Regenerative Hybrid-Electric Propulsion

RENSEA REPORT, Phase 1

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PREFACE

At present, boats for nature tourism activities suffer from not being environmentally friendly, and from being noisy and inefficient. This is also true for a number of other boats in a wide range of activities. As well, the economy of medium and short range vessels suffer from inefficient use of fossil fuel where renewable electricity could instead be utilised.

The objective of this report is to show how a regenerative hybrid-electric propulsion system can dramatically improve the economy as well as the experience during sailing of medium sized boats that operate by both motor and by sail. This report shows how these problems can be solved by using regenerative hybrid-electric propulsion instead of diesel engine based propulsion. A range of cases specific to concrete vessels are presented, as well as a discussion of the evaluations, choices, trade-offs, and tests that needs to be performed in order to pilot the application of regenerative hybrid-electric propulsion. Other energy efficiency measures onboard are also described, in particular capturing and utilising waste heat generated onboard.

Furthermore the report outlines a plan in three phases leading to a demonstration and qualification of the technology. During the phase 1 of this work, several partners have taken part and provided valuable know-how within the various specialist areas. Other partners have supported the project by providing funding.

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We want to acknowledge the contribution from the partners, which has made this project possible.

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1 SUMMARY

The RENSEA project is motivated by the large potential in maritime applications of regenerative hybrid-electric propulsion, a technology which has now become available as the result of the massive research and development in the automotive industry. Such a system will combine the strengths of an electric drive system, an ideally designed propeller, a modern battery system, and the optimised use of diesel as a source of energy. For a ship with sails, regeneration adds the benefit of capturing energy generated by the sails during good wind conditions, to recharge the batteries. Resulting from this, large savings are made, and the reduced use of fossil fuels means a much reduced carbon footprint, or for some use patterns, entirely eliminated. A ship of this kind can move silent, and stay silent for long durations while stationary at location, thus making the ship ideal for nature- and eco-tourism, leisure boating, cruising, and a range of other applications – possibly also creating new business, including tourism related jobs. These features also make hybrid-electric propulsion an attractive solution to a wider market in the medium/short range segment, e.g fish farming support vessels, ferries, SAR-vessels, harbour supervision boats, and more.

The drivetrain of a hybrid-electric propulsion system consists of a number of technologies and components that are all commercially available, but where each component to a high degree influences the efficiency and functionality of other components, and the total system. An in-depth study and iterative testing is required to develop the optimal system. Phase 2 of this project sets out to do this by engineering and retrofitting two vessels that are representative for nature tourism and medium range operation. The candidates that have been evaluated are the sailing vessels “Hildur” (58’) and “Opal” (76’), and the motorsailing vessel “Kallinika” (76’). This was done as part of phase 1 of this project, where the results indicate large potentials, both in economical terms as well as in an environmental perspective.

2 INTRODUCTION

The project is organised into three phases. The scope of each phase reflects that this is a piloting project were the final result can not and should not be predefined. The three phases are outlined below:

Phase 1:

Study of feasibility, scope, estimated performance, identification of relevant suppliers and partners for phase 2.

Phase 2:

Closing technology gaps, costing, engineering, building, testing, and optimisation of control software based on vessel operation.

Phase 3:

Data compilation, results, and lessons learnt. Evaluation of findings and identification of potential further work. Issue of Guideline document.

Phase 1 of the project is nearing completion, where the deliverable is this report and the results and learnings that are summarised here.

This report is broken into a description of a regenerative hybrid-electric drivetrain as applied on the case study vessels, a description with calculation of results for the three case studies:

- A market potential outline
- And a heat capture and use description and calculation.

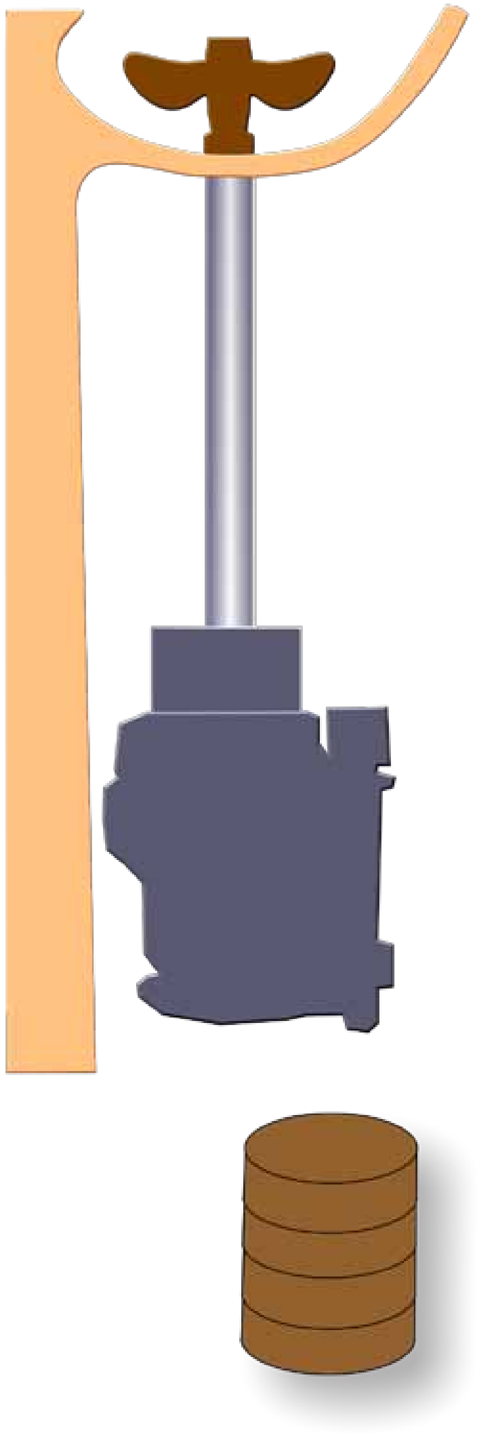
3. DRIVE TRAIN

The below section describes the drive system, including the individual components. For comparison purposes a conventional system is also briefly described.

Conventional drive

A conventional drive train, as shown schematically below, comprises a combustion engine, a reduction gear, and a propeller. When a controllable pitch propeller is chosen, a shaft extension control is also part of the drive train. Energy is normally supplied by means of diesel, but alternative fuels may also be used.

The conventional drive system suffers from a number of disadvantages, the major ones being environmentally harmful emissions using unsustainable hydrocarbon fuel, and the overall low system efficiency.



Relatively small propeller size
Running outside optimum curve due to engine speed.
May have controllable pitch in order to give the highest propulsive efficiency over a broad range of speeds and load conditions.
A fixed propeller has the highest efficiency, but only at one specific speed and load.

Medium efficiency

Drive shaft, with or without pitch control

Power loss 3-5%

Mechanical reduction gear and clutch, required to reduce drive shaft/propeller speed

Low efficiency <35%

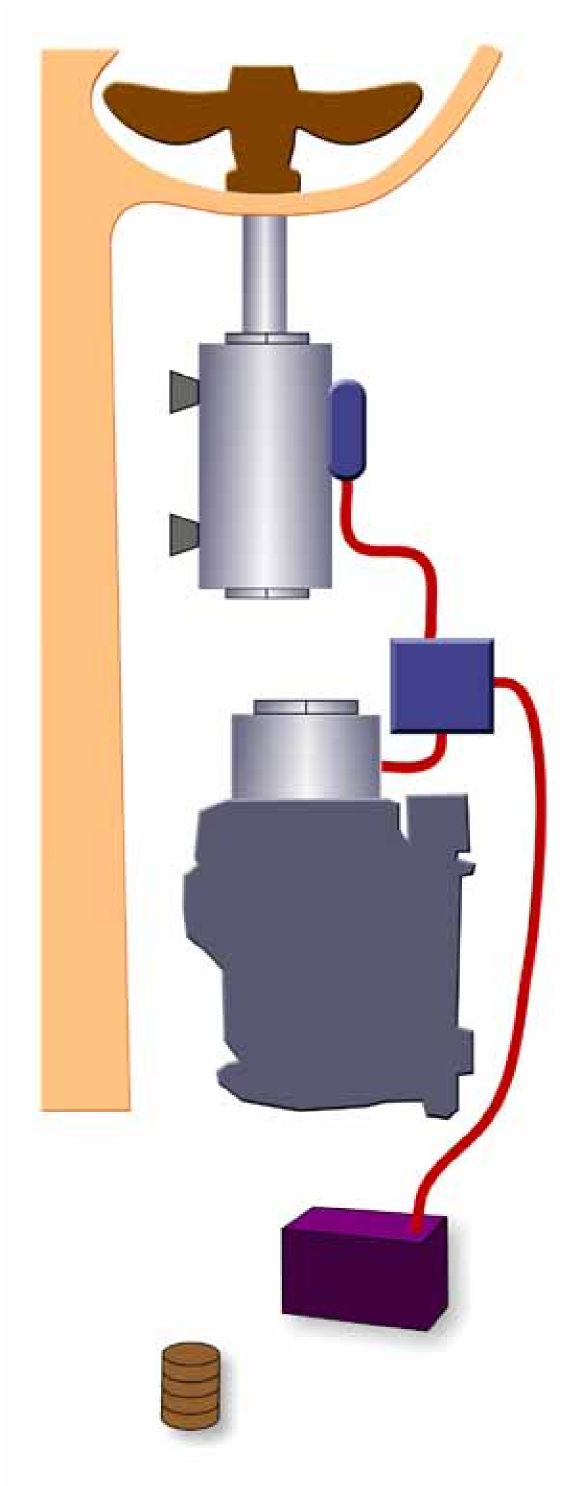
Combustion engine with inherent non-linear torque curve and fuel consumption efficiency.

Combustion of fossil fuel, no option for utilizing renewable energy

Emisssion for CO2, NOx, and SOx particles

Hybrid-electric drive

A hybrid-electric drive train, as shown schematically below, comprises a combustion engine running at constant speed driving an electrical generator, a charging control and variable speed drive power electronics system routing the generated electricity to the motor and/or batteries, and during sailing in regenerative mode, electricity from the shaft motor – operating as generator - flows back to the batteries. The system drives an adjustable pitch large propeller. No intermediate gear is required due to the low speed capabilities of the electric motor. Only when operating in diesel-powered mode, i.e. when generating electricity for propulsion and charging, will exhaust gas emission be produced.



High efficiency

A larger propeller which is optimised for low rpm. May have controllable pitch in order to give the highest propulsive efficiency over a broad range of speeds and load conditions. A fixed propeller has the highest efficiency, but only at one specific speed and load. A controllable pitch is essential for running the propeller efficiently as a generator driver

Efficiency: 85-95%

Drive shaft, with or without pitch control

Electric motor for driving shaft and propeller, and for regenerative charging during sailing

Efficiency: 90-97%

Variable Frequency Drive, and Charging control power electronics

Efficiency: 90-95%

Main electric generator

Efficiency: 30-40%

Combustion engine running at constant, optimal speed, running only intermittently - when required due to low battery level

Battery bank, storing and supplying electrical energy for the boat propulsion

Efficiency: 95-99%

Combustion of fossil fuel only when renewable energy is not available.

The hybrid-electric drive train components

This section describes the application, and each of the drive train components, together with design considerations and characteristics.

Hull

To understand the selection of drive train components, a high level description of hull characteristics is needed: The design of a seagoing vessel generally involves a trade-off between speed capabilities, loading & volume capacities, stability characteristics, heavy weather performance, and sailing versus motoring strengths.

Modern, commercial hulls generally have a design optimised for a high steaming speed and large loading capacity, whereas old ship hulls are optimised for being powered by sail, having less resistance through water at low to medium speed, and with a high keeling stability to allow for sailing in strong winds, as well as a slim foreship to reduce the slowing effect of going against rough seas. Traditional vessels of old design do not prioritise speed and loading capacity. The reduced power requirements are ideal for hybrid-electric propulsion.

As for all hulls moving *in* the water instead of *on* the water (displacement type hulls) there is a characteristic maximum speed where the drag increases steeply as a function of speed. This effect is utilised in the <u>Regenerative</u> Hybrid-Electric system: When sailing at close to maximum speed, a relatively high power can be re-generated at the cost of only a fractional loss of speed, even running the propeller-motor as a generator at a quite high load.

Propeller

The manner in which a propeller absorbs energy and transmits it to the water can be described by a propeller curve which plots the energy absorbed against the propeller’s speed of rotation. The resulting curve is almost always concave. If plotted on an engine fuel map, the propeller curve can never be made to follow the engine’s full power curve. As a result, propellers are typically sized such that the propeller curve crosses the engine’s full power curve at, or close to, the engine’s full rated speed. The goal of propeller selection is to optimise the match between motor torque and efficiency curve, and propeller optimum operating rpm. Further, to match the propulsion system characteristics with the vessel’s hull characteristics. There is a complex interaction between these elements, which is not possible to fully determine theoretically but requires sea trials and testing. However, the torque and efficiency curve of an electric motor is close to linear, as opposed to that of a combustion engine. This greatly simplifies the task of selecting an ideal propeller. An electric motor as driving unit enables running at a low speed as well as high speed with a minimum of losses. This again allows the propeller to be selected for optimum speed and size with regards to the hydrodynamics. A larger propeller is more efficient than a smaller one; hence a large propeller is chosen. The pitch of the propeller blades also plays an important role; optimum pitch closely relates to the speed through water and the loading of the propeller. This is an important factor both during normal steaming, as well as when sailing and regenerating power. For this reason a variable pitch propeller is chosen.

The geometry of the propellor blades will influence the efficiency in propulsion mode versus in regeneration mode, and needs to be further investigated. There is little knowledge of operating a conventional propellor as an open water turbine to generate power, and this area therefore needs to be further researched, involving expertise on hydrodynamics and propulsion development.

Propulsion Control System

The interaction between the propellor, the effects of the hull moving through water, the power from the sails, and the motor - or generator in regenerative mode - is very complex, and holds a great potential for optimisation of energy efficiency. Most importantly, the propellor pitch and the drive power - or regeneration power - must be optimally controlled. The behaviour and the physics can to some extent be mathematically modelled, but real life testing is required to tune these models. A Propulsion Control System will be developed specifically for the project, and will provide both the required propulsion control functionality, and a performance logging system.

Drive shaft

A drive shaft suited for variable pitch control is required. This kind of shaft is in general use also for conventional engine-powered vessels, and thus no specific development or testing is needed, assuming torsional strength is sufficient.

Electric motor

When selecting the best type of motor for hybrid-electric propulsion running the ship at a range of speeds, the priorities are different than for general application of electric motors. Efficiency is the most important factor, both for the motor itself, and for the system as a whole. For the system efficiency, performance at low rpm is the major factor, referring to the propeller characteristics. This translates into a requirement for running at high efficiency from low- to full speed rpm, with no significant dips in the torque curve. For these requirements an AC Permanent Magnet Motor (PMM) is sovereign over the more widespread AC Induction motor. PMM motors are inherently more efficient (10-20%) due to elimination of rotor conductor losses, lower resistance winding and flatter efficiency curve. However, thermal losses are still of a magnitude which requires efficient cooling in order to avoid overheating and consequently demagnetization. Water cooling is therefore chosen.

In a PMM, the rotor is fitted with a number of magnets instead of the electrical coils found in induction motor rotors. Both produce the required rotor magnetic field. The stator is in both cases fitted with several coils (multiphase) that are energised in sequence, creating a rotating magnetic field, thus making the rotor rotate. The principal difference between the two is that for the PMM, the rotor field is permanent and fixed, whereas for the induction motor the rotor field is created by induction from the rotating stator field. The induction requires that there is a difference in speed between rotor and stator, also known as 'slip'. For the PMM the rotation is at all times synchronous, i.e. no 'slip'.

The speed of a PMM is controlled by first determining the speed range by choosing the number of poles in the motor, and then by controlling the speed during operation by powering the motor from a Variable Frequency Drive. This gives a very wide range of very accurately controlled rpm.

The magnets in a PMM are made from Rare Earth materials (NdFeB, SmCo, NdFe, or other) that due to the limited supply are priced high, making a PMM more costly than an Induction motor. This can be alleviated somewhat by selecting the cheaper of the magnet materials, but that means a trade-off in higher weight and size.

Regeneration, i.e. running the motor as a generator, is straightforward for a PMM. Voltage and frequency is directly proportional to the rotational speed, and only needs to be electronically converted to the desired specifications before use.

The choice of motor operating voltage, frequency range, etc. is coordinated with the specification of the Variable Frequency Drive, which depends mainly on the required power.

Power electronics

The selection of power electronics is given by the selection of motor and batteries. Basically two types of power electronics are required in a hybrid-electric system: Variable Frequency Drive (VFD), and Battery Charger. These may be combined in any number of units, depending of manufacture, space, and cost considerations. The best option may be to combine all functions into one - in a bidirectional inverter/VFD.

The VFD takes DC power from the batteries and synthesizes the variable frequency sinusoidal AC which is used to power the electric motor. For low speed, a low frequency, low voltage output is created, and correspondingly a high frequency, high voltage for high speed. Additional controls are also included, such as controlled ramp-up to avoid overloading, torque control, and other motor-specific functions.

To enable regeneration and charge batteries and/or power utilities, electronics are included to convert electricity produced by the motor when running as a generator.

A Battery Charger converts AC electricity into DC, and feeds this to the batteries in a controlled fashion. Two charging regimes are required: Fast charging (fast, high current), and Normal charging (optimum time and current). In order to avoid damage or deterioration of the batteries – or even hazardous situations - the match between the control algorithms and the battery type is critical.

For fast charging a high-power shore connection is required, typically 3-phase 400V/400A.

In addition to the main Hybrid-Electric power electronics, inverters are required to convert the battery voltage to supply consumers onboard, e.g. 230V AC and 24V DC. These are not discussed here.

Generator package

The generator package comprises a combustion engine (diesel) and an electric generator, integrated into one package. The generator will run at optimum operating load, or not run at all. This is achieved by load-sharing between batteries and shaft, and allows for a highly optimised and efficient power generation and fuel utilisation. The duty of the generator package is to charge the batteries, and/or to power the motor (propulsion) when battery level is running low.

To determine generator capacity (kW), mainly three parameters are evaluated for each specific case (vessel): The steaming speed – the speed of the vessel which is efficient with regards to the hull characteristics and still is a satisfactory speed for the intended use. The maximum speed achievable with the power available onboard. And-, the maximum acceptable charging time during steaming. The choice of voltage level and AC or DC output will be determined by the overall system design.

As a default, the generator package will for practical reasons be fuelled by conventional diesel, whereas biodiesel or other environmentally friendly fuels could be considered for future solutions.

Batteries

First step in selecting a battery solution is to determine the capacity requirement. This is given by the average power consumption on board - typically when at marching speed, and for how long the vessel must be able to run on batteries under this load, and also including utility consumption onboard, such as instruments, accomodation, etc. Furthermore the batteries must be designed to handle the maximum load that can occur (e.g. at maximum speed). Other considerations such as estimated lifetime, temperature requirements, redundancy requirements, installation and layout, also play a role in the selection process.

Li-Ion batteries have a voltage range which the inverter needs to handle, typically 3…4 V per cell, a voltage which changes as it discharges. The Inverter or VFD is designed to match this voltage range, as well as the voltage and frequency range of the motor/generator.

Any range of battery voltages can be achieved simply by connecting the required number of battery cells in series, as long as the applicable insulation and installation requirements are met.

To decide which battery technology is most fit for purpose is a complex task, and involves a number of trade-offs:

- Cost is often a choice between high initial cost and low maintenance cost - or, low initial cost and high maintenance cost. The use pattern of the vessels chosen argues for choosing a high initial cost - because maintenance will be significant as the discharge/charge frequency is quite high - around 200 / year. Maintenance cost mainly comprises replacement cost of failed cells, and full replacement at the end-of-life of the batteries.

- Use pattern dictates the requirements for discharge rate/ time, charge rate, total number of discharges, ambient temperatures, capacity retention through lifetime, and for how long a low battery condition can be sustained without damaging the cells.
- The benefit of low weight and/or low volume often justifies the higher cost of more advanced batteries with a high power density (such as for electric cars). However, for a traditional sailing vessel weight or volume is not the most important factor, that is unless the weight and volume of installed battery capacity exceed a practical limit.
- There are safety issues with most types of batteries. These issues may be outgassing of explosive and/or toxic gases, risk of mechanical damage and leakage of harmful fluids, and risk of overheating and catching fire. For a passenger-carrying vessel operating in remote areas, these are particularly important considerations. The risks can in general be mitigated by ensuring a satisfactory installation (ventilation, monitoring, mechanical protection, fire extinguishing), by monitoring and shutdown functions, and by the choice of correct battery management system. However, choosing a battery which does not require a sophisticated support system could give the most robust solution.
- All the relevant battery technologies are using materials that are potentially pollutants and therefore have specific handling and recycling requirements. This can be a smaller or larger issue, depending on the materials. These are important environmental factors for choosing the battery technology.
- The environmental ‘footprint’ of a battery, as determined by a Life Cycle Analysis, shall be as small as possible, in particular when an environmentally friendly system is to be demonstrated. Such a ‘footprint’ comprises resource usage, energy use, carbon emissions, and pollutants - throughout the life cycle - from manufacture, through transport, and to recycling and disposal. A battery technology and manufacture with a the smallest environmental footprint is preferred.

The development of battery technologies is moving fast, and performance is steadily increasing, in particular with regards to energy density. There is a strong and growing demand and market for high performance batteries, which guarantees that the fast development will continue. This means that today’s technology quickly may become yesterday’s technology. When deciding the battery type, it is advisable to look forward, instead of basing the choice entirely on proven technology and energy/cost. This is even more true for a technology piloting and demonstration project where the next step may be a wider deployment of the solution demonstrated.

Battery comparison and selection

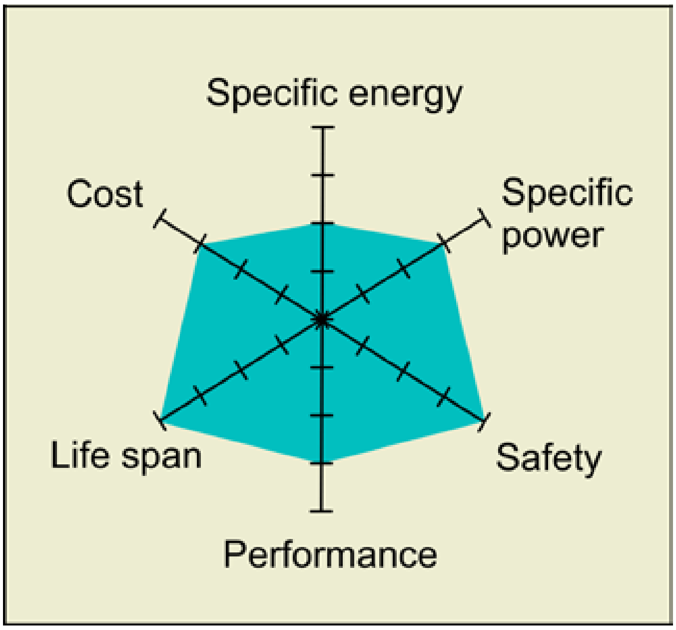
An extensive battery technology screening has been carried out, covering most proven, new, and emerging technology. The screening resulted in two alternative technologies being shortlisted for the project: Lead-Acid, and Lithium-Ion. Lead -Acid is the most cost-effective, whereas Lithium based batteries receive the most focus and development, and shows the most promise in the immediate future. A runner-up is the Lithium-Air battery, but the experience with these is still limited.
Below is a high-level comparison of the two shortlisted technologies, with the parameters most relevant for this application:

Comparison of battery technologies

Parameter \ Battery technology	Lead-Acid AGM	Lithium-Ion	Best technology
Cost, purchasing [$/kWh]	150	300 - 400	Lead-Acid (2-3x better)
Durability [cycles] (To when battery has degraded to 80% of nominal capacity)	300 - 500 @80% capacity discharge	200 - 5000 @80% capacity discharge	Lithium-Ion (up to 10x better)
Lifetime [years] (typically)	3 - 5	6 - 10	Lithium-Ion (2x better)
Discharge efficiency @ 4 hours [%]	80	99	Lithium-Ion (1.24x better)
Pollutant [material, disposal]	moderate	low (except Yttrium type)	Lithium-Ion
Carbon footprint [relative]	low	high	Lead-Acid
Safety [risk level]	low	medium	Lead-Acid
Reliability [risk of single cell failure]	low	high	Lead-Acid

Parameter \ Technology	Lead Acid	Li-Ion	Best technology
Specific Power [kW/l]	0,2…0,6	2,0…5,0	Lithium-Ion
Specific Energy [Wh/kg]	30…40	90…300	Lithium-Ion
Specific Energy [Wh/l]	Ca. 100	Max. 600	Lithium-Ion
Cell Voltage [V]	1,8…2,1	2,2…4,4	-
Typical round trip battery efficiency	85%	95-99%	Lithium-Ion
Technical challenge	Low temperatures, weight	Robustness and Safety	-

As can be seen from above tables, Lithium-Ion is generally better, except for cost, where Lead-Acid cost is significantly lower. However, the lifecycle cost would be lower for Lithium-Ion when the number of cycles exceed approximately 1000 cycles. The main purpose of the project is to pilot, test, and demonstrate a novel hybrid-electric regenerative propulsion system for different use patterns. The best available technologies (BOT) should be chosen, and not exclusively the lowest cost equipment.
The choice of Lithium-Ion is therefore the conclusion of this evaluation, and hence this technology is further evaluated below.



Suitable Li-Ion batteries

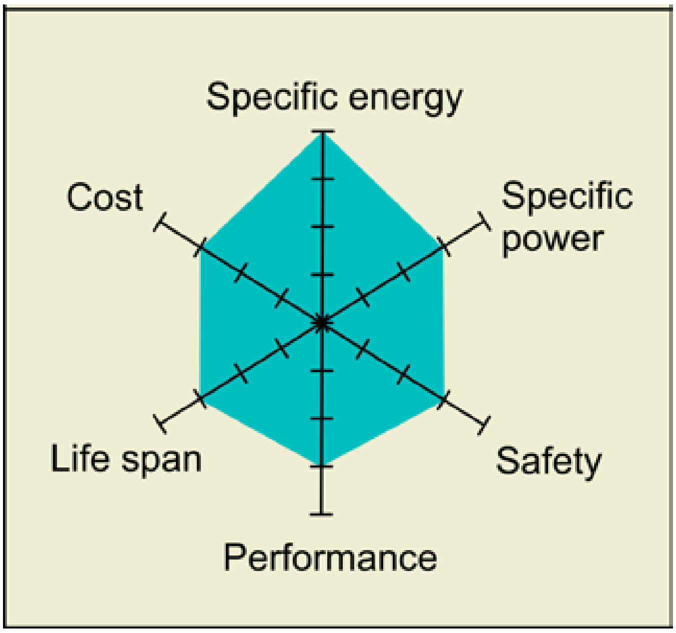
The term “Li-Ion” is referring to a whole group of different available chemistries, each one being tailored to serve a specific purpose (e.g. lifetime, charge/discharge profile, energy or power optimized, energy/power density, cooling etc.). In the following, two of those chemistry groups that are best suited for maritime applications and the typical requirements herein, are evaluated. The life time, cost and safety aspects are the most important factors for picking those two cathode chemistries.

PRO

- No oxygen evolution during a thermal event
- Cathode active material cost
- Basic cell level safety
- Potential cycle life
- Power density
- Cathode not composed of valuable or toxic elements.
- Widely used Yttrium additions to the cathode material can be considered mildly toxic.

CON

- Life time storage, risk of iron leakage from cathode
- Energy density
- Real life safety track record
- High amount of flammable electrolyte per Wh capacity
- Difficult SOC estimations because of limited slope on voltage curve
- Variable production yield, risk of free iron in cathode material



PRO

- Cycle life
- Life time in storage
- Energy density
- Safety track record
- Accurate SOC estimations possible
- High production yield

CON

- Cathode material cost
- Oxygen evolution during a thermal event
- Careful engineering required to avoid pack propagation
- Contains cobalt, expensive and mildly toxic. Cobalt containing alloys are used for hip replacements

Life cycle analysis and environmental impact

In an LCA study conducted by Professor Strømman's group at the NTNU, it has been shown that the environmental impact from batteries using Lithium Iron Phosphate ($LiFePO_4$) and Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$) can be considered similar. This is, however assuming that the production yield is similar. Because cells containing $LiFePO_4$ cathode materials are sensitive to unreacted iron in the cathode material it is assumed that the environmental impact from cells containing $LiFePO_4$ cathode materials are similar or slightly higher than for cells containing Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$) assuming all other factors being similar.

Safety

Each battery, independent from its chemistry or type, is an energy storage, just like a gas tank is. Specific safety issues around Li-Ion batteries are discussed in public and there are many videos e.g. on youtube, featuring thermal events in Li-Ion cells.

Though modern and well developed quality control mechanisms have decreased the probability of a thermal event considerably, in a cell due to internal faults, also external factors can lead to cell overheating and thermal decomposition. It is therefore recommended to take into account countermeasures against cell-to-cell propagation, which should prevent a thermal event from spreading over the complete battery pack and thus reduce the fire threat to other equipment and eventually the vessel.

There have been two famous incidents recently, which have caused some attention in the public and raised the awareness of potential dangers with large battery packs:

- The JAL “Dreamliner” battery fire. The root cause is still unclear but latest investigations point to an internal short circuit. This battery format/size combined with the specific chemistry would not be used in maritime applications.
- The battery fire on board the “Campbell Foss”. A tugboat with hybrid propulsion and a battery pack from Corvus Energy. Continuous overcharge due to a BMS software fault caused a thermal event in the large format pouch cell pack.

However, multiple levels of safety mechanisms should help preventing a worst case situation. In all battery management systems, the cell temperature is monitored and protective functions including alarms will be activated in case of abnormal levels are detected. Battery safety is not a single feature, but the result from carefully chosen parameters such as:

- Chemistry
- Cell construction
- Mechanical and electrical design, both of cells, packages, and battery assemblies
- Functional safety strategy incorporated in hardware and software
- Test and validation of quality and functionality

Since the cell voltage of Li-Ion chemistry batteries is comparably high, there is a risk that hydrogen is produced when the poles come into contact with saltwater. In addition, the electric/electronic equipment contained within a battery can be sensitive against water ingress or pollution. Therefore, the packaging for a battery system, e.g. a module, needs to fulfil certain minimum protection requirements against water, chemicals, particles etc.

It is furthermore recommended to portion the energy storage because of safety reasons, redundancy, maintenance and serviceability and last but not least for practical handling and installation reasons. This normally involves having a series of segregated groups, instead of one single assembly. Cooling might prove necessary in case of high charge/discharge rate, but for the vessel cases proposed, the pack sizes and operational profiles seem suitable for a system with passive cooling/ forced air cooling. However, a water cooled solution should be investigated, depending on ambient temperatures and available air flow.

Even with a high level of inherent safety features, a fire extinguishing system is nevertheless a necessity for large battery installations. Since the cells in a Li-Ion package are not accessible for fire extinguishers directly, and some Li-Ion chemistries produce their own oxygen during a thermal event, it is recommended to apply large amounts of water to cool down the battery installation as far, and as quick as possible.

Despite the relatively high energy densities of Li-Ion batteries, the weight of a large battery system could be a challenge for both the handling and installing, as well as for the load carrying structure in the vessel, especially in wooden boats and generally in all retrofitting projects with limited accessibility and space. A distributed battery system may therefore need to be considered.

Battery management system

Usually, battery system suppliers have their own, or a preferred, BMS in their portfolio. Serious suppliers have the best knowledge and experience with own products, and will therefore be closely involved in the project. However, functional safety in the BMS might not be always developed against the same guidelines and requirements. Customization of the BMS when integrating it into a vessel is also needed. In most cases, the BMS will require a permanent, independent power supply and functional integration with the power management system and/or the charger system on board or on shore.

Tasks	Monitoring	Protection	Computation	Communication	Optimization
Functions	Voltage Temperature State of Charge State of Health Coolant flow Current	Overcurrent Overvoltage Undervoltage Overtemperature Undertemperature	Maximum charge current Maximum discharge current Energy delivered Total energy delivered Total operating time	Most common: CAN Direct wiring DC-bus Wireless	Balancing

For the pilot project a remote monitoring and data logging system will also be installed, which closely interacts with the BMS and potentially with other systems on board, and makes available the data logged, relevant to the pilot project development.

Second Life of Li-Ion batteries

Since maritime applications typically demand large battery capacities and these batteries represent a considerable investment, it is natural to take second life applications into account. Several automotive OEMs are for this reason cooperating with e.g. solar energy companies to ensure a proper second life use of batteries. Examples are: Tesla with SolarCity and UC Berkeley, and Nissan with Sumitomo.

The basic idea is that the usage profile and requirements are less demanding for different applications. Since automotive has the toughest requirements and customers might just accept a range reduction down to 80% of the original range, a battery backup system can have both lower requirements regarding power and capacity. Therefore the batteries' second life could even be longer than its first life application.

For maritime applications, the potential installed amount of kWh, especially in large vessels is so big that the opportunity for a second life is obvious.

Potential maritime battery market growth, measured by accumulated installed capacity in larger marine applications (supply ships etc.), the Norwegian segment.

The forecast is based on an expected 50% market share in supply ships and offshore related working vessels (Norwegian shipyards only) of battery systems within the next 8 years, and an increasing capacity installed on board from 800 to 1.800 kWh per vessel over the same period.

Recycling

Once batteries have completed their second (and potentially third) life applications, recycling of the batteries to recover valuable materials is the next step. Recycling is also recommended for faulty batteries where a second life application is not possible.

Umicore N.V. is a multinational materials technology company headquartered in Brussels, who have built an industrial scale recycling facility of end-of-life rechargeable NiMH and Li-ion batteries. This recycling process has been subjected to a life cycle analysis; using this process to extract nickel and cobalt saves 50-70% of energy and emissions compared to extracting nickel and cobalt from ore. Large battery manufacturers are widely using this facility.

SUPPLEMENTAL ENERGY SOURCES

Solar energy

An optional energy source onboard is solar panels. However, large amounts of energy can not be expected due to the limited space and area available, and the infeasibility of being directed towards the sun at all times. Realistically, only up to a few hundred watts can be generated on board the vessels proposed for this project. A challenge with solar panels onboard a boat is that it is virtually impossible to avoid shadowing parts of a panel. This has a strong detrimental effect on the power output. A solar panel comprises a number of solar cells connected in series, and if only one cell is shadowed this may cause the total output to fall much more than that of the single cell.

There are mainly two types of solar panels: the (mono-, and poly-) crystalline type (most widespread), and the amorphous silicon type. What characterises the amorphous type is that it can be made to be flexible and resistant to impacts (stepping on), and that it is less susceptible to the shadow effect. The drawback is that it is almost half as efficient as the crystalline type - in strong sun conditions. On the other hand, in overcast weather the efficiency may be better. Onboard a sail ship it is not advisable to mount panels in the rig, but instead on the deck, where stepping on must be expected. Consequently the amorphous and much more robust type is selected for the project.

For any type of solar panel in this kind of application a converter is required to bring the voltage level up to the voltage required for charging the batteries.

Wind energy

A wind generator as a source of energy is used widely to charge the batteries in sailboats. A range of well proven products exist in the market. These products are in general targeted smaller sailboats, where the wind generator is mounted on a dedicated side-mounted pole in order not to interfere with the standing or running rig. These wind generators are of the horizontal axis 'classical' type (wind mill), where the unit has to swivel around to always head up against the wind. A strong benefit of a horizontal axis wind generator is the relatively high efficiency which is inherent in this design principle. But, the wind generator is very visible, and can be quite noisy.

An other principle is the vertical axis type where the rotor revolves around a vertical axis, and therefore does not depend on the wind direction. Many variations over this principle have been developed, but the type of greatest interest for this project is the 'tall slim cylinder' type. By principle the efficiency of this type of wind generator is close to half of that of a horizontal axis type, however robustness, an unobtrusive form-factor, and the tolerance to gale-force winds, makes this an attractive alternative, in particular when it can be integrated into the rig, and thus become virtually invisible. Depending on size, up to 500W of power could be achieved onboard.

4. CASE STUDIES

We performed measurement on the power need of Hildur, Náttfari, and Kallinika with a tow test on a speed between 6-10 knots. The results from the towing tests made on Náttfari and Kallinika were transferred over to Opal. The tests were done in Iceland and Norway and the results from the tests are presented in the tables below.

The data from these tests gives an indication of the hull performance vs speed through water, but due to the drag from the propellor as well as the hydrodynamic differences between towing and steaming, these figures were not used as basis for selecting the optimum propellor. Instead the hull dimensions were input into a software-based mathematical model, which output the rpm, torque and propellor parameters, from which the power requirements are calculated. On this basis the battery size is determined, and the sailing time and range calculated. To give a basis for choosing an optimum use pattern, the overall sailing efficiency and the regeneration potential is also calculated over the given speed range.

Overall sailing (by motor) efficiency

The efficiency of a vessel moving forward by means of propulsion is determined as: shaft power / thrust power, where the shaft power is the product of torque and rpm, and the thrust power is the product of speed and hull resistance (at this speed).

Hull resistance increases approximately exponentially to speed, for a displacement vessel,- meaning that the sailing efficiency (energy/distance) gets worse at higher speed. The hull resistance is commonly determined by towing tests, but the measured towing force will not be exactly equivalent to hull resistance during sailing, due to differences in water flow pattern. A correction factor is therefore needed.

Propellor efficiency

On a theoretical basis, using established empirical equations, the efficiency of a propellor is governed by rpm, shaft power, pitch, and propellor area, - and velocity through water. In addition, the water flow conditions where the propellor is located plays an important factor.

- Propellor efficiency is (approximately) inversely proportional to the rpm (for a controllable pitch propellor) within it's operating range. In practice this means that as low rpm as possible is preferred from an efficiency point of view.

- In general, at low/medium low speeds, a higher number of propellor blades will reduce efficiency due to the turbulence of the water, although less load on each blade allows thinner blades and therefor less drag.

- A fixed, multi-blade, slow-revolving propellor can be designed to have a very high efficiency at the design speed, but will suffer at other speeds, compared to a controllable pitch propellor.

- The blade design also plays an important role for the efficiency. A multiple of factors goes into deciding the best design for a given application. In all case studies, regenerative will be one of the operating modes, which means that the propellor should also be efficient when running as a turbine to drive a generator. This requires a more symmetric shape of the blades than would otherwise be chosen. The propellor will continue to run in the same direction in this mode, but now the hydrodynamic forces will apply to the front side of the propellor blades instead of the rear side.

- The location of the propellor, with the distance from the skeg, the hull, and the rudder, will influence on efficiency. Basically, the more free space, the better. This is a consideration that must taken when upsizing the propellor.

Measures to improve efficiency

To achieve the optimum energy efficiency, both the design and the use pattern must be considered. The main factors are:

- Reducing the rpm. (A factor of 2 gives an approximate 10% improved propellor efficiency for a variable pitch propellor.) To enable a lower rpm, the size (i.e. surface area) of the propellor must be increased - by means of propellor configuration and design, or propellor diameter.
  Few propellor blades gives higher efficiency than more blades, due to hydrodynamic effects. A 3-blade propellor may be the best compromise between performance, and strength dimensioning and drag, but this must be evaluated in for each case.

- Optimise propellor blade design. Find the best compromise between motive efficiency, and regeneration efficiency.

- Reducing the speed of the vessel reduces power required to move through the water - along an exponential curve (approximate), which means that reducing slightly from top speed gives a dramatic increase in efficiency, e.g. reducing speed from 100% to 90% results in 20-30% improved overall efficiency.

- Optimally control (software) the pitch and loading of the propellor, taking into account thrust, torque, rpm, speed through water, wave loads, etc.

Table data and calculations

Data method

1	Towing force is measured during towing tests, includes drag from propellor. Results used for reference only
2	Speed of boat is measured during towing test.
3	Shaft speed is determined by the selected propellor’s characteristics based on modelling the hull characteristics
4	Shaft torque is dertermined by the selected propellor’s characteristics based on modelling the hull characteristics
5	Propeller thrust is determined by the selected propellor’s characteristics, based on modelling the hull characteristics
6	Propeller (forward) effiency is estimated from propellor design and operation
7	Required motor power is calculated as the product of torque and rotational speed
8	Sailing time is calculated as 0,8 x Battery capacity/Required motor power
9	Battery capacity is chosen - to give acceptable sailing times
10	Sailing distance is calculated as Sailing time x Speed of boat
11	Relative sailing efficiency is an indicator of how efficiency energy is used for getting from point to point
12	Regeneration shows how much power is available by reducing speed 1 kn (from 1 kn higher speed) at 100% eff.

Case study data, Kallinika

Displacement	90	ton	Block coefficient	0,37	
Draft	2.2	m	Center span area	5,6	m2
Length, wl	24	m	C m	0,57	
Beam	5.5	m	Prismatic coefficient	0,65	

Kallinika with 1300mm propellor (standard, 3-blade), 500kWh battery bank

Towing force (kn)	Speed of boat (Knots)	Shaft speed required (rpm)	Shaft torque required (kNm)	Thrust (kN)	Propellor efficiency (%)	Propel-lor pitch (mm)	Required motor power (KW)	Sailing time on batteries	Battery capacity (KWh)@0 8 used	Sailing distance on batteries (nm)	Relative sailing efficiency (nm/10kWh)	Regenera-tion with 1 kn of speed conv. (kW)
8,3	6,0	279	1,3		57,0	967,0	38,0	10,5	500,0	63,2	1,3	13,6
10,1	7,0	308	1,6		58,5	993,0	51,6	7,8	500,0	54,3	1,1	32,7
14,3	8,0	366	2,2		57,3	976,0	84,3	4,7	500,0	38,0	0,8	75,3
23,0	9,0	462	3,3		53,9	931,0	159,6	2,5	500,0	22,6	0,5	85,4
30,5	10,0	532	4,4		52,9	916,0	245,0	1,6	500,0	16,3	0,3	

Kallinika with 1800mm propellor (large, 3-blade), 350kWh battery bank. INCREASED EFFICIENCY CASE with larger propellor

Towing force (kn)	Speed of boat (Knots)	Shaft speed required (rpm)	Shaft torque required (kNm)	Thrust (kN)	Propellor efficiency (%)	Propel-lor pitch (mm)	Required motor power (KW)	Sailing time on batteries	Battery capacity (KWh)@0 8 used	Sailing distance on batteries (nm)	Relative sailing efficiency (nm/10kWh)	Regeneration with 1 kn of speed conv. (kW)
8,3	6,0	139	2,4	8,6	68,2	1666,0	34,9	8,0	350,0	48,1	1,4	12,8
10,1	7,0	152	3,0	10,2	69,5		47,7	5,9	350,0	41,1	1,2	30,5
14,3	8,0	178	4,2	14,5	69,0		78,2	3,6	350,0	28,6	0,8	63,4
23,0	9,0	205	6,6	23,5	67,5	1820,0	141,6	2,0	350,0	17,8	0,5	66,9
30,5	10,0	240	8,3	31,0	66,7		208,5	1,3	350,0	13,4	0,4	

As can be seen from the above two tables, there is a significant efficiency gain by choosing a larger propellor, i.e. 1800mm instead of the standard 1300mm. As an example, at 8 kn the same sailing distance on batteries is achieved with a much smaller battery bank, i.e. 350kWh instead of 500kWh, due to the higher efficiency of the larger propellor.

Case study data, Hildur

Displacement	55	ton	Block coefficient
Draft	2.6	m	Center span area
Length, wl	18,1	m	C m
Beam	4,8	m	Prismatic coefficient

Hildur with 1300mm propellor (standard, 3-blade), 300kWh battery bank

Towing force (kn)	Speed of boat (Knots)	Shaft speed required (rpm)	Shaft torque required (kNm)	Thrust (kN)	Propellor efficiency (%)	Propel-lor pitch (mm)	Required motor power (KW)	Sailing time on batteries	Battery capacity (KWh)@08 used	Sailing distance on batteries (nm)	Relative sailing efficiency (nm/10kWh)	Regenera-tion with 1 kn of speed conv. (kW)
1,8	6,0	159	0,66	3,0	70,3	1255,0	11,0	21,8	300,0	130,9	4,4	6,0
2,9	7,0	185	0,88	4,1	70,3	1258,0	17,0	14,1	300,0	98,8	3,3	29,9
7,0	8,0	276	1,63	9,2	64,4	1050,0	46,9	5,1	300,0	40,9	1,4	19,1
9,4	8,5	313	2,02	11,8	62,8	1096,0	66,1	3,6	300,0	30,9	1,0	11,0
11,8	9,0	329	2,24	13,1	63,0	1020,0	77,0	3,1	300,0	28,0	0,9	

As can be seen from above results, “Hildur” will have a quite high propellor efficiency, and also a very long range on batteries when steaming at low a low speed, e.g. more than 130 nm at 6 knots.

Case study data, Opal

Displacement	120	ton	Block coefficient
Draft	3,1	m	Center span area
Length, wl	24	m	C m
Beam	6,85	m	Prismatic coefficient

Opal with 1500mm propellor (standard, 3-blade), 300kWh battery bank

Towing force (kn)	Speed of boat (Knots)	Shaft speed required (rpm)	Shaft torque required (kNm)	Thrust (kN)	Propellor efficiency (%)	Propel-lor pitch (mm)	Required motor power (KW)	Sailing time on batteries	Battery capacity (KWh)@08 used	Sailing distance on batteries (nm)	Relative sailing efficiency (nm/10kWh)	Regeneration with 1 kn of speed conv. (kW)
9,0	6,0	197	1,7	9,0	61,3	1662,0	35,1	6,8	300,0	41,1	1,4	12,3
11,0	7,0	226	2,0	11,0	62,6	1187,0	47,3	5,1	300,0	35,5	1,2	28,4
15,6	8,0	268	2,7	15,6	61,6	1168,0	75,7	3,2	300,0	25,4	0,8	97,6
25,9	9,0	345	4,8		59,9	1140,0	173,3	1,4	300,0	12,5	0,5	82,0
33,3	10,0	428	5,7		58,1	1111,0	255,3	0,9	300,0	9,4	0,4	

The results for Opal are similar to Kallinika even though there are significant differences between the two. This is due to that calculations are not based on in-depth study of characteristics and modelling, but on overall data. However, this is enough to identify opportunities for optimisation.

System level comparison of operating cost

Comparing costs of running 24 m whale-watching boat on diesel-, electric-, hybrid- and Regenerative Plug-in Hybrid Propulsion

Propulsion	Consumption litres per/h	Power demand kw (avg.)	Cost € per litre diesel	Cost € per kwh electricity	Average fuel cost € pr/h	Average fuel cost € pr/3h trip	Fuel cost € pr year 240 trip	Relative costs
a) Diesel	22	(90)	1		22	66	15.840	100%
b) Plugin electric		50		0,08	4,4	13	3.168	20%
c) Hybrid	15	55	1		15	45	10.800	68%

The following calculations need sea-trials before completion:

- d1) RPHP Sail & battery
- d2) RPHP Sail & diesel
- d3) RPHP Sails only

a) Diesel

We base the calculation of fuel consumption on estimated numbers from a 3-hour whale watching tour. In a conventional whale watching tour the boat runs at 8 knots for approximately 90 minutes, and at 6 knots for approximately 90 minutes as well, without too much variation. Each year the boats of North Sailing, sail around 1100 tours and estimated numbers used in these calculations are based on many hundred trips. The boat that is used as a reference is 23 m long and uses approximately 22 liters pr. hour.

b) Plug in Electric

When estimating the power consumption of a boat that is run solely on electricity from shore, we base the calculations on results from the tow test on the same boat as in example a) (see numbers from table on Opal). To run the boat on 8 knots 75 kw of power is needed, but only 35 kw of power is needed to run it at 6 knots. If sailing for 1.5 hour at the speed of 8 knots and another 1.5 hour at a constant speed of 6 knots, the total energy need in a 3 hour trip is about 165 kwh.

c) Hybrid

The example c) is based on the same propulsion system as in the example b) above. The batteries are charged with diesel generators and no electricity from shore. We assume that the power need is the same for a 3 hour trip as in the previous example. The numbers for oil consumption pr. kwh are provided by producers of diesel electric equipment. The diesel generator can be used as a back-up during longer trips if the batteries run empty and the sails cannot be utilized.

d) RPHP (Regenerative Plugin Hybrid Propulsion)

Only based on experience from different usage patterns is it possible to calculate the exact costs for example d1 through d3. RPHP is a combination of alternative b) and c) with the possibility of using sails as well. In certain conditions, a boat equipped with RPHP can work as a wind (sail) power plant providing power to charge empty batteries and even return to shore with the batteries fully loaded. This is achieved by taking off some of the speed to run the propellor as a generator driver.

Three scenarios are described below:

d1) The boat leaves the harbour in the morning, having fully charged batteries, which means that a range of 2 hours plus return should be possible on batteries alone. The planned trip requires 3 hours plus return, which would in quiet weather require running the diesel generator for 2 hours of the trip, using fuel. When arriving at the destination ¾ of the battery capacity is spent. However, in the afternoon the regular evening breeze sets in, and the boat can make the return trip by sail without needing the diesel generator at all. The wind is not strong, so to maintain speed half of the required power is provided by the sails, the other half by the batteries, with no fuel cost as the result.

d2) The boat leaves on a trip/return from a harbour without power from shore. The batteries are only half charged. This is an 8 hour trip on a day with heavy seas and varying wind. Travelling powered by batteries and sails will not provide acceptable speed, so running the diesel generator is required. Still, sails are set. They provide power throughout the trip - although varying due to gusts and seas - which relieves some of the load on the diesel generator. The surplus capacity of the generator is instead used to charge the batteries. Upon return the batteries are therefore fully charged.

d3) The boat leaves the harbour with almost empty batteries and little diesel, therefore by sails only. During the 10 hours trip, the sailing conditions are good, with a strong, steady wind. At the start the speed averages at 8kn, so it is decided to take 2kn off, to power the propellor-generator for charging batteries. Cruising speed becomes 6kn, and at the end of the trip, the batteries are fully charged, with no fuel cost, and no shore electricity cost.

Discussion

When using a conventional propulsion system consisting of a diesel motor and propeller, vast amount of the energy is used to run machinery in itself, whereas an electrical motor when it is not loaded do not require any energy to run. The power need of the electrical motor decreases proportionally to the reduction in load, i.e. to drive the vessel forward, and this is handled automatically by the control system. This means that when motoring under sail at a fixed speed, the power from the wind will reduce the load on the motor (and batteries) dynamically and proportionally to wind strength - this will also include the effects of varying resistance from the seas. During sufficiently strong winds, there will be no load on the motor at all, but instead electricity will be generated and used for charging the batteries. The result of this is an almost perfect energy efficiency.

One important aim of this project is to find the specific numbers for net power demand for operating the vessels in different typical scenarios. The savings from combining diesel- shore- and wind (sail)-power are significant, and sometimes huge, but is generally an unexplored area. High level estimates indicate both cost- and environmental savings when combining wind power from sails and the renewable electricity from charging at shore, in order to minimize fuel consumption. An important goal of the project is to gain know-how and experience in this field, by piloting the application in real life situations.

The combination of sails along with propeller propulsion has influence on the propeller’s efficiency. Less power is needed to drive the propeller with sails set, compared to a situation when the total propulsion happens through the propeller. The efficiency of a propeller is a complex calculation but the basic principle is that large and slowly rotating propeller has higher efficiency than a small propeller that has to rotate fast in order to create the same thrust. However, whether a propeller is “small” or “large” is still relative and depends foremost on the amount of thrust it has to deliver. When using sails in addition to propeller, the proportions change. When the wind provides larger share of power, the pressure on the propeller decreases and the propeller “scales up” with regard to the decreased thrust it has to deliver. To maintain the same rotation speed at these circumstances, the propellers pitch can be increased.

It will be important to develop models and software which can calculate the maximum efficiency of a propeller resulting from changed power need of the motor when using the sails. Such software will allow the pitch and the rotation of the propeller to be continuously controlled in the most efficient way, in every different situation. To design and qualify such software, an iteration between theoretical modelling and real-life testing is required.

When there is considerable wind for sailing it will be possible to use excess power from the sails to drive the propeller, letting the electrical motor work as a generator. It is at present impossible to calculate the exact amount of power that can be created this way, but from the data tables we have some indications.

It is evident that it requires almost three times as much power to sail the boat at 7 knots compared to 6 knots. By decreasing the speed of the boat with 1 knot considerable power is saved. To decide exactly how much energy is available one must first deduct the energy losses in the different parts of the system. The biggest loss is in the propeller. Hildur needs 47kw to reach 8 knots with efficiency of the propeller of 64%. (other losses in the system not included). The net energy is 30 kw and we have to calculate the possible regenerative energy from that.

Although it is difficult to calculate the exact efficiency of the propeller in a situation when regenerating (without testing it), one can assume that the efficiency of the propeller is higher when the power is taken from the peak of the power curve (reducing vessel speed from a high speed down), thus the same calculations do not apply when the propeller is used for the heavy load of propulsion the boat. When the propeller is used for generating power one can assume it to be more efficient to have steeper pitch compared to when the propeller is required to deliver highest output for the propulsion of the boat.

According to the theory a rotating propeller is most efficient with a pitch/diameter ratio at the optimum value around 2.2. On the other hand, a higher pitch implies a lower rotation speed, which may have a negative effect on the efficiency of the generator.

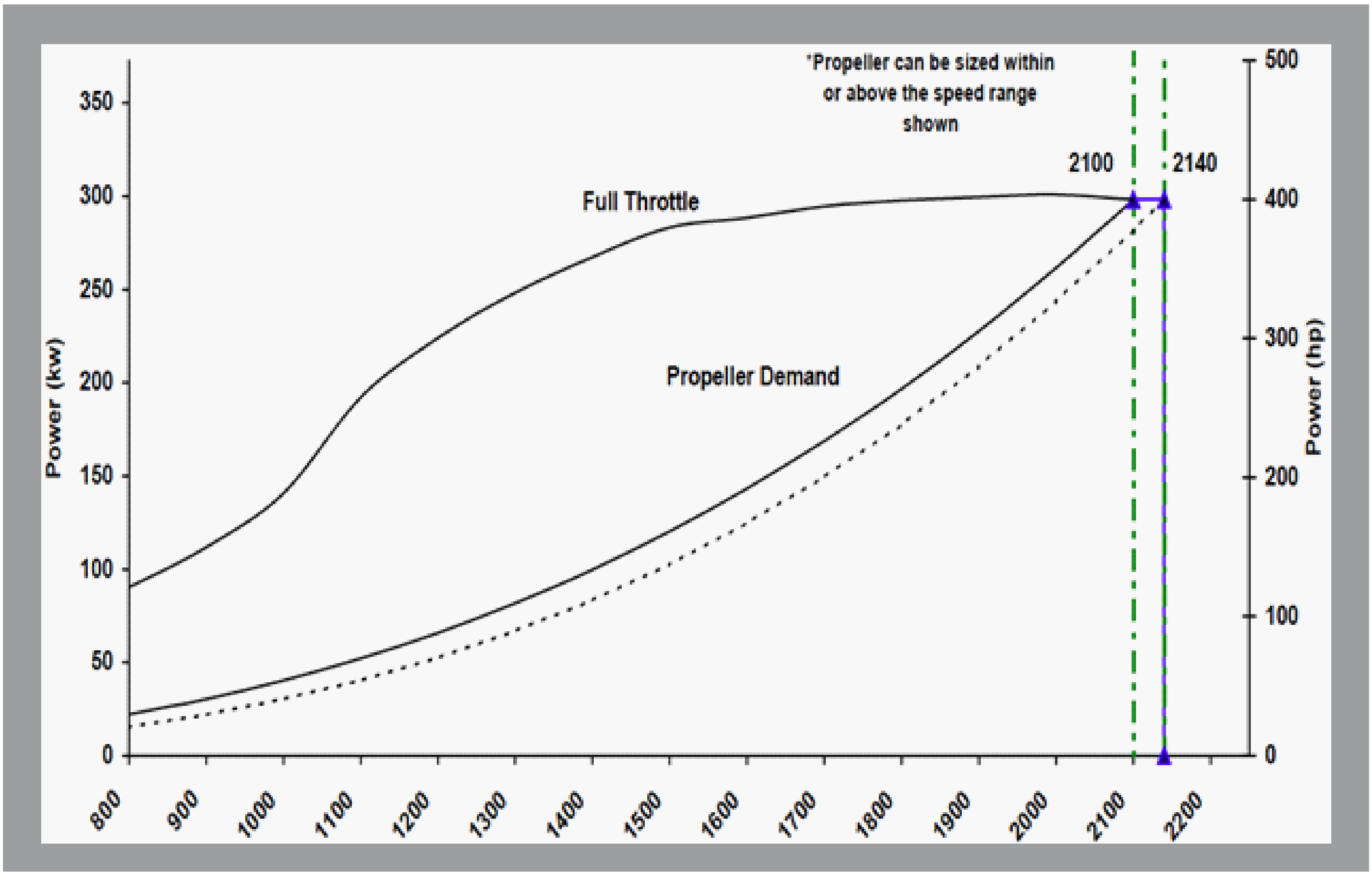
It is necessary to find out through testing in different circumstances, how much power it is possible to produce when using propeller and generator to capture wind power. These data are also necessary when developing software and a complete system aimed at maximizing efficiency.

According to calculations for propulsion mode c), , the indications are that the power efficiency is close to 40% higher in a hybrid system with adjustable propeller and using diesel generator to produce energy on board, compared to direct diesel propulsion with a fixed propeller. The conclusion is similar in example a) where the case is that if the 22 l of diesel that the boat uses per hour is converted into electricity, the power need is 90 kwh compared to 60 kwh power need in the hybrid system.

A permanent magnet electric motor (PMM) has a high efficiency and a linear torque-curve throughout the whole speed range. A high low-speed torque makes a gear unnecessary. A PMM can vary the torque between 25 and 100% without changing the speed, and still operate at maximum efficiency. As an example, the PMM that turns at 200 rpm can deliver between 20-80 kw with an efficiency above 90 %, without changing the rotational speed. These qualities of a PMM directly connected to a propeller with adjustable pitch, makes it possible to deliver precisely the torque and rotation that is necessary for maximizing the efficiency in each circumstance. Thus the possible fuel saving, compared to direct diesel propulsion, is high.

A conventional propulsion system with diesel motor, gear and fixed propeller is designed so that only at one point on the curve will the propeller fully use the potential power of the engine, and that is at maximum rotation. This design has emerged because the increasing power demand of the propeller (in proportion to increasing rotation) is higher than proportional power increase of the diesel engine at increasing rotational speed. Therefore, the power need of the propeller and the power supply of the engine only meet at the point where the rotation is at its maximum. Otherwise the engine cannot deliver maximum power. At this point we are far above the range of what is efficient for a regular displacement hull. The calculations show that Hildur needs 11kW to run 6 knots, but as much as 77 kW to run 9 knots. To increase the speed with 50%, one needs to increase the power with 700 %. In other words, behind every knot to reach 6 knots you need 1.83kW, but 8.56kW to reach 9 knots.

As can be seen in the graph below, at a speed where the boat needs minimum power for each knot, the distance between the power need of the propeller and the supply of the engine is large. With increased engine power (beyond what is needed to reach a speed that is efficient for the hull of the boat) the incongruence between efficiency of the hull and engine is likely to increase. In a hybrid system with adjustable propeller it is possible to harmonize the power need of the propeller with the engine, which explains why the calculations show considerable fuel saving in a hybrid system, even when producing the electricity with diesel generators on board.



Only through research and experience is it possible to calculate exactly how much fuel saving one can reach in a hybrid system, compared to conventional solutions. Experience from the ship Restauration shows that from recorded sailing time, the engine was only running about 60% of the time. From these results one can assume that the saving can be even larger with a varied cruising mode (like in whale watching tours), than the examples this document indicate.

Furthermore, we still have to find out how to maximize the efficiency in a hybrid system equipped with PMM connected to a slow revolving adjustable propeller. Because of the qualities of the system it is possible to match the operation of the engine with propeller in a way that has not been done before. This efficiency gain will be incorporated into models and control software. By gaining experience with RPHP, knowledge about the possibilities of running a fully optimized RPHP system will be acquired. Furthermore, we will acquire knowledge that can be used to design and develop a business case for a much simpler Plug-in electric propulsion system which uses of electricity from shore alone. The learnings from piloting a RPHP system will also be used as a basis for the development of a similar system, but without sails (PHP).

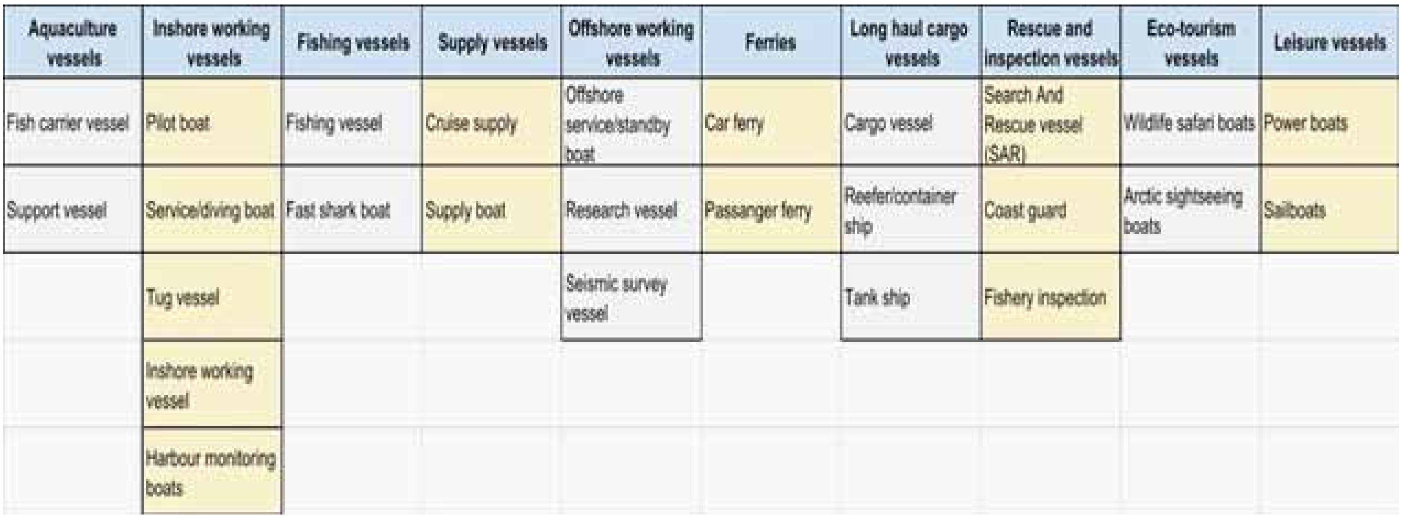
Conclusion

The results from the first phase of the RENSEA project are above all expectations, and therefore the project partners are convinced that the project should be taken to phase 2, which is installation and testing of RPHP. The next and final phase (3) is about optimisation knowledge results, lessons learnt, and demonstration and campaigns.

MARKET POTENTIAL

An extensive market study on what would have been the potential for hybrid applications in commercial vessels built in Norway has been performed. The target was to analyse electrification potential and to identify the major players for specific market segments.

The maritime vessel market is diverse, but the individual applications can be grouped into segments, with specific properties, requirements, and market potentials.



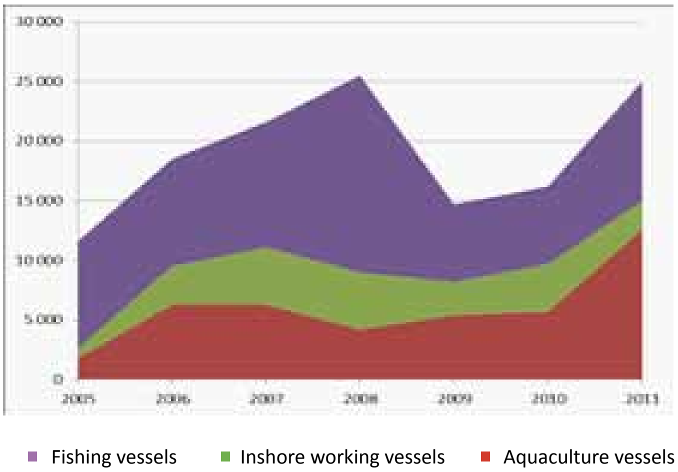
Aquaculture vessels	Inshore working vessels	Fishing vessels	Supply vessels	Offshore working vessels	Ferries	Long haul cargo vessels	Rescue and inspection vessels	Eco-tourism vessels	Leisure vessels
Fish carrier vessel	Pilot boat	Fishing vessel	Cruise supply	Offshore service/standby boat	Car ferry	Cargo vessel	Search And Rescue vessel (SAR)	Wildlife safari boats	Power boats
Support vessel	Service/diving boat	Fast shark boat	Supply boat	Research vessel	Passanger ferry	Reefer/container ship	Coast guard	Arctic sightseeing boats	Sailboats
	Tug vessel			Seismic survey vessel		Tank ship	Fishery inspection		
	Inshore working vessel								
	Harbour monitoring boats								

Market segments

The market can be split into small and large applications, as well applications with low potential in the immediate future. For the RENSEA project, the "small application" segment might be most interesting and from this perspective the applications and customers within this segment are very well suited for an early adoption of this new technology.
The segments which contain smaller applications, in accordance with Figure 1 and their anticipated typical battery system size are:

- Aquaculture vessels (300 kWh)
- Inshore working vessels (400 kWh)
- Fishing vessels (500 kWh)

An especially interesting segment is aquaculture vessels, which are produced in Norway for the local market. They typically have a near-coast operation and fixed points or harbours to operate from. Staff working onboard is presently exposed to particle emission from internal combustion engines. Cranes, pumps or other additional equipment can be in operation while mooring. Working vessel operational cost is a major factor in aquaculture operation cost.



Potential for installed capacity in small applications (kWh) *(based on boats built during the period)*

In Figure 2, the potential market size in kWh is shown for the three segments within the group "small applications". It can be seen that aquaculture working vessels are on the way up and therefore a commercially interesting segment.
Three market segments that are to a less extent mapped out, but that carries a significant potential in the immediate future, are nature tourism cruising, leisure boats, and official inspection and supervision:

- Nature- and Ecotourism
  Increasingly, the mindset of tourists wanting to experience rare, unspoiled nature, is that a 'green' profile is a condition. There is a fast growing market potential for electrically operated vessels, with no exhaust, no pollution, and no noise. Typical activities are excursions to bird hatching locations, whale watching, arctic sightseeing, etc.
- Yachting and leisure boating
  This market is already large and well established in USA. Both power boats - as in the picture below - and sailboats are part of this market. All three solutions are found: diesel-electric, hybrid-electric, and all-electric propulsion systems are offered. Engine noise is a major disturbance onboard a leisure boat, and therefore the hybrid-electric and electric boats launched into the market have created strong enthusiasm. Norway have one of the most extensive and attractive coastlines for leisure boating, and the electrical power is relatively cheap. The market for 'silent' boats will probably experience a large growth, as this type of vessels become more commonplace.

  Official inspection - 'Green Image'
  It is anticipated that governmental and authorities' vessels for overseeing, inspecting, supervising, etc. will promote electrically operated vessels by taking a lead in this area. The benefit of a 'green' profile will probably be more and more valuable in a national perspective.

Icelandic market
Today the Icelandic marked consist of commercial boats only. Mainly fishing vessels but also recreational and other boats. The ship register of Iceland contains about 2300 vessels. The main category of vessels is fishing boats (1500) and the majority of these boats are under 15 meters (1300). These are boats that are doing their fishery around the coast of Iceland and are suitable for hybrid electric systems. One special advantage for the Icelandic marked is that the energy prices for electricity is relatively low. For the domestic market in Iceland, a pilot project with a whale watching vessel will be an important showcase.

Norwegian market
The Norwegian leisure market is big. The registry for small boats contains about 65 000 vessels, but this represents only a fraction. The number of boats derived from demographic data is much higher, as can be seen in the graph below.

The Norwegian market should be an important market in a European context. It is hard to estimate the future of this market and it is also dependent on governmental instruments and incentives. There are already companies looking into these products and opportunities.

Future market

There are basically two parts of this market; new-builds, and retrofits. In the new-builds part, the market value will to some extent be represented by the value of the complete vessels, as the 'silent' factor will give a clear competitive factor. In the retrofit market, the value will be in the installed propulsion system itself, but also in the potential extension of the vessel's lifetime, due to the more attractive features offered. The growth and progress in both the segments closely follows the market for electric- and hybrid-electric cars, although with a significant lag. The development in the car market gives a good indication of what is to come in the boat market, and the pointers are positive.

Actors in Norway

Actors in Norway are targeting both new-built boats as well as retrofitting existing boats. Developing new models of boats is relatively capital-intensive, and therefore the move from retrofitting to building new boats takes time and financial strength. On the other hand, Norway has a very large fleet of leisure boats, with a considerable turnover and modernisation, so the future potential is large. Another factor is that presently boats benefit from access to tax-free diesel (for historic reasons). Norway is alone in having this arrangement, and it is highly probable that it will be ended, and that diesel for boats will be taxed equally to diesel for cars. The actors in the market would directly benefit from this, as electric power will suddenly become more economically attractive, and could serve as a trigger of a faster market growth.

In the forefront in Norway are two suppliers:

Goldfish boats

Sandvik boats

Both of these suppliers are in the startup phase in Norway. It is estimated that the frontrunners in the market will experience a growth for electric boats to 50% of their sales (in number of boats) within 5-10 years.

5. HEAT CAPTURE AND USE

In a hybrid-electric propulsion system, with conventional diesel-engines, there will be a surplus of energy in terms of heat. This heat is possible to exploit by making a heat storage and distribution system. There is a need for heating of components in the system and for hot water and general heating purposes.

Components that generate heat during operation

- Diesel engine
- Generator
- Power electronics
- Electric motor

Heat producing components

Diesel Engine

A diesel generator has a low efficiency relative to the work measured. In average 30 - 40 % of the energy input (diesel) comes out on the shaft. One liter of diesel contains 10,7 kWh of energy. This shows that more than 60 % of the energy is converted to heat. This heat energy is normally lost, using water to cool the engine, and then through a heat exchanger using seawater to dispose the heat overboard.

For our diesel-electric system to be as efficient as possible, we have designed a system to capture, store and distribute this energy. This will utilize the energy and enhance the total efficiency of the system.

Electric motor

An electric component with an energy efficiency at 95 % will generate 5 % heat. The electric motor mounted on the shaft, using 100 kW will generate 5 kW of heat. The motor will be water cooled, which will make it easy to capture this heat.

Other Power Electronics

There are components in the system that generate heat, like chargers, frequency converters, battery bank etc. Compared with the diesel engine and the electric motor, the amount of heat is relatively low. The calculation therefore does not incorporate this heat.

Heat consuming components

There are a number of of components in the system and the ship that need heat;

- Battery bank needs stable temperature conditions, heating or cooling depending on ambient condition and battery loading
- Hot water for the living quarters
- Hot water for the central heating system

Heat storage

In Kallinika there are 4 freshwater tanks, each 1,5 m3. One of these tanks will be used for heat storage. To heat 1 liter of water with one degree celsius 1,16 Watt/hours is needed. This means 1,7 kWh is needed to heat this tank by 1 degree Celsius. Thus, the max. heat storage capacity, based on rise temperature from 10 to 80 degrees Celsius is 1,7 kWh x 70 degC = 119 kWh

To make an example Kallinika is taken as a case study. The operational mode is selected which gives a high generation and use of heat.

Operational mode: continuous operation over 24 hours
Speed: 7 knots (average)
Outdoor temperature: 8 degrees Celsius (spring and autumn)
Number of crew: 6 persons

The values from table 8 in the Case study chapter provides the kW and kWh values. A fully charged battery bank before start is assumed.

Power use of the electric motor: 51,5 kW, with an efficiency of 95%

Battery bank installed capacity: 500 kWh, with 80% capacity available

A diesel engine rated 150 kW is selected for this example, with and efficiency of 40%

First period of operation is on batteries only: 80% of 500 kWh divided by 51,5 kW equals 7 hours 45 minutes duration possible.

Heat generation during this period: 5% of 51,5 kW for 7,75 hours results in: 20 kWh heat energy.

Next period of operation is by diesel generator - charging 400 kWh to the battery bank while also supplying power to the electric motor, for propulsion.

Available for charging is 150 kW (generator capacity) minus 51,5 kW for propulsion which gives 98,5 kW.

Charging time will be 400 kWh divided by 98,5 kW, which gives 4 hours runtime to fill the battery bank to 100%.

Heat generated by the diesel engine is 225 kW (when 40% efficiency is chosen).

Heat generation from the electric motor is 5 % of 51.5 kW, which equals 10,3 kW.

Total heat generation over this period is (225 kW + 10.3 kW) for 4 hours, which equals 940 kWh heat energy.

Total heat production over the first two periods (11.75 hours) is 20 kWh + 941.2 kWh = 960 kWh heat energy.

For a full day cycle, the two periods (11.75 hours) are repeated, giving a total duration of 23,5 hours, and a total amount of heat energy collected 2x 961.2kWh = 1920 kWh of heat energy.

Heat utilisation

Taking the above calculated heat energy divided over 24 hours gives a theoretical available energy for heating onboard of 80 kW in average.

However, this amount of energy is only theoretical. In order to utilize the heat, it needs to be transferred from the engine- and motor water circulation loops, and to the hot water and heating water loops. This is done by means of Heat Exchangers. Heat exchangers operate on the principle that heat is conducted from the hotter medium to the colder medium. The larger the temperature difference, the more efficient is the transfer. Consequently, the heat transfer will be less and less efficient as the temperature in the freshwater tank approaches the temperature of the hot water from the engine/motor. This curve is not linear, but inverse exponential, therefore maximum temperature will take a very long time to reach (theoretically infinite). A good compromise is to assume maximum temperature of the freshwater to be 0.65 x temperature from engine and motor, i.e. 0.65 x 80 = 52 deg C. The other practical limitation is that when the heat in storage is depleted, at some point in time it reaches a temperature too low for utilisation - for washing/showering this is around 35 deg C. This means that only a portion of the stored heat can in practise be utilised. Only 52-35 deg C of the stored heat capacity can be used, i.e. 17 of 70 deg C heated, which equals 25%.

Taking this into account, the available heat is approximately 15% of that calculated above, i.e. 80.1 kW x 15% = 12kW, which should be far above what is needed. With electrical after-heaters installed the utilisation can even be taken below the 35 deg C limit, improving the total heat utilisation above 15%.

To avoid further heat exchange loss from the freshwater tank to the radiator circulation water, the freshwater must be utilized directly, without a water/water heat exchanger. The freshwater tank will therefore have two compartments, one for circulated radiator water, and one for consumed water, such as showers and hot water taps. Since the two compartments together form one large tank, the large heat storage capacity is maintained.

There may be need for hot water hotter than 52 deg C, in which case a small electrical hot-water tank is used to raise the temperature from 52 degC to say, 85 deg C.

6. SCOPE OF WORK, PHASE 2 AND 3

Based on the results from the first phase of the RENSEA project, the project in phase 2 of the project will set out to develop, engineer, build, retrofit, demonstrate and test Regenerative Hybrid-Electric Propulsion in real applications. The proposed pilots are based on three case studies of the vessels Hildur, Kallinika, and Opal. All three vessels are representative for the primary market of nature-tourism and other medium/long range operations.

The research and analysis undertaken in phase 1 has revealed that although regenerative hybrid-electric systems are to some extent mature and proven in the car industry, very little has been done in the area of marine vessel propulsion. In larger ships diesel-electric systems are widely used, but these are systems without a battery bank, and adds little to the knowledge base.

The study in phase 1 has resulted in an overall innovative system design, an exercise which has never been undertaken before. The study has identified the need for- and the great potentials of designing a system where each component plays together in an optimal way.

All the needed key components have been specified, and it has been shown that there are no major obstacles towards a full implementation. In general, the components required to build a full system are available off the shelf. However, due to the fact that a regenerative hybrid-electric propulsion system in no way is an established solution, nor does a complete knowledge base exist in this area , each of the components must be evaluated in-depth with regards to this specific application.

Taken together, the component evaluation and selection, and the optimisation of the system design, will represent a unique innovation and knowledge-building.

To succeed reaching the objective of the RENSEA project, it is necessary to demonstrate a regenerative hybrid-electric propulsion system in real world applications. Both to prove the technology, as well as creating a showcase which proves the feasibility to a wider audience. This requires the retrofitting of a regenerative hybrid-electric propulsion systems to the specific vessels that were evaluated as cases during phase 1.

When the system is installed, the vessels will undertake a number of sea trials, testing, improving, and optimising of the performance. There are at present large knowledge gaps, in particular related to the interaction between components in the drive train, and the propellor/water interface during propulsion versus during regeneration. To some extent the behaviour and characteristics can be modelled, but only in full scale-, real life tests, can the knowledge be acquired, which is required.

A particular area which stands out - based on findings in phase 1 - is the propellor, and the potentials for vastly improving performance when driven from a controlled-torque motor. Another area is the use of the propellor as a water turbine to generate power during sailing. Very little knowledge exist in this area, but findings from phase one indicates that much more power could be generated than was before believed to be possible.

The idea of an ‘intelligent’ system which actively controls the settings of the key components in a system and application such as this, is unique, and holds a great potential for improving performance. A Propulsion Control System will be developed to implement this functionality. During real-life testing this system will also capture the test results, such that through iterations of tuning parameters and testing performance, an optimised system is developed.

During the last phase (3) of the project, campaigns will be run to demonstrate and promote regenerative hybrid-electric propulsion, the same time carrying out testing. Results from testing will be gathered and analysed. This phase will be summarised in a report, with the purpose of open knowledge dissemination, and as an input to improving incentives and regulations. It is also the objective in this phase to follow up on other innovative technologies that could further improve performance. The scope of this is by definition not known at present, but rather it will be identified based on learnings throughout the project. To illustrate, examples could be new battery technologies, game-changing propellor design, etc.

It is the overall deliverable from phase 1, 2, and 3 that the regenerative hybrid-electric propulsion system becomes a proven, established and widespread solution, which will enable and promote a transition into environmental friendly operation of small and medium-sized vessels.

KEY BENEFITS

- Utilizes fuel more efficient when motoring
- Captures energy when sailing
- Reduces fossil fuel dependency
- Can run on renewable energy, charged when in harbour
- Allows voyages without engine noise or vibration
- Provides down to zero emission means of transport
- Gives increased safety, with multiple choice of power
- Triggers technology development and new business
- Leverages the massive development efforts in electric car industries
- Demonstrates a propulsion system which can also be applied in larger ships
- Increase the possibilities for use in larger ships

Gives industry chance to reveal further benefits of technology development

BELLONA

The Bellona Foundation is an international environmental NGO based in Norway. Founded in 1986 as a direct action protest group, Bellona has become a recognised technology and solution-oriented organization and established in Oslo, Brussels, Washington D.C., St. Petersburg and Murmansk. Altogether, some 65 engineers, ecologists, nuclear physicists, economists, lawyers, political scientists and journalists work at Bellona.

North Sailing
HÚSAVÍK

Since the outset in 1995, when North Sailing commenced regular whale watching tours, the company has lead in the development of whale watching practices and the study of nature around the coast of Iceland.

North Sailing aims to become a leader in environmentally sound tourism around the coasts of Iceland and Eastern Greenland. We therefore consider our obligation to be twofold: the minimization of greenhouse gas emissions by our ships, as well as the enlightenment of our passengers with respect to environmental protection and sustainable resource usage.

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