Hybrid Efficiency versus Optimized Conventional Installations

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Thanks to the European Union for funding the HYbrid MARine (HYMAR) project
Serial and parallel:

E.g. Chevy ‘Volt’/Opel ‘Ampera’

E.g. Toyota ‘Prius’

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Engine fuel map: Specific Fuel Consumption (SFC) for a 55kW/75hp diesel engine
The hybrid window of opportunity: the window is a little wider than laboratory data suggests...
The theoretical window for hybrids

Oversized propellers

Undersized propeller

SFC versus boat speed for a wide range of propellers

230 g/kWh
Initial HYMAR assumptions:

- Engine within 5% of peak efficiency, i.e. $230/0.95 = 242 \text{ g/kWh}$
- 90% generator electrical efficiency, i.e. $242/0.9 = 269 \text{ g/kWh}$
- 90% electric machine + controller efficiency, i.e. $269/0.9 = 299 \text{ g/kWh}$
- 85% TPPL efficiency, i.e. $299/0.85 = 352 \text{ g/kWh}$ (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
Target SFC

Nominal 22 kW/144v Polar Power generator, stator winding 1

24v & 12v alternator loads

kW

SFC (g/kWh)

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The conflict between marketing, life expectancy and fuel efficiency

All power ratings assuming 90% electrical efficiency

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.
Electric machine + controller efficiency
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
Absolute fuel consumption, conventional versus serial hybrid

Note: this is one of the most efficient conventional engine + propeller combinations – i.e. it maximizes the challenge for the hybrid.

- Conventional
- Series hybrid without TPPL
- Series hybrid with TPPL

Cross-over point with TPPL batteries
Cross-over point without TPPL batteries

Volvo-Penta, 22” x 20”
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
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.