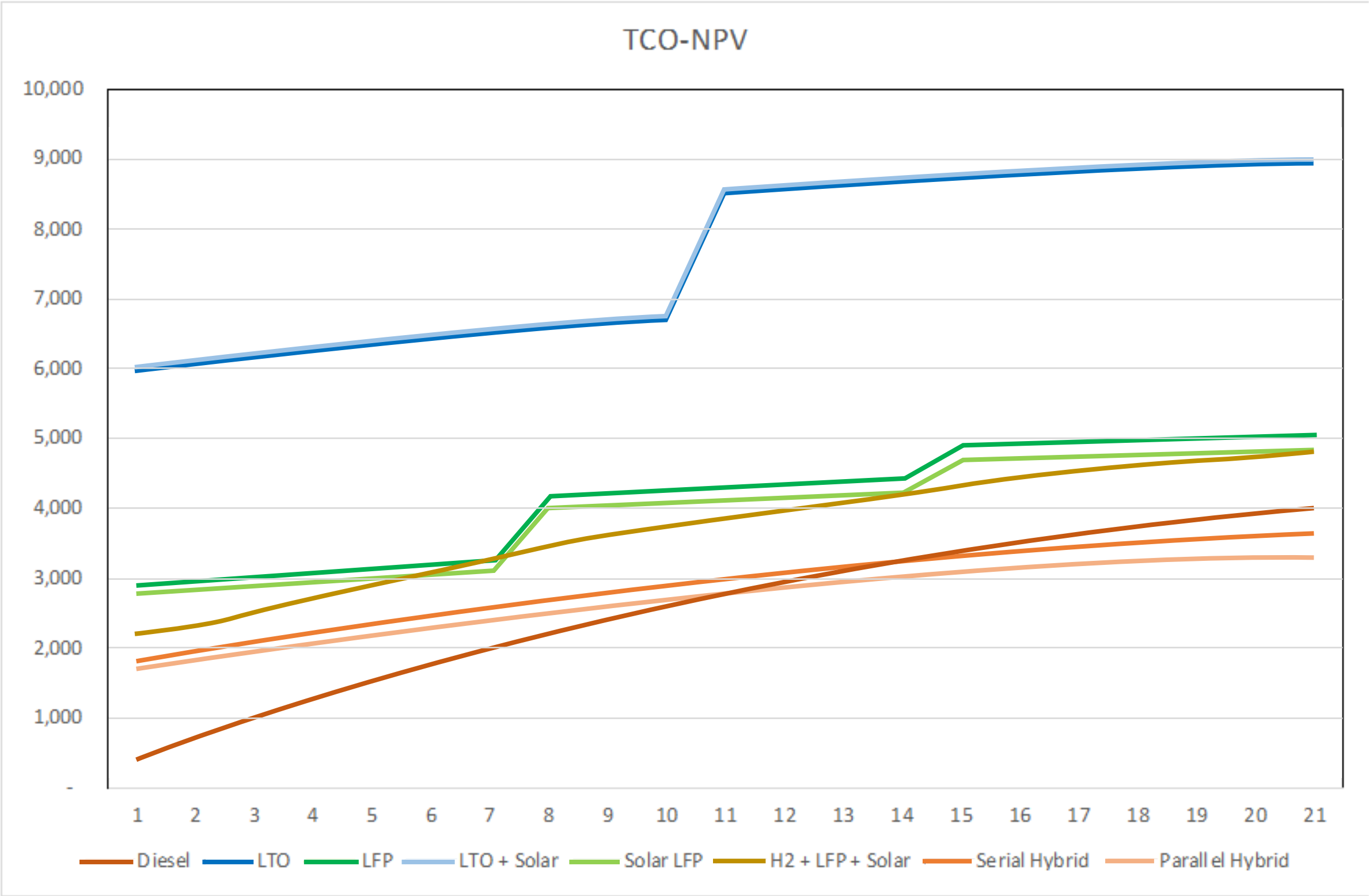


H2 @ USD/Kg



H2 @ USD/Kg

What changes with high speed and high trip range?



Speed-Range	Energy/day	Diesel	LTO	LFP	LTO + Solar	LFP + Solar	5 USD/kg		3 USD/kg		2 USD/kg		Serial Hybrid	Parallel Hybrid	
							H2 + LFP + Solar	H2 + LFP + Solar	H2 + LFP + Solar	H2 + LFP + Solar	H2 + LFP + Solar	H2 + LFP + Solar			
12 kn-200 km	1898	4009	8985	5049	9004	4822	4,798	3,783	3,336	3623	3350	in 1000 USD			



**Thank
you.**