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Regenerative electric/hybrid drive train for ships

RENSEA II

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Content

Executive summary

The objective of this project was to develop, design, integrate and test a ***regenerative plugin hybrid-electric propulsion*** (RPHP) for sail boats. Opal, a whale watching boat used for shorter trips as well as for expeditions at the coast of Iceland and in Eastern Greenland, was used as a case demonstrator for this project. The driving force behind this project was the vision that a regenerative hybrid-electric propulsion system could dramatically improve the environmental footprint of the boat operation, the economy as well as the customer experience during sailing of boats that operate by both motor and by sail. This could lead to large reduction in greenhouse gas emissions during operations. Of great importance is also is the possibility of using the almost silent electric motor to get closer to whales than with diesel engines, thus enhancing customer experience.

The modular hybrid-electric system combines the strengths of an electric drive system (already extensively used in ships), an ideally designed propeller and a modern battery system. Regeneration adds the benefit of capturing energy generated from sails during good wind conditions to recharge the batteries.

The key component of the RPHP system for Opal are the following:

- **Batteries.** The company "Lithium Storage" in Switzerland designed and manufactured new compact 60 kWh batteries, taking into account all requirements needed for certification of the batteries. Four batteries were installed under the floor in Opal, without sacrificing any of the space for crew and customers. Two more batteries can be installed under the floor, increasing total battery capacity to 360 kWh. Two batteries connected in series provide the voltage (600 V) needed for the electric motor.

- **Electric generator.** An electric generator (150 kW) was identified and installed on the old Scania diesel engine previously installed in Opal. The diesel engine was moved to make place for the electric motor attached to the propeller shaft. The diesel engine with the electric generator can be used to r un the electric motor or charge the batteries when other sources of electricity are not available or sufficient (electricity from grid or electricity from the regenerative system). The diesel engine can run on biodiesel, thus enabling completely carbon free operation of Opal.

- **Electric motor and generator.** A permanent magnet motor (PMM) capable of low and controllable speed of rotation is one of the main components of the drive system. The motor is attached directly to the propeller shaft, thus eliminating the need for any gears. A 144 kW motor from Baumuller was found to satisfy the needs of the propulsion system for Opal. The motor works as a generator when generating electric energy from propeller and shaft in good wind conditions.

- **Propeller.** Caterpillar Propulsion and Wave Propulsion designed a new propeller for Opal. The propeller is a controllable pitch propeller enabling the adjustment of the propeller blades to different operational modes of Opal. The diameter of the new propeller is 1.8 m as compared to the previous 1.4 m diameter propeller on Opal. The enlarged diameter permits high efficiency low rotation speed of the propeller, resulting in very low noise levels, which is an advantage when approaching whales.

- **Control system.** In order for all the components of the system to work together it is necessary to have control systems. The battery management system (BMS) controls the charging of the batteries from the different electricity sources (grid, generator and regenerative system). The energy management system (EMS) is a software that has automatic functions to run the system in an optimal way under different conditions.

All components and systems were installed in Opal and tested in the first half of 2015, which made it possible for Opal to set sails for Greenland on July 13, 2015.

The regenerative plugin hybrid-electric propulsion (RPHP) system developed and installed in OPAL has been found to be extremely energy efficient, compared to the diesel propulsion system previously installed in Opal. The two main reasons for this large improvement in energy efficiency are the high efficiency of the electric system and the new large diameter propeller specially designed for Opal and the electric propulsion system.

The new propeller is of the feathered design with controllable pitch of the propeller blades. The pitch of the blades can be adjusted according to the operational mode of the sailing boat Opal. An interesting feature of this designs is the possibility of adjusting the blades during sailing with sails so that electricity can be generated with propeller and motor for charging the batteries. When sailing at 5 knots it is possible to generate 4 – 5 kW of electric power with this regenerative system.

Performance of all components of the new RPHP system in Opal was found to be satisfactory during the operation of Opal in the latter half of 2015. The main work that needs to be done is the improvement of the energy management system (EMS) and the battery management system (BMS).

The lessons learnt in in this project will make design and installation of electric drive systems for sailing boats and other boats more effective.

Introduction

The objective of this project was to develop, design, integrate and test a ***regenerative plugin hybrid-electric propulsion*** (RPHP) for sail boats. Opal, a whale watching boat used for shorter trips as well as for expeditions at the coast of Iceland and in Eastern Greenland, was used as a case demonstrator for this project. The driving force behind this project was the vision that a regenerative hybrid-electric propulsion system could dramatically improve the environmental footprint of the boat operation, the economy as well as the customer experience during sailing of boats that operate by both motor and by sail. This could lead to large reductions in greenhouse gas emissions during operations. Of great importance is also is the possibility of using the almost silent electric motor to get closer to whales than with diesel engines, thus enhancing customer experience.

A modular hybrid-electric system combines the strengths of an electric drive system (already extensively using in ships), an ideally designed propeller and a modern battery system. Regeneration adds the benefit of capturing energy generated from sails during good wind conditions, to recharge the batteries.

Before the project started a part of the project group had conducted an extensive pre-study called "RENSEA phase I". In RENSEA I, funded by NORA (www.nora.fo), Orkusjóður (an Icelandic energy fund) and Transnova (a Norwegian funding agency, now Enova), a regenerative hybrid-electric propulsion system for sail boats was outlined, preliminary system size was estimated and performance was calculated, areas of optimisation were located and innovative research and development tasks were identified. The results indicated large potential, both in economic terms as well as from an environmental perspective.

This report describes the results of the work of an enlarged Nordic project group in phase II of the RENSEA project. The new partners provided important expertise that enabled the design of an effective RPHP system for Opal and showed how RPHP systems for other vessels could be approached. The partners in the RENSEA II and their role in the projects were broadly as follow: North Sailing (IS), Bellona (NO) and Lakeside Excursions (FO) were potential users of the technology to be developed.

Wave Propulsion (NO) in cooperation with Caterpillar Propulsion (SE) designed the propeller and the propeller system was manufactured by Caterpillar Propulsion. Clean eMarine (DK) provided input on design of battery, selection of auxiliary components and installation of the electrical system and Naust Marine (IS) designed the electrical system. Project management was carried out in cooperation between Icelandic New Energy and Innovation Center Iceland. Well into the project Lithium Storage (CH) was selected to provide expertise on battery design and manufacture the batteries.

Here it should be pointed out that the funds from Nordic Innovation and NORA were used to design, install and test the system and make necessary modifications in system design. The hardware components for the system used in Opal were financed by North Sailing, the Icelandic Maritime Fund and Orkusjóður.

When designing the RPHP system for Opal it was first necessary to consider the operational modes of Opal, see the next chapter.

The key components of the RPHP system are the following:

- Batteries, 200 – 300 kWh.
- The electric generator attached to the old Scania diesel engine as backup for electricity generation
- The electric motor/generator attached to the propeller shaft. The motor can also be used as a generator when generating electric energy in good wind conditions
- Propeller, optimised for regeneration, propulsion and sailing
- Control system

The work on developing these components and the whole system is outlined in a chapter entitled “Development of the system and its components”, followed by a chapter on certification of the system. The energy efficiency of Opal before (with only diesel engine) and after conversion to the RPHP system is then described in a separate chapter. This is followed by a chapter outlining how experience gained from design and installation of the electric drive system in Opal has been used in design of electric propulsion systems for other boats. Conclusions are presented in the final chapter, together with description of future work.

The RENSEA II project and the RPHP system in Opal have been presented at many conferences and seminars, and the changes have been presented in a TV program and videos, as shown in the Appendix. And last but not least, the RPHP system in Opal has been presented “live” to interested parties during Opal’s voyage to Scandinavia in the fall of 2015, see the Appendix.

Operational modes of Opal

Opal is used for taking tourists on about four hour whale watching tours from its home harbour in Húsavík and for several day expedition tours in Scoresby Sound fjord in Eastern Greenland. During these tours Opal and its crew experience many different weather and sea conditions, see Figure 1, that were taken into account when designing the RPHP system in Opal. The operational modes shown in Table 1 were identified as most relevant for the operation of Opal. This is especially important to consider when designing the propulsion system, propeller etc.

Figure 1. Opal under different operating conditions in Eastern Greenland (Granath 2015).

No	Operational mode	Condition	Note
1	Manoeuvring	Open water	Harbour manoeuvring
2	Manoeuvring	Ice	Ice operation
3	Free running	Calm	Normal cruise condition
4	Free running	Strong wind	Wave compensation
5	Sailing	Low wind	Locked propeller shaft
6	Sailing	Medium wind	Propeller assisted sailing
7	Sailing	Strong wind	Power regeneration

Table 1. Operational modes of Opal (Granath 2015)

Development of the system for Opal and its components

Batteries

In the beginning of the project quotes on batteries were obtained from four different battery producers. The key parameters in the evaluation of the quotes were physical design, capacity and cost. The key problem with most of the offers obtained was that the physical design of the battery packs was not flexible nor compact enough to fit into the limited space available in an old boat. Fitting of theses batteries into Opal would have called for major and expensive changes in the interior of Opal which would have taken part of the available space used for servicing customers. Most of the battery producers were not willing to do any redesign of the batteries as they did not see the project a major customer or that the cost of redesigning a 200-300 kWh battery pack would be very expensive. This created some issues as most of the batteries that could be fitted into the available space would only hold 140 – 200 kWh, which would be too small for a conventional whale watching tour.

Lithium Storage (http://www.lithiumstorage.eu/) in Switzerland, which is producing batteries for the lorry and van market (i.e. vehicles), turned out to be willing to design and construct batteries that could fit in to the available space in Opal. Following a contract signature the company redesigned the battery packaging so it would fit into Opal and fulfil the needs of certification for maritime use, see Figure 2. This flexibility in design makes the batteries more competitive for the marine market – something that future projects can benefit from. Each battery is 60 kWh and two batteries are connected in series to give a voltage of about 600 V needed for the electric motor. In the space available in Opal it is possible to add two more batteries, which would bring the total battery capacity to 360 kWh.

The batteries were installed under the floor in Opal, without sacrificing any of the space intended for crew and customers, see Figure 3.

The relationship with Lithium Storage has now been strengthened with the goal to utilise their batteries in more marine applications and in future research, development and demonstration projects.

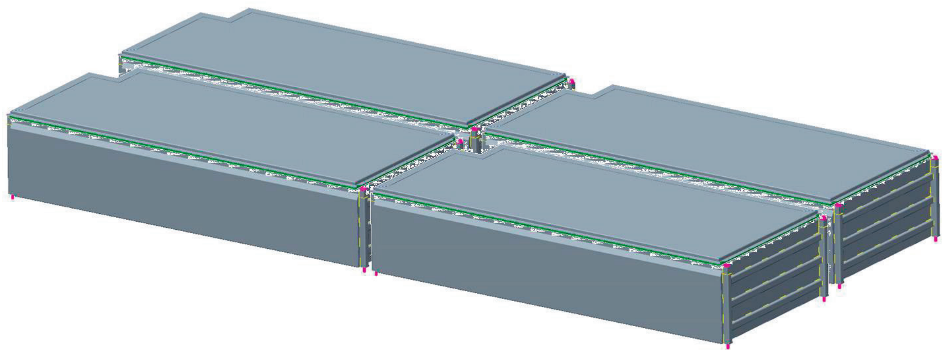

Figure 2. Arrangement of the four batteries delivered by Lithium Storage. Each battery is 60 kWh with a nominal voltage of 300V and peak current of 500 A. The mass of each battery is about 600 kg and the dimensions of each battery are 1700x750x150 mm. (Miauton 2015)

Figure 3. Installation of one of the batteries under the floor in Opal.

Electric motor and generator for propeller shaft

Baumuller in the Netherlands was identified early as the supplier of the 144 kW permanent magnet motor (PMM). The key to the choice was to maximise the efficiency between the motor and the new propeller. To confirm that everything would fit correctly and no issues would arise, the motor was sent to Sweden where the shaft and propeller were to be assembled to see if all was working correctly. This FAT (factory acceptance test) was very important as the motor and the shaft did not fit 100% and all junctions could be corrected before all the components were shipped to Iceland and installed into Opal, see Figure 4.

Figure 4. Installation of the permanent magnet motor into Opal.

After installation of the motor the team was faced with problems connected to electromagnetic current (EMC) noise from the control system delivered with the motor. This is a known problem when combining different components and can become a major obstacle if it is not possible to isolate the EMC and reduce it so the system functions properly. Fortunately the issue could be solved quickly by changing the control unit delivered with the motor to a control system from Aradex. Following this solution and some rewiring of the system the EMC issue was eliminated and the system worked according to plan.

The installation in Húsavík was very successful and the system has been proven to be extremely efficient. To get exact numbers, a special monitoring system has to be installed to collect data that can be used to optimise the system. Based on collected data the plan is to develop software that can have automatic functions to run the system in an optimal way under different conditions, i.e. to develop a better energy management system (EMS).

The calculations based on the towing test in February 2014 estimated that the main electric motor will use 32 kW to sail the boat at 6 knots and 46 kW at 7 knots. The experience from the first trip to Greenland indicates that the energy use is lower than that. When sailing only with sails at 5 knots, testing shows that it was possible to regenerate 4-5 kW of electric power. That seems to be close to the calculations. The first experience with the regenerating also indicates that the motor controller has to be programmed differently when regenerating as compared to propulsion. The overall outcome is therefore beyond expectations and shows that there is a huge viability to install similar systems in various boat types and for various operations.

However, both the EMS and the BMS need to be developed further in order to realise the full potential of the RPHP system. This will be the focal point of work at North Sailing before more boats are converted to electric operation.

Generator

Opal was equipped with a Scania diesel engine. At the onset the goal was to move the engine to make place for the electric motor and to use the diesel engine as a generator of electricity for charging the batteries if needed. The task of identifying the appropriate electric generator for the old 210 kW Scania became a bit complicated, mainly because of the interface between the generator and batteries. In the end a 150 kW generator motor from Leroy Somer was chosen and motor controller from Aradex was chosen to control the current to the batteries.

The fuel consumption when electricity is produced with generator seems to vary a lot due to operational profile. To find exact figures for fuel consumption, further testing needs to be done over time and under various circumstances. But as stated above it is important to improve the EMS system, install a sea-log and upgrade the BMS to be able to monitor losses in different system components.

The diesel engine can be run on biodiesel thus enabling operation of Opal with sustainable energy sources: wind, renewable electricity and biofuel.

Propeller

In the initial stages of the project a new propeller design was identified as the key to maximise system efficiency. When the project expanded into a Nordic project, Berg Propulsion (SE), which later in the project became Caterpillar Propulsion, in cooperation with Wave Propulsion in Norway, took on the task of designing a propeller for Opal. The team wanted to have the propeller as large as possible and with a controllable pitch. In short – to maximise the efficiency the propeller should be large and have much lower speed of rotation than a conventional propeller for a diesel motor. As stated earlier, Caterpillar Propulsion did a FAT test with the propeller shaft and the motor which saved a lot of time during installation and also demonstrated functionality of the motor and propeller, since during the FAT test a new mechanical adaptor/flange to connect the propeller shaft and electric motor was designed and made by Caterpillar Propulsion.

The feathered design came early on the drawing board so the utilisation of sails could be maximised, i.e. the blades can be flat during sailing with strong wind, see Figure 5. But just as important was to be able to control the possible regeneration (like regenerative breaking) of energy during sailing with sails. In the first trips all of these features were tested with results better than expected, see above. It demonstrates that all components have to be evaluated when maximising the total efficiency of a system. Of course all design parameters of the propeller do not have to be used in all applications, for example when there are no regeneration possibilities.

Figure 5. Installation of the propeller into Opal. The blades are in the flat sailing position.

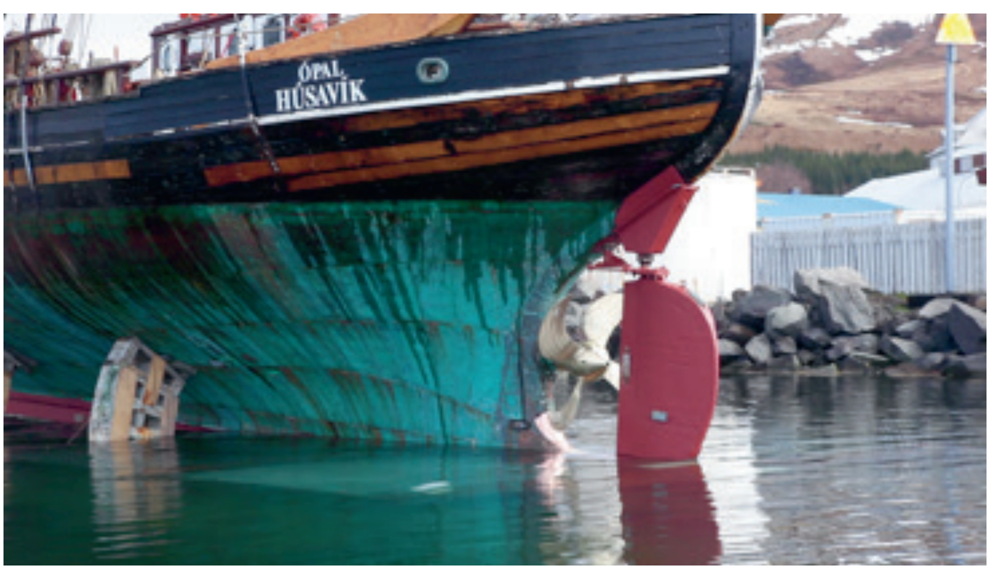

Figure 6. The propeller and rudder mounted on Opal.

Because of increase in diameter of the propeller from 1.4 m to 1.8 m, the propeller had to be placed farther astern than before. This called for redesign of the rudder and its attachment to the boat, see Figure 6.

The use of the new propeller is one of the most exciting component regarding efficiency gain. There are indications that the efficiency of the propeller is almost twice that of the previous propeller, saving drastically on diesel consumption if only run on diesel. This though needs to be investigated further. For example if it is economical to actually convert the conventional fleet of North Sailing only by changing the propeller. Would the fuel savings match the investment cost of installing a new propeller?

Control system

As can be understood from above, most of the components were not specially designed for the project. However to get them all to work correctly together it was necessary to design the control system. This became a more time consuming part of the project and more complex than anticipated in the beginning, which is very common in such projects.

A lot of learning had to be done by doing and mistakes had to be corrected as they came up. During the original testing of the boat and later during the first voyage to Greenland it became evident that the control system can be improved and be made simpler to use for the crew. Despite some flaws in the system, it works as intended but it has needed a bit more attendance than originally planned.

During the first months of operation the team has already identified the key flaws which will be corrected in the near future, resulting in improved BMS and EMS systems that may be applied to other boats.

Certification

Certification of the new system on board Opal was necessary in order to be allowed to sail with passengers. Early in the project the project group involved Lloyds Registry for the certification of the system. They did the original certification for Opal and therefore it is an advantage to use the same players for the next step. They were fed with information as they became available so they could recommend changes or necessary safety equipment and in that sense avoiding that in the final stage there will be issues with certification.

As the project was delayed and the communication with the classification societies became more complex, and a formal certification from them was not necessary to get operation licence, the work with them was postponed. With a marine approval for the batteries, the Maritime Authority in Iceland inspected the installation, drawings, design, etc. and approved of the ship's operation.

This is another learning step for the project partners and something that has to be worked on if similar systems are to be put into other ships. Already Lithium Storage and other partners in this project are working with the classification societies to get a formal certificate for marine operation on the batteries so they can be marketed directly for other ships.

Electric vs. diesel whale watching tours

Because of the delays in installation of the RPHP system in Opal the operation of the boat in conventional whale watching trips was very limited. Also the EMS system did not collect all the data needed for detailed comparison of Opal before and after conversion to the RPHP system. The data presented below should therefore be viewed with some caution.

Before conversion to the RPHP system, Opal consumed about 100 l of diesel per four hour whale watching tour, or about 1170 kWh of energy (1 l of diesel contains 11.7 kWh of energy). After conversion to the RPHP system the electric energy consumption per four hour whale watching tour was estimated to be about 170 kWh, or only about 14% of the energy consumption before conversion to the RPHP system.

This large improvement in the energy efficiency is partly due to the high efficiency of the electric drive system and partly due to the high efficiency of the large diameter propeller, which has a much slower rotation speed than the previous propeller.

	Whale watching tour		250 whale watching tours	
	Energy (MWh)	Cost (€)	Energy (MWh)	Cost (€)
Before conversion to RPHP system[a]	1.17	98.6	292.5	24650
After conversion to RPHP system[b]	0.17	13.4	42.5	3350
Savings due to RPHP system	1.00	85.2	250.0	21300

[a]Cost of diesel is assumed to be 0.986 €/l or 84.3 €/MWh
[b]Cost of electricity is assumed to be 78.6 €/MWh

Table 2. Energy consumption and cost of energy per four hour whale watching tour and for 250 tours per year, before and after conversion to the RPHP system. Saving in energy and cost due to RPHP system are also shown.

The savings in energy and cost due to conversion to the RPHP system in Opal are show in Table 2. The annual saving in cost are 21300 €. To this it is possible to add savings due to reduced CO_2 emissions which are 66 tonnes per year. When setting cost for CO_2 emission we here choose to follow the ASEK 5.2 guidelines published by Trafikverket in Sweden, which give values to be used for cost benefit analysis in the Swedish transport sector (Trafikverket 2015). According to these guidelines the cost of CO_2 emissions in December 2015 is about 133 €/tonne CO_2. Savings to society due to reduced CO_2 emissions are therefore now about 8800 €/year. This is expected to increase by 1.8% per year (inflation not included).

In order to make a thorough analysis of total cost of operation (TCO) of a RPHP ship and diesel operated ship it would be necessary to take into account total capital cost and all operating and maintenance costs. This is difficult because one would be comparing the developed diesel technology with the still under development RPHP technology. The cost of a diesel propulsion system is now lower than that of a RPHP system. Preliminary calculations indicate that the TCO of diesel and RPHP system are similar, when not taking into account savings due to reduced CO_2 emissions. Savings due to reduced CO_2 emissions are expected to be of more importance in the coming decades.

Hybrid electric systems in other boats

Electric drive system for Bellona´s Kallinika

Bellona has been investigating various options for conversion of SY Kallinika, a motor sail boat used by Bellona for campaigning and communication with the public. The initial plan was based on installing a propeller with a diameter of 1800 mm together with 350 - 500 kWh battery bank. This would give an operation range of approx. 48 nautical miles at speed of 6 knots. With a propeller similar to the concept used on Opal, this would give approx. 12 kW regenerative effect when sailing at 6 knots

However, during the detail-engineering phase, it became clear that the existing propeller shaft with 100 mm diameter would not be sufficient for the increased torque from the larger propeller diameter. To install a new propeller shaft will require a substantial redesign of the internal structures of the vessel, and the increased complexity will raise a substantial challenge for Bellona's ability to finance the project.

Bellona is currently looking into alternative and less expensive solutions ("plan B") where the existing fixed pitch propeller is kept. Even if this will reduce the effect of regenerative charging when sailing, the concept will still be very interesting for demonstrating the possibilities for retrofit solutions of hybrid battery solutions for older vessels.

The experience acquired from the design, implementation and initial operation of the OPAL solution can be used for implementing the optimal solution for Kallinika.

New electric boat for Lakeside Excursions

Lakeside Excursions has since 2005 been offering boat excursion on lake Leitisvatn, near the Vagar Airport in the Faroe Islands. A diesel driven boat has been used for these excursion until now. In the RENSEA II project the first steps were taken in designing an electrically driven boat for these excursions with the aim of drastically decreasing the carbon footprint of the excursion offered.

The new boat will be a catamaran with two independent drivelines, one in each hull. Each driveline will consist of charger, battery, motor controller, motor, gear and propeller. The drivelines have been designed so that if one component of a driveline fails, for example the battery, then it is possible to bypass that component and use the same component in the other driveline.

Wave Propulsion has compared the power consumption of hulls constructed of steel and composite. For a cruising speed of 6 knots it was estimated that the composite hull would need 8 kW for both propellers (900 mm) whereas the steel hull would need 13 kW. The necessary battery size has been estimated to be about 120 kWh for the length of tours offered by Lakeside.

The batteries in the new boat will mainly be charged from the national electric grid, but the use of solar cells for charging the batteries will also be considered. About 70% of the electricity produced in the Faroes Islands is now made from oil, but there are ambitious plans to increase the share of renewables to 100% in 2030. With the electric boat it will therefore be possible for Lakeside Excursions to offer excursions with reduced carbon footprint and in the long run completely carbon free excursions.

Conclusions and future work

The regenerative plugin hybrid-electric propulsion (RPHP) system developed and installed in OPAL has been found to be extremely energy efficient, as compared with a diesel propulsion system previously installed in Opal. The two main reasons for this large improvement in energy efficiency are the high efficiency of the electric system end the new large diameter propeller specially designed for Opal and the electric propulsion system. The old propeller had a diameter of 1.4 m whereas the new propeller has a diameter of 1.8 m. The rotation speed of the new propeller is also much lower than that of the old propeller.

The new propeller is of the feathered design with controllable pitch of the propeller blades. The pitch of the blades can be adjusted according to the operational mode of the sailing boat Opal. An interesting feature of this designs is this possibility of adjusting the blades during sailing with sails so that electricity can be generated with propeller and motor/generator for charging the batteries. When sailing at 5 knots it is possible to generate 4 – 5 kW of electric power with this regenerative system.

New compact batteries were developed that will facilitate the installation of electric drive systems in boats where space is limited.

Performance of all components of the new RPHP system in Opal was found to be satisfactory during the operation of Opal in the latter half of 2015. The main work that needs to be done is the improvement of the energy management system (EMS) and of the battery management system (BMS).

The lessons learnt in in this project will make design and installation of electric drive system for sailing boats and other boats more effective.

Before this project started a RPHP system for a sailboat had never been designed and installed. In order to achieve this in an effective manner the expertise of Nordic partners was sought, both because of the strong maritime sector in these countries and because experience from other Nordic projects has shown that it is easy for Nordic partners to cooperate, probably because of cultural similarities. The RENSEA II project demonstrates very well this added value of working together in a Nordic innovation project.

Without the Nordic cooperation in RENSEA II it would have taken a much longer time to develop and install the complete RPHP system in Opal. A further added value is that the lessons learnt can easily be applied to design of electric propulsion systems in other boats.

North Sailing has already decided to install an electric propulsion system in an old wooden boat. This boat, which takes 70 passengers, will be used for up to four whale watching tours per day from Húsavík, each tour being about three hours. The old diesel propulsion system has been removed and it will be replaced with a 240 kWh battery pack, electric motor, specially designed propeller and control system. Backup electricity will be provided with a small (30 kW) diesel generator. The batteries will be charged from land connections while in harbour in between tours, allowing charging of 100 – 150 kWh between tours, and full charging during the night. This boat will start operation in July 2016.

Some of the key partners have decided to form a joint company to exploit the results of the project. These partners are convinced that there is a commercial potential in the findings of the project and plan toutilize this in the near future. Jointly they will exhibit at the Electric and Hybrid Marine Expo in Amsterdam 21-23 June, 2016. After that a detailed business and marketing plan will be developed.

The knowledge gained in the project is also exploited via other activities and connections have been established with other key Nordic stakeholders. More projects are being formed which in some cases will seek national funding, while others are exploring Nordic or EU funding for projects. All key stakeholders in the project are convinced that increased cooperation in this field can lead to prosperous future including increased use of eco-friendly fuels in the Nordic countries in marine connected activities.

Finally it can be mentioned that the conference “Making Marine Applications Greener 2016“ will be held in Iceland, where Opal will be demonstrated.

Appendix: Communication activities

Conference/seminar presentations

- Árni Sigurbjarnarson "RENSEA – electrically powered whale watching boat". Presented on September 17, 2014 at the seminar "Sustainable transport" in Reykjavík.
- Fredric Hauge "Market opportunities for marine environmental technology". Presented at the Norwegian shipyard association annual conference in Ålesund on November 4 – 5, 2014.
- Jón Björn Skúlason "Utilising regenerative plug-in hybrid-electric propulsion on a sailboat", presented at the "Electric&hybrid marine world expo", June 23 – 25, 2015, in Amsterdam.
- Jonas Granath "Opal rebuild improving energy efficiency", Presented at "Making marine applications greener", Gothenburg, Sweden, October 21 – 22, 2015.
- Árni Sigurbjarnarson "Opal – regenerative plug-in hybrid electric propulsion". Presented at "Making marine applications greener", Gothenburg, Sweden, October 21 – 22, 2015.
- Roger Miauton "Requirements and solutions for marine high-voltage batteries" Presented at "Making marine applications greener", Gothenburg, Sweden, October 21 – 22, 2015.

Coverage of changes to Opal in an Icelandic TV program

The changes being made to Opal are were presented in the TV program "Landinn" show on April 24, 2015 on RUV.

Videos of Opal

Caterpillar made a video describing Opal in Greenland, see https://www.youtube.com/watch?v=Jc0Bxwjj9_g.

Nordic Innovation made a video on Opal and the Rensea II project when Opal arrived in October 2015 in Oslo. This video is available in two versions on You Tube, see
https://www.youtube.com/watch?v=yceewl2PUpA (ca 3 min)
https://www.youtube.com/watch?v=5qeyIRU5Sdc (ca 5 min)

Launching of Opal

Opal and it's regenerative plug-in hybrid-electric propulsion system was presented to the public on July 12, 2015, in Húsavík. A fact sheet was prepared for this event and a press release in several languages was released. This resulted in extensive media coverage in Iceland and some media coverage in foreign media.

Sailing of Opal to Scandinavia

In October 2015 Opal sailed to Scandinavia. In Oslo Opal was presented to the media and Nordic Innovation on October 19 and in Gothenburg on October 21 to the participants in the conference "Making marine applications greener". On the return trip to Iceland it is the plan to stop in Torshavn, where Opal and the RPHP system will be presented.

Awards and award nominations to North Sailing for Opal

In the category "Best innovation for carbon reduction" North Sailing won the silver award in "World responsible tourism awards" for 2015, see http://www.responsibletravel.com/awards/categories/low-carbon.htm.

The Icelandic Tourist Board awarded North Sailing the Environmental Recognition Awards 2015 in October 2015, see http://www.northsailing.is/news/nr/3619/north-sailing-awarded-the-environmental-recognition-awards-2015/

North Sailing has been nominated for Europe's largest environmental- and business prize, the GreenTec Awards for 2016, in the Travel Category, for the regenerative plug-in hybrid-electric propulsion system in Opal, see http://www.greentec-awards.com/en/competition/online-voting-2016.html.

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Table of abstract

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Author(s): Guðmundur Gunnarsson, Jón Björn Skúlason, Árni Sigurbjarnarson and Sigurd Enge	
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Title (Full title of the report): **Regenerative electric/hybrid drive train for ships** RENSEA II	
Abstract: The development, design, integration and testing of a regenerative plugin hybrid-electric propulsion (RPHP) into Opal, a whale watching sail boat, is described. The key components of the RPHP system are: a) four specially developed compact batteries (60 kWh each) that can be fitted into the limited space available, b) electric generator installed on the old diesel engine as backup electricity generator, c) permanent magnet electric motor (144 kW) mounted directly on the propeller shaft capable of high torque rotation at low speed, d) large diameter (1.8 m) controllable pitch propeller, e) battery management system and energy management system for integration of different components and optimisation of energy use. The RPHP system developed and installed in OPAL has been found to be extremely energy efficient, as compared to diesel propulsion system previously installed in Opal. The two main reasons for this large improvement in energy efficiency are the high efficiency of the electric drive system end the new large diameter propeller specially designed for Opal and the electric propulsion system. The capacity of the regenerative system (propeller and motor/generator) was found to be 4 - 5 kW at 5 knot speed when using sails. The lessons learnt in during the design and installation of the system for Opal have been used for the design of similar systems for other boats.	
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Regenerative electric/hybrid drive train for ships

RENSEA II

A highly energy efficient regenerative plugin electric drive system for Opal, a whale watching sail boat, has been developed, installed and tested. The system is based on specially developed compact batteries that can be installed in the limited space available in many boats, electric backup generator, permanent magnet motor/generator and specially developed pitch controllable propeller that as a high energy efficiency at low rotation speed. These components are integrated and their use optimised with the battery management system and the energy management system. The energy use in four hour whale watching tours with the electric drive system is less than 20 % of the energy consumption of the previous diesel system. The high efficiency of the new drive system is both due to the high efficiency of the electric drive system and to the high efficiency of the new propeller, which has larger diameter than the previous propeller and operates at much lower speed. The electric drive system, and the adjustable propeller blades, also make it possible to regenerate electric energy in an optimum manner since the motor can be used as a generator when the boat is sailing under sails in good wind conditions.

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