Where did the Energy Go?

Dave Jesse

This presentation was delivered at the Electrica 2024 conferencein May 2024. The slides were designed to be spoken to, not read, so this version is provided with notes to “fill in the gaps” for the viewer.

This slide shows my wife. Roma, with our electric narrowboat Perseverance at Odiham on the Basingstoke Canal.

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Who am I?

Engineer

- Chartered Engineer
- Member of:
  - Institute of Mechanical Engineers
  - Institute of Engineering and Technology
  - Royal Aeronautical Society
- Aviation Safety Specialist

Boater

- Father restored dredger “Perseverance” on the Basingstoke Canal
- Renting since 1976
- Timeshare since 2001
- Ortomariner since 2021

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This slide shows my girlfriend. Roma, and my father, on the steam dredger Perseverance at Odiham on the Basingstoke Canal.

Diesels are Simple

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Energy flow on a diesel boat is simpler to explain than on a hybrid boat, so we'll start here.

Diesel Fuel

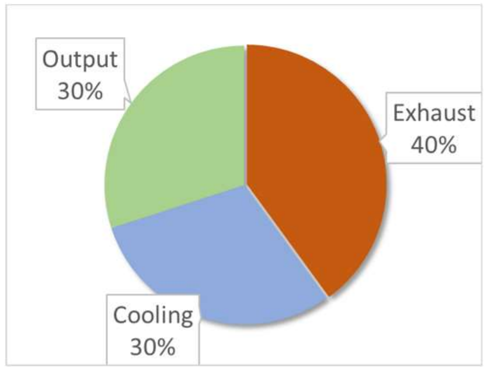
- Chemical Energy 10 kWh per litre
  - Same for HVO
- 2.68 kg of CO_2 per litre

10 kWh

Energy is measured in KWh (kilowatt-hours). For example, a 1 kW heater turned on for one hour converts 1 kWh of electrical energy into 1 kWh of heat energy.

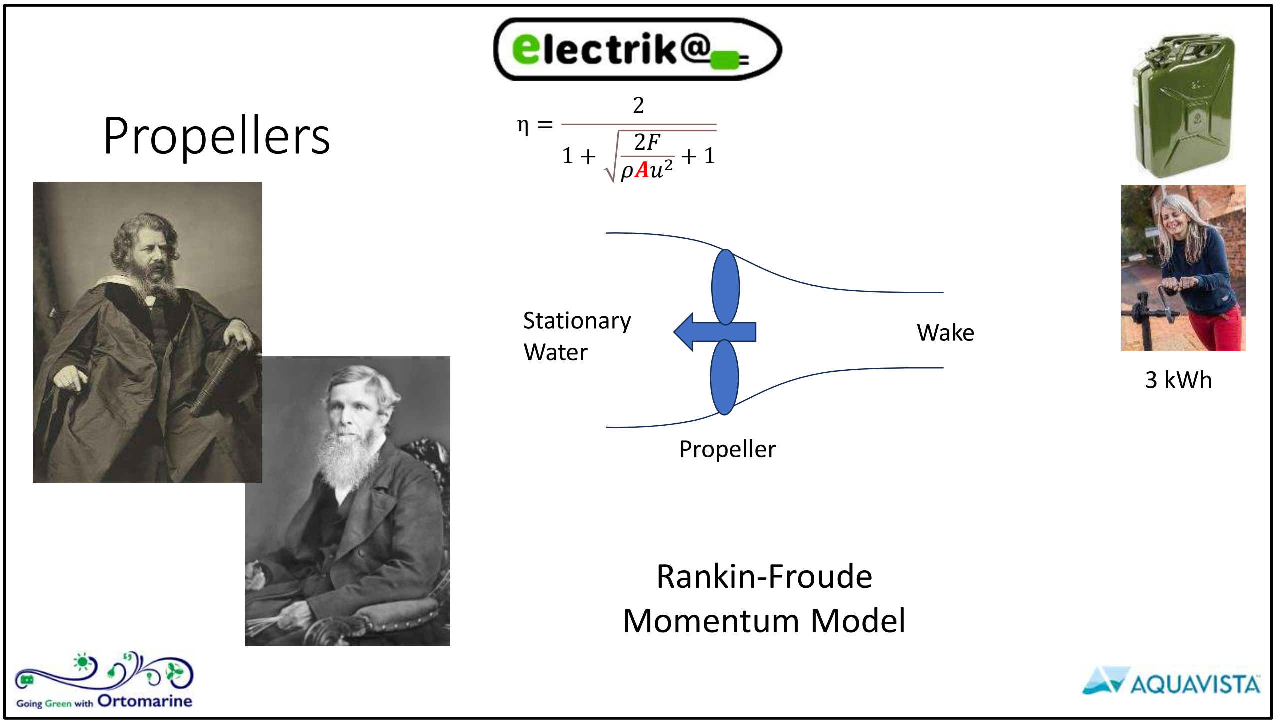
Diesel Engines

$$\eta = \frac{Q_{in} - Q_{out}}{Q_{in}}$$



3 kWh

Equations are for those interested, but can be ignored.
A typical diesel engine emits 40% of the input energy as hot exhaust, 30% is rejected into the cooling system and 30% is mechanical output. Energy in a turning shaft is how hard it is to turn (torque) times the number of turns.



To change rotational energy into linear energy we use a propeller. Low pressure on the front (left) of the propeller draws water into the disk, and high pressure on the back (right) of the propeller pushes the water away. This difference in pressure pushes the boat forwards.

The efficiency equation allows us to predict the highest possible efficiency of a propeller, and how it varies with area “A”.

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Propellers

$$\eta = \frac{2}{1 + \sqrt{\frac{2F}{\rho A u^2} + 1}}$$

- 16 in diameter
  - Theory = 0.50
  - Practice = 0.31

- 18 in diameter
  - Theory = 0.54

1 kWh

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In practice, energy wasted by swirling movement of the wake means the practical efficiency is lower than theory. 3 kWh x 0.31 = 1 kWh of linear energy (using sloppy engineering calculations!).
Linear energy is how hard the horse pulls times the distance he travels.

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How far can we go?

$$Distance = \frac{Energy}{Drag}$$

$$Drag = \frac{kU^2W}{L^{3/2}}$$

1 kWh

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To get distance, we divide energy by drag and so we need to understand the elements of the drag equation.

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Hull drag

$$D = \frac{kU^2W}{L^{3/2}}$$

- Long is Good

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For the same weight and speed, a longer boat has less drag.

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Hull drag

$$D = \frac{kU^2\mathbf{W}}{L^{3/2}}$$

- Heavy is Bad

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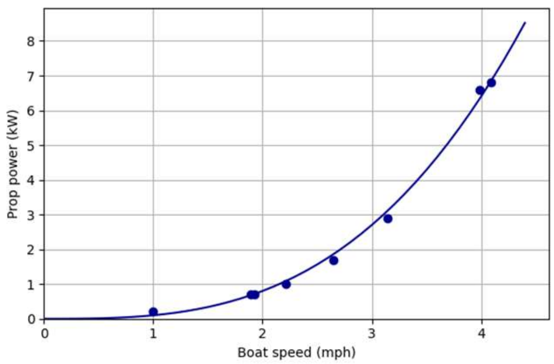
A heavier boat offers more drag.

Hull drag

$$D = \frac{k\boldsymbol{U^2}W}{L^{3/2}}$$

- Fast is Very Bad



	Slow	Fast	Ratio
Distance	2 miles	2 miles	
Time	1 hour	½ hour	
Speed	2 mph	4 mph	X 2
Drag	1 kN	4 kN	X 4
Prop Energy	3 kWh	12 kWh	X 4
Prop Power	3 kW	24 kW	X 8

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Left chart shows the power goes up significantly with the speed.
Table on the right shows how parameters vary with doubling speed – note that a doubling of speed results in EIGHT times the power.

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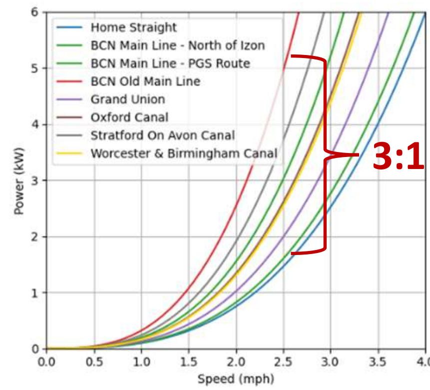
Hull drag

$$D = \frac{kU^2W}{L^{3/2}}$$

- k is Dave's Canal Factor
- Shallow is Bad



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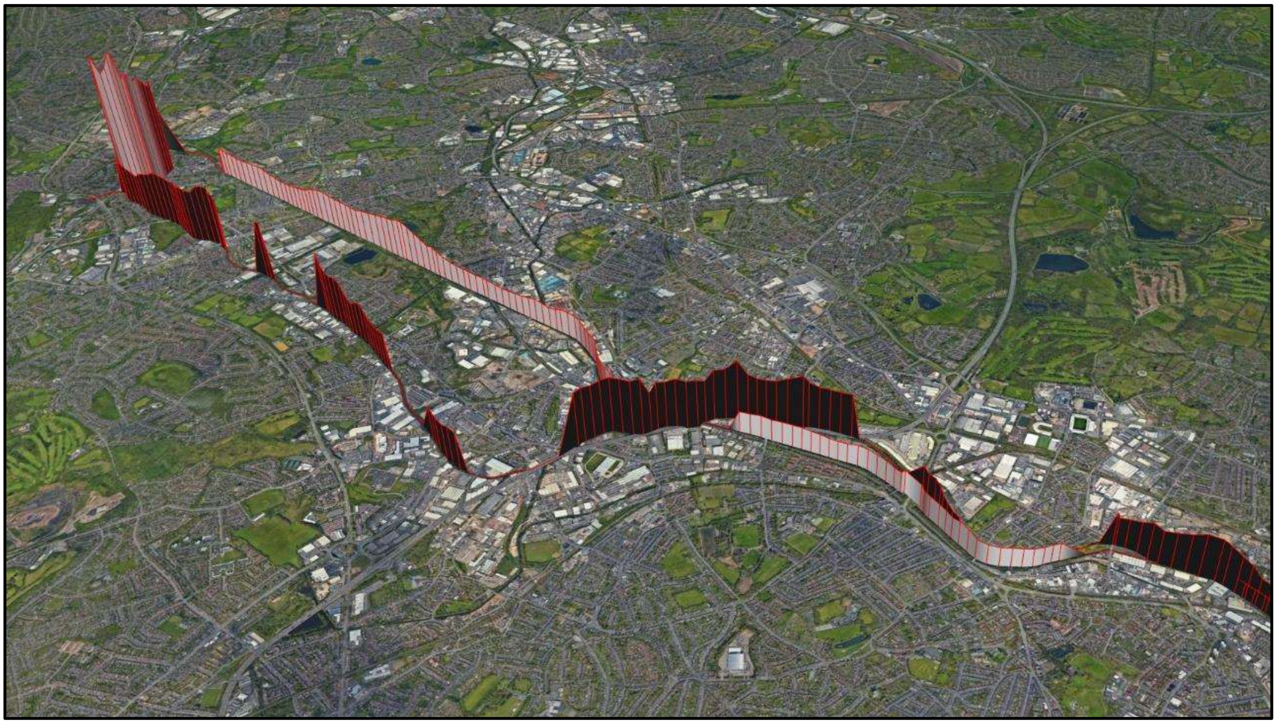
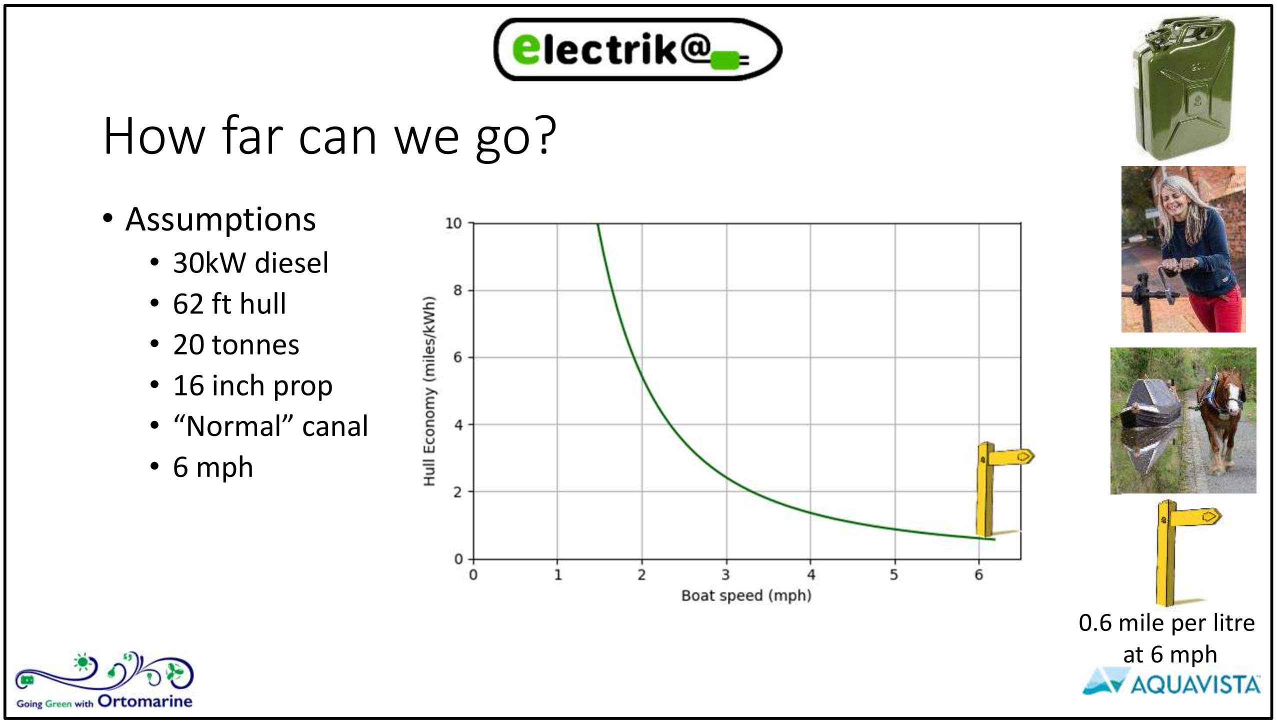
The factor k allows us to reflect the difference in canal drags. For a given speed, the power required to travel can vary by 3:1. (The right chart was measurements taken from Perseverance cruising different waterways).



This shows minute by minute values for k plotted on the canals of Birmingham.



The green line is hull economy, that is, how far it will travel for 1 kWh of energy. The signpost is the data point for a 30kW engine running at full power.

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Where Theory Meets Practice

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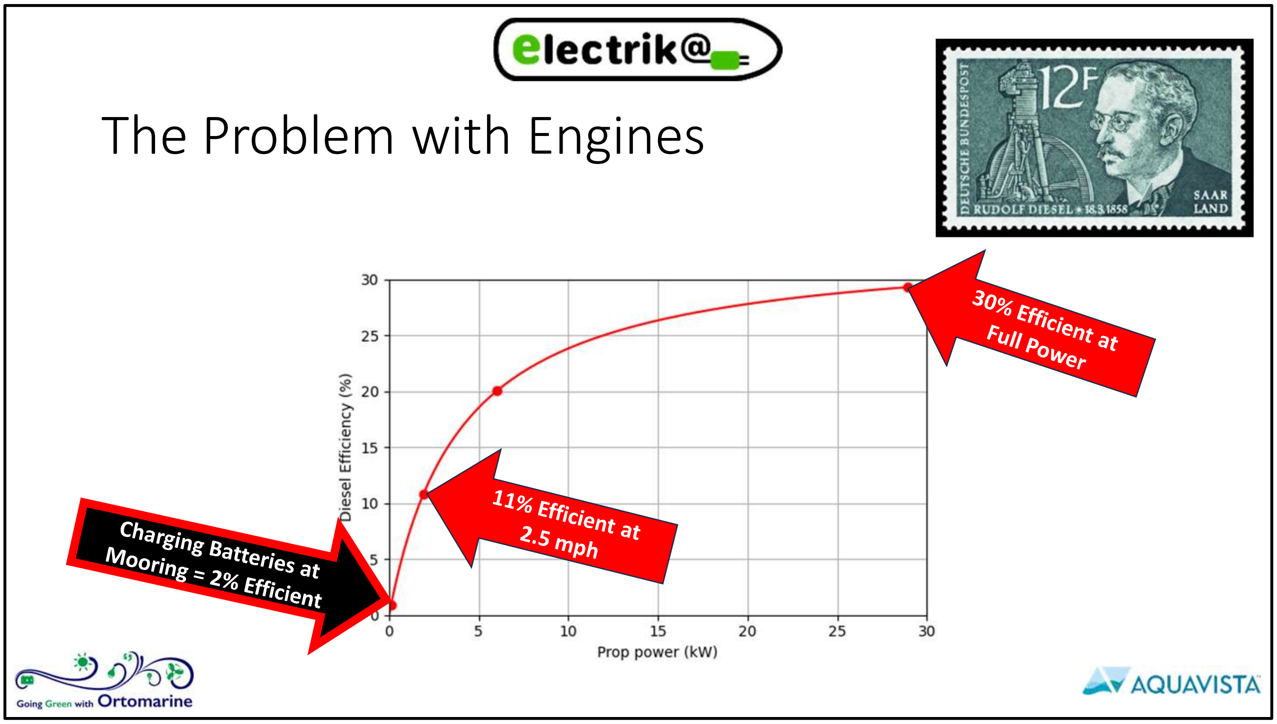
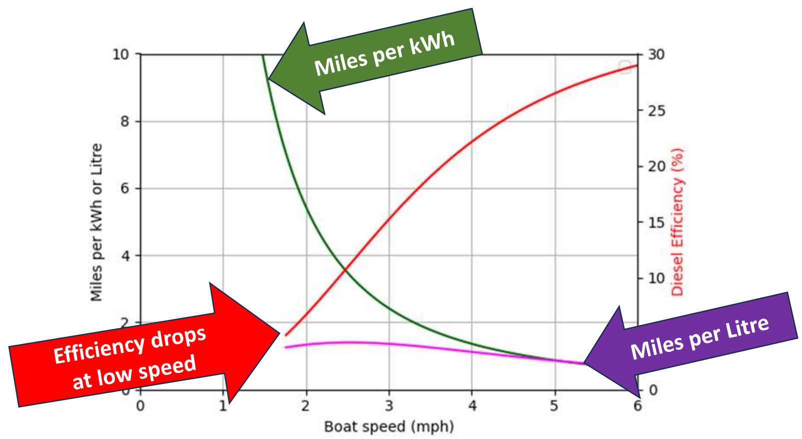
…but it's not all that easy…

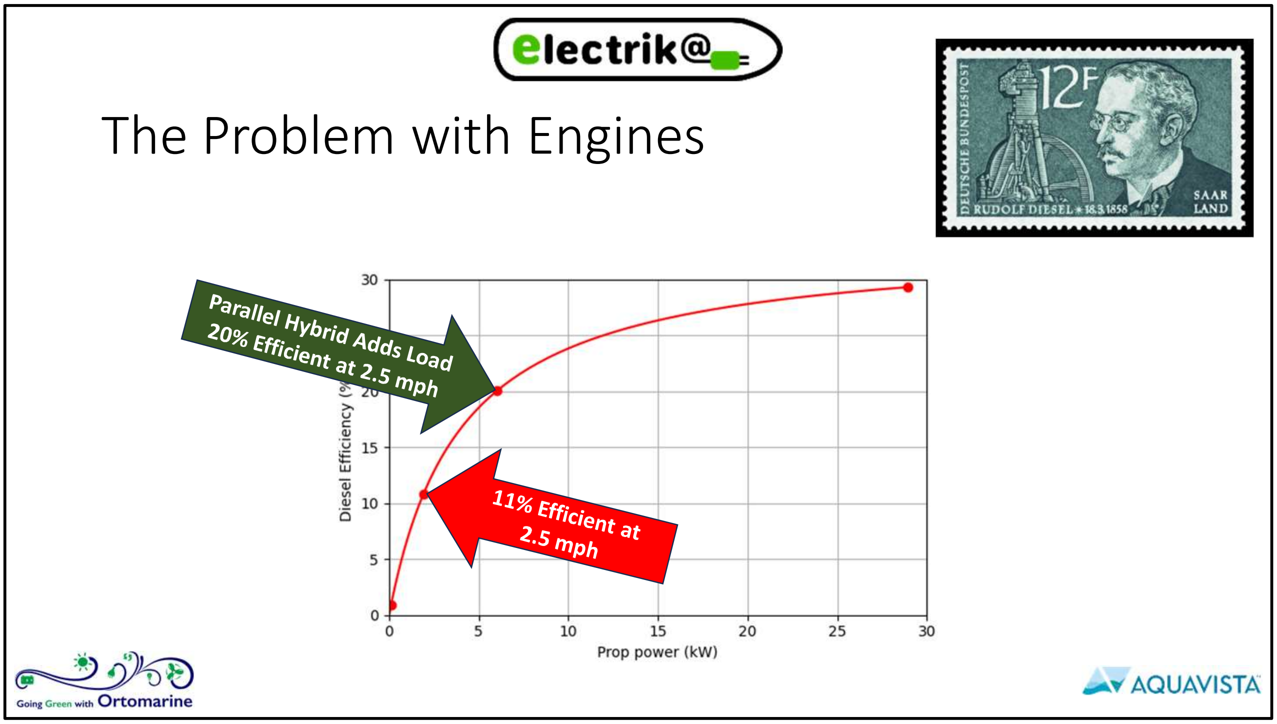


The efficiency of a diesel engine varies with power. The example points are:
Diesel at full power
30%
Diesel at 2.5 mph boat speed
11%
Sit at mooring, idling to top up lead-acid domestic batteries
2%

How far can we go?

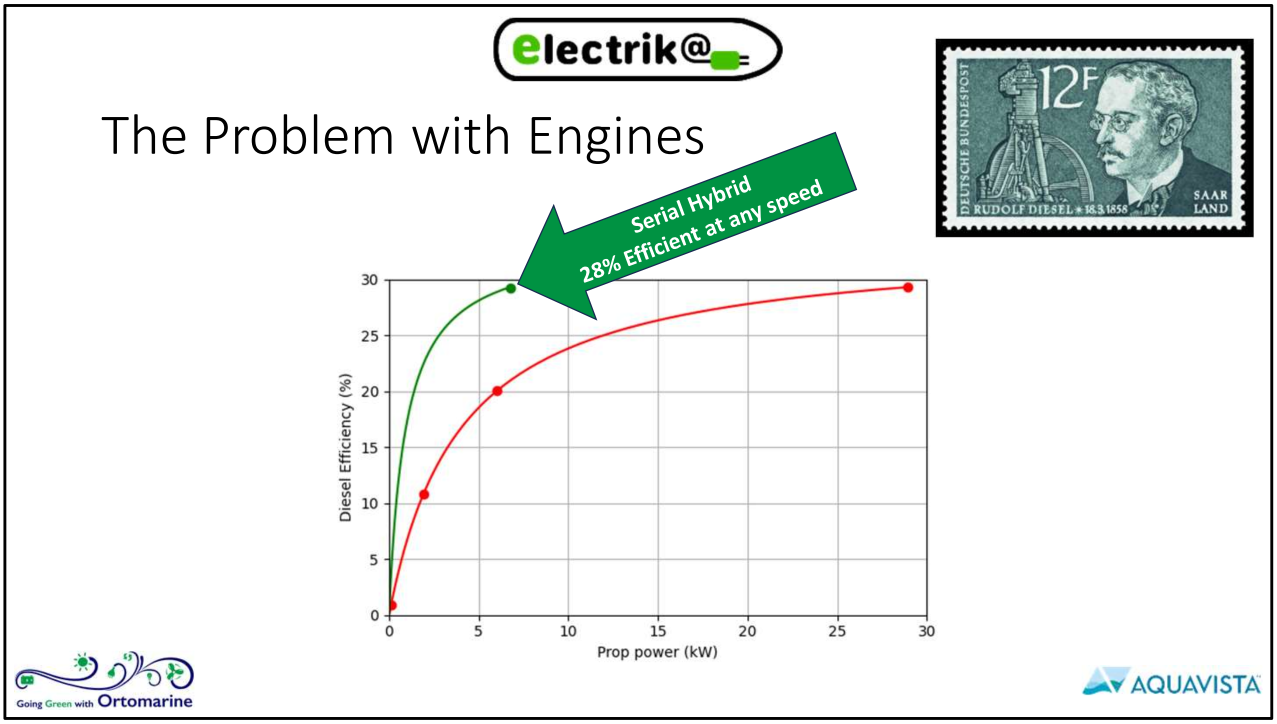


As boat speed reduces, the improvement of boat efficiency is offset by the reducing diesel efficiency at low powers. The net result is an almost constant fuel economy (purple) for a diesel powered boat. From 2mph to 4 moh, the miles per litre varies very little.



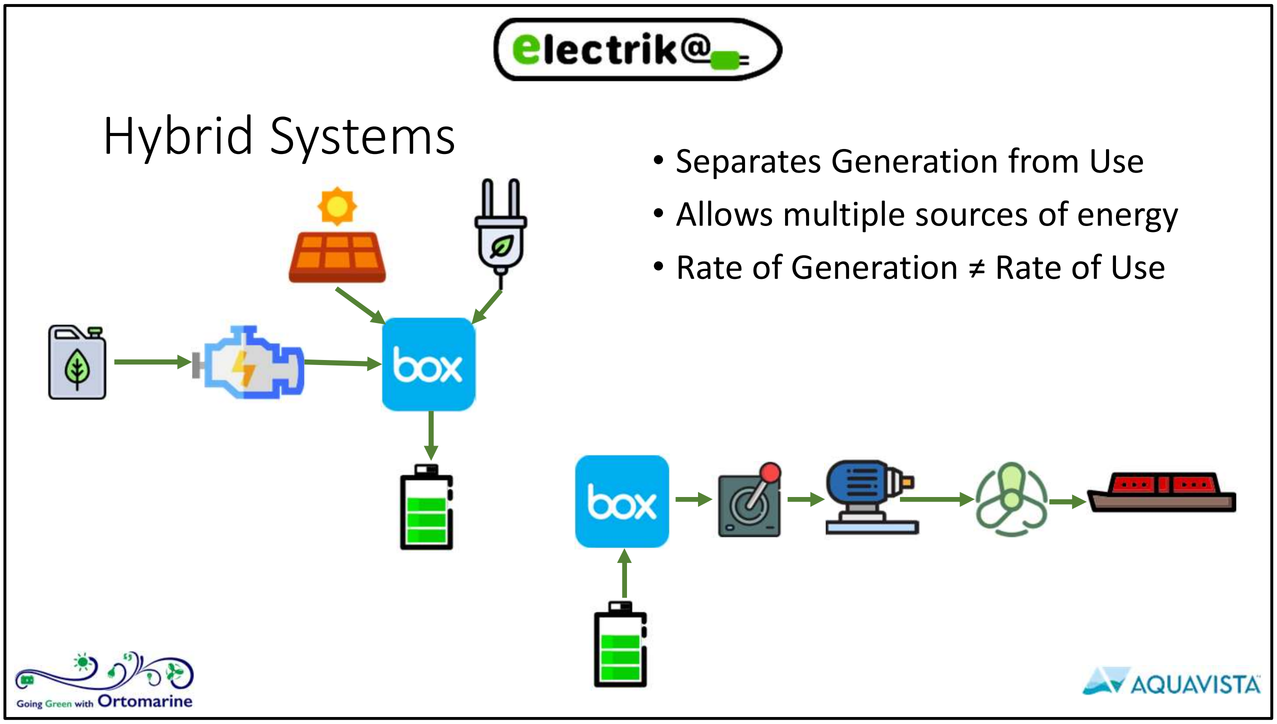
We can improve diesel efficiency by adding load, and in a parallel hybrid we add alternators so that it can generate electricity at the same time as driving the boat

Parallel hybrid
21%



To get the best efficiency we can install a smaller engine and run this at its high power/high efficiency point. Diesel engines reduce efficiency with size, so a typical 7kW engine will be 28% efficient at best, compared to 30% for a 30kW engine.

Fit smaller engine for generator
29%



Hybrid systems separate energy generation (left side of diagram) from use (right side).

A complete system uses one box of electronics to control both charging and discharging of the single battery.

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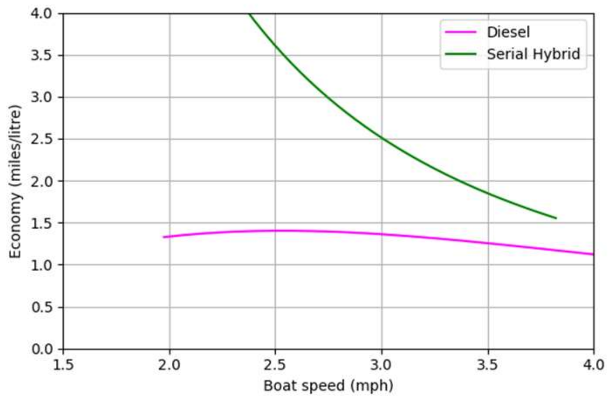
How far can we go?

- Serial Hybrid using diesel fuel – no solar or shore power



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A serial hybrid makes full use of the improving efficiency of the hull as speed reduces. Even generating all our power from diesel fuel, the miles per litre is far greater at lower speeds.

But…

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Hybrid System Efficiencies

Perseverance Components

Component	Efficiency
Alternator	85%
Electronics	96%
Battery	99%
Motor and Controller	80%

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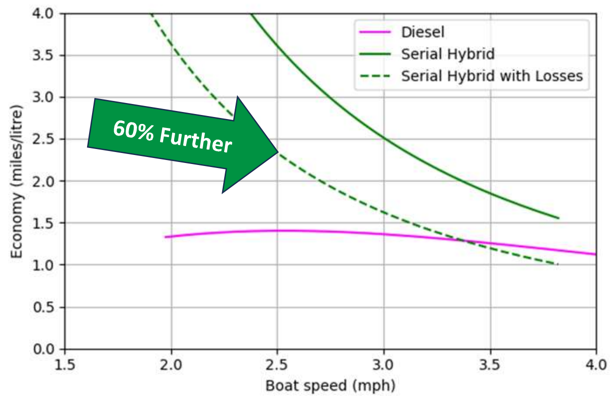
…we have added many electrical components, each of which has its own energy losses. These efficiency figures come from the Perseverance system.

The alternator in Perseverance is an induction machine, whereas more modern permanent magnet devices are more efficient.

The efficiency of electrical motors falls as you move away from the design operating point, in a similar manner to the characteristic we saw earlier for diesel engines. Fitting a motor of higher power may introduce greater losses at normal cruising powers in the range 1.5 to 3kW.

How far can we go?



Allowing for all the inefficiencies in the preceding slide, Perseverance still travels 60% further per litre than if it were fitted with a normal diesel engine.

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Reducing Emissions

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Emissions

Speed	Power	Emissions (kg of CO_2/mile)			
(mph)	(kW)	Diesel	Serial Hybrid		
			Generator	Plug In	Sunshine
2	1.0	2.0	0.8	0.04	0
2.5	1.9	1.9	1.1	0.06	0
3	3.3	2.0	1.7	0.09	0
4	7.9	2.4	3.0	0.15	0

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This table shows the emissions for a boat travelling at the speeds and powers given in the left two columns.

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So What?

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What does this analysis tell us about what we should do?

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What can Boat Builders Do?

Topic	Change	Improvement
Longer Hull	55 ft to 58 ft	8%
Longer swim (especially stern swim)		
Lighter Boat	Avoid 1 tonne of batteries	5%
Keep motor small	20 kW to 10 kW	20% ?
Component selection critical	e.g. Permanent Magnet not induction	10%

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Recommendations for boat builders.

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What can IWA/CRT Do?

Objective	Solution
Reduce canal drag	Collate canal restriction data Dredge where appropriate
Supply low carbon energy	Fit more charging points Be ready for charging point disputes

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The canal restriction chart here shows a spike of high resistance on the Northampton arm of the Grand Union. A collated set of resistance data could be used to quantify the benefits of dredging.

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What can Owners Do?

Topic	Change	Improvement
Parallel Hybrid Operation	Maximize charging rates	
Go slowly	3 mph to 2.5 mph	42% less power 30% less energy
Don’t rush shallow sections	Allow the speed to fall away	50% less power in places

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Recommendations for boaters.

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What can a Buyer Do?

Objective	Solution
Listed to the chug of an old diesel	Fit a Bolinder
Smell the fumes , be deafened in tunnels and support global warming	Fit a diesel
Travel the rivers and estuaries with reduced emissions	Fit a parallel hybrid
Travel the canals with minimum environmental impact	Fit a serial hybrid Fit big solar panels – large batteries help
Travel the canals in silence at all times	Fit a serial hybrid – generator in the bow

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Ribble Link

- Requirement = 2.5 hours at 6 mph
- 2 x speed = 4 x energy = 8 x power
- Say, 3kW @ 3 mph > 24 kW @ 6 mph
- 24 kW for 2.5 hours = 60 kWh battery
- Impractical for current generation serial hybrids

Beneteau Antares 760

- 3 tonnes
- 140 kW
- Cruising speed 20 mph
- Max speed 27 mph

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Not shown at Electrika, this illustrates how the formulae can be used to predict the power and energy requirements for a given task.
The photograph is from the Ribble Link website, showing a more suitable vessel for this crossing. It has a 100 times greater power:weight raio than most electric narrowboats.

Energy, Power and Efficiency

- Power
  - Mechanical
    - 1 kW = 1.34 hp or 3 kW = 4 hp
    - Linear Power = Force x mph
    - Rotational Power = Torque x rpm
  - Electrical
    - Amps x Volts = Watts
- Energy
    - Power (kW) x time (hours) = kWh
  - Chemical:
    - 1 litre of Diesel = 10 kWh
  - Electrical:
    - Amp.Hours x Volts / 1000 = kWh
- Efficiency
  - What we want out / What we have to put in (%)

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Formula for reference

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  - My own
- Propellor
  - In common use across the shipping industry – could not identify copyright owner
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