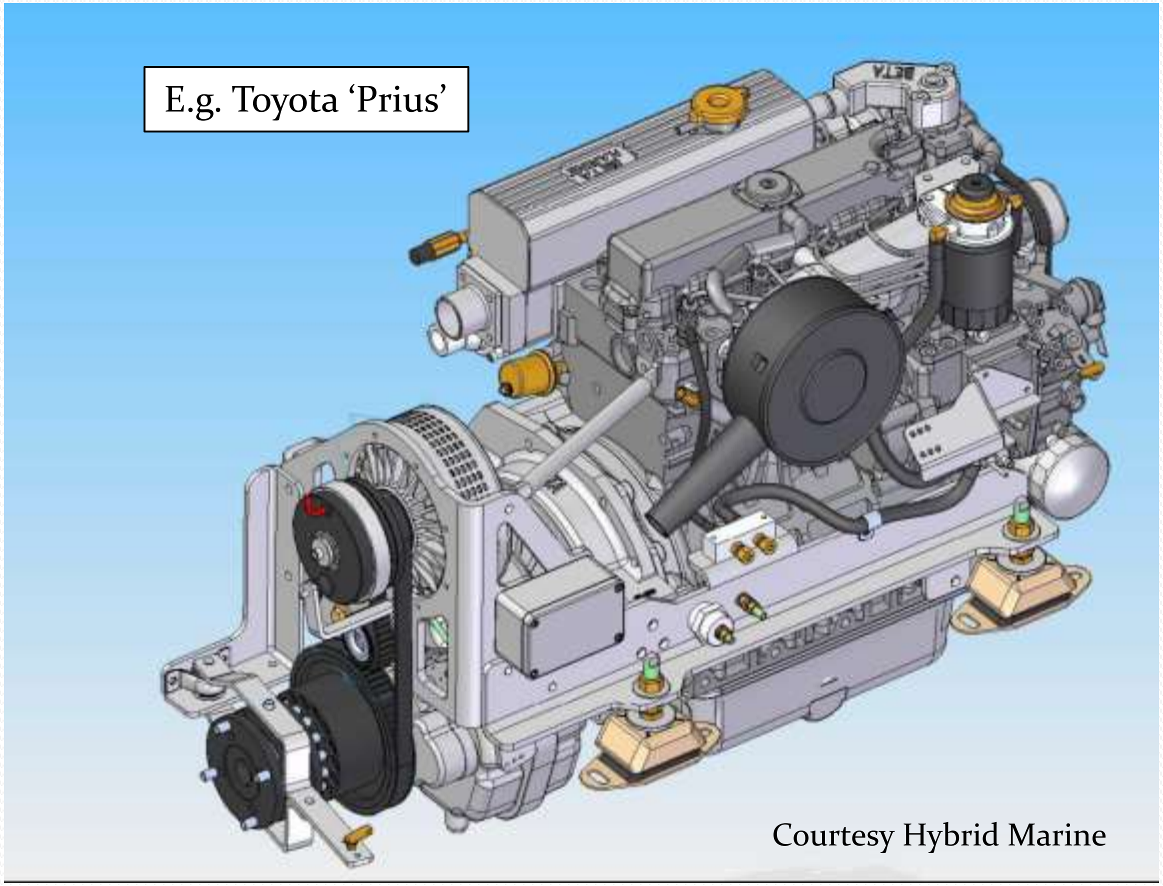
Hybrid Efficiency versus Optimized Conventional Installations

Nigel Calder

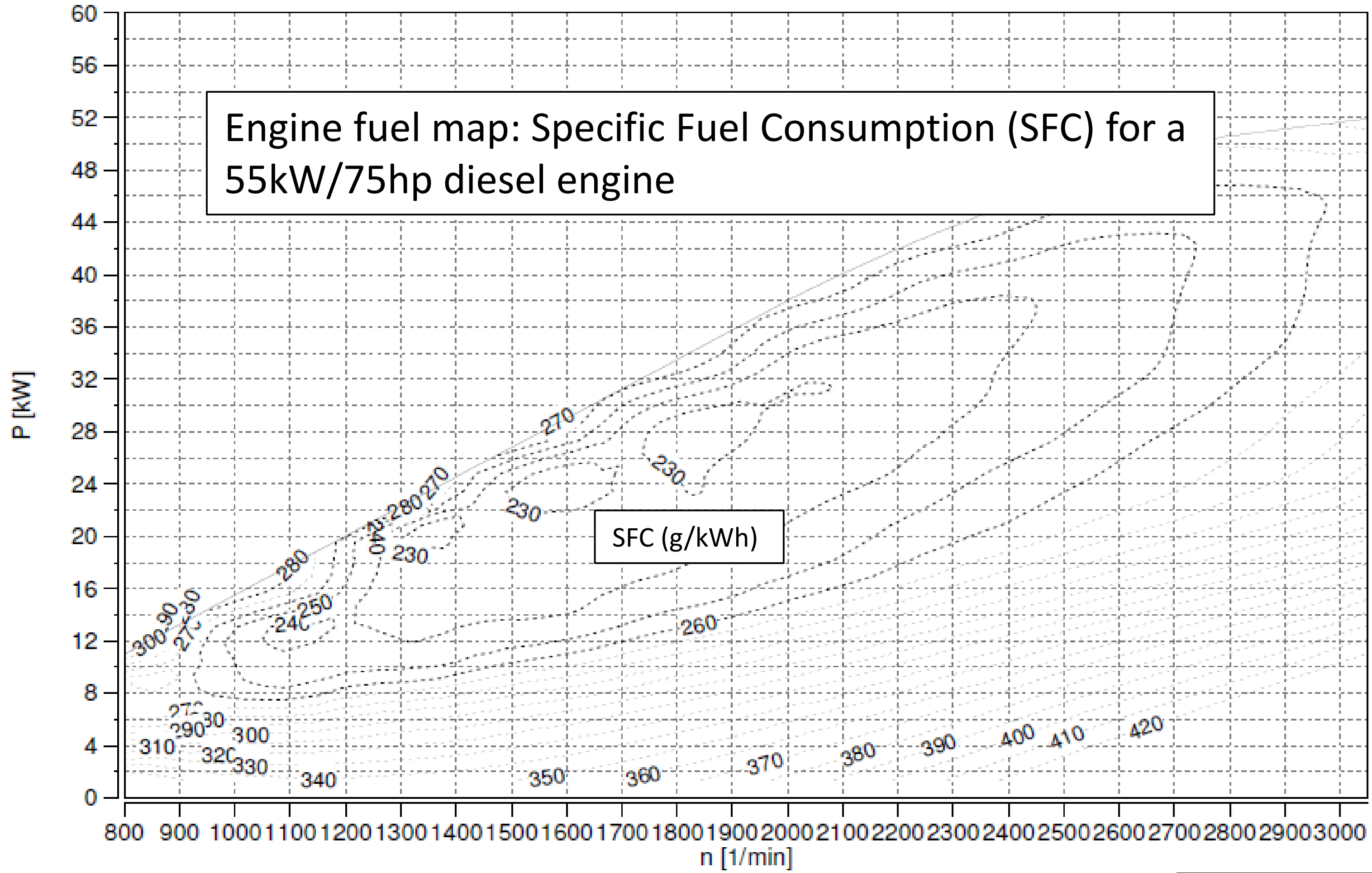
Thanks to the European Union for funding the HYbrid MARine (HYMAR) project

Serial and parallel:

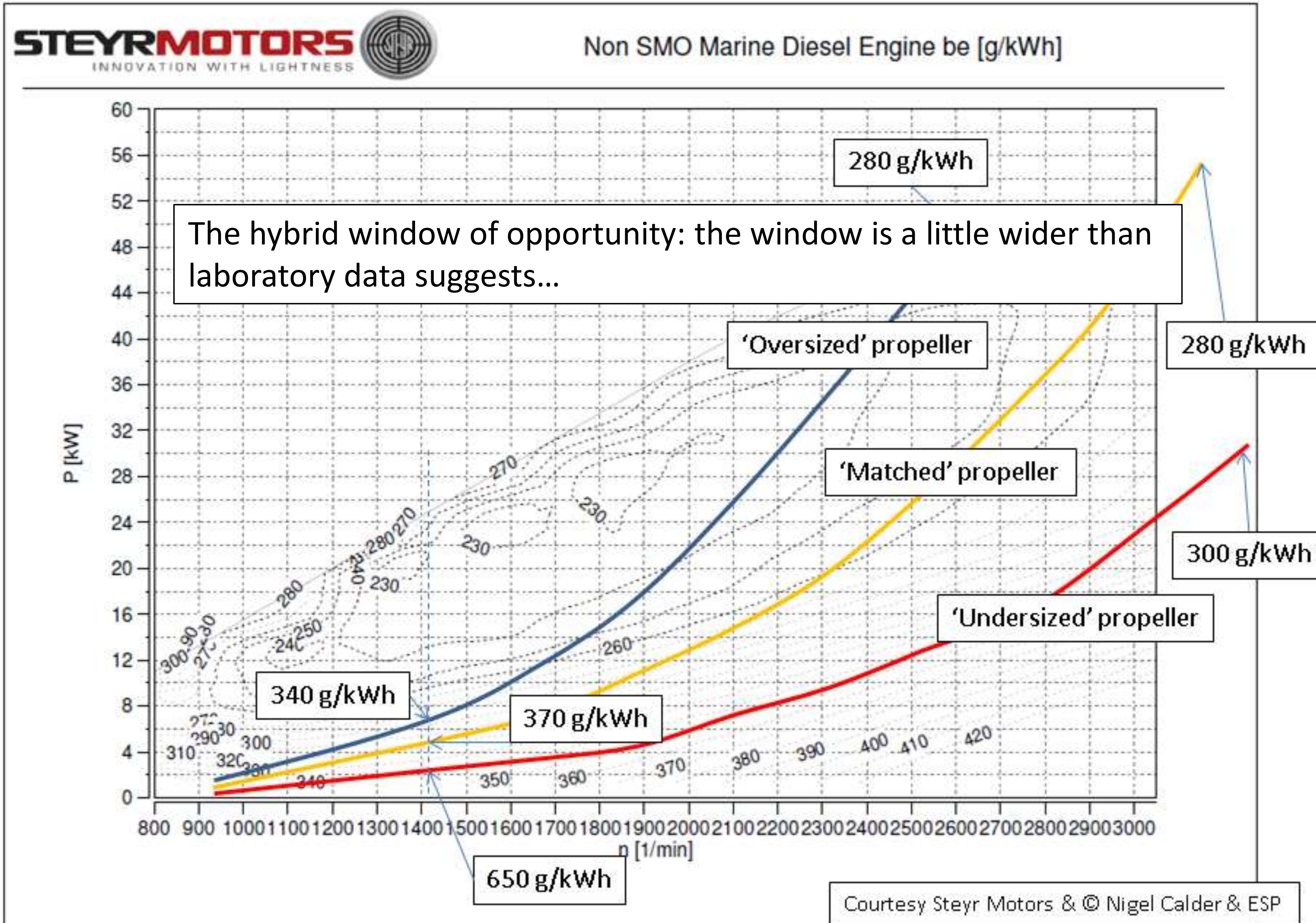


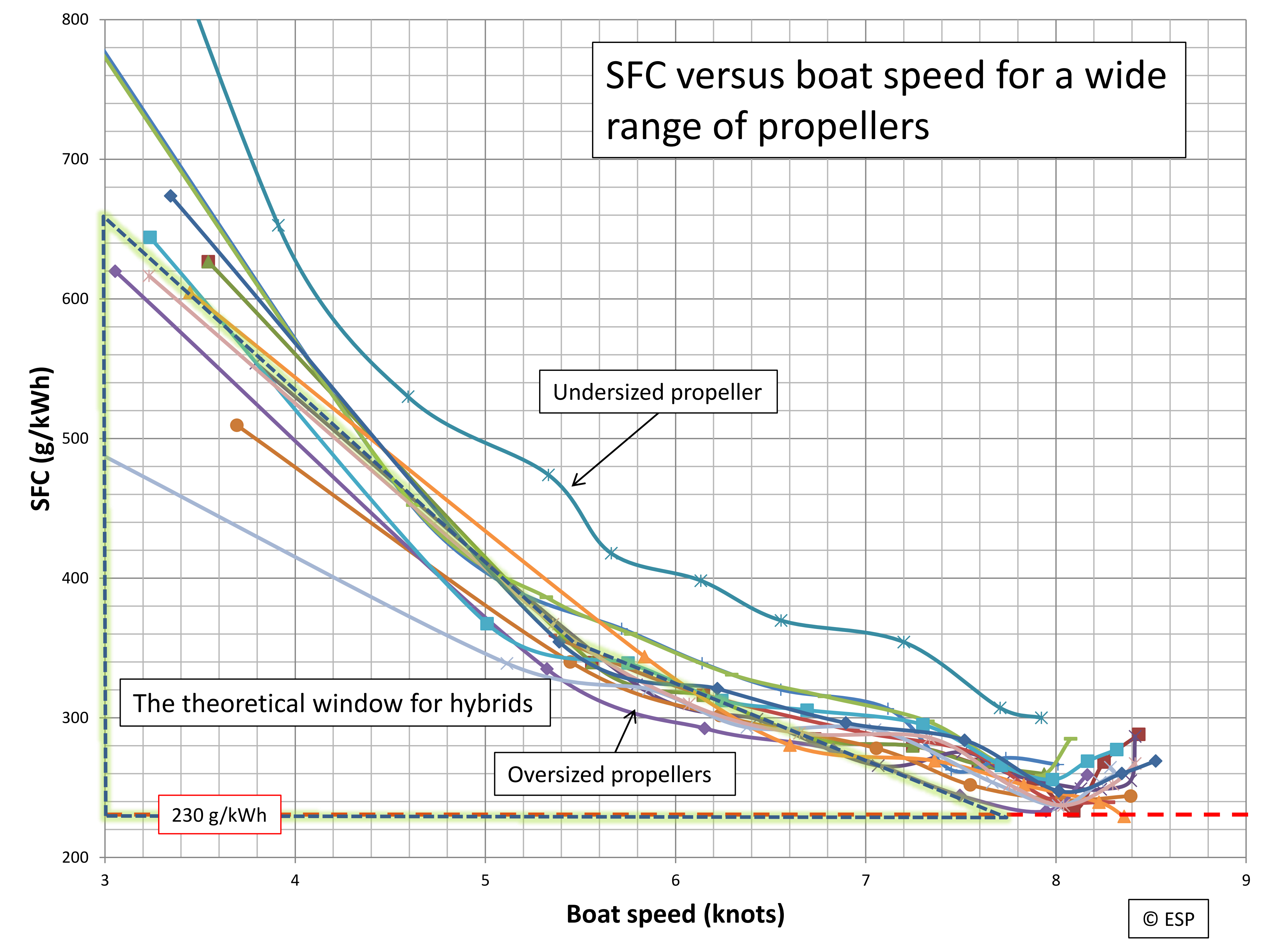
STEYR MOTORS
INNOVATION WITH LIGHTNESS

Non SMO Marine Diesel Engine be [g/kWh]



Courtesy Steyr Motors

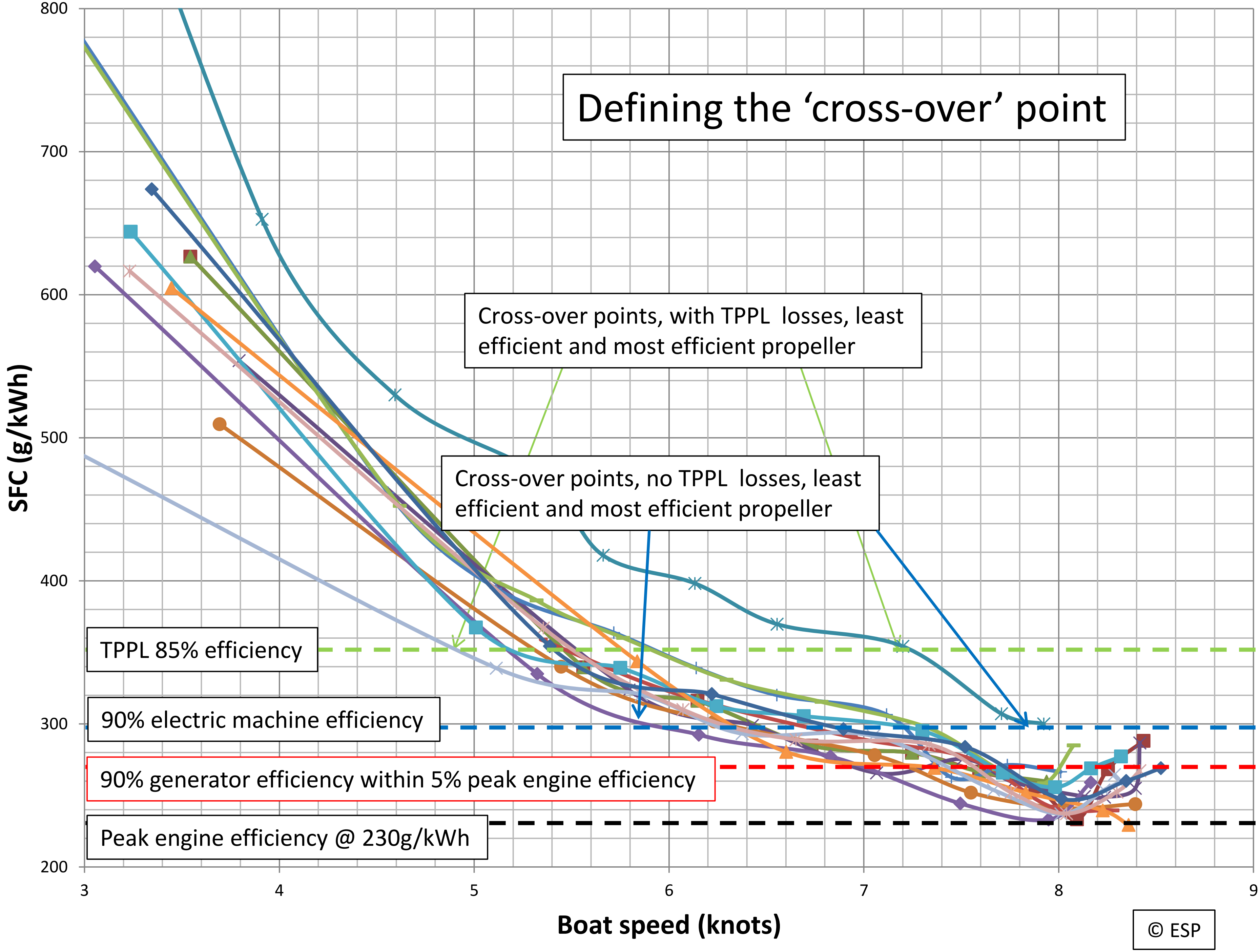

STEYRMOTORS
INNOVATION WITH LIGHTNESS
Non SMO Marine Diesel Engine be [g/kWh]
280 g/kWh
The hybrid window of opportunity: the window is a little wider than laboratory data suggests…
'Oversized' propeller
280 g/kWh
'Matched' propeller
300 g/kWh
'Undersized' propeller
340 g/kWh
370 g/kWh
650 g/kWh
P [kW]
n [1/min]
Courtesy Steyr Motors & © Nigel Calder & ESP

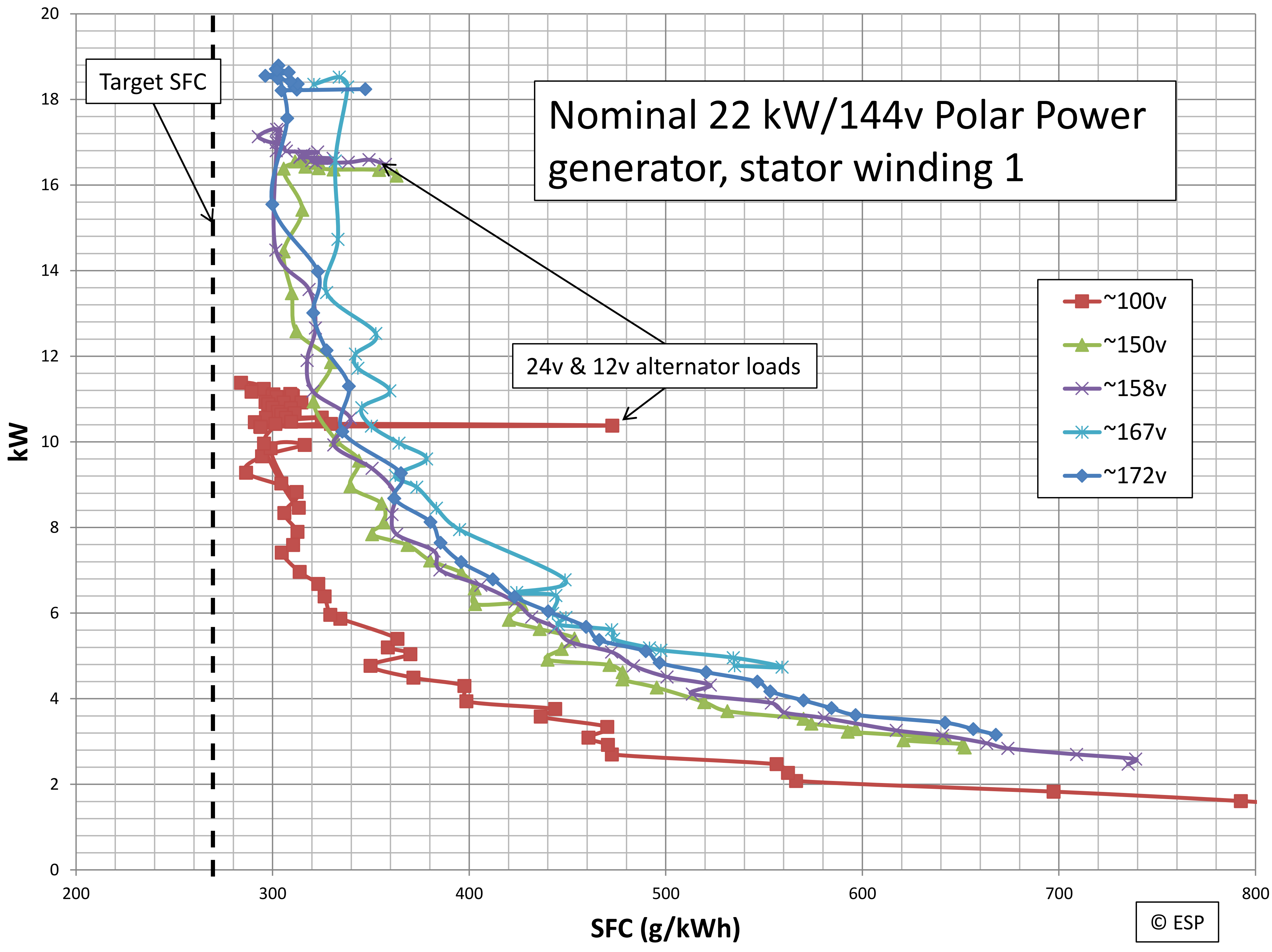


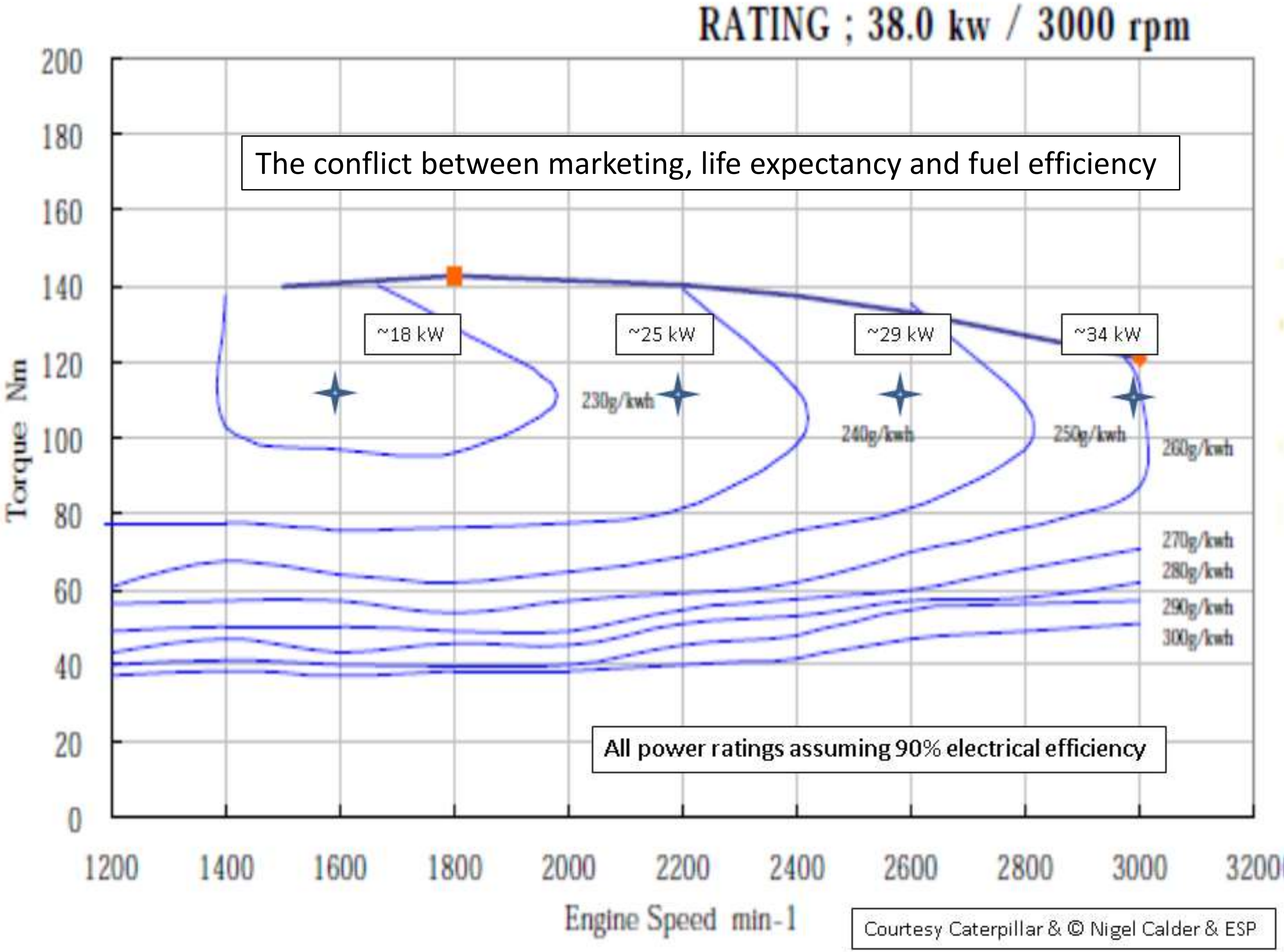
SFC versus boat speed for a wide range of propellers
Undersized propeller
Oversized propellers
The theoretical window for hybrids
230 g/kWh
SFC (g/kWh)
Boat speed (knots)
800
700
600
500
400
300
200
3
4
5
6
7
8
9
© ESP

Initial HYMAR assumptions:

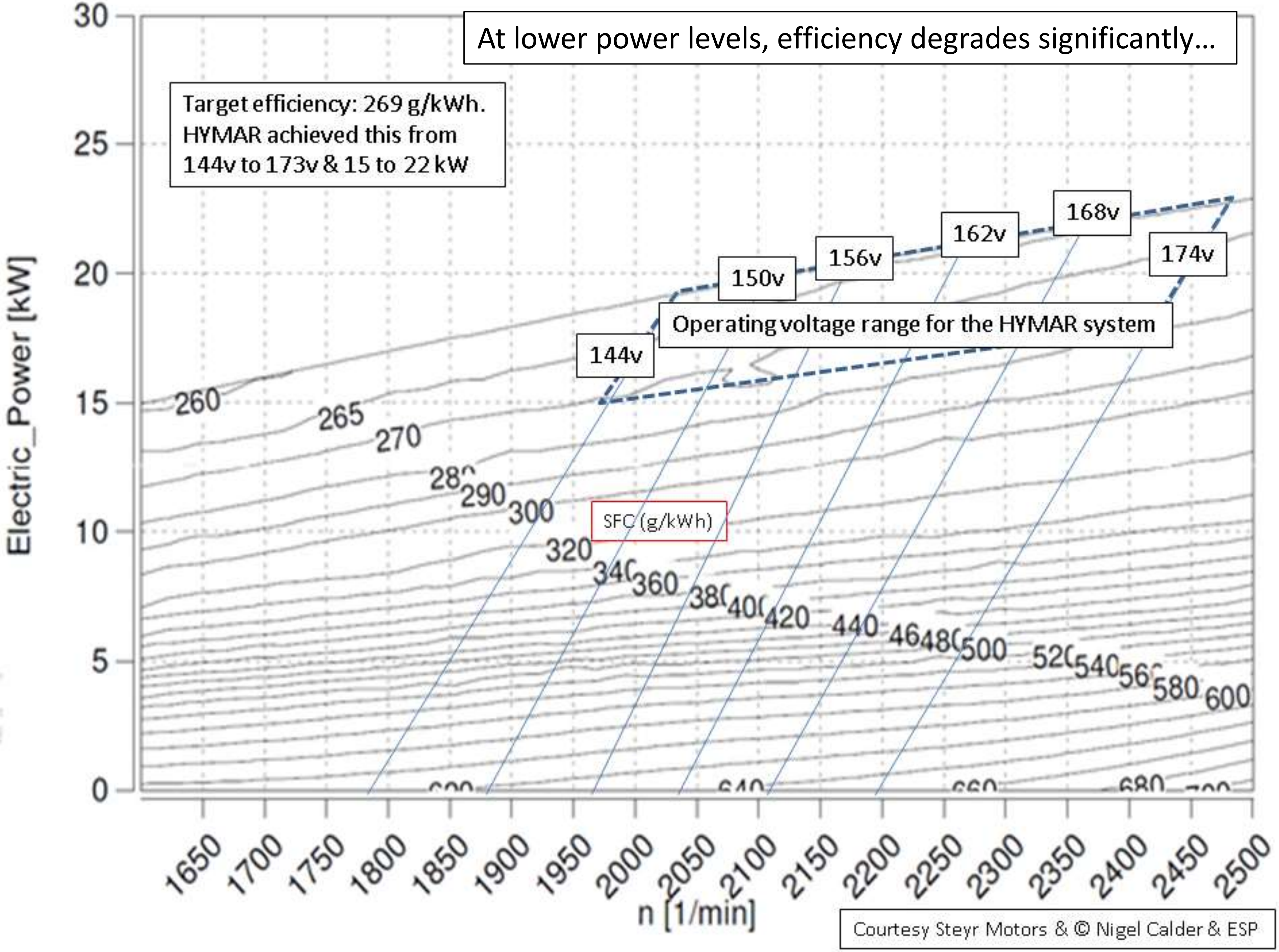
- Engine within 5% of peak efficiency, i.e.
  230/0.95 = 242 g/kWh
- 90% generator electrical efficiency, i.e.
  242/0.9 = 269 g/kWh
- 90% electric machine + controller efficiency, i.e.
  269/0.9 = 299 g/kWh
- 85% TPPL efficiency, i.e. 299/0.85 = 352 g/kWh (lithium-ion would be 90+% efficient)


Defining the 'cross-over' point
Cross-over points, with TPPL losses, least efficient and most efficient propeller
Cross-over points, no TPPL losses, least efficient and most efficient propeller
TPPL 85% efficiency
90% electric machine efficiency
90% generator efficiency within 5% peak engine efficiency
Peak engine efficiency @ 230g/kWh
SFC (g/kWh)
Boat speed (knots)
800
700
600
500
400
300
200
3
4
5
6
7
8
9
© ESP

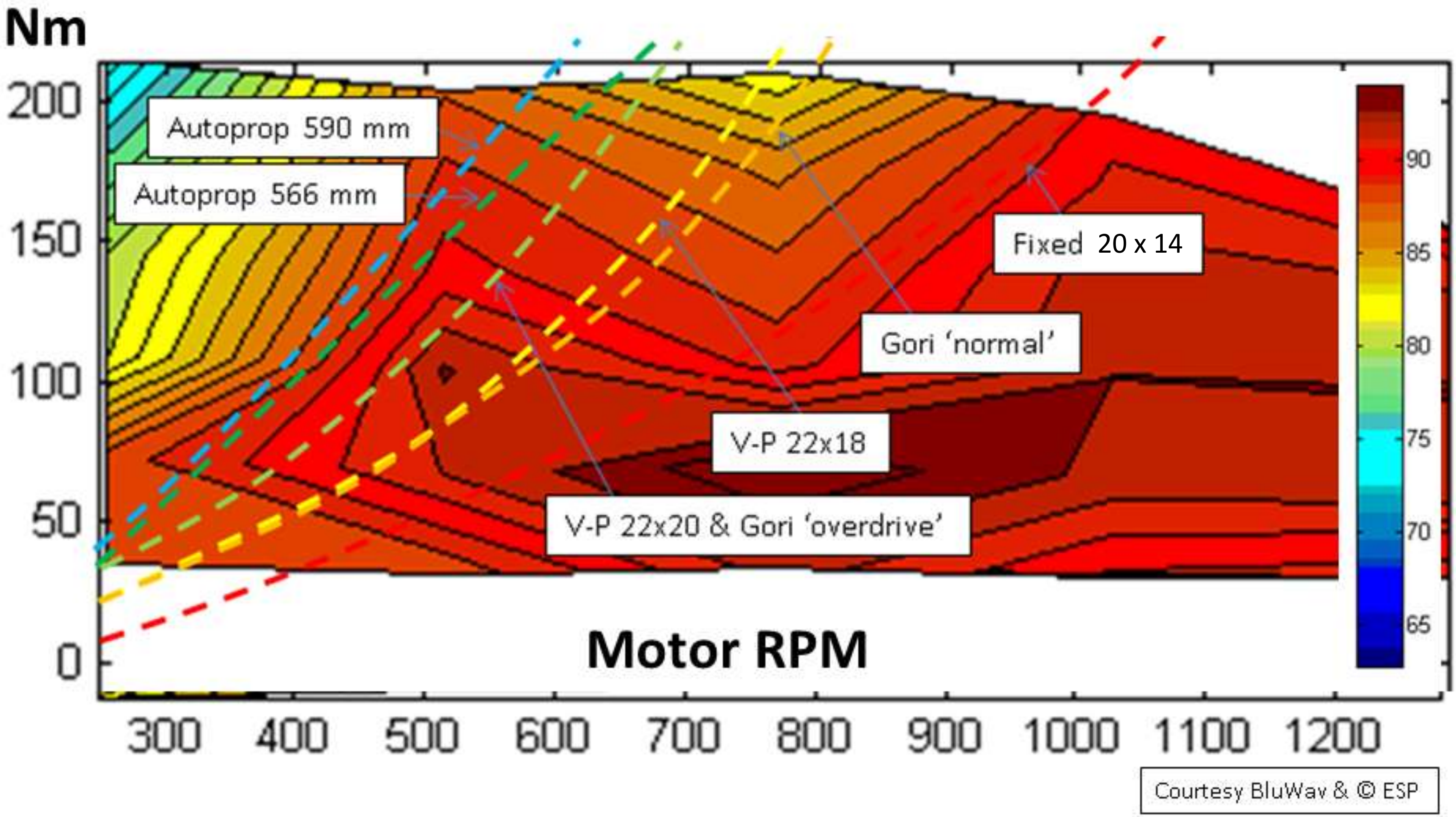

Nominal 22 kW/144v Polar Power generator, stator winding 1
Target SFC
24v & 12v alternator loads
~100v
~150v
~158v
~167v
~172v
kW
SFC (g/kWh)
0
2
4
6
8
10
12
14
16
18
20
200
300
400
500
600
700
800
© ESP

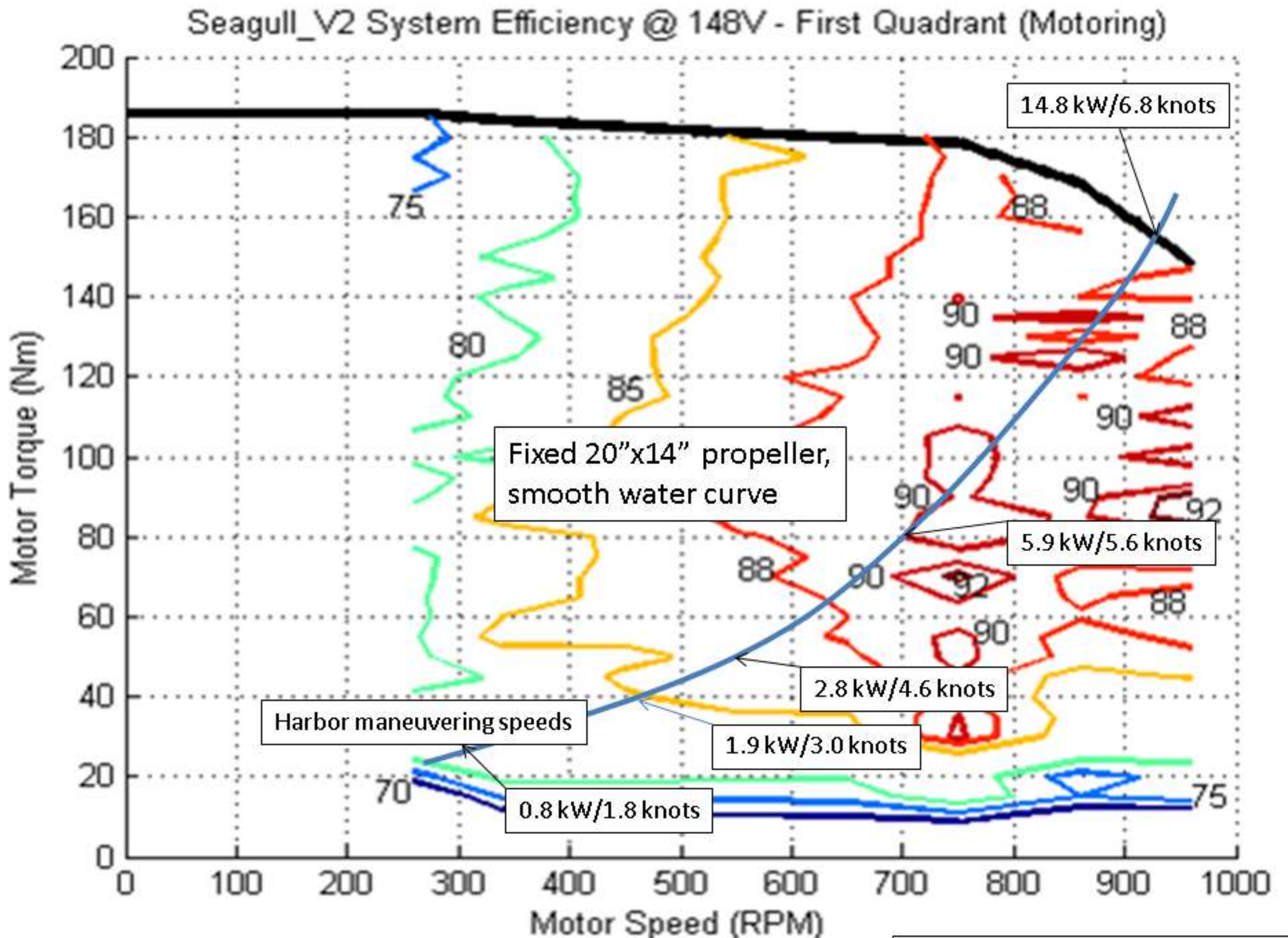


RATING ; 38.0 kw / 3000 rpm
The conflict between marketing, life expectancy and fuel efficiency
~18 kW
~25 kW
~29 kW
~34 kW
230g/kwh
240g/kwh
250g/kwh
260g/kwh
270g/kwh
280g/kwh
290g/kwh
300g/kwh
All power ratings assuming 90% electrical efficiency
Torque Nm
Engine Speed min-1
200
180
160
140
120
100
80
60
40
20
0
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
Courtesy Caterpillar & © Nigel Calder & ESP


At lower power levels, efficiency degrades significantly…
Target efficiency: 269 g/kWh.
HYMAR achieved this from
144v to 173v & 15 to 22 kW
144v
150v
156v
162v
168v
174v
Operating voltage range for the HYMAR system
SFC (g/kWh)
Electric_Power [kW]
n [1/min]
Courtesy Steyr Motors & © Nigel Calder & ESP

Electric machine + controller efficiency





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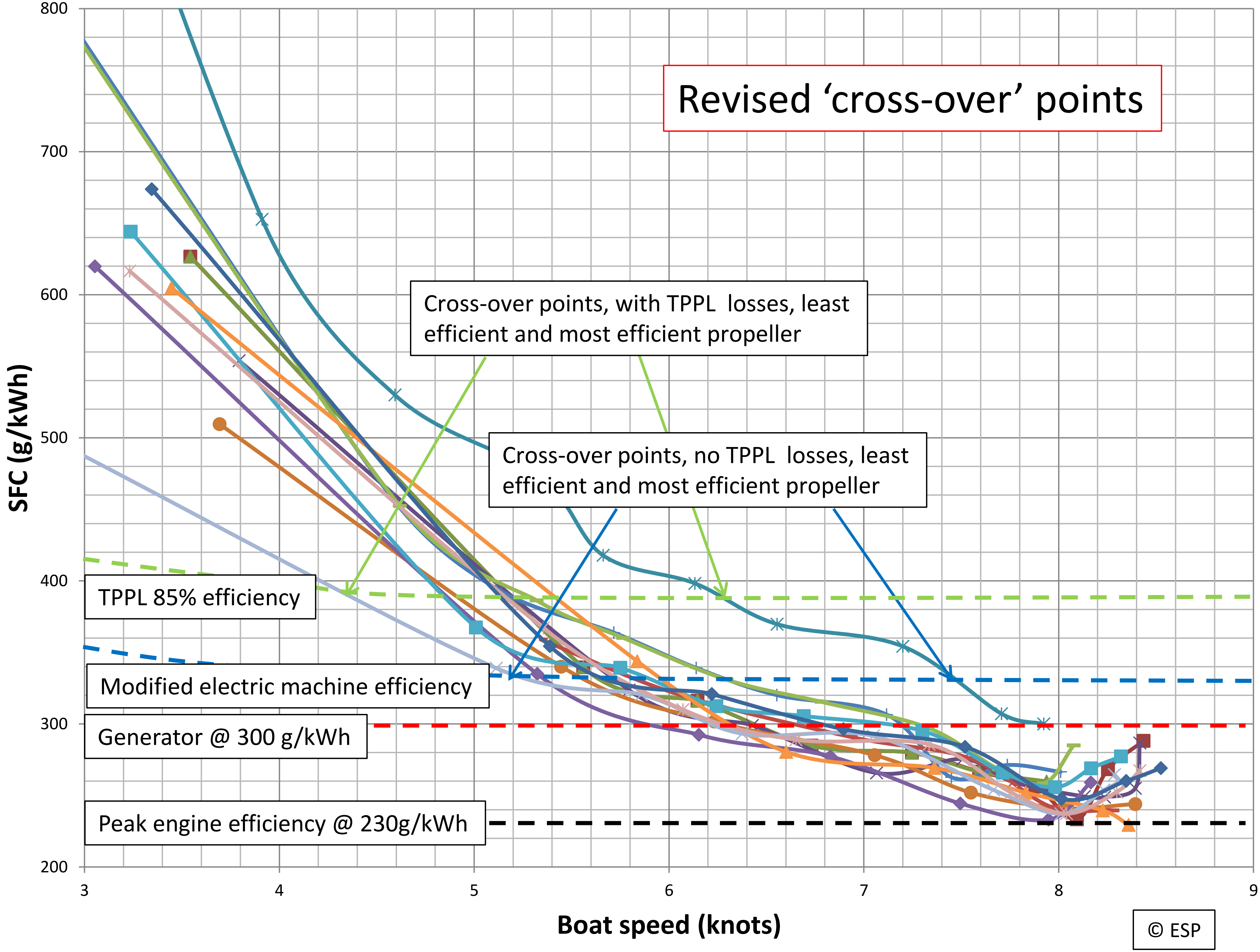
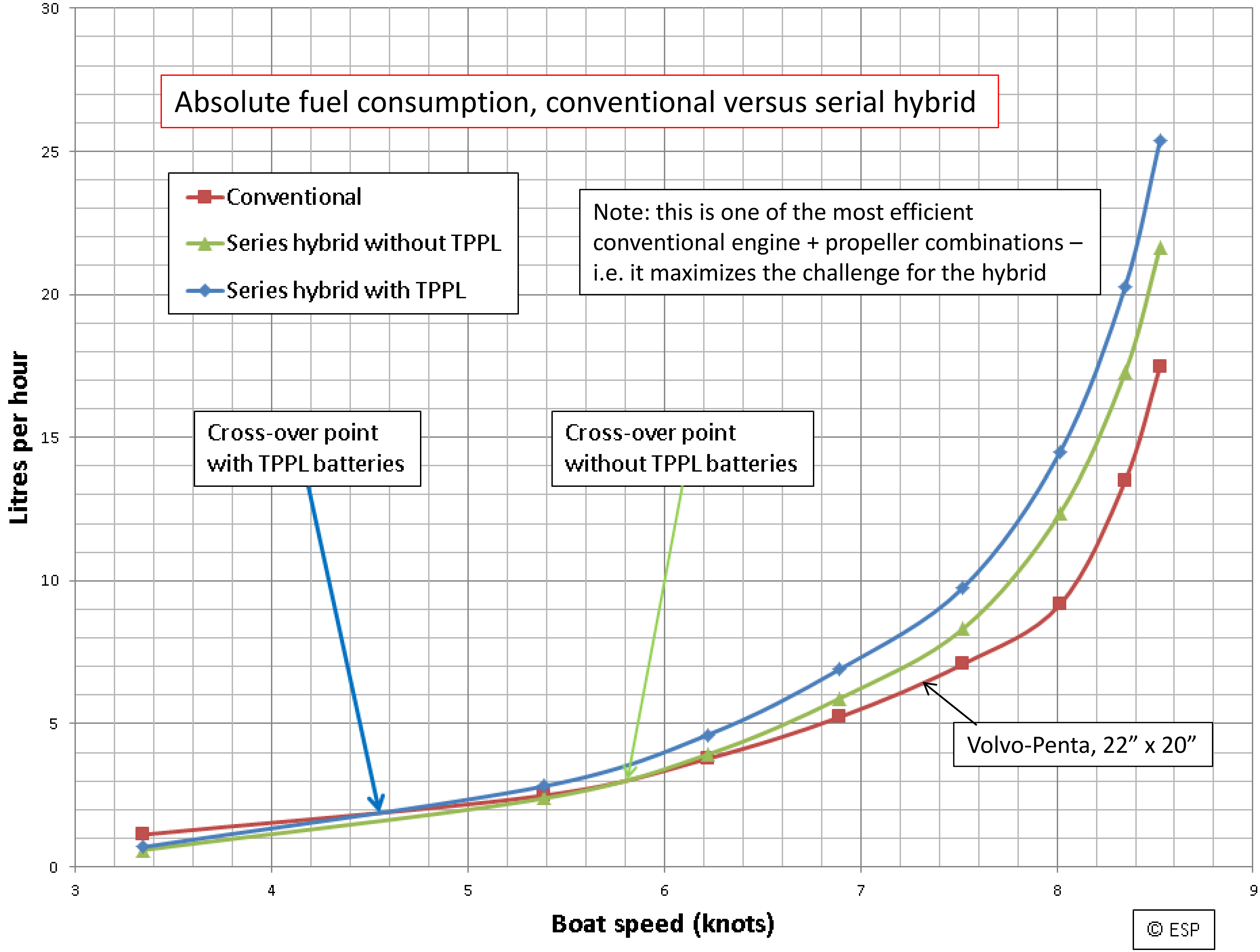
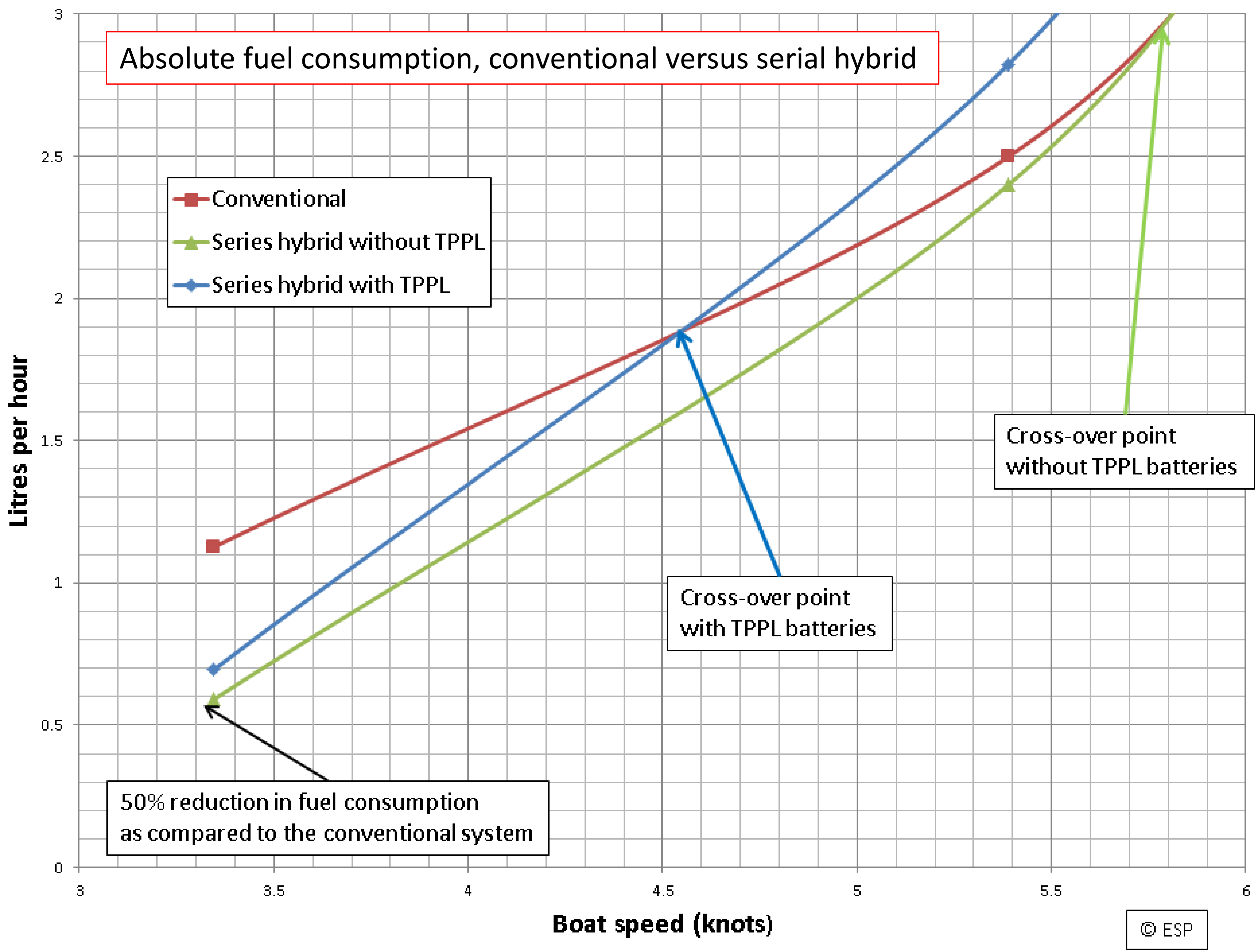


Revised 'cross-over' points
Cross-over points, with TPPL losses, least efficient and most efficient propeller
Cross-over points, no TPPL losses, least efficient and most efficient propeller
TPPL 85% efficiency
Modified electric machine efficiency
Generator @ 300 g/kWh
Peak engine efficiency @ 230g/kWh
SFC (g/kWh)
800
700
600
500
400
300
200
3
4
5
6
7
8
9
Boat speed (knots)
© ESP


Absolute fuel consumption, conventional versus serial hybrid
Conventional
Series hybrid without TPPL
Series hybrid with TPPL
Note: this is one of the most efficient conventional engine + propeller combinations – i.e. it maximizes the challenge for the hybrid
Cross-over point with TPPL batteries
Cross-over point without TPPL batteries
Volvo-Penta, 22” x 20”
Litres per hour
Boat speed (knots)
0
5
10
15
20
25
30
3
4
5
6
7
8
9
© ESP


Absolute fuel consumption, conventional versus serial hybrid
Conventional
Series hybrid without TPPL
Series hybrid with TPPL
Cross-over point
without TPPL batteries
Cross-over point
with TPPL batteries
50% reduction in fuel consumption
as compared to the conventional system
Litres per hour
Boat speed (knots)
0
0.5
1
1.5
2
2.5
3
3
3.5
4
4.5
5
5.5
6
© ESP

Percentages versus liters:

- The percentage fuel savings at low speeds can be high (e.g. >50% at 3.25 knots) trending towards 100% (e.g. elimination of dockside idling)
- The absolute savings are low (e.g. 0.5 l/h at 3.25 knots)
- The percentage fuel losses at higher speeds may be relatively low (e.g. 18% at 7.5 knots)
- The absolute losses are relatively high (e.g. 1.3 l/h at 7.5 knots)
- ***In any application with sustained periods of operation above the cross-over speed, the losses will outweigh the gains for a net loss of fuel efficiency***

Energy displacement:

- The assumption so far has been that all energy for propulsion comes from an engine
- This is necessarily so for the conventional system but not the hybrid
- The hybrid can significantly alter the efficiency equation by incorporating other sources:
  - Shorepower
  - Renewables (solar and wind)
  - Regeneration on sailboats
  - Fuel cells
- Even if the hybrid is less efficient when its energy comes from the generator, it can be more efficient overall – e.g. Chevy ‘Volt’/Opel ‘Ampera’ drivers average 111 mpg

The limits of energy displacement:

- The duty cycle of boats is radically different to that of cars…
- Shorepower and regeneration are *absolutely* limited by battery capacity; it takes a lot of batteries to get even a 20 mile range *at less than ½ power…*
- Solar and wind are *relatively* limited by battery capacity
- *The relatively high loads of even a modest propulsion demand will rapidly exceed the capability of solar and wind, and/or deplete battery banks*

Serial versus parallel

- A serial system must have enough electric power for the worst-case situation
- A parallel system only needs enough power to maneuver in harbor
- The powerful motor in a serial system will result in the inefficient area of operation migrating into harbor maneuvering and other low-speed, low power (e.g. motorsailing) applications
- The smaller motor in the parallel system will be more efficient to lower boat speeds
- The parallel system always includes the battery losses whereas the serial does not when in diesel-electric mode

Serial versus parallel:

- The parallel system captures all the efficiency benefits below the ‘cross-over’ speed without paying any of the penalties above it
- Both systems eliminate dockside idling, enable pollution-free harbors, and consolidate engine run hours
- The parallel system requires far less battery capacity
- The parallel system can exploit non-engine energy sources just as well as the serial
- ***The bottom line:*** *with either system, it will be extremely difficult to beat the efficiency of a well optimized conventional installation in any application that involves sustained operation at, or above, ‘cruising’ speeds*