Performance Reliability Simplicity

14 m Fire and Rescue Vessel – Germany

Vessel Particulars

Length OA	14.0 m
Length WL	12.0 m
Beam	4.60 m
Displacement	23.9 t light
	25.5 t full load
Waterjets	2 x Doen DJ172-HE
	432 mm axial build with hybrid PTI
Engines	2 x Volvo D13-700
	rated 515 kW at 2250 rpm
Gearboxes	2 x ZF 325-1 ratio 1.459:1
Electric Motors	2 x Molabo Aries i50
	Rated: 50 kW at 4350-6500 rpm
	Designed: 35 kW at 3050-6500 rpm
	Neugart planetary gearbox 3:1 ratio
PTI/PTO	Carbon belt
	1.422:1 drive belt ratio
Performance	31.3 kn at 25.5 t (diesel mode)
	33.5 kn at 25.5 t (boost mode)
	6.8 kn at 25.5 t (electric mode)

Project Overview

Kewatec Shipyards in Kokkola, Finland, was contracted by the City of Kiel Fire Department in Germany to construct a fire and rescue boat (HLB) following its successful 2022 tender bid. The City of Kiel acquired the vessel for use in fire protection, rescue services, disaster response and civil protection in the Kiel Canal, Kiel Fjord and up to 10 nautical miles offshore. *Kewatec* tendered a variant of its *e-Work 1470 FiFi* design.

Waterjets have become standard equipment on high-speed firefighting vessels with their ability to position the vessel dynamically and to maintain station using vectored waterjet thrust to offset the thrust forces of the fire monitor. Similarly, vessels required to perform in-water rescues rely on waterjet propulsion for its inherent manoeuvrability and safety around people in the water. An additional requirement of the design brief was for a hybrid electric propulsion capability maintaining speeds of up to six knots for up to two hours to facilitate loitering and rescue. Doen's hybrid waterjet design is the only hybrid waterjet solution with an integrated PTI and is the lightest and most cost-effective system available. Doen's hybrid jet models can be configured to operate in any of the following modes:

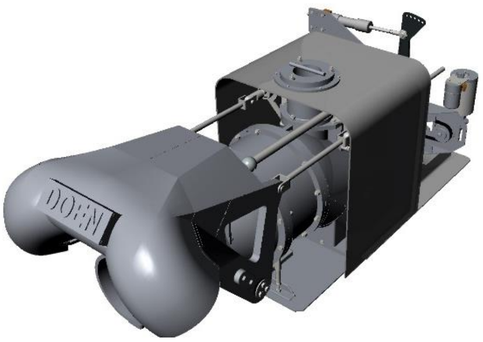
Diesel Mode – diesel engine only
Electric Mode – electric motor only
Boost Mode – diesel engine and electric motor combined
Charge Mode – diesel engine driving the electric motor as a generator to charge the batteries

The Doen DJ172-HE hybrid waterjet model was selected by Doen as the most appropriate solution. For this application, the DJ172-HE jets were configured for operation in *diesel*, *electric* and *boost* modes only, with *charge* mode not required by the end user.

DJ172 Waterjet Design

The DJ172 model is the largest model in the *Kompakt Series* of transom-mounted units. It was originally conceived as a heavy duty workboat jet for vessels requiring high bollard pull with modest input power but has since been applied successfully in applications up to 35 knots. As with all Doen waterjets, the DJ172 model has an axial build configuration with mixed flow properties based on the pump's specific speed. It has a 432 mm diameter impeller and a speed-dependent maximum power rating of 710 kW (950 hp).

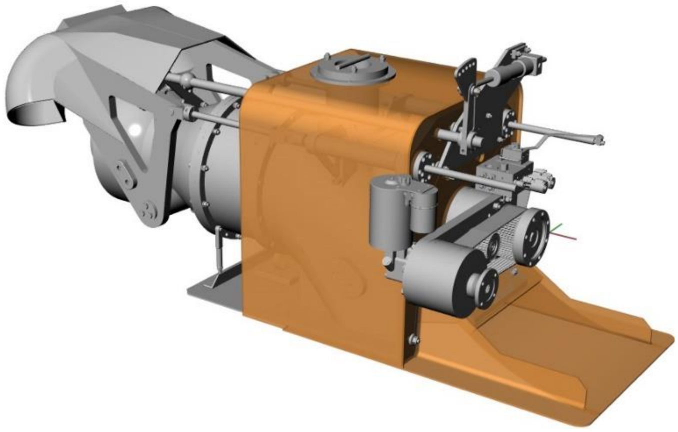
The *Kompakt Series* units are configured to fit into a transom insert of variable depth, allowing flexibility in machinery position and hull design. The insert can be manufactured by the boatbuilder or supplied by Doen as either a fabricated item for welding/bolting into the hull or as a mould insert for FRP hull construction. The design makes the DJ172 jet up to 32% lighter than competing models and avoids the use of heavy castings, bolted flanges and gaskets in the watertight hull envelope.



Standard DJ172 waterjet showing the deep insert option that allows the inspection port to be moved inboard.

Hybrid PTI Design Concept

Doen's PTI design differs from other hybrid systems: the Doen PTI drives the jet shaft in parallel to the diesel engine rather than through either the diesel engine's drive system (PTI gearbox) or an *in series* arrangement through an inline drive component or an inline electric motor. At first glance the gearbox PTI appears to be a neat solution, but modifications to a major item of machinery such as a gearbox are not easy to engineer and are expensive (small craft production gearboxes are not designed to be customisable). The weaknesses of the inline arrangements are their high capital cost, the need for the inline hybrid drive system to carry the full torque of the diesel engine, the system weight, and the loss of the entire drivetrain functionality in case of failure of one component.



Doen DJ172-HE hybrid waterjet, featuring a belt-driven PTI handed port and starboard. In this application, the hydraulic pump is driven off the hybrid PTI shaft rather than using a DC powerpack.

The Doen PTI design has another inherent advantage over others – the ability to be customised to project requirements. Matching the operating characteristics of the diesels, gearboxes, electric motors and jets to the operational requirements of the vessel and customer cannot be achieved with an off-the-shelf product without inviting compromises that could jeopardise the application.

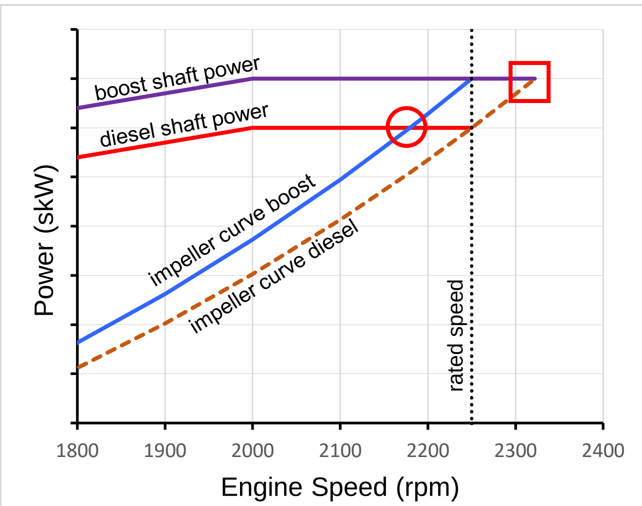
Technically, there are few limits to the input electrical power that the PTI can accommodate. Practically, there are limits set by the power transmission components (toothed carbon belts for low to moderate electric motor power and chain drives for higher electric motor power) as well as system matching. The most practical limit is not the PTI but the size, cost and capacity of batteries driving the electric motors. At present, the upper limit is around 150 kW into the PTI – a limit that is unlikely to be reached in practice due to the limitations of onboard hybrid energy storage.

PTI Design Challenges

The relationship between power and rotational speed (and therefore torque characteristics) of a diesel engine, waterjet and electric motor are fundamentally dissimilar. A further complication is that there are four possible hybrid operating modes – diesel, electric, boost and charge. Of the four, the diesel and electric modes are relatively easy to configure as they operate separately. Charge and boost modes each introduce increased complexity, and both combined have the highest degree of complexity. One of the principal parameters governing the system design is the ratio of electric motor power to diesel engine power (E/D ratio).

Most modern diesel engines with electronic governing have a narrow window of acceptable rated speed, with overspeed leading to power limitations imposed by the governor. In the boost condition, it's necessary to configure the waterjet impeller for the boost power rather than just the diesel power but at the diesel engine's rated speed. When operating in diesel mode without the additional boost power, the impeller pitched for boost mode overloads the diesel engine. That can be critical to the viability of the hybrid proposal if the E/D ratio is higher than about 0.3, which may cause excessive overload in diesel mode. Another limitation is that the PTI designed for the boost condition (and with a lower PTI drive ratio) may not allow the electric motor to develop full power in electric mode, with limitation caused by the waterjet power absorption characteristics. Means to circumvent this depend on any charge mode requirements and the mechanical speed limitations of the various system components.

It is sometimes necessary to select an electric motor with a larger frame size and higher torque capacity to provide a better system match. Unlike diesel engines, electric motors have only upper power/torque/speed limits and will operate at intermediate conditions with few constraints, though not always at peak efficiency.



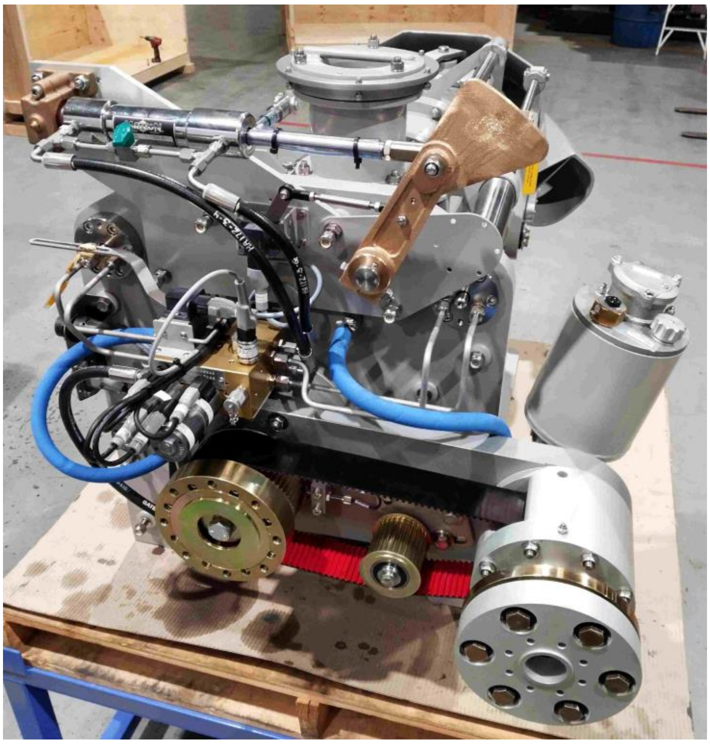
Boost mode design challenge for the 500 skW diesel at 2250 rpm with 50 kW electric motor: the impeller configured for boost mode can overload the diesel engine in diesel mode (red circle, 2180 rpm). If the impeller is pitched for the rated conditions in diesel mode, the impeller curve moves to the right and leads to an overspeed condition in boost mode (red square, 2322 rpm).

Another challenge is the need for some electric motors to be declutched to avoid an overspeed condition when not in use. The high torque output of larger electric motors requires use of a hydraulic clutch rather than an electric clutch, which itself introduces complication by requiring a hydraulic supply independent of the main machinery (to provide hydraulic functionality to engage the clutch whenever the diesel engine is shut down). The clutch unit may also have its own mechanical speed limit. Similarly, there is also a rotation speed limit for the diesel engine's gearbox to consider when the gearbox is freewheeling in electric mode. Few small marine gearboxes have trailing oil pumps as an option, though most will tolerate windmilling shaft speeds up to 1000 rpm.

Lastly, the waterjet controls must have additional functionality that recognise the hybrid mode options and control both the diesel engine and electric motor. The waterjet controls must also integrate with the battery storage and electric power supply components.

Doen DJ172-HE Project Solution

The specific project requirement was for an electric mode speed of 6 knots. Boost mode was also required to provide a power margin to meet the contract maximum speed of 25 knots at 85% diesel engine power.

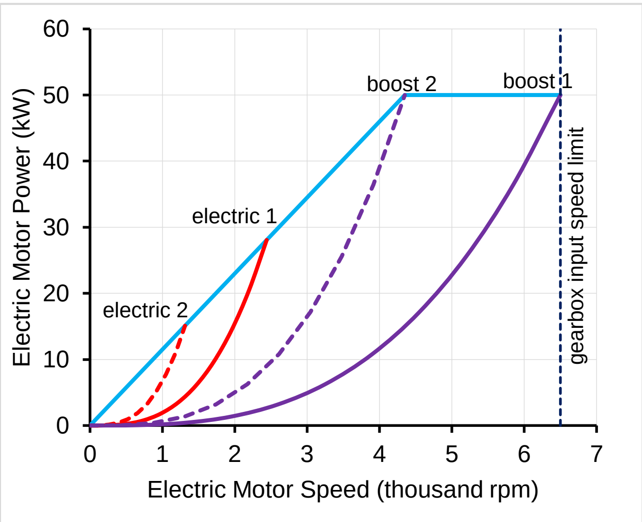


DJ172-HE hybrid design, with jet coupling left and PTI flexible coupling right. In a twin-jet application, the PTI equipment is handed for ease of installation.

The *Molabo* electric motor is one of several options preferred by builders because of its 48 volt designed operating voltage, avoiding the need for the specialised battery and motor installers required when the voltage exceeds 50 V. Another of its benefits is the capacity to freewheel when not in use, eliminating the need for a clutch on the PTI input.

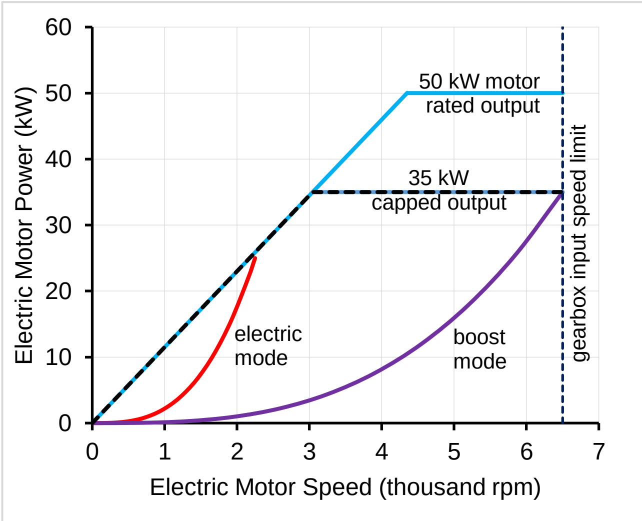
The selected drive belt ratio of 1.422:1 was a compromise between electric and boost modes. Although the *Molabo* motor has a maximum output speed of 8,000 rpm, the *Neugart* planetary gearbox has a maximum input speed of just 6,500 rpm. To maximise the power output of the *Molabo* motor, a belt drive ratio was selected so that the *Molabo* motor ran close to the 6500-rpm limit of the planetary gearbox in boost mode. In electric mode the torque characteristics of the impeller limited the available motor power to 25 kW.

The characteristics of the drive belt ratio match are shown in the following figure. The electric motor has two operating bands – a maximum torque band (the blue ramped power line to 4350 rpm) and a maximum power band (the blue flat power line from 4350 rpm to 8000 rpm but limited to 6500 rpm by the planetary gearbox). The electric motor can operate anywhere below those limiting values. The solution that maximised both boost mode and electric mode power was to design the belt ratio to achieve the highest electric motor speed in boost mode, moving both boost and electric mode impeller absorbed power curves to the right.

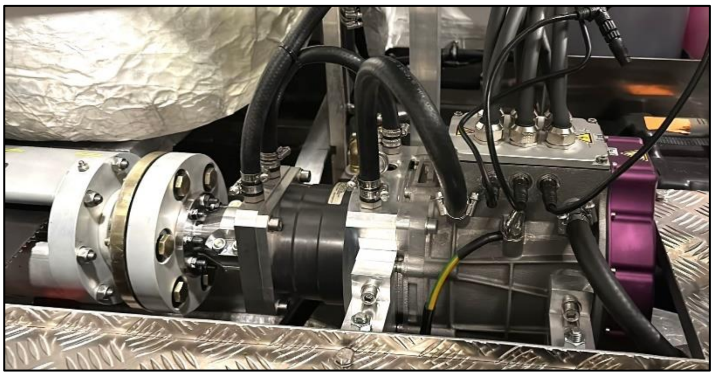


*PTI design matching for boost mode: **Option 1** boost match point is the maximum electric motor power at maximum motor speed. **Option 2** boost match point is the maximum electric motor power at minimum motor speed. The available power in electric mode is greatest when maximizing the electric motor speed in boost mode.*

The contract requirement of 6 knots speed in electric mode could be met with less than the maximum available 25 kW of electric mode power per jet. This effectively extended the electric mode operating range well beyond two hours. The contract maximum speed condition could also be met without resorting to boost mode and so the decision was made to cap the boost mode output of the *Molabo* motor at 35 kW.

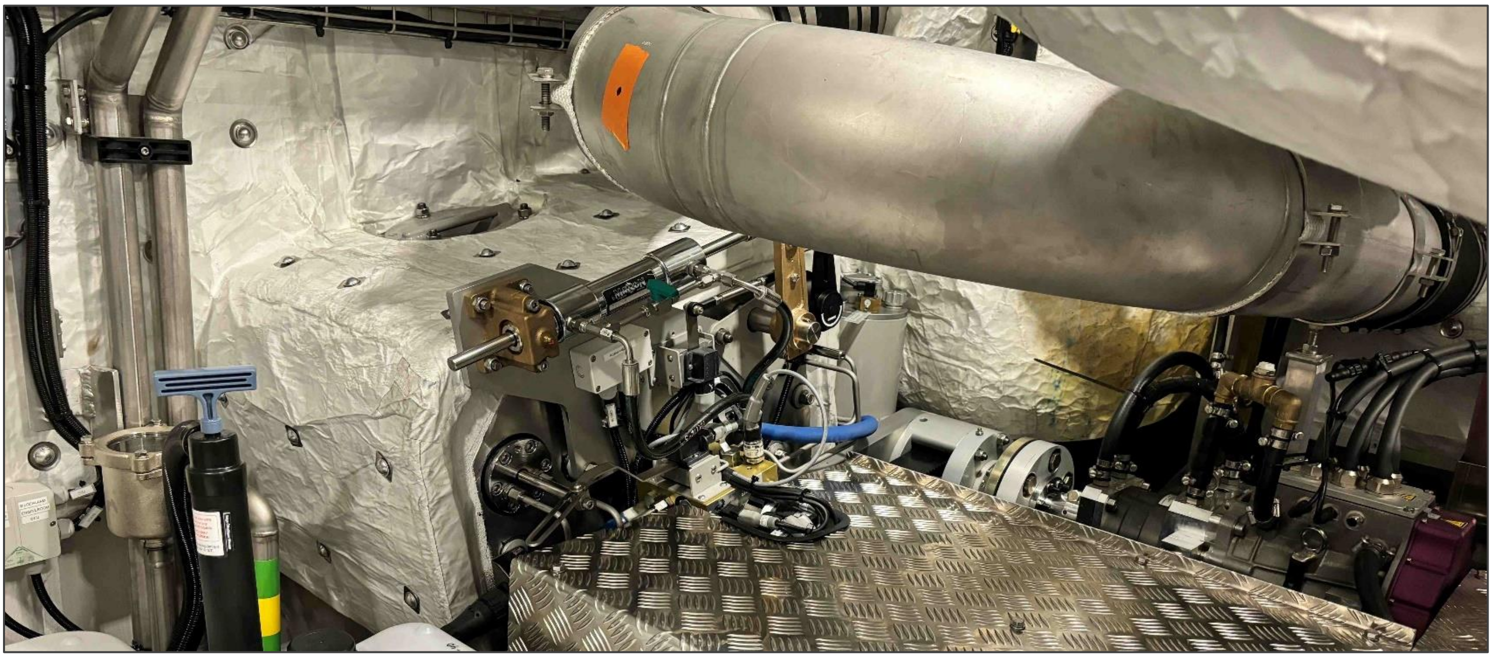


As-fitted electric motor power characteristics, with output power capped at 35 kW.



Final installation (port jet, looking outboard). The Molabo electric motor (right) drives though the Neugart planetary gearbox (centre) and into the PTI through a pin-and-bush flexible coupling (manufactured by Doen, left). Both the electric motor and planetary gearbox are freshwater cooled using a heat exchanger.

Doen's standard arrangement for the waterjet hydraulic pump in non-hybrid applications is to fit a pump to the live PTO on the main engine gearbox. In this way there is always hydraulic functionality whenever the diesel engine is running and before the jet shaft is engaged. In a hybrid application when the main engine may be shut down in electric mode, the gearbox PTO arrangement cannot be used. The two remaining options are either jet-driven hydraulics or a DC powerpack.



Port jet, looking aft. The DJ172-HE waterjet bolts into an aluminium insert supplied by Doen that is both simple to install and flexible in its positioning. The deep insert option shown here allows the waterjet inspection opening to be accessed from inside the vessel. All hydraulics are located inboard, with the hydraulic tank built into the waterjet body for passive cooling.

A jet-driven hydraulic pump provides functionality only when the jet shaft is engaged and running above a threshold operating speed for the hydraulic pump. Although it appears to be the simplest method, it requires the jet's electronic controls to enter a *minimum speed* condition when electric mode is engaged, ensuring the hydraulic pump exceeds its threshold minimum rpm (electric motors can operate down to zero speed; diesel engines cannot and so are easier to configure). That means it's not possible to take the electric motor down from the hydraulic pump's nominal *minimum speed* to a *zero speed* condition - a range which is usually too low for usable jet thrust anyway. Very slow vessel speeds can be achieved by using the reverse bucket to modulate the ahead thrust at the nominal minimum motor rpm condition to retain hydraulic functionality, which is not the most effective use of limited onboard battery capacity.

Doen can supply an optional self-contained DC powerpack for jet hydraulics. This is the only viable option when an optional hydraulic clutch is used between the electric motor and the PTI (with the diesel engine shut down and the jet shaft not turning, there can be no hydraulic functionality to engage the optional hydraulic clutch unless external to the drive system). Although the current draw of the DC powerpack can be over 70 amps at full power, the current draw varies with hydraulic pressure and flow demand and so the average current draw is relatively low. High demand is only seen during manoeuvring when bucket and steering usage is high, though never as high as the full pump capacity.

Waterjet Controls

To maximise the efficacy of waterjet installations with hybrid electric drive, the waterjet controls must retain their full functionality regardless of the operating mode. Doen has configured its standard ECS400 electronic controls to provide that functionality by allowing the operator to select any of the available hybrid modes (*diesel*, *electric*, *boost* and *charge*) from the station screen. Once selected, the control program logic sets the parameters for the machinery and gives the operator the necessary seamless transition between all four possible modes from a common set of controls.

Doen's ECS400 electronic control system has been expanded to take full control of hybrid drives, allowing the operator to select the required hybrid mode from the LCD touch screen and use the Doen control levers to control the hybrid system. The system can be configured as required.

The vessel is fitted with an *Undheim Systems JPOS* DP0 (dynamic positioning class zero) system, which enables both single joystick docking manoeuvres and station keeping when firefighting. The *JPOS* links the waterjets, main engine throttles and hydraulic bow thruster and replaces Doen's optional *eDOCK* joystick docking control.

Trials Performance

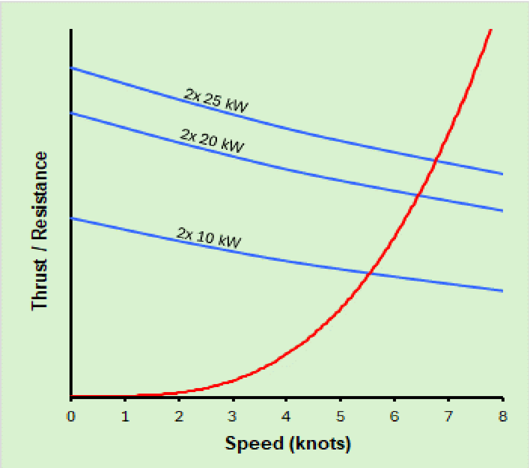
The vessel achieved a speed in the full load condition of 31.3 knots in diesel mode (2x 500 skW), 33.5 knots in boost mode condition (2x 535 skW), and 6.8 knots in electric mode (2x 25 skW), which correlated exactly with the predicted speeds.

The prediction of the speed in electric mode is challenging for several reasons. Firstly, there is very little available information on the drag of transom-sterned planing hulls at slow speeds, as it's not a condition of interest when such vessels have considerably more power and capacity for higher speeds. Secondly, waterjets experience positive thrust deduction whenever the transom is wet and the jets discharge underwater. This is not actually a reduction in thrust but an increase in hull resistance as the high-speed efflux from the jet nozzles increases flow around the aft part of the hull and generates reduced pressure on the immersed transom. Propellers create a similar effect on the hull, and it is customary to account for it by subtracting from the available thrust rather than adding to the resistance.

The predicted resistance exhibits the characteristics typical of a relatively short planing vessel laden with a suite of fire and rescue equipment. The steep rise through the semi-displacement condition and the flattened curve in the semi-planing condition reflect the vessel's low slenderness ratio (4.11) and low L/B ratio (2.72). Cruise performance is enhanced by the Humphree interceptors that provide dynamic optimisation of running trim. The performance and efficiency of the DJ172-HE waterjets validates Kewatec's decision to install jets of a size and pump configuration that underpin through-life performance.

Two other salient points from the trials performance graphs are relevant to hybrid installations. As with all vessels operating in the displacement and semi-displacement speed regimes, resistance increases sharply with increasing speed, requiring a disproportionate increase in power to achieve a modest speed increase. That has an impact on battery capacity and project viability. Conversely, a modest reduction in speed leads to a substantial reduction in power. For the fire and rescue vessel, reducing the speed from six to five knots more than halves the required power and hence either reduces the required battery capacity by 56% (based on fixed electric mode operating time) or doubles the range (based on fixed battery capacity).

Doen's recommendation when running on batteries is to operate at a speed so that the length Froude number is not more than about 0.25 (where $Fr_L = V/\sqrt{gL}$, with speed V in m/s and static waterline length L in metres). That condition is just under two-thirds of *hull speed*. For the fire and rescue vessel (and referring to the trials performance graph), hull speed is 8.4 knots and the recommended maximum electric mode speed would be 5.3 knots.



Electric mode results. With the motor power limited to 25 kW by the belt ratio, the predicted speed (with thrust deduction fraction of 0.2) matches the trials speed of 6.8 knots exactly.

Although there is a consistent belief that waterjets are inefficient at slow speeds, that's not necessarily the case. While it's true that the thrust deduction phenomenon, which also affects propeller installations, does reduce thrust at slow speeds, waterjet efficiency improves when the input power is reduced. Reducing power relative to jet size is the same in effect as increasing jet size relative to input power, both of which result in improved propulsive efficiency.