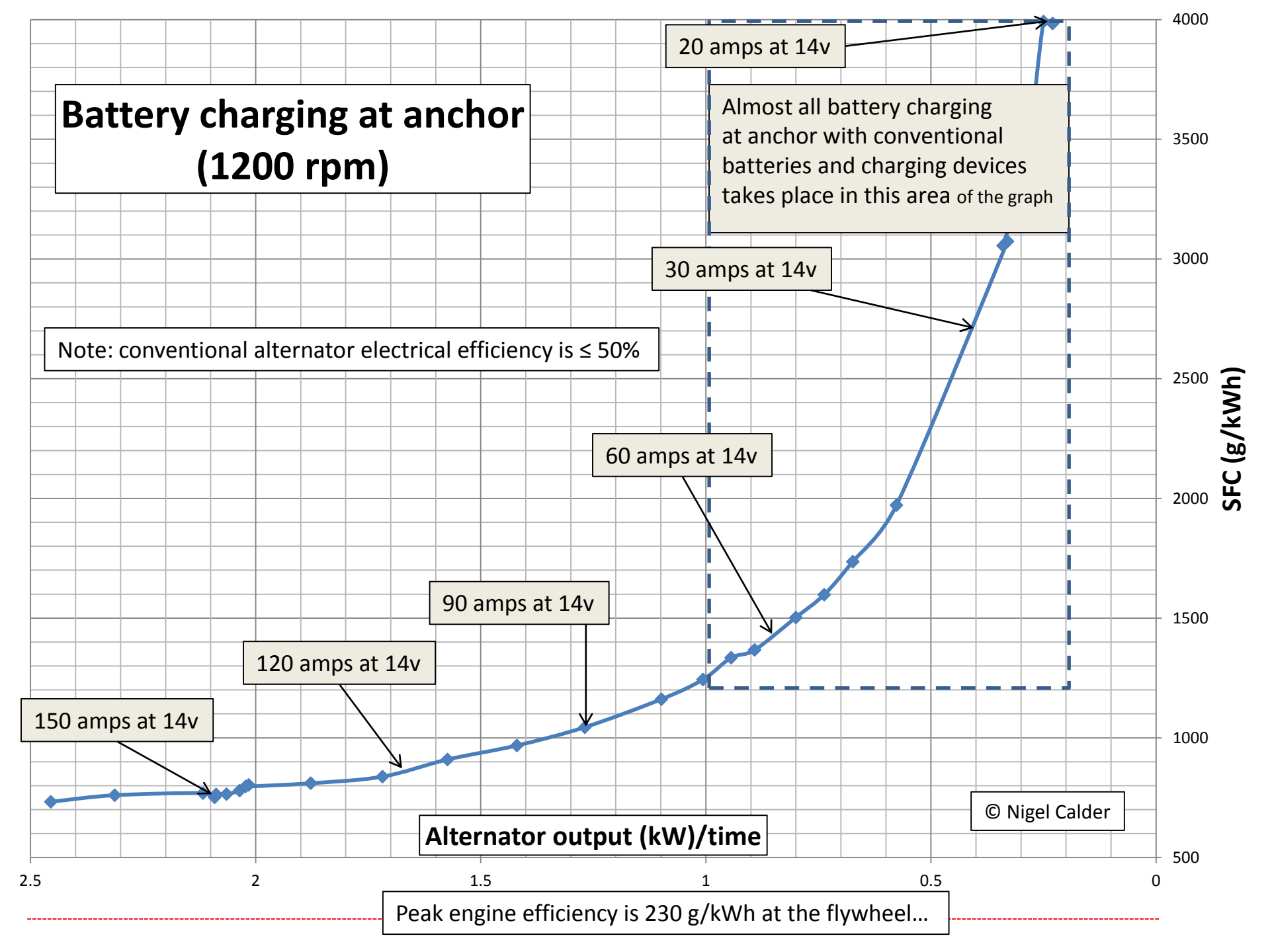
Minimizing the Extraordinarily High Cost of Generating House Energy on Boats

Nigel Calder

The principal mechanisms for generating electrical power on boats at sea:

- Engine-driven alternators
- Generators:
  - AC
  - DC
- All rely on fossil-fueled engines which are typically operated in an extraordinarily inefficient manner


Battery charging at anchor (1200 rpm)
20 amps at 14v
Almost all battery charging at anchor with conventional batteries and charging devices takes place in this area of the graph
30 amps at 14v
Note: conventional alternator electrical efficiency is ≤ 50%
60 amps at 14v
90 amps at 14v
120 amps at 14v
150 amps at 14v
4000
3500
3000
2500
2000
1500
1000
500
SFC (g/kWh)
2.5
2
1.5
1
0.5
0
Alternator output (kW)/time
© Nigel Calder
Peak engine efficiency is 230 g/kWh at the flywheel…

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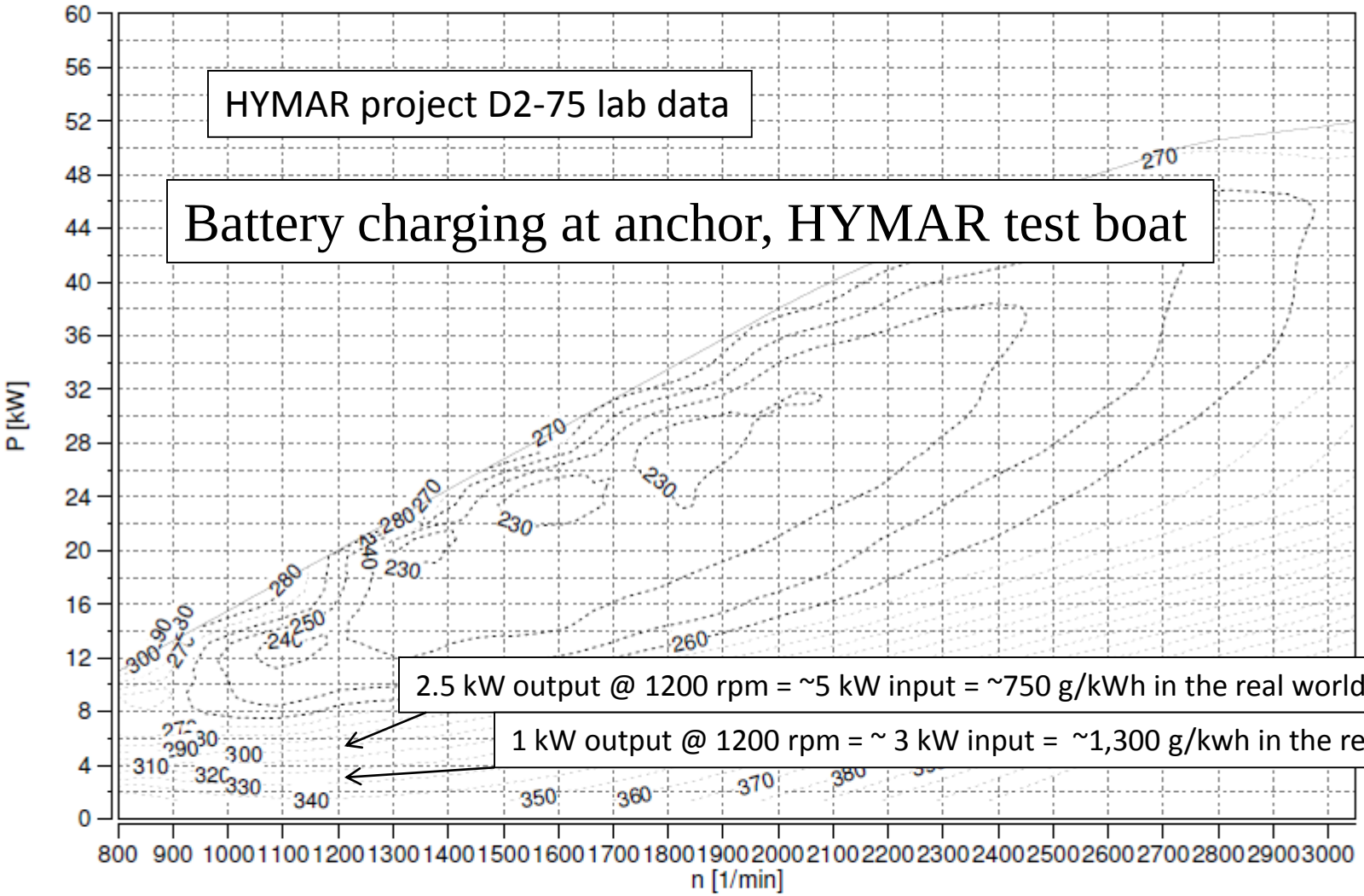
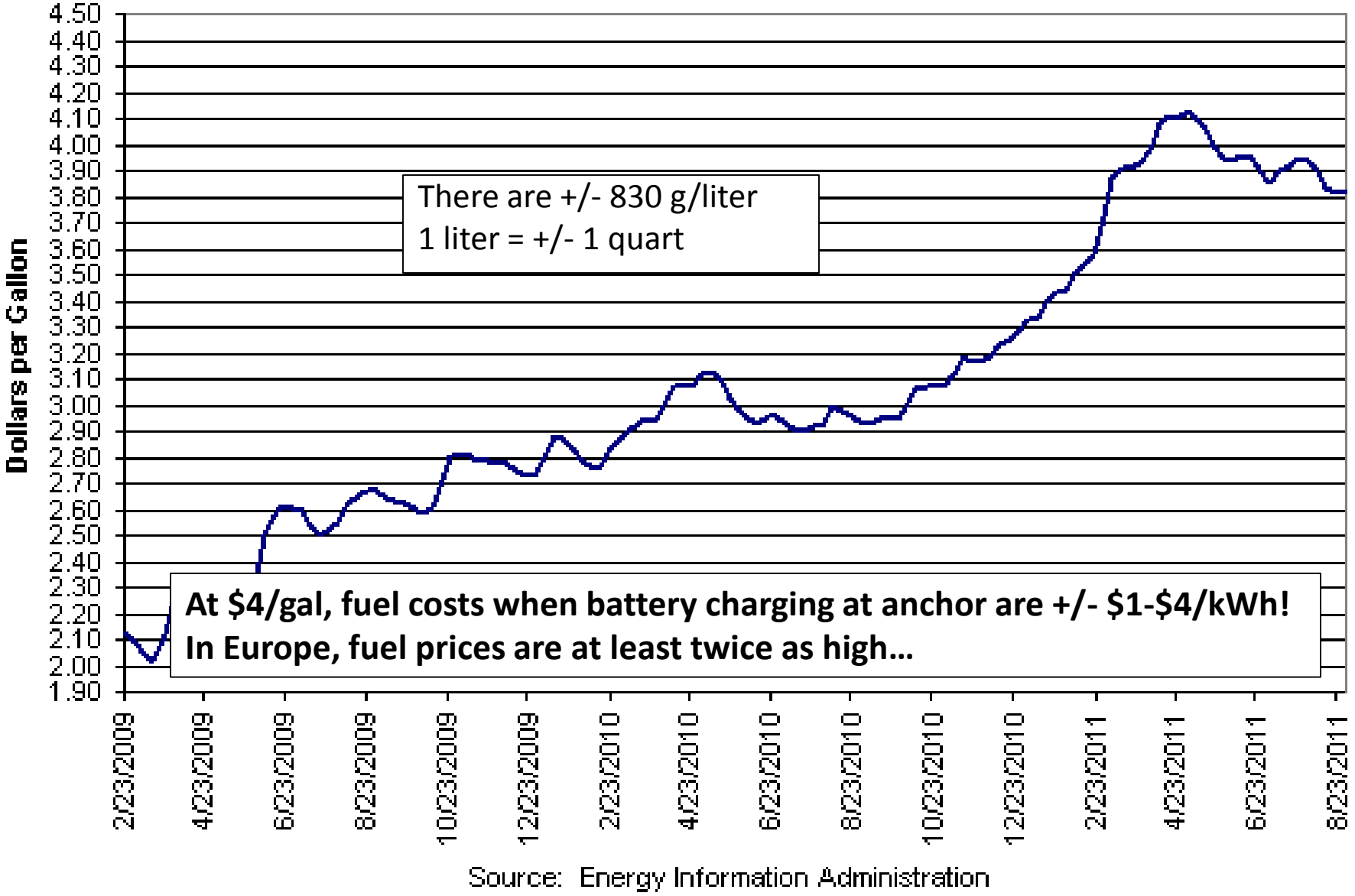
Non SMO Marine Diesel Engine be [g/kWh]



Courtesy Steyr Motors

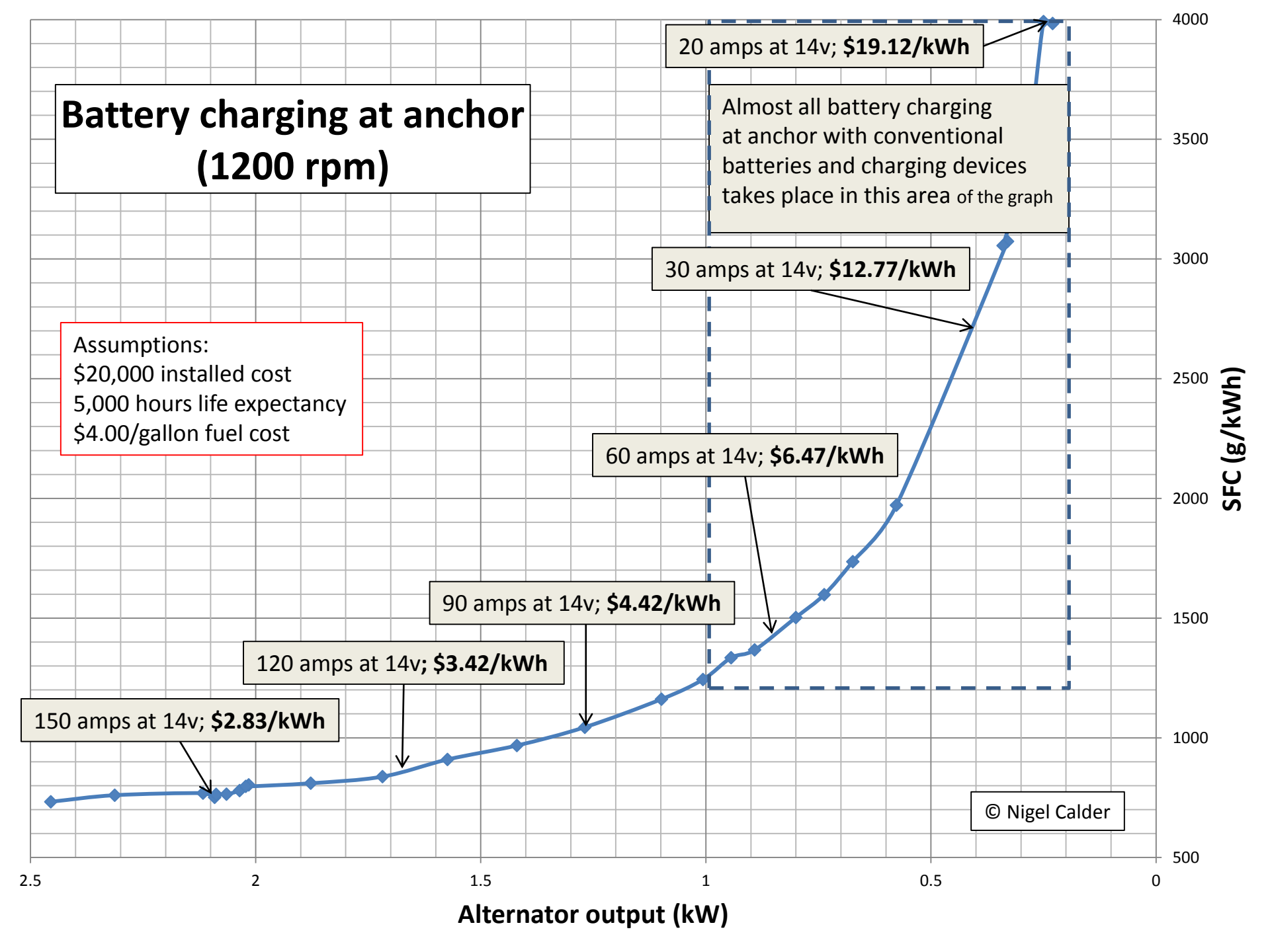
Weekly U.S Retail On-Highway Diesel Prices



Source: Energy Information Administration

As bad as it is, the fuel cost is often not the highest energy cost:

- Assume an installed cost of $20,000 and an operating life of 5,000 hours = $4 an hour amortized cost
- Traditional battery charging *at anchor* results in an average charge rate of 0.85kW (60 amps @ 14 volts) or less = **$4.70/kWh** amortization cost
- Fuel consumption is **$1.75/kWh** for a total cost of **$6.45/kWh**


Battery charging at anchor (1200 rpm)
Assumptions:
$20,000 installed cost
5,000 hours life expectancy
$4.00/gallon fuel cost
20 amps at 14v; $19.12/kWh
Almost all battery charging at anchor with conventional batteries and charging devices takes place in this area of the graph
30 amps at 14v; $12.77/kWh
60 amps at 14v; $6.47/kWh
90 amps at 14v; $4.42/kWh
120 amps at 14v; $3.42/kWh
150 amps at 14v; $2.83/kWh
© Nigel Calder
4000
3500
3000
2500
2000
1500
1000
500
SFC (g/kWh)
2.5
2
1.5
1
0.5
0
Alternator output (kW)

Increasing the load:

- With no other changes to the boat, a high output alternator ***coupled to a battery bank with a CAR that can absorb its output*** can increase the average charge rate to 2kW = **$2/kWh** amortized cost, + fuel is **$1.00/kWh** for a total cost of **$3.00/kWh**, + cutting the battery-charging engine run hours in half (lifestyle issues…)
- Emerging PMDC technologies will give us 85+% electrical efficiency with very high outputs
- Battery CAR is critical…
- *Underway*, higher generating loads can optimize both propulsion and electrical generation fuel efficiency and drop the amortization cost considerably…

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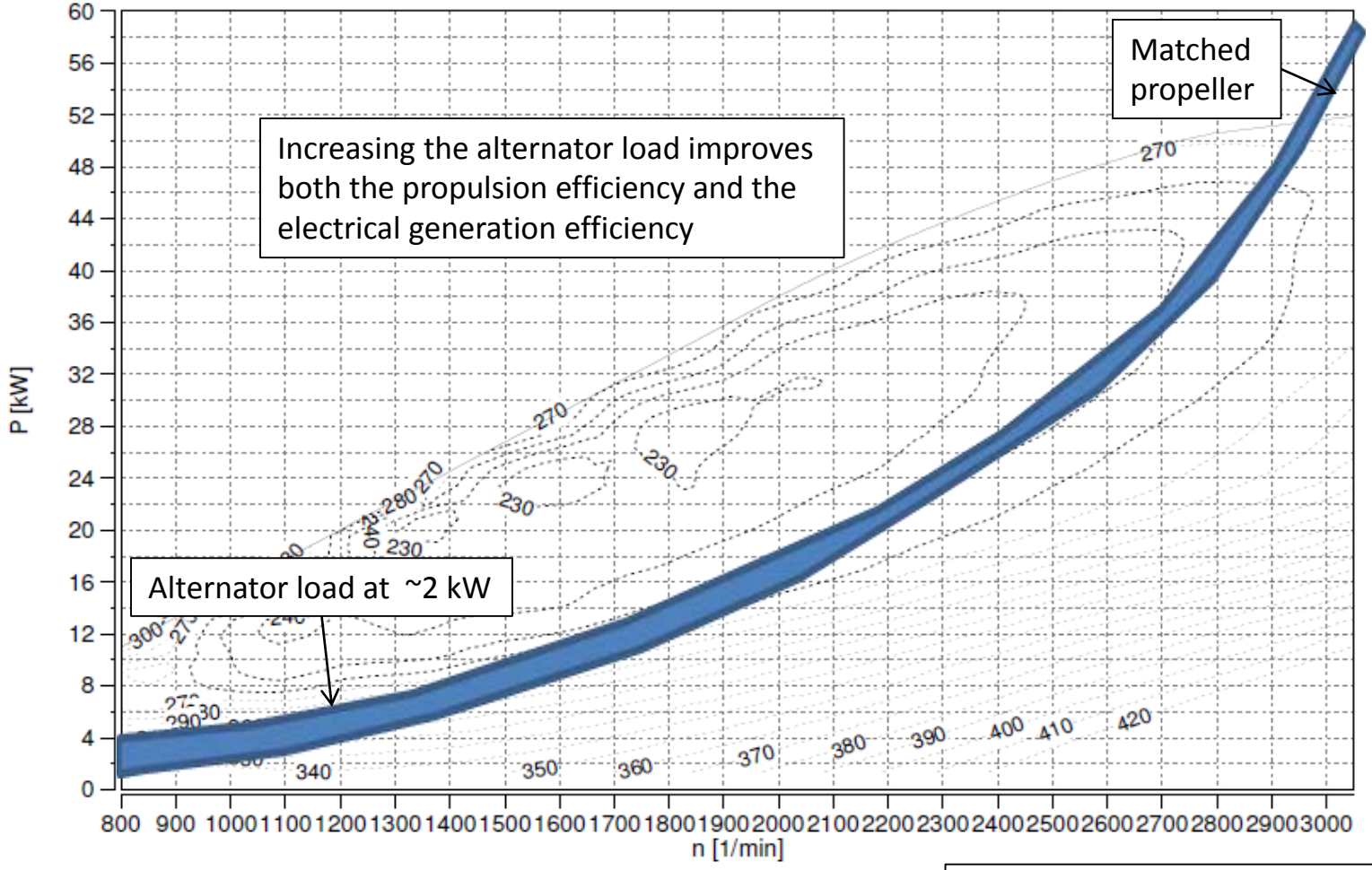
Non SMO Marine Diesel Engine be [g/kWh]



Courtesy Steyr Motors & © Nigel Calder

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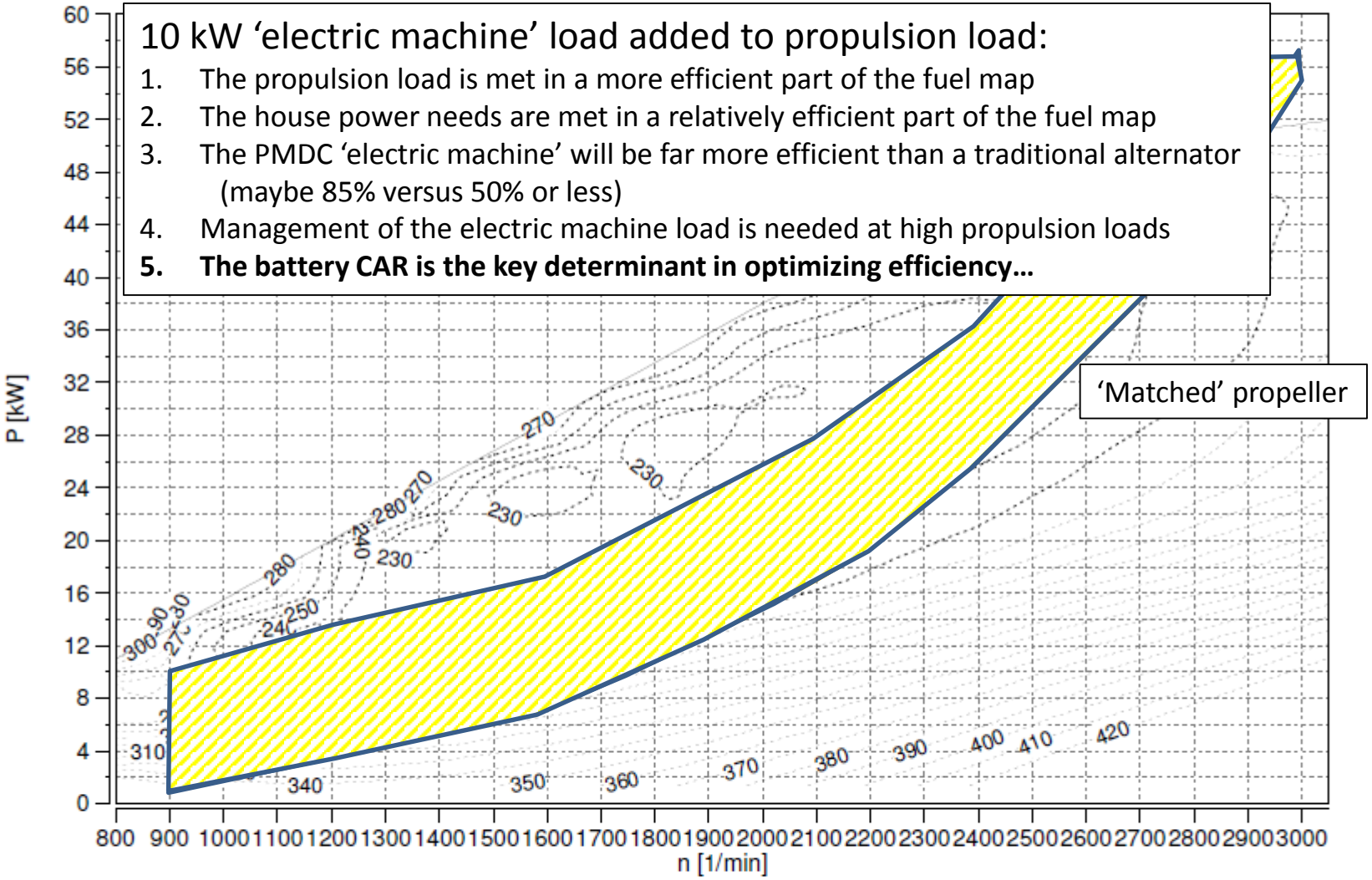
Non SMO Marine Diesel Engine be [g/kWh]

10 kW ‘electric machine’ load added to propulsion load:

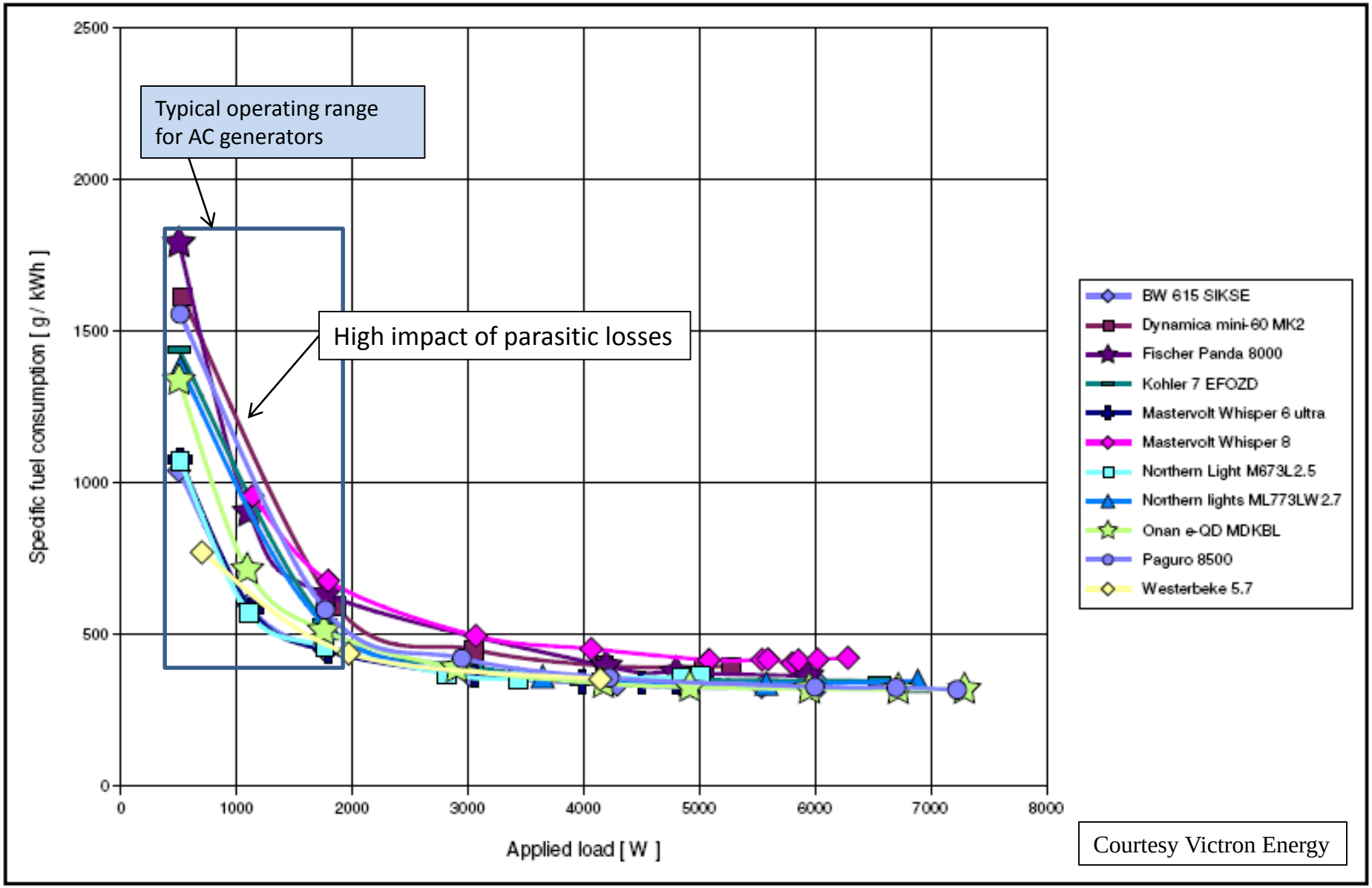
1. The propulsion load is met in a more efficient part of the fuel map
2. The house power needs are met in a relatively efficient part of the fuel map
3. The PMDC ‘electric machine’ will be far more efficient than a traditional alternator (maybe 85% versus 50% or less)
4. Management of the electric machine load is needed at high propulsion loads
5. **The battery CAR is the key determinant in optimizing efficiency…**



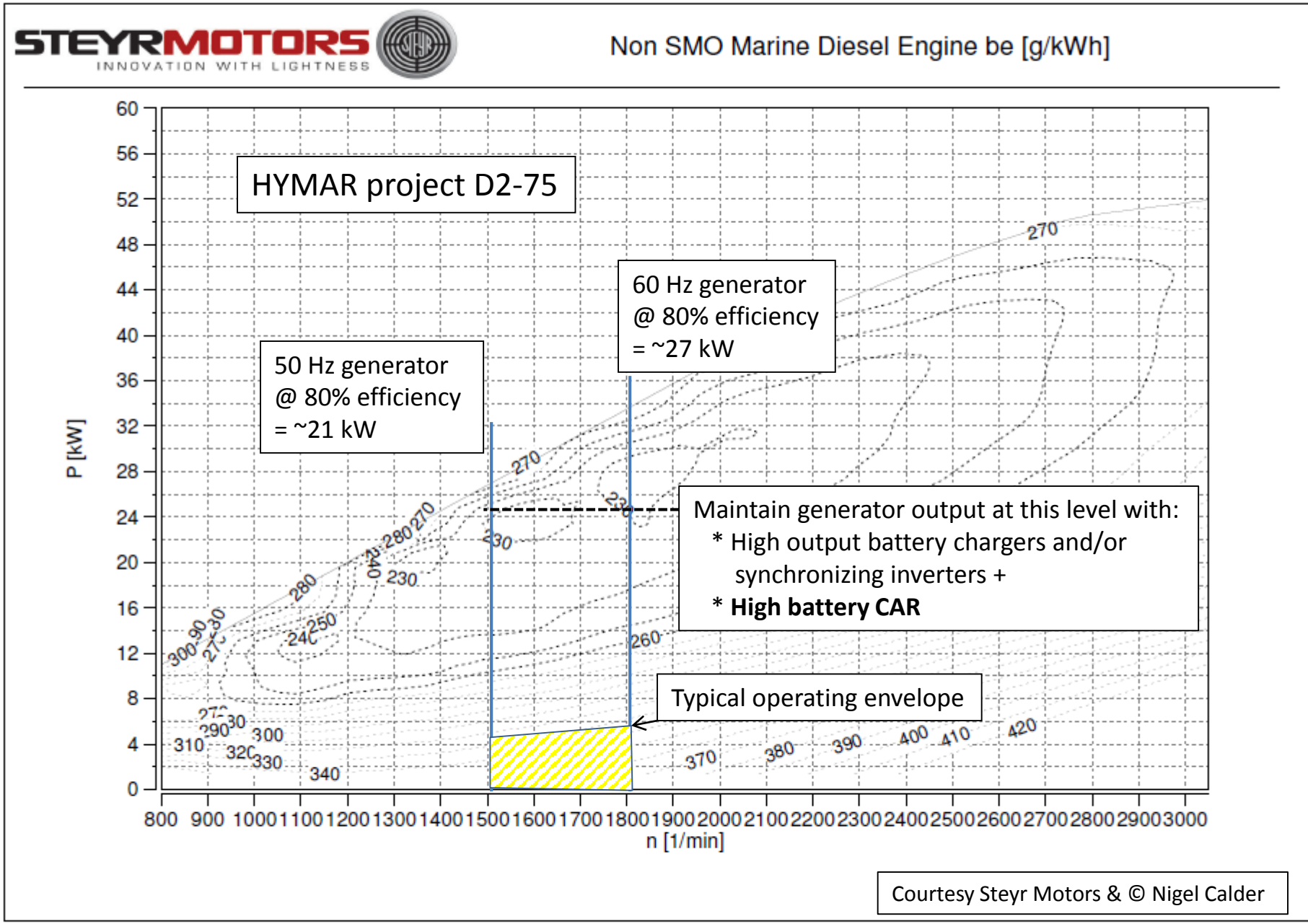
Courtesy Steyr Motors & © Nigel Calder

Conventional AC generators:

- Must run at a fixed speed regardless of load in order to maintain the correct frequency (Hz) (exception: inverter/generators)
- Must be sized to handle the peak load on the system, which is typically at least several times the average running load, and, without load management, may be many times the average running load


Typical operating range for AC generators
High impact of parasitic losses
Specific fuel consumption [g / kWh]
Applied load [W]
2500
2000
1500
1000
500
0
0
1000
2000
3000
4000
5000
6000
7000
8000
BW 615 SIKSE
Dynamica mini-60 MK2
Fischer Panda 8000
Kohler 7 EFOZD
Mastervolt Whisper 6 ultra
Mastervolt Whisper 8
Northern Light M673L2.5
Northern lights ML773LW2.7
Onan e-QD MDKBL
Paguro 8500
Westerbeke 5.7
Courtesy Victron Energy

Conventional AC generators:



SFC	€/kWh	Electrical output, kW									
(g/kWh)	(fuel)	0.25	0.5	0.75	1	2	4	6	8	10	15
		€/kWh, including amortization									
200	0.35	8.35	4.35	3.02	2.35	1.35	0.85	0.68	0.60	0.55	0.48
220	0.39	8.39	4.39	3.05	2.39	1.39	0.89	0.72	0.64	0.59	0.52
240	0.42								0.67	0.62	0.55
260	0.46								0.71	0.66	0.59
280	0.49	8.49	4.49	3.16	2.49	1.49	0.99	0.82	0.74	0.69	0.62
300	0.53	8.53	4.53	3.19	2.53	1.53	1.03	0.86	0.78	0.73	0.66
325	0.57	8.57	4.57	3.24	2.57	1.57	1.07	0.90	0.82	0.77	0.70
350	0.61	8.61	4.61	3.28	2.61	1.61	1.11	0.95	0.86	0.81	0.75
375	0.66	8.66	4.66	3.32	2.66	1.66	1.16	0.99	0.91	0.86	0.79
400	0.70	8.70	4.70	3.37	2.70	1.70	1.20	1.03	0.95	0.90	0.83
450	0.79	8.79	4.79	3.45	2.79	1.79	1.29	1.12	1.04	0.99	0.92
500	0.88	8.88	4.88	3.54	2.88	1.88	1.38	1.21	1.13	1.08	1.01
550	0.96	8.96	4.96	3.63	2.96	1.96	1.46	1.30	1.21	1.16	1.10
600	1.05	9.05	5.05	3.72	3.05	2.05	1.55	1.3			.18
700	1.23	9.23	5.23	3.89	3.23	2.23	1.73	1.5			.36
800	1.40	9.40	5.40	4.07	3.40	2.40	1.90	1.7			.53
900	1.58	9.58	5.58	4.24	3.58	2.58	2.08	1.91	1.83	1.78	1.71
1000	1.75	9.75	5.75	4.42	3.75	2.75	2.25	2.08	2.00	1.93	1.86

Cost of power from generators, $/kWh

Assumptions:
$10,000 installed cost
3,000 hours life expectancy
$5.00/gallon fuel cost

Raising average power levels:

- Dramatically improves fuel efficiency in low-power propulsion and house power applications
- *Reduces engine run hours in proportion to the increase in average load*
- Dramatically reduces kWh amortization costs for both propulsion and house power
- Substantially reduces maintenance
- Has significant lifestyle benefits

New batteries are the enabling technology:

- Primary need is for high CAR to high states of charge
- Must be able to tolerate PSOC operation
- If conditioning cycles are required, mechanisms are necessary that don't require extended low-load engine operation
- Lithium & VRLA AGM, especially TPPL + new battery management techniques…
- Lead-carbon…

Battery ‘throughput’ costs: the importance of high cycle life

€/kWh through-put cost	Cost/kWh of battery capacity (€)							
	100.00	150.00	200.00	250.00	300.00	350.00	400.00	450.00
	Life cycles, assuming 80% DoD at each cycle and no efficiency losses through the battery							
0.01	12,500	18,750	25,000	31,250	37,500	43,750	50,000	56,250
0.02	6,250	9,375	12,500	15,625	18,750	21,875	25,000	28,125
0.03	4,167	6,250	8,333	10,417	12,500	14,583	16,667	18,750
0.04	3,125	4,688	6,250	7,813	9,375	10,938	12,500	14,063
0.05	2,500	3,750					0,000	11,250
0.06	2,083	3,125					8,333	9,375
0.07	1,786	2,679					7,143	8,036
0.08	1,563	2,344	3,125	3,906	4,688	5,469	6,250	7,031
0.09	1,389	2,083	2,778	3,472	4,167	4,861	5,556	6,250
0.1	1,250	1,875	2,500	3,125	3,750	4,375	5,000	5,625
0.11	1,136	1,						14
0.12	1,042	1,						38
0.13	962	1,						27
0.14	893	1,						18
0.15	833	1,						50
0.2	625							13
0.25	500							50
0.3	417	625	833	1,042	1,250	1,458	1,667	1,875
0.35	357	536	714	893	1,071	1,250	1,429	1,607
0.4	313	469	625	781	938	1,094	1,250	1,406
0.45	278	417	556	694	833	972	1,111	1,250
0.5	250	375	500	625	750	875	1,000	1,125
0.6	208	313	417	521	625	729	833	938
0.7	179	268	357	446	536	625	714	804
0.8	156	234	313	391	469	547	625	703
0.9	139	208	278	347	417	486	5	25
1	125	188	250	313	375	438	5	63

E.g. 8D 12v battery rated at 250 Ah, costs $400, with 400 cycles to 80% DoD:
Capacity is 12v x 250 Ah = 3,000Wh = 3kWh
Cost is $400/3 = $133.33/kWh
80% DoD = 200 Ah = 2.4kWh
400 cycles = 2.4 x 400 = 960 lifetime kWh
‘Throughput’ cost = $400/960 = $0.42/kWh
There will be additional costs associated with the losses in charging & discharging…

High CAR batteries will drive charging devices to full continuous output for extended periods of time:

- Risk of burn-out
  - Need temperature sensing at alternators
  - Need greatly improved ventilation of engine compartments
- Tripping the shoreside breaker
  - Need adjustable current limit in battery chargers

Conventional alternators are not up to the task…

Hybrid *energy* systems:

- High CAR batteries have substantially blurred the line between DC & AC systems
- Efficient AC systems design should now always include a DC component:
  - Via synchronizing inverters
  - Using DC generators & conventional inverters
- In general, *the greater the charging capability and the higher the battery CAR the less the engine run hours and the more efficient the system*
- ***In almost all house energy systems, increasing the average load when engines are running dramatically improves fuel efficiency and radically reduces energy generation costs***