NTNU – Trondheim
Norwegian University of
Science and Technology

Electric Cable Ferry

Feasibility study of an electric ferry concept

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Submission date: June 2014
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Norwegian University of Science and Technology
Department of Marine Technology

Master Thesis in Marine Systems Design

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"Electric Cable Ferry"

Spring 2014

Overall aim and focus

The overall objective of this thesis is to evaluate the feasibility of an electric cable ferry for the Norwegian transport market.

Scope and main activities

The candidate should presumably cover the following main points:

1. *Identify and analyse the market potential, including possible routes for an electric cable ferry*
2. *Clearly state requirements, in particular with respect to emissions to air*
3. *Develop a function structure for the ferry, and develop main functional requirements focusing on those functions that are particular for this concept*
4. *Generate and analyse alternative conceptual solutions for the main functions*
5. *Synthesise the part solutions into a complete design. Evaluate the proposed solution towards the design requirements, and benchmark towards a traditional ferry and/or a battery driven ferry*
6. *Discuss the results and make a clear conclusion on the feasibility of this concept*

Modus operandi

At NTNU, Professor Stein Ove Erikstad will be the responsible supervisor.

The work shall follow the guidelines given by NTNU for the MSc Thesis work. The work load shall be in accordance with 30 ECTS, corresponding to one semester.

Stein Ove Erikstad
Professor/Responsible Advisor

Preface

The report in hand is written as a thesis in the two-year master program of Marine Technology at the Norwegian University of Science and Technology NTNU, spring 2014. It has been written with a specialization project from autumn 2013, which has the same name, as a preliminary project for this thesis.

The thesis has been conducted using knowledge gathered from courses in the master program, and expert experience and knowledge. It has been an educational and interesting project that has resulted in knowledge and insight in various shipboard and offshore technologies and systems, as well as construction processes.

I would like to thank technical supervisor Professor Stein Ove Erikstad at the Department of Marine Technology at NTNU for providing the conceptual idea and for support throughout the project conduction.

I would also like to thank Lars Øyvind Moen and Øystein Tvedt at Nexans Norway for providing expert knowledge on cable technology.

Lastly, I would like to thank Hans Kristian Dyrli at Multi Maritime AS for providing information and drawings regarding the M/F Hidraferja ferry.

Abstract

The thesis in hand has investigated the feasibility of a cable electric ferry concept. The concept investigated is based on that a short route ferry receives its propulsive power through a cable connected to the land power grid. Four cable transfer configurations and associated equipment have been looked upon. The cable can either be stretched in the air over the route, it can float after the ferry, it can be towed submerged after the ferry, or it can follow the bottom contours after the ferry. The three latter configurations required storage and cable handling equipment, which can either be located onboard the ferry or on shore. The cable is reeled out under transit and spooled in on the way back. The air stretched configuration requires an arm type connection between the ferry and the cable in order to receive power. Current available technology has been assessed for concept realization in terms of cable and handling equipment. In addition, regulations for power onboard and emergency power systems are viewed upon, as well as regulations on emissions to air. Competing and alternative power systems to the concept have also been assessed. Lastly, a case study for concept implementation has been conducted.

Findings made in the thesis include that current cable material composition and layer configurations will need engineering in terms of increasing strength, and reducing weight and dimension without influencing conductivity. Current cable handling equipment used in offshore cable laying vessels have good tension specifications for the concept, but compared to alternative power sources such as diesel- and LNG-gensets they have large weights and dimensions, and their operational handling speed is low for high tension levels. This gives that current technology would need development for concept realization. Weights and dimensions must be reduced, and handling speed must be increased such that the ferry is able to operate in normal transit with speed and payload.

Further, the concept has also been economically compared with alternative power sources. With current technology the concept costs exceed the cost of competing alternatives, where the most expensive concept component is the cable. The cable cost exceeds the cost of a new LNG-genset. Cable handling equipment costs are relatively low compared to the cable. As for operational costs, electricity is found comparable with current LNG prices. But for maintenance costs, the concept is far more expensive than for instance a LNG-genset, because the cable will have relatively low operational lifecycle due to wear and fatigue, and

will have to be replaced a lot sooner than gensets. And a genset can increase operational lifecycle by being overhauled, where pistons, bearings and seals are replaced.

The concept is found physically feasible, but to meet the specification requirements equipment and components will need engineering and analyses. Economically, the concept is rather insufficient, but future local emission regulations and fuel costs may make the concept achievable.

Sammendrag

Avhandlingen har undersøkt muligheten for et kabel-elektrisk fergekonsept. Konseptet som er undersøkt er basert på at en kortrute-ferge mottar propulsjonskraft gjennom en strømkabel som er koblet opp til det landbaserte kraftnettet. Fire overføringsalternativer og tilhørende utstyr har blitt sett på. Kabelen kan enten strekkes i luftspenn over ruten, den kan flyte etter fergen, den kan taues i en neddykket kurve etter fergen, eller den kan ligge på havbunnen etter fergen. De tre sistnevnte konfigurasjonene krever håndtering og lagring av kabelen. Utstyret til dette kan enten plasseres på land eller ombord. Kabelen spoles ut ved transitten og spole inn når fergen seiler tilbake. Luftspennskonfigurasjonen krever en armlignende forbindelse mellom fergen og kabelen slik at strømmen kan overføres. Nåværende tilgjengelig teknologi innen kabel og håndteringsutstyr har blitt vurdert for realisering av konseptet. I tillegg har regelverk for kraft ombord og nød kraftsystemer blitt sett på, samt regelverk for utslipp til luft. Det har også blitt sett på konkurrerende og alternative løsninger til konseptet. Til slutt har et case-studie for konsept implementering blitt gjennomført.

Funn gjort i avhandlingen inkluderer at eksisterende kabel-materialsammensetting og lag konfigurasjon vil trenge prosjektering i forhold til å øke styrken, og redusere vekten og dimensjonene uten å påvirke lederevnen. Kabelhåndteringsutstyr brukt i offshore kabelleggingsfartøy har gode spenningsspesifikasjoner som kan brukes i konseptet, men sammenlignet med alternative kraftkilder som diesel- og LNG-generatorset har de stor vekt og store dimensjoner, og operasjonshastigheten deres er lav i forhold til spenningsnivået. Vekt og dimensjoner må reduseres, og håndteringshastigheten må økes slik at fergen kan operere normalt med tanke på hastighet og lasteevne.

Konseptet har også blitt sammenlignet økonomisk med alternative kraftkilder. Med nåværende teknologi vil kostnadene ved konseptet overskride konkurrerende alternativer. Kabelen er den dyreste komponenten i konseptet, og er dyrere enn et nytt LNG-generatorsett. Kabelhåndteringssutstyrskostnader er regnet som lave i forhold til kabelen. Når det gjelder operasjonskostnader er elektrisitetspriser sammenlignbare med nåværende LNG-priser. Men for vedlikeholdskostnader er konseptet ansett som mye dyrere enn for eksempel et LNG-generatorset, da kabelen har begrenset levetid grunnet slitasje og

utmatting, og vil dermed måtte byttes ut tidligere enn et generatorsett. For et generatorsett vil levetiden kunne økes ved å overhales med utskifting av stempler, lagre og pakninger.

Konseptet har blitt funnet som fysisk mulig, men for å imøtekomme spesifikasjonskrav må utstyr og komponenter prosjekteres og analyseres. Økonomisk er konseptet ganske tilstrekkelig, men fremtidige regelverk for lokale utslipp og drivstoffkostnader kan gjøre konseptet oppnåelig.

List of abbreviations

Abbreviations	***Descriptions***
AFC	Alkaline Fuel Cell
BSEC	Brake Specific Energy Consumption
CDE	Cable Drum Engine
CFC	Chlorofluorocarbons
DMFC	Direct Methanol Fuel Cell
DNV	Det Norske Veritas
DOC	Diesel Oxidation Catalyst
EEDI	Energy Efficiency Design Index
EGR	Exhaust Gas Recirculation
EIA	US Energy Information Administration
HAM	Humid Air Motor
HFO	Heavy Fuel Oil
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IMO	International Maritime Organization
ISO	International Standards Organization
LCE	Linear Cable Engine
LNG	Liquefied Natural Gas
LNT	Lean NO_x Trap
MARPOL	International Convention for the Prevention of Pollution from Ships
MCFC	Molten Carbonate Fuel Cell
MGO	Marine Gas Oil

NAC	NO_x Absorber Catalyst
NOV	National Oilwell Varco
OECD	The Organization for Economic Co-operation and Development
PAFC	Phosphoric Acid Fuel Cell
PaxCar	Passenger-Car-Ship/Ferry
PBCT	Plasma Based Catalytic Treatment
PEMFC	Proton Exchange Membrane Fuel Cell
PM	Particular Matter
PVC	PolyVinyl Chloride
RoPax	Roll-On-Roll-Off-Passenger-Ship/Ferry
RoRo	Roll-On-Roll-Off
SCR	Selective Catalytic Reduction
SEEMP	Ship Energy Efficiency Management Plan
SNCR	Selective Non-Catalytic Reduction
SOFC	Solid Oxide Fuel Cell
TCE	Linear Tracked Cable Engine
TDP	Touch Down Point
VHF	Very High Frequency
XLPE	Cross-Linked PolyEthyline

List of symbols

Electricity calculations

R = resistance (ohms, Ω)

ρ = resistivity (ohm meter, Ω m)

l = length of conductor (m)

A = cross-sectional area of conductor (m^2)

P = power in watts (W)

V = voltage in volt (V)

I = current in amperes (A)

Towing calculations – strength

z = random vertical point on the submerged cable (-m)

z_m = vertical position of the midpoint on the submerged cable (-m)

H = horizontal cable tension component (N)

w = cable weight in air (kg/m)

x = random horizontal point on the submerged cable (m)

T = axial cable tension (N)

w_0 = unstretched submerged cable weight (kg/m)

s = axial tension at a random point on the submerged cable (N)

E = modulus of elasticity (GPa)

A = cable cross sectional area (mm^2)

φ = angle between the axial component and the horizontal plane

p_s= stretched coordinate for s (m)

ε = axial strain in the cable (GPa)

p = hydrostatic pressure (GPa)

ρ = the seawater density (kg/m^3)

g = gravitational acceleration (m/s^2)

μ = Poisson's ratio

T_E = effective tension (N)

L_s = stretched cable length (m)

L = cable length (m)

V = vertical tension component (N)

Mooring calculations

Strength

T_{eff} = effective tension (N)

σ_p = pipe wall stress (MPa)

P_i = internal pressure (MPa)

P_e = external pressure (MPa)

A_i = pipe internal cross sectional area (mm^2)

A_e = pipe external cross sectional area (mm^2)

A_p = pipe wall cross sectional area (mm^2)

T_p = pipe wall tension (N)

T_{p0} = pipe wall tension at origin positioned at the seabed touchdown point (N)

w_p = pipe weight in air (kg/m)

w_s = pipe weight submerged (kg/m)

y = vertical position on the submerged pipe (m)

ρ_w = seawater density (kg/m^3)

g = gravitational acceleration (m/s^2)

d = water depth (m)

T_{eff0} = effective tension at the seabed touchdown point (N)

T =effective pipe tension (N)

T_0 = effective pipe tension (N)

θ = angle between the pipe and the vertical plane

s = pipe curvature length between the surface and the touchdown point (m)

s^* = the catenary length (m)

$d\theta$ = catenary curve angle at a random segment

ds = catenary curve length at a random segment (m)

C = additional factors

θ_0 = slope angle at the touchdown point

α = angle between the pipe and the horizontal plane

x = horizontal point on the submerged pipe (m)

x^*= layback, horizontal length between the touchdown point and the top connection point (m)

μ = Poisson's ratio

R_{min} = minimum horizontal radius (m)

Drag forces

F_D = drag force (N)

C_d = drag coefficient

D = cable diameter (m)

u = flow velocity (m/s)

u_{max} = maximum (surface) flow velocity (m/s)

u_z = flow velocity at a random point on the cable (m/s)

h = water depth (m)

z = random vertical point on the submerged cable (m)

Table of Contents

List of Figures

List of Tables

1 Introduction

Since the focus on emissions from fossil fuels is increasing, the goal of increasing efficiencies, and finding emission reduction measures and alternative energy sources is ever thrived after. Classification companies provide strict regulations for fossil fuel emissions in sea transport which force the energy technologies to leap forward for better solutions and efficiencies. Over the years there have been many concepts and solutions, and most recently LNG-engines, hybrids and fast chargeable battery packs have been developed.

LNG-engines consume liquefied natural gas to produce energy. The emissions to air are significantly reduced compared to the use of diesel oil and heavy fuel oil. In addition the efficiency is higher, i.e. more energy is preserved. By adding a battery pack, it becomes a hybrid with even higher efficiency. Pure fast chargeable battery packs are a new solution for short route ferries with frequent transits, where charging is done at the quays through large capacitors connected to the land power grid. Compared to fossil fuel engines the capacity is limited giving restriction to operational distances before recharging. Battery packs are therefore not considered for longer transport routes.

Future regulations may lead to stricter requirements in terms of fuel consumption and local emissions. Therefore, a competitive concept to fast chargeable battery packs has been assessed where the power is rather supplied constantly than through capacitors from the land based electric power grid. Given that the electric power comes from hydropower or wind power, the concept will be emission free in operation. The concept solution assessed is based on that a short route ferry receives electric propulsion power from the land based electrical grid through an electric power cable, which the ferry lays after it and reels in during transit. The thesis in hand is conducted as a feasibility study for such a cable electric ferry concept. It will enlighten challenges and difficulties with the concept. And main components needed for realization of the concept will here be assessed, where available technology is considered.

It has been assessed different power transfer configurations, cable alternatives and associated handling equipment, such as brake unit, retractor unit and storage. Focus has been given on cable tension on the different transfer configurations, and on storage and cable handling onboard with associated challenges.

In chapter 6 it is presented different functions that a ferry must meet and what functions that will change with concept implementation. Chapter 7 includes assessment of cable technology and cable strength calculations, as well as the different components and equipment involved in the concept. And in chapter 9 it is benchmarked the differences between the concept and competing solutions in terms of specifications and costs. In addition, a case study involving a Norwegian short route ferry transit and implementation of the concept, has been conducted in chapter 10.

In this thesis, it has not been performed dynamic strength calculations of the cable configurations due to limiting timeframe and need of dedicated software. Cable layout and composition has therefore not been analyzed. Further, it has not been performed any engineering of the concept and its components other than preliminary illustrations. Stability calculations for the case study have not been performed due to limited timeframe. Also, structural strength and foundations in the hull relative to the concept components have not been addressed.

2 Ferry

There are many different types of ferries around the globe, but they all have in common that they transport either people or vehicles, or both, from one location to another. Kai Levander presents some ferry types in the book of System Based Ship Design (Levander 2012) such as high speed light craft ferries, RoPax ferries, PaxCar ferries and Cruise ferries. Below, the different ferry types presented have been explained and illustrated in order to visualize their functions.

The high speed light craft ferry carries a relatively small number of passengers and vehicles on short routes in high speeds, e.g. above 15-20knots. To achieve these speeds, the ferries are constructed of light materials such as either high strength steel alloys, aluminum alloys or glass reinforced plastics, or a combination of these. In addition, the hull form is constructed for low resistance in the water, e.g. a twin hull catamaran type.

Figure 1: Catamaran high speed light craft ferry (NorthernNorway 2013)

Then there is the RoPax ferry, where vehicles and RoRo-cargo can be driven on and off board in the bow and/or stern. It also has passenger facilities such that it can transport both people and their vehicles for longer distances across open sea, in addition to other RoRo-cargos for payload transportation (Levander 2012). The ferry has several cargo decks and carries more vehicles and other RoRo-cargo than passengers.

Figure 2: RoPax ferry (Cargotec 2013)

Next, there is the PaxCar ferry, which is passenger ferries with cargo hold areas for passenger cars, called “Passenger-Car” ferries. It functions like a cruise/tourist ferry with passenger cabins and facilities, and is utilized for longer routes and night services (Levander 2012).

Figure 3: PaxCar ferry (YachtWorld.com 2012)

Cruise ferries have cabins for all passengers and large public spaces in addition to restaurants and bars, etc. There may also be swimming pools and casinos onboard, and the ferry can also transport some passenger cars on small RoRo-decks. The ferries can operates as overnight- and longer route cruise, as well as tourist cruise vessels traveling for instance between cities in the Mediterranean (Levander 2012).

Figure 4: Cruise ferry (Cruisemates 2013)

In this project, the focus is given on short rout ferries, which functions as road extensions. Ferry transportation is essential for some locations as there may not be any other road alternative as a result of landscape and budget. So the ferry is set in as a substitute to tunnels, bridges and roads for vehicles to shorten the distances and provide an economically feasible solution. Such ferries can have open, partially open or closed car decks (single or double decks), and passenger facility areas with salons and cafeteria. The calculated size of the facilities and the car decks, depend on the assigned location's transportation demand.

Figure 5: Costal short route ferry in Norway (www.blv.no 2010)

2.1 System Based Design

Ship design follows certain procedures from idea until finished vessel. A customer, for instance a shipowner, needs a ship which must fulfill certain tasks. He or she presents the idea with requirements to a few design companies. These design companies then start working with ideas and concepts that fulfills the costumer's requirements. Then the design companies' concepts are presented for the costumer, with different solutions to the problems. From these concepts the costumer decides which concept he or she would like to purchase. Now after the concept decision is made, the design company starts evolving the vessel concept and design before a yard starts construction of the ship

One design process is presented by Kai Levander in his book of System Based Ship Design (Levander 2012) where the process is arranged in a spiral, i.e. the design spiral (figure 6), with major points and systems important for the design process.

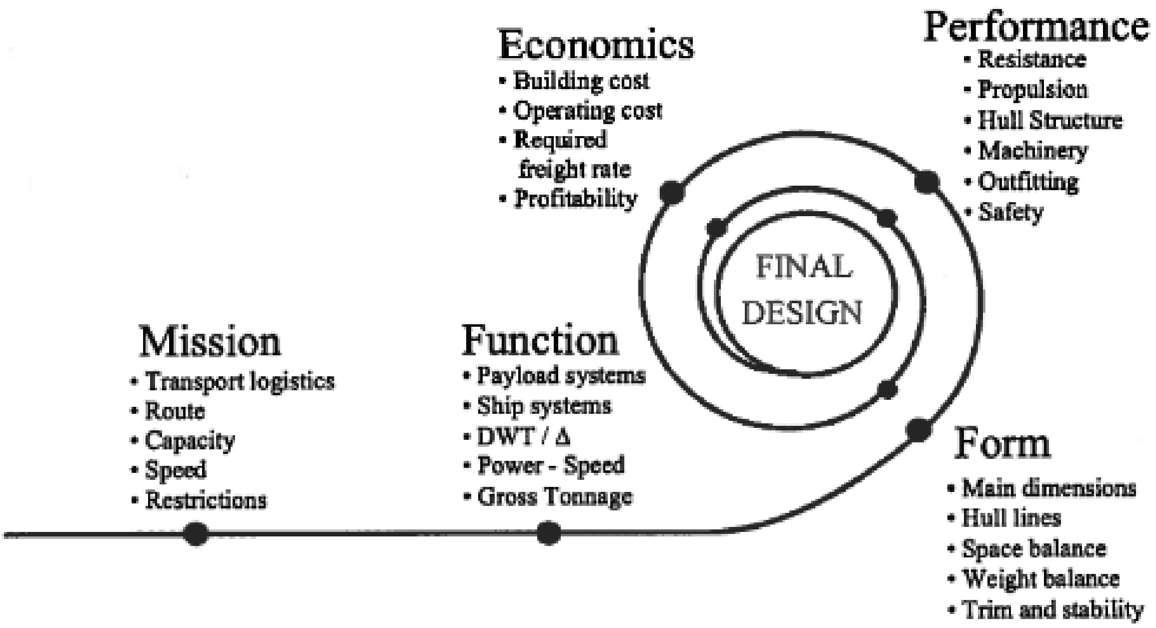


Figure 6: System based design process (Levander 2012)

Here the starting point is determining the mission of the ship, what tasks it shall perform and which properties it should hold, such as operational areas, cargo capacity, speed and technical performances, etc. Next step is the functions of the ship which is based on for instance what payload- and onboard ship systems, deadweight over displacement, and gross tonnage the ship should operate with. Then the design process continues by determining form and shape of the ship, i.e. the initial design with dimensioning and hull lines, in addition to stability calculations based on weight and space balancing. Further procedure is to calculate the performance of the ship. This is done by optimizing the machinery and propulsion system based on hull structure and resistance for the specific ship according to its mission. Also, in the performance step it is taken into consideration various outfitting activities needed for mission handling, and safety equipment required for operation in certain areas. Last we have the economics step where calculations on various costs are made, such as build and construction costs, operational costs (fuel, maintenance, and crew), and required freight rate when it comes to profitability of the ship. From the figure we see that the three last steps, i.e. the form, performance and economics, will be repeated with adjustments to the design until final design is chosen and construction can be started. It is stated that “System based design is like a checklist that reminds the designer off all the factors that affect the design and record his choices”(Levander 2012).

Kai Levander further presents in the design process for ferries a system division of the function step in the design spiral. He states that it can be divided into a payload system and a ship system, as seen in figure 7.

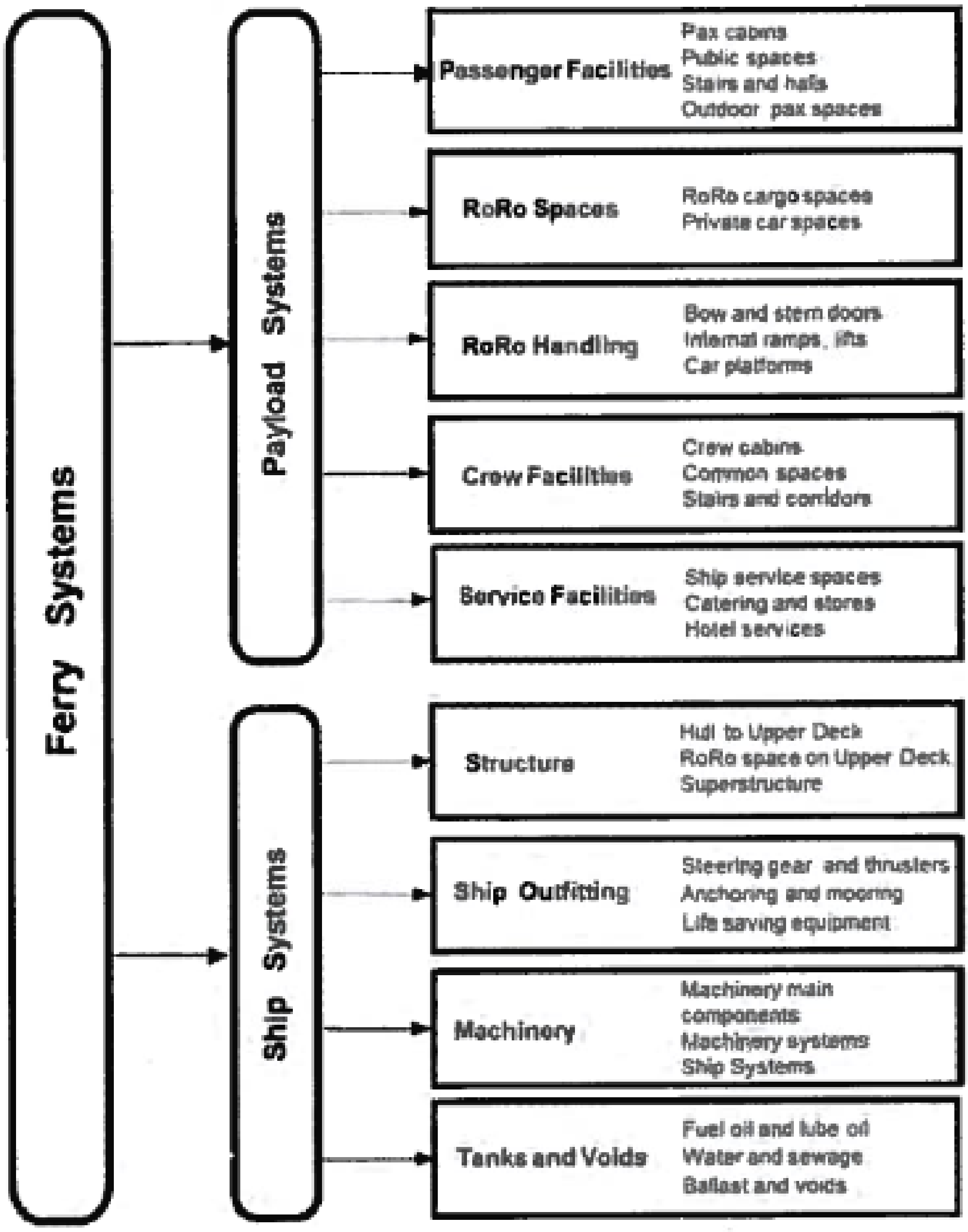


Figure 7: Ferry System (Levander 2012)

The figure shows the division of the ship functions, but it is representing RoPax ferries. Here the crew facilities are displayed on the payload system. This because passengers are served by more crew members compared to the number of deck & engine crew needed for ship operation. As the number of service crew in a short route ferry is normally less than or the same as deck & engine crew, the crew facilities would be transferred from payload system too ship systems.

3 Concept – the idea

The focus on reduction of emissions and use of fossil fuel has propelled the outside-of-the-box thinking of engineers. One alternative propulsion solution for short route ferries is presented here. The idea is that the ferry operates completely on electric power with no use of any combustion engines. The electric power shall be delivered to the ferry through a cable which is connected to the land power grid. Questions whether this is beneficial and if it will work are raised.

The cable is connected to the land power grid through a transformer inside a control house on shore, such that the correct amount of power is delivered to the ferry through the cable. The cable runs into a securing/locking system by the control house. The systems mission is to prevent damages to the connection point and cause short circuits due to tension on the connection point. On board the ferry the cable is connected to a transformer and the main switchboard such that the power is divided to the different onboard consumers. Also here the connection point shall have no tension in order to keep the connection durable.

3.1 Configurations

There are a number of possible configurations in mind regarding cable connection and transfer. The cable can either be stored in a drum spool or a basket carousel onboard the ferry or on shore, or the cable can be stretched in the air over the route. For either storage on shore or onboard, the cable is feed out from the storage unit when the ferry sails away from shore and spooled in when it sails back, i.e. the ferry drags the cable after it under transit and the cable is then spooled back in on the storage unit when the ferry returns. For the drum spool selection it can be situated either vertically or horizontally. For the air stretched cable, the ferry is connected to the cable and follows it over the transit.

3.1.1 Storage units

Figure 8 displays a drum spool system for storage of cable onboard a cable laying vessel. Given that the drum spool displayed stores cable for offshore applications connecting for instance a rig with land or a different rig at another field, the distances and depths are assumed much greater than what is expected for a short route ferry transit where the concept is applicable. In that context, the size of the drum spool is assumed to be much smaller. The same yields for the basket carousel cable storage concept for cable laying vessels displayed in figure 9.

The storage unit will rotate respectively clockwise and counter clockwise when either the cable is feed out or reel in. As mentioned, the drum spool may be situated either vertically or horizontally wich ever is best sutiable for the specific route and ferry. However, this is not practicall for the basket caroucel as the cable may fall out of the basket causing tangling.

Figure 8: Horizontal cable drum spool storage system (SHIPPING 2013)

Figure 9: Basket carousel cable storage system (System 2013)

3.1.2 Power transfer

Next, the function of transferring the power from land to the ferry can be configured four different ways. Figure 10 illustrates the configuration alternatives in mind where the cable could follow the sea bottom and its contour, the cable could “float” fully immerged below the water surface at a specific water depth, i.e. the cable has less weight than the bottom solution and has higher tension (the cable is “towed”). Or the cable can float on the water surface, or it can be stretched in the air across the strait or fjord. The option selected depends very much on what transit route the concept is to be incorporated where the location may have varying limitations such as transit length, water depth, sea bottom formations, vessel traffic, and environmental conditions.

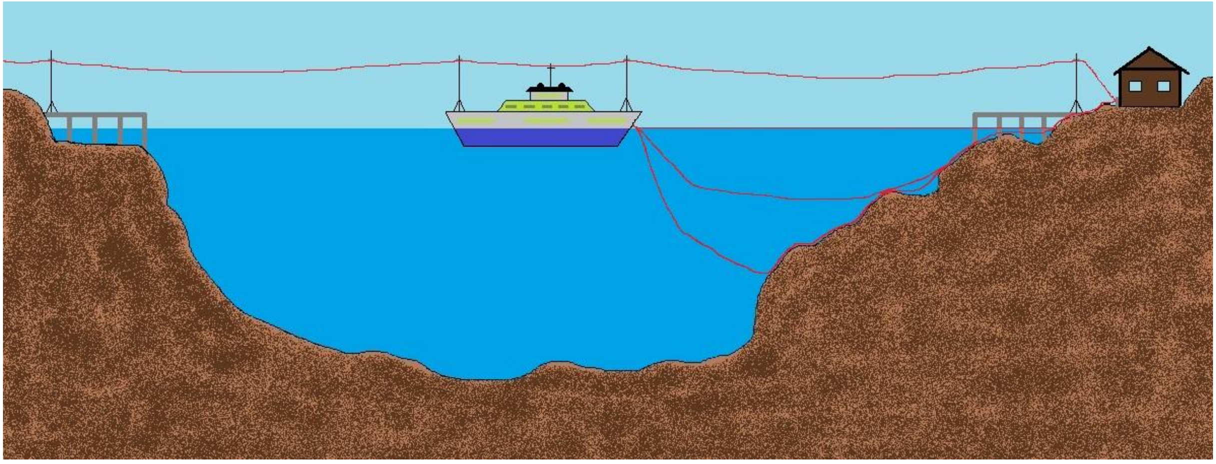


Figure 10: Cable transfer possibilities

For the three water options the cable enters the ferry through a guider-hole in the hull (stern or bow) similar to a recessed anchor hole, regardless whether the storage unit is located onboard or on shore. By the onboard transformer connection point, the cable is secured similar to the transformer locking system on shore, such that the connection point is without tension. After the transformer, the power is directed to the main switchboard. If storage onboard is chosen, the cable connects to the transformer after the storage unit. Here, the cable will go through a set of cable handling equipment before entering the storage unit.

For the air stretched cable alternative the ferry gets its power through arms similar to a trolleybus system, illustrated in figure 11, or like a pantograph on electric trains and trams viewed in figure 12. The trolley arms and the cable stretch are configured high above the water surface such that traffic is allowed to pass underneath. In order to not lose power during transit due to trolley arms detaching because of affects from wind and waves, the arms must be long and under upward tension. The trolley arm “guides” the power down to the hull foundation and further down through the superstructure before it connects to the main switchboard.

Figure 11: Trolleybus in Bergen (Manö 2005)

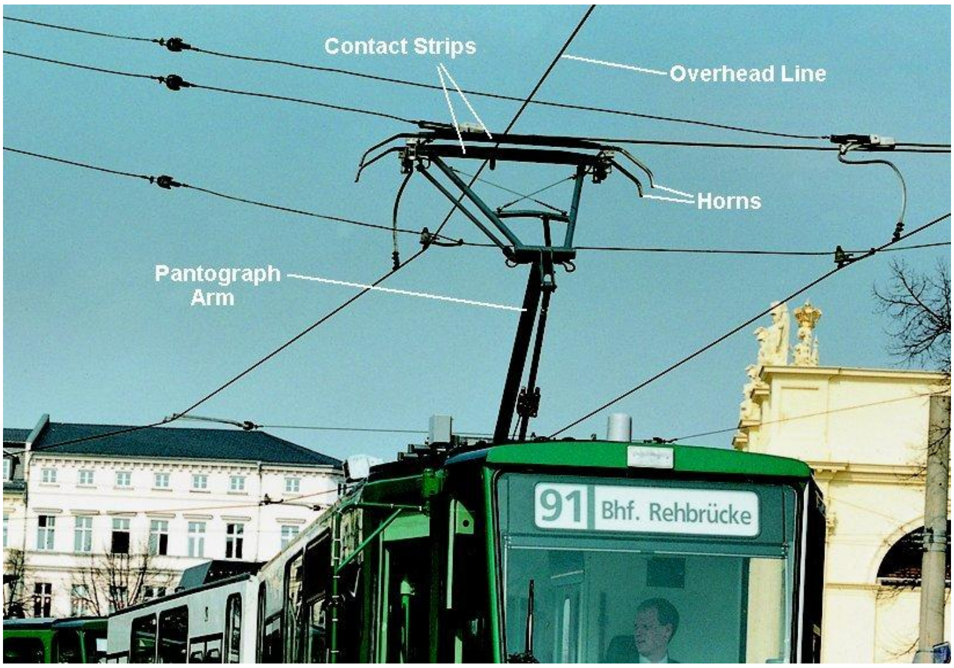


Figure 12: Pantograph system on a tram (Pages 2013)

3.1.3 Risks

As mentioned, the cable transfer configuration option selected depends on the location of the route transit. Either option gives reason to realize that the ferry route must be in an as straight configuration as possible. The more curved the route is, the more tension is given on the cable, i.e. for instance the route goes around small islets and rocks, or the quays are oblique relatively to the route. Wind, waves and current will also affect the tension on the cable, also through ferry movements.

The option of having the cable lying on the seabed may result in damage from sharp edges and rocks, depending on the seabed formation and contours. This would be of even greater concern if the ferry drifts or the route is curved. If the route has a lot of traffic crossing, a surface floating cable option might result in damage to or cutting the cable by for instance propellers, rudders and hulls. Options can be submerging the cable and tensioning it such that it maximum reaches a given water depth, or stretching it in the air at a given height to avoid high masts.

If a blackout or shutdown occurs during transit, the type of transfer configuration selected will give high requirements to cable strength, i.e. in terms of ferry drift. For the floating cable option, environmental forces may cause the ferry to move back and forth during a blackout, which can lead to sudden jerks of the cable. This may cause damages and fractures to the cable with possible shortcuts and potential electrocution of the ferry. This also yields for the two other water options, but here the cable length gives less risk since the ferry will have larger room to drift (and thus more time to restore power).

For the air stretched cable alternative it is a risk of cutting the cable off (e.g. if the tension provided by the arms is to high due to for instance ferry drift, or the cable is hanging too low for crossing traffic) and potentially electrocution of the ferry itself due to fracture and short circuit, if the tension level gets too high from for instance ferry drifting. If the cable is fractured or damaged, a short circuit may cause the ferry to lose power and a blackout occurs. A damaged cable may give problems restoring power onboard the ferry which thus may start drifting. Drifting may cause the cable to snap off or the ferry can get serious hull damage from hitting rocks and islets or land. If the ferry fails to restore the main power within a given time, an emergency power source shall give the ferry enough propulsive power such that it is able to reach shore.

The cable experience heat generation due to electrical resistance, but in sea water the cable has good cooling. However, storing the cable in a storage unit (drum spool or basket carousel) with staking/piling of cable, the heat is somewhat trapped. If the storage unit isn’t applied sufficient cooling, the heat may cause a blackout or in worst case fire. For safety, a mechanism for emergency shut down due to overheating should be applied, in addition to good cooling system.

3.1.4 Cable handling equipment

For the options of storing cable either onboard or on shore it is required a retraction- and braking system respectively onboard or on shore. The retraction system’s function is to spool in the cable with constant speed and force, and the braking system’s mission is to keep a constant tension on the cable when spooling in and out to avoid the cable. This in order such that it doesn’t drop the whole cable out when spooling out or giving to much tension on the cable when spooling in. However, the retraction- and braking system must be constructed such that under a blackout or shutdown situation where the systems don’t work, a safety function will kick in when a given tension level is reached. The safety function will release the tension on the cable such that it can be dragged out without damages if the ferry drifts.

After the braking- and retraction systems the cable will run through some movable guiding pins or arm towards the storage unit, such that the cable is reeled in a spiral matter (see the blue guider in figure 9).

3.1.5 Onboard storage

The storage unit's location onboard is optimized for the specific ferry for weight distribution and stability calculations. As for the space, the storage unit could be situated either vertical or horizontal, depending on the cable size and length, and space available onboard the specific ferry. The cable end is then connected to an onboard transformer which transforms the electricity into correct voltages and amperes for propulsion and other onboard systems. The power is distributed through the main switchboard using a power management system.

3.2 Cable

As mentioned, the power transfer can be configured four different ways, which all will give different cable properties. This will require different cable technologies. The cable will either way have similar cores with three conductors in order to provide the three-phase power needed on the ferry. The air stretched alternative requires three separated parallel cables stretched over the route. The conductors will however vary in dimension for different cable lengths as of the resistance of the conductor material. The longer the cable needs to be, the thicker the conductor has to be. This will affect the total diameter on the different cable transfer configurations. For the cable following the sea bottom the cable will be the longest alternative, giving the thickest conductors, but the cable does not need any floating cap giving it a smaller overall diameter. For the submerged tensioned alternative, the conductor diameter will be larger than the surface floating alternative, but smaller overall diameter. The air stretched alternative will have the overall smallest diameter as the three cables aren't isolated and the length is relatively short. In common for the three water alternatives is that the cable needs to be robust, strong and flexible, this in order to cope with tensions from ferry drifting and environmental forces, as well as prevent damage from sea bottom contours and formations. And it needs to be durable and flexible when it comes to spooling. The air stretched cables should be strong and robust such that damages is prevented if the ferry drifts – applying significant tension on the cables.

4 Marked analysis – Ferry routes in Norway

There are many ferry routes in Norway with varying transit distances and ferry sizes. A study of ferry shipping companies and the Norwegian coast in maps and satellite images (Google 2014), results show that of the ferries operating short coastal routes, transporting both passengers and cars, there are 129 all year routes in Norway. An overview of these routes is listed in the Appendix A. The ferries operating these routes vary in size as of the number of passengers and vehicles that uses and depend on the transportation route, as well as the environmental conditions at the route location. Of these 129 routes there are 38 routes that are within 6km distance along the Norwegian coast. These 38 routes are of different character. Some are zigzagging between small islands and islets and relatively protected from large environmental effects. While others are short and straight in weather exposed areas, and some are crossing fjords. The routes are spread along the whole Norwegian coast from Vestfold to Finnmark county.

The ideal route would be short, straight with quays aligned in the route direction, in protected waters, and with low crossing traffic. A number of routes satisfy most of the criteria, but others may need some alteration to for instance quay facilities and locations in order to enable the concept solution. 15.5% of the Norwegian all year routes requires very little or no changes to quays and transits, i.e. 20 routes. The relevant routes are presented in the table below with distances and some difficulties for consideration.

County	Route	Distance	Addition
Vestfold	Kragerø – Skåtøyroa	Ca. 2.1km	Possible, but slightly curved and risk of traffic
Agderfylkene	Launes/Hitra – Kvellandstrand	Ca. 1.3km	Possible. Weather and risk of traffic?
Rogaland	Sand – Ropeid	Ca. 2.1km	Possible, but small curve
Hordaland	Jondal – Tørvikbygd	Ca. 5km	Possible. Weather?
	Valestrand – Breistein	Ca. 2.1km	Possible, but slightly curved
	Duesund – Masfjordnes	Ca. 0.8km	Possible
Sogn og Fjordane	Lavik – Oppedal	Ca. 5.3km	Possible, but oblique quays
	Stårheim – Isane	Ca. 3.8km	Possible, but oblique quays
	Lota – Anda	Ca. 2km	Possible, but oblique quays
	Solvorn – Ornes	Ca. 3.4km	Possible, but small curve
	Barmsund – Barmen	Ca. 1.6km	Possible. Weather?
Møre og Romsdal	Folkestad – Volda	Ca. 3.5km	Possible, but some curve and little oblique quays
	Stranda – Liabygda	Ca. 3km	Possible, but little oblique quays
	Festøya – Solavågen	Ca. 4.4km	Possible, but little oblique quays. Weather?
	Hundeidvika – Festøya	Ca. 5km	Possible, but slightly curved. Weather?
	Kvanne – Rykjem	Ca. 2.8km	Possible
	Halsa – Kanestraum	Ca. 5.6km	Possible
	Arasvika – Henneset	Ca. 3.4km	Possible, but little oblique quays
Nordland	Forøy – Ågskardet	Ca. 2.7km	Possible. Weather?
Troms	Svensby - Breivikedet	Ca. 6.2km	Possible, but slightly curved

Table 1: Relevant routes in Norway

We see that the routes have varying distances and different degree of difficulties. Studying the maps of the routes one can see that there are areas where the concept is better suited then other, be it weather exposed and/or curved routes, and/or oblique quays, which can give challenges in implementing the concept. Small quay alterations may be good solutions, but weather challengers might be harder to cope with as wind and waves may affect the cable and the ferry, and thus the tension levels. Never the less, despite the challenges the number of short routes along the coast indicate that there is a marked for implementation of the cable electric concept.

5 Competing solutions

Is the cable electric concept a good idea? As described, the concept may be suitable for small car ferries at short transit distances. The dominating solutions for such ferries in Norway are diesel and diesel-electric propulsion systems, but examples of LNG and LNG-electric propulsion are also present.

5.1 Regulations – emissions

And many of the ferries operating the routes have been in service for a long time, e.g. decades. At the time the engine manufactures didn't have as strict regulations as what is presented today. This means that the fuel used per hour and emissions where quite high. But over the years there have been established conventions and treaties to improve safety at sea and help the environment. One such convention is the MARPOL 73/78, "International Convention on the Prevention of Pollution from Ships", which's purpose is to prevent pollution of the marine environment by ships from either operational or accidental causes (IMO 2014) . The convention consists of two treaties, i.e. the -73 convention and the -78 protocol. MARPOL was adopted by IMO (International Maritime Organization) on 2 November 1973. It covered measures to prevent pollution from "oil, chemicals, harmful substances in packaged form, sewage and garbage"(IMO 2014). In order for the convention to enter into force, it had to be ratified by 15 states "with a combined merchant fleet of not less than 50 percent of world shipping by gross tonnage"(IMO 2012). In 1978, due to a number of oil tanker accidents in 1976-1977, there was created a protocol with measures affecting tanker design and operation. The protocol was incorporated into the 1973 International Convention for the Prevention of Pollution from Ships (1978 MARPOL Protocol) and also the 1974 convention of Safety of Life at Sea (1978 SOLAS Protocol) (IMO 2014). Combined, the convention and protocol is referred to as MARPOL 73/78 – the International Convention for the Prevention of Marine Pollution from Ships. Over the years there have been amendments and alterations to the convention as research has resulted in new information on environmental hazards. The convention consists now of 6 annexes (IMO 2012) :

Annex I: Prevention of pollution by oil

Annex II: Control of pollution by noxious liquid substances

Annex III: Prevention of pollution by harmful substances in packaged form

Annex IV: Prevention of pollution by sewage from ships

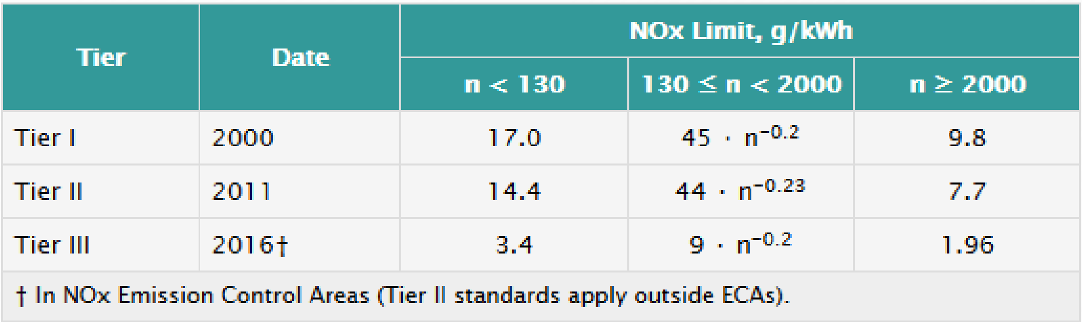
Annex V: Prevention of pollution by garbage from ships

Annex VI: Prevention of Air Pollution from Ships

5.1.1 Air emission regulations

Annex VI, Prevention of Air Pollution from Ships, came in 1997 and entered into force on 19 May 2005 (IMO 2012). This annex aims to minimize the emissions of gasses through ship exhaust such as sulphur oxide (SO_x), nitrogen oxide (NO_x) and prohibit deliberate emissions of ozone depleting substances (which include halons and chlorofluorocarbons (CFCs)). This in order to reduce and prevent the local and global air pollution contributions from ships, and thus environmental problems emissions may cause (IMO 2012). Annex VI was amended in 2005 with incorporation of the North Sea as a SO_x Emission Control Area (SECA) in addition to updated NO_x Technical Code. And in 2008 the annex was revised and amended with further reductions of the sulphur emissions, i.e. the global sulphur cap would be reduced gradually from the 2008 value of 4.50% to 0.50% effective from 1 January 2020. It was also agreed that marine engines should fall into the “Tier III” restrictions for engines installed in ships constructed after 1 January 2016 that will operate in Emission Control Areas. In 2011 there was added a new chapter in Annex VI which states that the Energy Efficiency Design Index (EEDI) is mandatory for all new ships and that the Ship Energy Efficiency Management Plan (SEEMP) is mandatory for all ships. This would affect all ships of gross tonnage of 400 and above, besides exceptions.

As the conventions entered into force and the ship owners needed new ships, the focus on both emissions and the fuel consumption per hour forced the engine manufactures to rethink and develop more efficient and cleaner engines. The 1997 protocol, i.e. the IMO emission standard, was defined in the Annex VI with engine standard Tier I (IMO 2012). As 15 states was needed to ratify the protocol in order for it to enter into force with not less than 50% of the world merchant shipping tonnage, the protocol didn’t enter into force until 2005. Now the protocol applied retroactively for new engines “greater than 130 kW *installed on vessels constructed on or after January 1, 2000*, or which undergo a major conversion after that date”, as well as rigs and platforms (DieselNet 2011). In 2008, amendments to Annex VI gave demands on fuel quality to further reduce the NOx emissions from July 2010. Tier II and Tier III (Tier III standard in Emission Control Areas from 1 January 2016) emission standards were introduced for new engines, and Tier I emission requirements for engines built before 2000 (DieselNet 2011).



Tier	Date	NOx Limit, g/kWh		
		$n < 130$	$130 \leq n < 2000$	$n \geq 2000$
Tier I	2000	17.0	$45 \cdot n^{-0.2}$	9.8
Tier II	2011	14.4	$44 \cdot n^{-0.23}$	7.7
Tier III	2016†	3.4	$9 \cdot n^{-0.2}$	1.96

† In NOx Emission Control Areas (Tier II standards apply outside ECAs).

Table 2: MARPOL Annex VI NO$_x$ engine emission limits (n = engine rpm) (DieselNet 2011)

Table 2 and figure 13 represents marine engine NO$_x$ limits as a function of engine revolutions provided in the 2008 amendment of Annex VI of the MARPOL 73/78 convention.

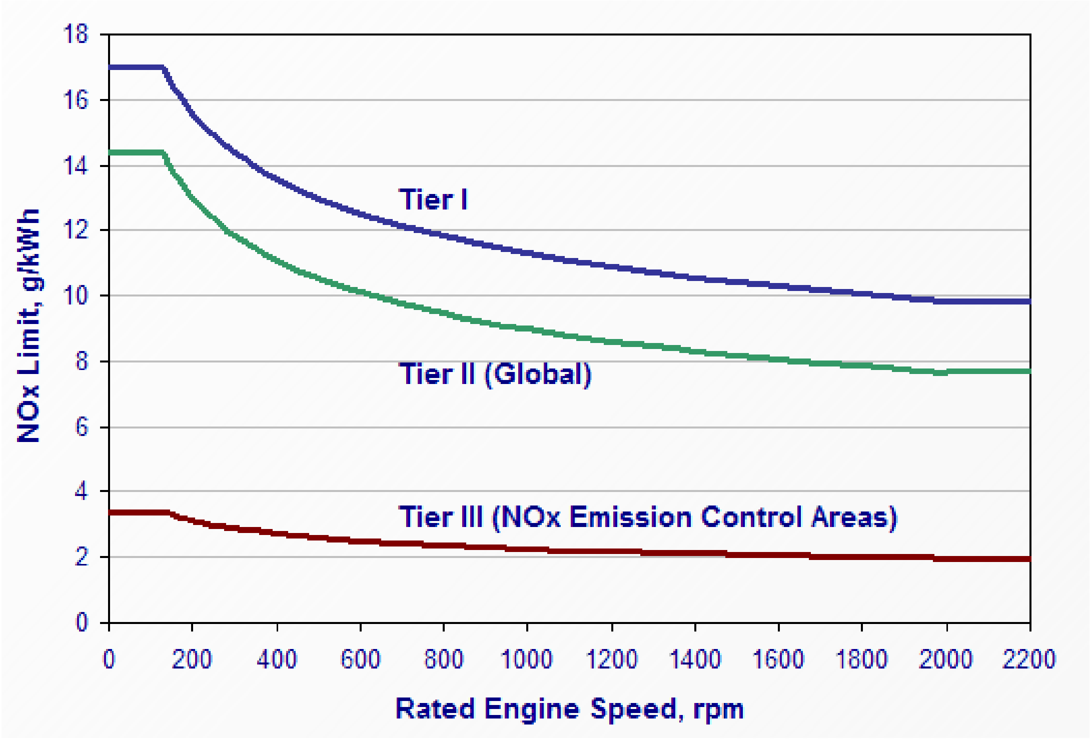


Figure 13: MARPOL Annex VI NO_x engine emission limitations (DieselNet 2011)

As many of the short route ferries along the Norwegian coast are old and ripe for replacements, new power sources are also needed. Resent years more new ships and ferries have installed LNG (Liquefied Natural Gas) powered engines which are proven to be very efficient and environmental. They also have low maintenance needs. This is because of the fuel, which when burned correct produce “only” carbon dioxide (CO_2) gas and almost no NO_x or SO_x gasses. Unfortunately CO_2 is a great greenhouse gas which affects the atmosphere giving warmer climate. CO_2 gas in the atmosphere prevents the earth’s reflection of heat from the sun, thus warming up the atmosphere more than what is ideal. This can result in melting of polar icecaps and changing the global climate, thus forcing human adaption.

Both new diesel engines and LNG-engines must follow the rules for emission reduction above, and in the near future there will come stricter regulations to further reduce the emissions of NO_x and SO_x gasses, and especially CO_2. In the following chapter, measures to improve engine efficiency and reduce emissions are discussed.

5.2 Emission reduction measures

Measures have been taken in order to reduce air emissions, such as more fuel efficient sailing (slow streaming), and more efficient engines with lower fuel consumption and exhaust treatment. Measures to give more efficient engines are in the Journal of KONES Powertrain and Transport, divided in three categories (MyĞków, Borkowski et al. 2011):

- *Preliminary fuel and air treatment*
- *Construction changes of combustion chamber, fuel injection shaping, etc.*
- *Exhaust gas after-treatment*

Preliminary fuel and air treatment measures to reduce the emissions are achieved by adding water to the fuel or mixing steam in the air (MyĞków, Borkowski et al. 2011). Fuel and water can be mixed through a homogenizer. Adding water to the fuel may reduce the emissions by almost 40% with maximum of 20% water concentration in the fuel. One solution can be to mix compressed inlet air with steam giving a higher humidity of the combustion air. Adding steam gives reduced combustion air temperature allowing more oxygen to enter the combustion chamber. This can reduce the NO_x emissions up to 50% depending on the engine's technology, e.g. humid air motor – HAM (MyĞków, Borkowski et al. 2011).

Engine manufactures are optimizing the combustion process in order to reduce the NO_x emissions by modifying and changing the combustion chambers and fuel injectors (MyĞków, Borkowski et al. 2011). Recirculation of exhaust gases – EGR (un-combusted air and fuel in the exhaust gases) and adding water or urea to the combustion (in air or fuel, or separate injection in the combustion chamber) are also measures. Recirculation of exhaust gases may achieve up to 50% reduction of NO_x emissions, but may increase the emissions of carbon monoxide and particulate matter. The engine control can also be optimized by for instance tweaking the combustion time and compression ratio, improve valve timing, fuel injection pressure and timing, etc. (Hefazi and Rahai 2008).

Then there are the exhaust treatment technologies with various catalysts and scrubbers available for emission control. Current after-treatment technologies for reduction of NO_x emissions include Plasma Based Catalytic Treatment – PBCT, Selective Catalytic Reduction – SCR. Selective Non-Catalytic Reduction – SNCR, Lean NO_x Trap – LNT, Diesel Oxidation Catalyst – DOC, and NO_x Absorber Catalyst – NAC (MyĞków, Borkowski et al. 2011). Further, there is the seawater scrubber which removes sulphur oxides SO_x and particulate matter PM from the exhaust, and Diesel Particulate Filters which prevents emissions of soot, particulate matter PM and NO_x (Hefazi and Rahai 2008). In addition, fuel manufactures are filtering the fuel in order to reduce the sulphur content.

The efficiency of diesel engines has due to fuel and combustion optimization proven to increase over the years. Engine manufactures have also incorporated measures to preserve some of the heat loss from the engine. By for instance adding a steam boiler and a steam turbine in a “combined cycle” connection one can use some of the excess heat from the engine and/or exhaust to produce electricity. Another way is to use a boiler in order to preserve heat in terms of steam or hot water to be used as onboard heating (WÄRTSILÄ 2008). This could increase the engine efficiency significantly.

LNG engines are much cleaner than diesel engines, with as much as 30% reduction of CO_2 emissions and virtually no SO_x or NO_x gas emissions. However, there have been some issues with combustion of the methane gas – MH_4 on the early engines as some of the gas is un-combusted. Methane gas is a greenhouse gas which has over 20 times larger greenhouse effect than CO_2 (Leader 2012). However, later and new models have better combustion, increased efficiency and reduced emissions.

5.3 Electric solutions

LNG electric- as well as diesel electric propulsion are both good solutions in terms of efficient combustion, load variations, lifecycle and maneuvering. The engines can run at an optimum revolutions and the ship can with pods or azimuth thrusters increase maneuverability.

But as the focus on fossil fuel and emission is increasing one would assume that the use of electric power system is a reasonable and good substitute to combustion engines for given ships. Electric propulsion is becoming more usual for ships which require high maneuverability and large load variations. Electric motor driven pods and thrusters are efficient and provide good maneuverability compared to conventional direct shaft connections with rudders. The thrusters are provided electricity from gensets, which are either LNG or Diesel powered engines driving generators to convert combustion energy, i.e. mechanical energy, into electricity.

In order to reduce the local emissions as well as greenhouse gasses one option could be to utilize all electric power for propulsion. For instance a battery powered system with boost/speed charging at the quays, or perhaps the given concept solution. Both these options have limited range and large impact on the land power grid, but for short transits and environmental vulnerable areas, the options may be good solutions.

Now, one question is whether a battery solution is better or worse than the concept. There are a number of battery technologies available, but the most promising option is Lithium-ion battery technology (Opdal 2010). Lithium-ion batteries have high energy density, low self-discharging and good resistance to ageing. However, large battery packs have disadvantages in terms of large production- and investment costs, and weight. Even though the Lithium-ion batteries have good aging resistance they do age over time, requiring replacement in order to keep the capacity levels. As for the concept solution wear and tear, and fatigue are factors which would affect the cable lifecycle. Production and investment costs are harder to estimate as the cable technology for the concept is not available currently, but it is assumed that current power cables can be modified to fit the requirements and not escalade costs largely.

An example of a promising battery power solution is the new ferry ZeroCat, illustrated in figure 14, which will operate between Oppedal and Lavik in Sognefjorden (Fjellstrand 2012). The ferry is currently under construction but will start service 1. January 2015. Each transit will take approximately 20 minutes in 10 knots speed. The ferry will have a capacity of 120 cars and 360 passengers. Its lithium-ion batteries are charged during the 10 minute docking sequence when the ferry is unloaded and loaded. This doesn’t fully charge the batteries, therefore are they fully charged at night when the ferry is taken of duty/service. Charging of the onboard battery pack is done by a cable connection under docking. The electricity is fed by an on shore battery pack (capacitor) on each side of the transit. These on shore battery packs are charged from the land power grid when the ferry is under transit.

Figure 14: ZeroCat battery ferry (Fjellstrand 2012)

6 Functions

A ferry is designed and constructed in order to accommodate payload demands for given operation locations, i.e. number of passengers, vehicles and weight that is considered to utilize the transportation offer. The main function of the ferry is thus to transport passengers and their vehicles from one location to another. However, in order to perform this main function the ferry has to fulfill several tasks, such as power transfer from engine to thrust, maneuvering, handling of vehicles and passengers, etc.

6.1 Systems and power

A complete ferry consists of several systems working together. For instance, the main switchboard divides and manages the power generated and assigns the required amount to the different onboard consumers like propulsion (if the ferry has electric propulsion, e.g. pods or azimuth thrusters) and tunnel thrusters, bridge- and navigation equipment, and accommodation like café, salons, galley, control room, etc. Power is delivered to the main switchboard from a generator which's function is to convert mechanical energy into electrical energy. The generator is mechanically connected to an engine, i.e. diesel or LNG driven. This combination of engine and generator is often called a genset and can be configured as a main power supply delivering power to all consumers including propulsion or as a separate power supply for other onboard systems (e.g. accommodation, navigation equipment, etc.). The generators generate electric power at normally 50/60 Hz (Hertz) (depending on generator specifications, i.e. poles and revolutions) to the main power bus (Patel 2011). The connection between the gensets, the switchboard and the consumers are referred to as a bus. The bus power (voltage level) is usually larger than what the consumers require, such that the power needs to be transformed into low voltage power in order for the consumers to set the power to use, for instance the three-phase propulsion motors and the one-phase service load. If the power isn't transformed accordingly to the consumers' needs, one may risk a short circuit that could result in an explosion, fire and/or blackout.

Figure 15 shows an example of a single line diagram representing a possible solution for a diesel-electric or LNG-electric propulsion system where gensets generate power to all consumers. The power here is somewhat redundant distributed with two switchboards, which means that power can be distributed from one switchboard if the other one fails, or for instance a genset fails. Figure 16 and 17 illustrates the different components which includes in a diesel-electric or LNG-electric propulsion system.

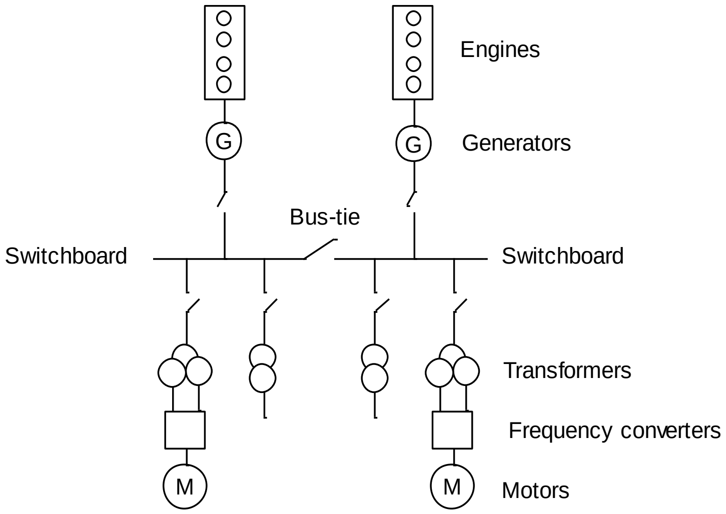
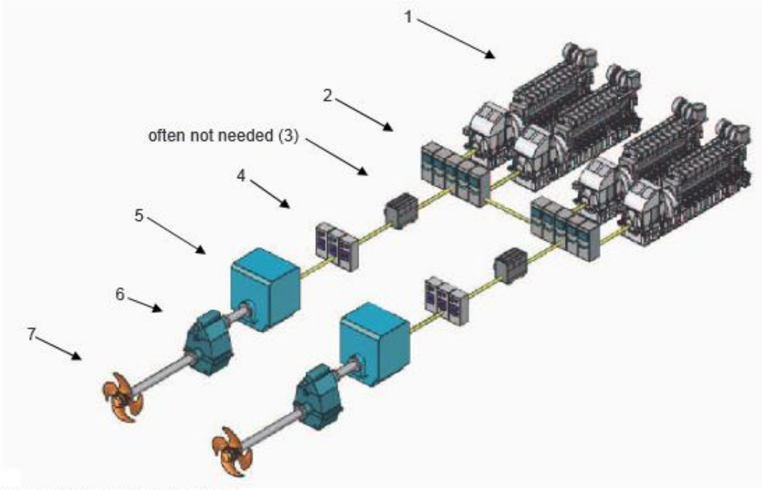


Figure 15: Single line diagram



Example: Diesel-electric propulsion plant

Legend

1	Gensets: Diesel engines + alternators
2	Main switchboards
(3)	Supply transformers (optional): Dependent on the type of the converter. Not needed in case of the use of frequency converters with 6 pulses, an Active Front End or a Sinusoidal Drive
4	Frequency converters / Variable speed drives
5	Electric propulsion motors
6	Gearboxes (optional): Dependent on the speed of the E-propulsion motor
7	Propellers / propulsors

Figure 16: Components of a diesel-electric propulsion plan (MAN 2013)

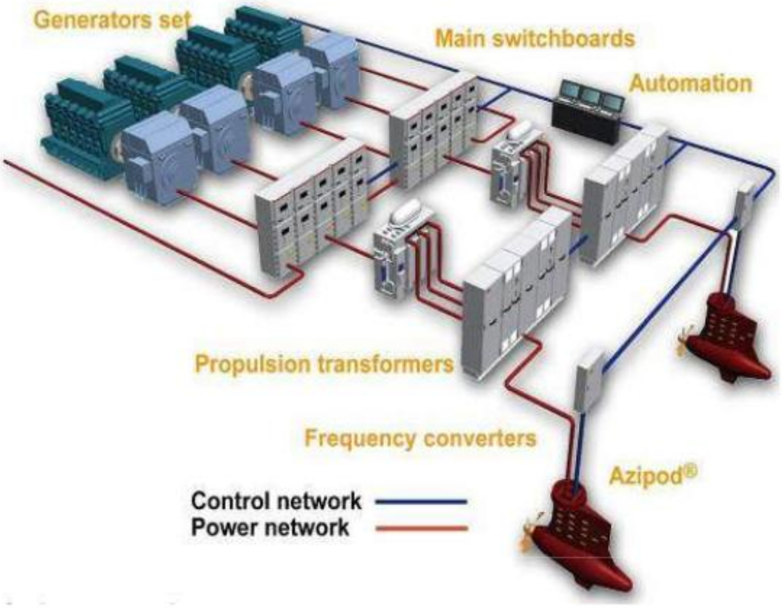


Figure 17: Components of a diesel-electric propulsion plan 2 (Group 2012)

The engines need fuel in order to produce mechanical energy and lube oil in order to prevent tear and wear on the engine. Both fuel and lube oil is stored onboard in separate tanks. The engine control room monitors and controls the engines and generators, displaying power generated and consumed, fuel consumption, and other engine related information. As for the bridge, all navigation equipment and maneuvering systems are controlled and monitored here. So the operators at the bridge can control the propulsion speed and rudder through the engine control room.

6.1.1 Power requirements

The classification society DNV (Det Norske Veritas) says in their rules (Electrical Installation) that the main power supply system, consisting of engines and generators, shall have significant capacity such that all necessary services for keeping the vessel in normal operation is supplied, without use of emergency power (DNV 2013). Further, it is stated that there shall in the main power supply system, be component redundancy for the power sources, transformers and converters. This such that if there is a fault in a power source, a transformer or a converter, there is a back-up system which can supply power to the services listed (DNV 2013):

- *those services necessary to provide normal operational conditions for propulsion and safety*
- *starting the largest essential or important electric motor on board, except auxiliary thrusters, without the transient voltage and frequency variations exceeding the limits specified in A200*
- *ensuring minimum comfortable conditions of habitability which shall include at least adequate services for cooking, heating, domestic refrigeration (except refrigerators for air conditioning), mechanical ventilation, sanitary and fresh water*
- *for a duplicated essential or important auxiliary, one being supplied non-electrically and the other electrically (e.g. lubricating oil pump No. 1 driven by the main engine, No. 2 by electric motor), it is not expected that the electrically driven auxiliary is used when one generator is out of service*
- *For dead ship recover, see 204.*

In addition to these requirements, there can be other services requiring power, depending on which class notation the vessel shall fulfill.

According to NORSOK, for total installed power of under 4MW, the bus voltage level is recommended to be 690volts, which means that the switchboards experience 690volts (Association 2007). Further, the low voltage consumer propulsion motors is recommended to operate at 400volts and in the accommodation at 230volts. The installed generator power depends on the vessels specifications and loading, such as size, cargo capacity, speed etc. This will thus give changes to the bus voltage level, to the main switchboard and transformers. For a ferry, the installed power on board is rather small compared to for instance a bulk carrier. This is because the payload, i.e. weight of cars and passengers, is much smaller than what a bulk carrier transports, in addition to operations close to shore and environmental condition limitations.

6.1.2 Emergency power

When it comes to emergency power onboard a ship, there are certain regulations engineers must follow. DNV provides a set of regulations for emergency power sources onboard vessels (DNV 2013):

101 *Emergency power source*

- *The emergency source of power shall be automatically connected to the emergency switchboard in case of failure of the main source of electric power. If the power source is a generator, it shall be automatically started and within 45 s supply at least the services required to be supplied by transitional power as listed in Table C1.*
- *If the emergency source of power is not automatically connected to the emergency switchboard, a transitional source of emergency electrical power, suitably located for use in an emergency, with sufficient capacity of supplying the consumers listed in Table C1, may be accepted.*
- *The emergency source of power shall not be used for supplying power during normal operation of the vessel. Exceptionally, and for short periods, the emergency source of power may be used for blackout situations, starting from dead ship, short term parallel operation with the main source of electrical power for the purpose of load transfer and for routine testing of the emergency source of power.*

From the regulations, emergency power must be available at all times and provided fast if needed, and be available for a certain amount of time. Further, all systems and components regarded as necessary in emergency situations shall be provided power simultaneously from the emergency power source. The emergency power source may be either a genset or an accumulator battery pack. Regulations state capacity demands for the emergency power in correlation to systems requiring power in emergency situations (DNV 2013):

102 *Capacity*

a) *The electrical power available shall be sufficient to supply all services essential for safety in an emergency, due regard being paid to such services as may have to be operated simultaneously, also taking into account starting currents and transitory nature of certain loads. (Interpretation of SOLAS Ch. II-1/43.2)*

b) *Where the emergency source of electrical power is an accumulator battery it shall be capable of carrying the emergency electrical load without recharging while maintaining the voltage of the battery as required by A200. (Interpretation of SOLAS Ch. II-1/43.3.2.1)*

c) *When non-emergency consumers are supplied by the emergency source of power, it shall either be possible to supply all consumers simultaneously, or automatic disconnection of non-emergency consumers upon start of the generator shall be* *arranged. The system shall be so arranged that the largest consumer connected to the emergency power supply system can be started at all times without overloading the generator unless automatically disconnected upon start of the emergency generator. (Interpretation of SOLAS Ch. II-1/43.5.5)*

d) Starting air compressors, preheaters and lubrication oil pumps for the main engine or auxiliary engines may be equipped for automatic disconnection from the emergency switchboard. Such consumers necessary for starting from dead ship, if supplied from the emergency source of power, shall be possible to connect manually at the emergency switchboard also when the emergency generator is running. If they may cause overloading of the emergency generator, warning signs shall be fitted also stating the load of the consumers.

DNV provides a table showing a list of systems and services requiring emergency power and for what duration, systems like emergency- and navigational lighting, fire detection and alarms, VHF-radio, watertight doors and hatches, etc. This table, Table C1, is displayed in Appendix B.

As for the cable electric concept, it is assumed that the ferry shall in addition to comply with the emergency power regulations by DNV, have the ability to propel itself to shore by the emergency power source installed on board, in case of a fault in the main power supply, e.g. the power cable gets fractured, cut off or experience a short circuit. The capacity of the emergency power source will thus depend on the distance of the operation route and environmental conditions, which gives requirements to a minimum timeframe of emergency power operation. The required capacity is most probable not to give the ferry the same speed as the main power supply as the distances are relatively short, but it must be such that the ferry can propel itself in the worst weather conditions at the location, i.e. certain amount of wind, current and waves.

6.2 Function demands

Within the concept there are some functions onboard the ferry that changes, some functions are removed and some functions are added. But many functions will stay the same, for instance the bridge will still control navigation and maneuvering in the same way as before, the main switchboard will still distribute and assign required amount of power to different consumers. Power production is changed significantly as the main engines will be removed along with the large fuel and lube oil tanks. Now, the cable will provide the required power for the onboard systems and consumers, which is received from the land main power grid. However, for an all cable electric ferry it is assumed as mentioned that an emergency power source is required in order to maintain the safety of crew and passengers in case of damage or fracture to the cable. Removal of main engines and tanks enables space for cable storage and handling equipment, given the configuration of onboard cable storage. These are new functions which consist of systems for cable guidance, braking and retraction systems, as well as a storage unit. These latter functions are added for storage of cable onboard or on shore, while the air stretched configuration has added the function of receiving power from the air stretched cable.

Also, in order for the ferry to be able to operate, the power delivered from the land main power grid must be transformed into usable amount with correct current and voltage. A transformer onboard is needed. And the cable, which delivers power to the ferry, must have some specifications and functions in order for the concept to work as described. These functions and specifications depend on which cable transfer configuration is selected. In common, the cable must be light, flexible, strong, durable, and have good conductivity, etc.

Figure 18 displays the ferry's functions with main categories in payload functions and ship functions. The figure is based on figure 7 provided for ferry system based design by Kai Levander, but has function changes related to the concept solution. Thus, the figure gives new demands for system based design of the concept ferry.

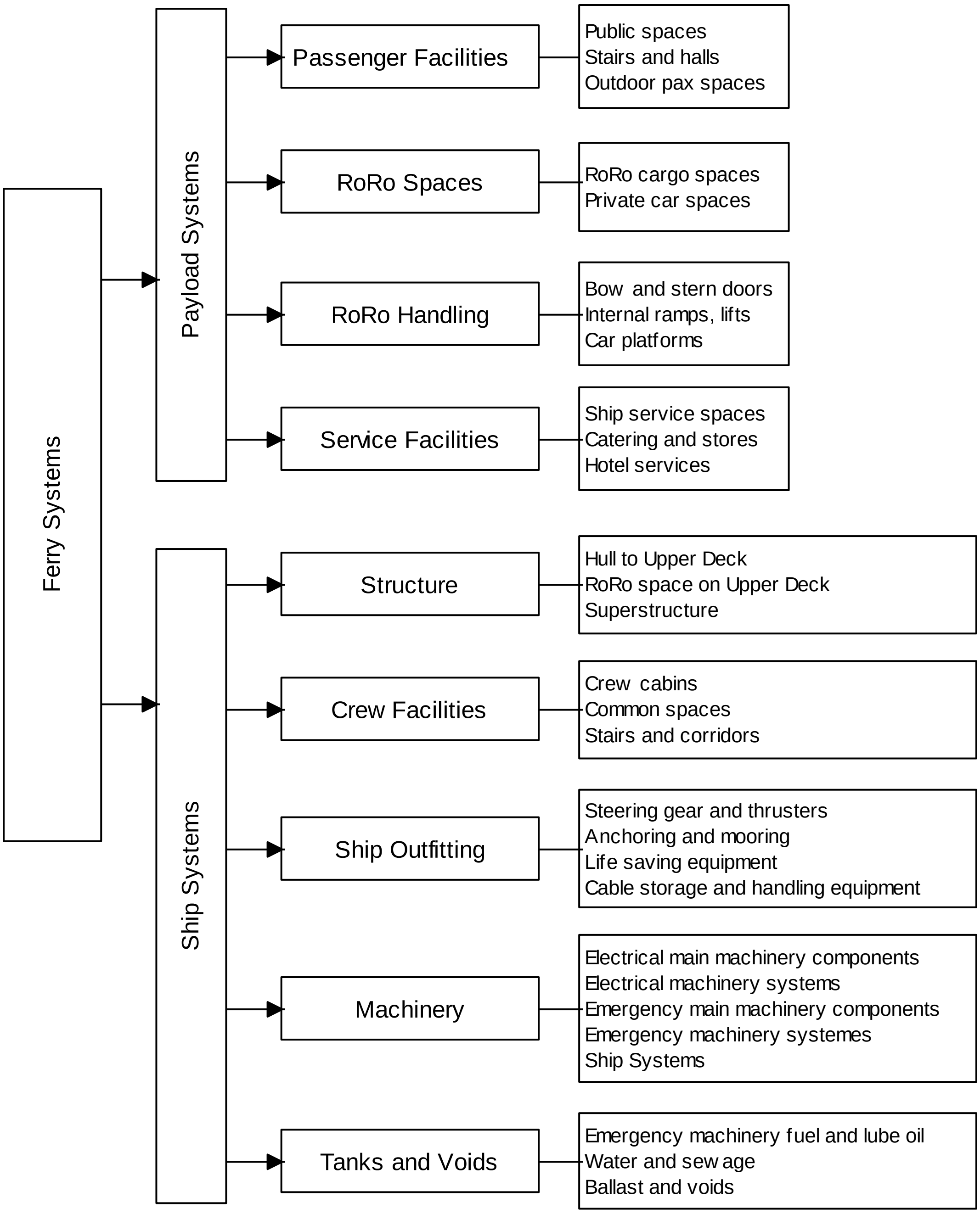


Figure 18: Ferry systems

The concept will as mentioned have some functional changes and much will stay the same. It is assumed that the payload systems will not change for the ferry. This means that it is expected that the passenger- and service facilities along with the car decks and car handling is unaffected. Within the ship systems, unaffected elements are crew facilities and vessel structure. In short, accommodation, bridge and car decks will have little or no changes.

However, structural strength of the deck below the car deck may need reengineering in areas where the concept components are to be placed, as the weights and momentum may differ from conventional systems, i.e. engines and associated equipment. Structural supports and foundations are thus needed. In this thesis the structural strength calculations required for concept implementation is not taken further and thus here assumed sufficient.

When it comes to the ship outfitting point, cable systems are implemented and replace previous engine systems, i.e. cable storage and handling equipment as well as electrical systems with changes to the main switchboard and transformers. Thrusters and steering may also change depending on what such systems already are onboard, e.g. electrically driven thrusters must replace engine shaft driven thrusters/propellers, but not if such thrusters already is used. Further, anchor and mooring equipment, as well as lifesaving equipment, will not change since these systems have no direct connection to engines or gensets.

Now, it is given that the machinery systems, tanks and voids are highly affected. Diesel engines and gensets are removed along with fuel and lube oil tanks. This enables space for concept components, with storage unit and handling equipment, given that onboard cable storage configuration is chosen. However, if the emergency power source is chosen to be a diesel- or LNG-genset, some fuel and lube oil is required, but the amount depends on requirements and operational location. If a battery solution is chosen, then no fuel and lube oil tanks are needed. But in both configurations ballast water and sewage tanks are required. The sewage tanks are assumed to be unchanged, but realistically the size of the ballast water tanks may change as the weight of concept components may differ from previous power systems.

In addition, the operation of electrical machinery is controlled through the machinery system, i.e. power management control using the main switchboard. This implies that there will be alterations here. New components and systems require operation through the switchboard. And as some systems are removed (e.g. engine control), system control and monitoring will alter the main switchboard layout and operation, for monitoring of power generated and consumed, controlling brakes and winches and spooling. The emergency switchboard will also experience some alterations as new requirements are given with respect to provide navigational power, in addition to all other standard emergency operation systems stated in the regulations. This gives that the switchboard must offer control and monitoring of the emergency power generated and consumed for emergency operation as well as display operational timeframe.

Figure 19 displays systems and functions that changes for the concept compared to a conventional ferry.

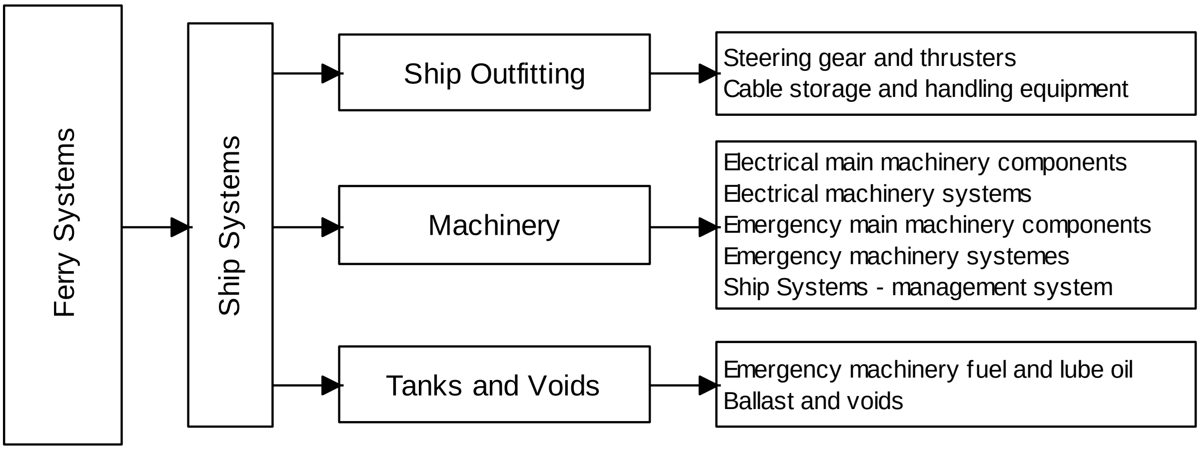


Figure 19: Concept ferry systems

6.3 Consequences

By changing the main power supply from combustion engines to full electrical through a cable, restrictions for the ferry are given. For instance, a cable fastened to the ferry and to shore will limit the operation of the ferry greatly. The ferry can only operate in the given location restricted by the cable length, i.e. the ferry can only sail so long – a maximum distance. And since the emergency power source most likely only gives operational power for a limited amount of time, the ferry will not be able to sail longer distances to for instance another route location to step in for a ferry there. It is known that ferries tend to step in for and help each other if for instance the capacity on the route is to low or the ferry at the respective route has to dock for service or overhauls. In order for the concept solution to be able to operate and assist on another route, the ferry must be towed to location. Another cable must be installed and connected to the ferry. This cable may be longer and thicker as the route distances are different. Storage onboard may then be difficult as the equipment may not be able to handle the cable and the storage unit may be too small. A cable electric ferry will be designed to operate on one particular route, and thus making the ferry able to operate on a different route is costly because of the changes needed both onboard and at the location (e.g. different storage unit due to changed cable length, new converter onboard, new transformers on shore, etc.).

Another issue is conversion of existing vessels, where old machinery is removed and the concept solution is implemented. In order to perform the conversion, the hull side must be cut open or in worst case a separation between hull and superstructure may be needed. This requires long dry docking with serious planning of the operation, in order for the conversion to be performed efficiently and good, such that the structural strength of the ferry is undamaged. A conversion would also affect the stability and weight balance of the ferry, giving demand of new stability calculations with new ballast requirement. Thus, a conversion over a new build must be discussed and analyzed both structurally and financially. In a new build, the concept solution can be implemented during construction, and calculations for stability and strength are here made in advance in the design and engineering stages.

7 Partial solutions

The functions that in this thesis will be mainly focused on are power transfer configuration, cable- storage and handling. Steering and thrusters are assumed to be the same unchanged, i.e. given a diesel electric propulsion system. Further, ship systems with changes to main switchboard and power management control will not be taken into account here, although such changes will affect the concept greatly.

7.1 Power transfer configuration – cable technology

In order to have a functional cable, a number of parameters need to be fulfilled when engineering and designing the cable configurations. The four alternatives for power transfer (i.e. bottom, submerged, surface floating and air stretched) will require different technologies, but the main function which needs addressing is that enough power is provided for the ferry operation.

7.1.1 Resistance

When developing the cable technologies for the concept, engineers must take into account power loss in terms of conductor resistance over the cable length, i.e. the longer the cable is, the thicker conductor diameter and larger cross sectional area the cable must have in order to ensure enough electrical power reaches the other end. This is because of the natural resistance in the conductor material. With increasing length the resistance results in more and more power loss in form of heat generation and voltage drop. Therefore, calculations are needed to find optimal conductor diameters to ensure enough power at the cable end. The conductor dimensions are given as cross sectional area, i.e. mm^2.

In water the cable will have good cooling, but storing the cable on a drum spool or a basket carousel gives the cable little space for cooling, i.e. spooling/piling the cable over itself tightens the room around the cable which hinders the heat escape. To prevent high power losses and reduce heat generation the voltage can be increased and thus the current reduced (the current is the main concern when it comes to heat generation as of friction in the conductor material (Meier 2006)). This would also reduce the conductor diameter. Additional cooling of the storage unit may be required.

Conductor resistance can be expressed through an expression as (ToolBox):

$R=\rho l/A$

where

R = *resistance (ohms,* Ω*)*

ρ = *resistivity (ohm meter,* $\Omega\ m$*)*

l = *length of conductor (m)*

A = *cross-sectional area of conductor (*m^2*)*

***The resistivity of some Common Conductors*:**

Aluminum has a resistivity of $2.6 \times 10^{-8}\ \Omega\ m$

Copper has a resistivity of $1.7 \times 10^{-8}\ \Omega\ m$

As seen, conductors are commonly either aluminum or copper, as these materials have low resistance and therefore high electric conductance. In addition, they are much cheaper than silver and cold, which have even better conductivity. Further the relationship between power, resistance, voltage and current is (Patel 2011):

$P = V \cdot I$

$V = I \cdot R$

P *is the power in watts (W)*

V *is the voltage in volt (V)*

I *is the current in amperes (A)*

R *is the resistance in ohms (Ω)*

7.1.2 Design parameters

Engineers must also address functions like flexural rigidity, yield strength, fracture toughness and fatigue strength when designing cables. The cable needs to be flexible such that it can be reeled in onto to storage unit and handled by the cable handling equipment, i.e. the cable must have sufficient bend radius. And it has to have high yield strength such that it can cope with stresses and tensions caused by ferry drift and/or environmental forces, as well as from cable handling equipment. In addition, the cable must have high fracture toughness and fatigue strength, i.e. long lifecycle, as it will constantly be spooled in and out on the storage unit. Also, for the floating alternative, a floating cap must be added to ensure floatation. The floating cap will affect the cable diameter as well as the flexibility and the weight. The air stretched cable will not have any insulation, giving difficulties with fracture toughness. However, the cable must be strong and have high fatigue strength since the arms will constantly apply upward tension during transit.

Cable design should follow the International Organization for Standardization (ISO) standard 13 628-5 for electric power cables, with influence from DNV's recommended practice of "Electrical Power Cables in Subsea Applications". This recommended practice also covers requirements for cables that are submerged in large water depths in seawater and cables exposed to dynamic excitation. In that context, the International Electrotechnical Commission (IEC) standards for cables are used when designing with the recommended practice, (DNV 2012):

- **IEC 60 502-1**. Power cables with extruded insulation and their accessories for rated voltages from 1kV (Um = 1,2 kV) up to 30 kV (Um = 36 kV) – Part 1: cables for rated voltages of 1 kV (Um = 1,2 kV) and 3 kV (Um = 3,6 kV)
- **IEC 60 502-2**. Power cables with extruded insulation and their accessories for rated voltages from 1kV (Um = 1,2 kV) up to 30 kV (Um = 36 kV) – Part 2: cables for rated voltages of 6 kV (Um = 7,2 kV) up to 30 kV (Um = 36 kV)
- **ICE 60 228**. Conductors of insulated cables

In addition, there are some standards that can be relevant for the concept cable solutions. Standards for power cables used in offshore context, both for cable design and installation are here listed (openelectrical.org 2013):

- ISO 13628-5, “Petroleum and natural gas industries – Design and operation of subsea production systems – Part 5: Subsea umbilicals”
- DNV RP E305, “On-Bottom Stability Design of Submarine Pipelines”.
- IEC 60502, “Power Cables with Extruded Insulation and Their Accessories for Rated Voltages from 1 kV (Um = 1,2 kV) up to 30 kV (Um = 36 kV) - Part 2: Cables for Rated Voltages from 6 kV (Um = 7,2 kV) and up to 30 kV (Um = 36 kV)”
- CIGRE Electra No. 68 “Recommendations for Mechanical Tests on Submarine Cables”
- IEEE STD 1120, "IEEE Guide for the Planning, Design, Installation and Repair of Submarine Power Cable Systems"

7.1.3 Floating capability

In order to make the cable float, a number of different insulation and jacket materials can be utilized to cover the conductors and armor. One such material used in cables and wires is TPR (Thermoplastic rubber), which in addition to floating capabilities has good temperature properties and good flexibility, and it is flame retardant (ANIXTER 2013). However, heat transfer may be an issue. This cover can function either as e complete insulation material (jacket) and floating cap, or as a floating cap outside a jacket material covering the armor threading, e.g. PVC – polyvinylchloride.

Unique Seaflex delivers a floating system for shallow water cable laying, called Seaflex SeaSerpent (UniqueSEAFLEX 2014). The system is designed as an inflatable tube attached/hooked up to the cable each 1.2m with buoyancy capacity between 15kg/m - 132kg/m. The cable is floated out to its location where the air is vented out at one end (e.g. at shore) when the cable is being laid from the other side, such that the cable will get an s-curve during the laying process. By inflating the tube again the cable can be raised and reposition or reeled in for instance for replacement. The inflatable tube comes on a separate reel in a flat configuration. For the concept ferry, such an inflatable tube can be used to keep the cable afloat at both the surface or submerged at a given level. But for the ferry where which the cable is constantly spooled in an out, maybe a system where the inflatable tube is threaded around the cable can be a better solution, given that the inflatable tube is durable in terms of spooling. Such a solution may reduce the diameter of the cable when stored compared to a floating cap, and avoid having to constantly attach and detach the tube and the cable when spooling in or out.

7.1.4 Cable layer configuration

The electric thruster motors are mostly three-phase power driven and gensets usually provide three-phase power in a diesel-electric or LNG-electric propulsion system (ABB Oy 2012). This implies that for the concept solution, the electric propulsive motors are most favorably also three-phase power driven. Which again implies that the power delivered to the onboard ferry power system is in three phases. For a cable to provide three-phase power, it needs three separate conductor wires. Typical three-phase power cables are illustrated in the figures 20 and 21 with construction layers, i.e. conductors, insulation, armor, jacket, etc.

Figure 20: Possible layout for a power cable (TRATOS 2010)

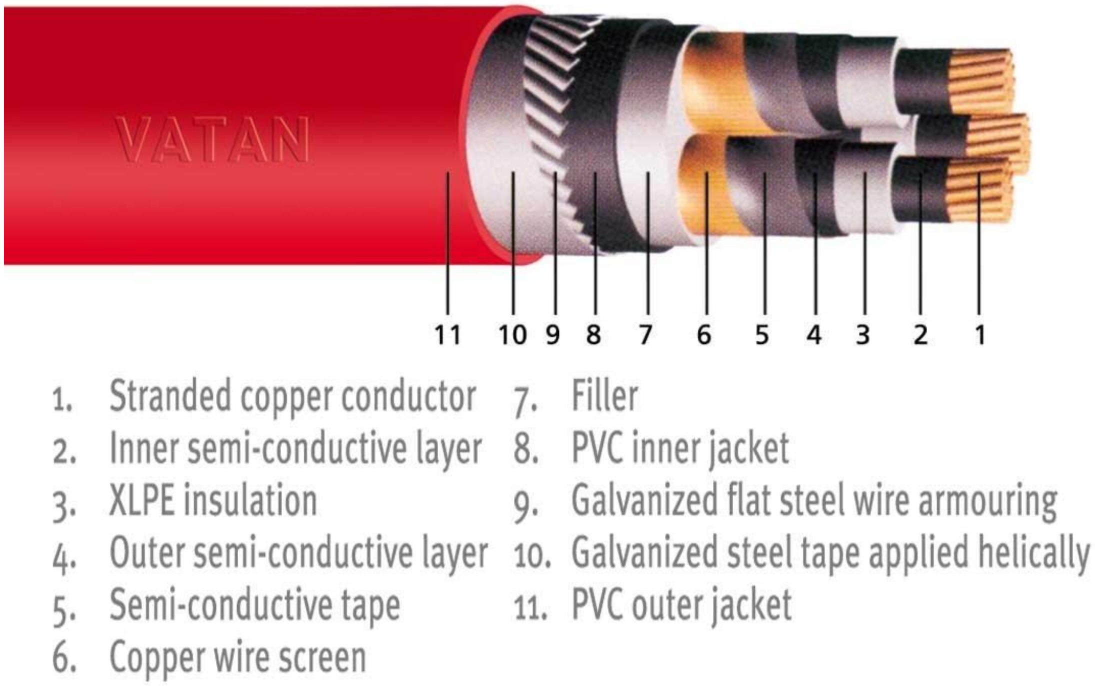


Figure 21: Cable structure layers (alibaba.com 2013)

Similar three phase cable layouts will be used for the three water configurations, but the layers will differ with varying sizes of conductors and armor. The cable which follows the sea bottom will have a standard jacket similar to an offshore power cable. This jacket material needs to be very tough and durable in order to cope with for instance current forces and ferry drifting which can cause friction and hassle of the cable on the sea bed and rock formations. It is important that the cable doesn’t get damaged or fractured, as it may cause loss of power for the ferry. In order to reduce the motions these forces may cause, the cable must be somewhat heavy such that the friction is reduced.

However, since this cable configuration will not require that much high tensile strength in armor, its weight is primarily applied from the conductor weight. The cables length will allow the ferry to drift longer, before the cable experience much tension from ferry drifting. This gives the ferry greater chance to get back on power during a blackout situation. Thus, the armor can be smaller than for the other water configuration alternatives.

The surface floating configuration requires the most strength to cope with ferry drift, since the room for drifting is much smaller because of the shorter cable. This gives thicker armor, and to keep the cable a float, thicker floating cap is therefore required. However, the conductors are smaller since the cable is shorter.

The submerged configuration will thus require thinner armor. It also will have somewhat thicker conductors than the surface floating configuration to ensure power delivery. The room for ferry drift is limited compared to the bottom configuration, as the cable length is shorter.

However, for the air stretched alternative with the trolley system, three separated single conductor cables stretched over the route distance are needed, and thus three contact arms connected to the ferry. In order to receive electricity from these three cables, no insulation or any other insulating layer must cover the conductor such that the contact surfaces are conductor against conductor. This such that the ferry doesn't lose power due to bad connections. In order to cope with bad connections, the trolley arms could be of surrounding character. For instance a half tube like a tray which the cable can lay in. In figure 21 it is displayed a possible overhead cable layout of an aluminum conductor with reinforced steal core for strength.

Figure 22: Overhead cable layout (Nexans 2014)

7.1.5 Cable strength

When it comes to the cable's strength towards ferry drift and environmental forces, the cable materials, i.e. conductors and armor, must never yield. Only in extreme/emergency situations, as a last option, with ferry drift in severe weather it may be allowed for the materials to yield in order for the ferry to restore power. After which the cable would need to be replaced. The main strength parameter in the cable design is the armor. Therefore, there should be large safety margins with regards to yield strength, with basis to the fact that the cable is powering a ferry carrying humans. The armor is, as seen from figure 20 and 21, located in the outer part of the cable in direct interaction with the jacket, with a twisting/spiral configuration, and in the core for the air stretched cables (in figure 22). The twisting configuration significantly increases the flexibility of the cable in combination with high strength, compared to a straight configuration.

Generally the armor material is steel alloys, but in this case one should optimize the armor material selection to gain strength required for given route tensions. One could experiment with high strength steel alloys, titanium and aramid fibers (e.g. Kevlar). Kevlar has according to DuPont five times the strength of steel at the same weight (DuPont 2013). This implies that Kevlar could be a good armor alone or in combination with high strength steel alloys. But one downside with using aramid here is that it is thermal protective, which means that it hinders heat transfer giving reduced cooling. Heat is generated in the cable due to the amount of power that goes through it, experience current resistance in the conductors. One would therefore need to perform tests and analysis of different materials and combinations to optimize the armor, both in mind of strength and heat transfer, as well as weight.

Anyhow, the amount of tension on the cable in the different configurations, will give strength requirements and thus different weights per meter thereafter. The cable would need to withstand some forces in terms of spooling (towing), environmental forces, and ferry drift. For a stiff system (i.e. with no tension slackening) it is assumed that the greatest force provided on the cable comes from ferry drifting and dragging the cable. So the cable must be dimensioned thereafter with respect to armor in the different configurations. Wind, waves and current affects the ferry's position on the route leg both during operation and most importantly in a powerless situation, e.g. when the propellers have stopped the positioning of the ferry due to an emergency situation with loss of power, etc. So the ferry's operational "window" is restricted to a maximum weather condition for either configuration.

Now, the cable is not intended to function as a mooring or anchor line since the cable is constantly feed out and spooled in, giving less strength requirements as such lines. To increase the lifetime of the cable and the system (i.e. for the three water configurations) a safety function is incorporated to the system, where the brake and retractor will for a given cable tension start slackening the tension and spool cable out in accordance with the applied drift tension. It is however assumed that the cable strength requirements for the configurations could be calculated using mooring and towing calculations, i.e. mooring calculations for the bottom configuration and towing calculations for the floating-, submerged- and air stretched configurations.

For the air stretched configuration, the cable strength requirements must be determined from ferry drift. The ferry's trolley arms are only so long such that the ferry has just a narrow "street" to operate in, i.e. the ferry is limited to go so long outside the cable stretch on starboard and port side. It is assumed that the trolley arms are mounted on a turntable which will give the ferry a little wider street to operate in. However, the cable stretches are fairly long, where the cables are supported and fastened on shore on either side of the water crossing in high masts. The cable will hang in a curve between the masts. This gives that the street is somewhat wider as the cables can be pulled somewhat to the sides, starboard and port. But if the ferry starts to drift and starts to move further away outside the limiting street, the tension on the cables grows as the ferry starts pulling on the cables. The cables must therefore be dimensioned thereafter to a given tension limitation, such that the cables don't fail immediately. The trolley arms themselves and their connection to both the cables and the turntable must be strong and thus dimensioned in order to counteract failure. However, as a safety function, the trolley arms connections to the cables will with the tray solution disconnect from and jump off the cable if a given tension is reached, such that damage to the cables are prevented. So the trolley arms would fail before the cables, as they would be cheaper to repair or replace, in addition to the risk of cutting the cables and creating potential electrocution of the ferry.

7.1.5.1 Towing calculations – floating-, submerged- and air stretched configurations:

In the book of Marine Operations by Finn Gunnar Nielsen, static calculation formulas for towing lines with some assumptions are given (Nielsen 2006). Since the concept ferry is "dragging" the cable after it in a towing similar matter, it is assumed that towing formulas can be utilized here for strength calculations. The towing formulas yield for cables hanging in a curve like formation with increasing tension for increasing length with a certain height above the seabed. Since the air stretched cable configuration is curved, it is assumed that the formulas can be used here as well, only that the height is above the waterline. However, additional strength due to ferry drift must be accounted for, since the ferry then will drag the air stretched cable with greater force than just the weight of the cable under drift. As for the floating configuration, the curve is very little, i.e. curved only when entering the hull and shore. Even though the height is zero, it is assumed that the towing calculations can be utilized.

In order to dimension the cables sufficiently, an extensive dynamic analysis is required. In the book of Marie Operations (Nielsen 2006) it is stated the following, why towing lines and mooring lines may experience dynamic loads:

- *The cable may vibrate. The reason may be excitation at the end points of the cable or distributed loads as e.g. vortex shedding. To analyze this situation the cable must be modeled as a continuous mass – spring system, see e.g. (Triantafyllou 1990). The motion of the cable may be described by superposition of eigenmodes.*
- *A different class of dynamics occurs when the end point of the cable is moving but the velocity of the motion is so small that the change of geometry may be considered quasistatic. In this case a first approximation is to consider the line as a pure (non-linear) spring. However, due to viscous drag forces on the cable velocity-dependent forces will add to the pure restoring forces.*

The cable will be dynamically affected by waves, current and the ferry's motion. However, because of a limiting time frame and the need of dedicated software for more correct strength calculations, the dynamic forces are therefore disregarded and the focus is given on static forces. Although the use of static force calculations has flaws, they give a good overall picture and an approximation of the strength needed. The static calculation formulas as given in Marine Operations (Nielsen 2006) are here presented:

3.4.1 Static geometry

The static solution of the inelastic and elastic mooring cable equations are given by e.g. (Faltinsen 1990) and (Triantafyllou 1990). Considering a towed structure, we may as an first approximation assume that the towing cable to be supported at the same vertical level at both ends. We further assume constant mechanical properties along the whole length of the cable. We then obtain the following relation for an inelastic cable, see figure 3.21:

$$z = z_m + \frac{H}{w}\left[cosh\left(\frac{wx}{H}\right) - 1\right] \tag{3.19}$$

Here z_m *is the vertical position of the midpoint of the cable. H is the horizontal force and w is the (submerged) weight per unit length. The tension in the cable is given by:*

$$T = H\ cosh\left(\frac{wx}{H}\right) \tag{3.20}$$

The above expressions do not account for the stretching of the cable. The effect of stretching may be accounted for as described by (Faltinsen 1990), chapter 8. To make the results valid for a towing cable we define the cable coordinate s as zero for x=0. We consider half the catenary only. I.e. positive x values. The z coordinate along the cable is then obtained:

$$z = z_m + \frac{H}{w_0}\left\{\left[1 + \left(\frac{w_0 s}{H}\right)^2\right]^{\frac{1}{2}} - 1\right\} + \frac{w_0}{2EA}s^2$$

$$= z_m + \frac{H}{w_0}\left[(1 + tan^2\varphi)^{\frac{1}{2}} - 1\right] + \frac{w_0}{2EA}s^2 \tag{3.21}$$

$$= z_m + \frac{H}{w_0}\left[\frac{1}{\cos\varphi} - 1\right] + \frac{w_0}{2EA}s^2$$

Here the relation $\tan\varphi = \frac{w_0 s}{H}$ *has been utilized.* w_0 *is the weight per unit length in unstretched condition and s is the unstretched coordinate along the line. Similarly the horizontal coordinate is given by:*

$$x = \frac{H}{w_0}\operatorname{arcsin}h\ \left(\frac{w_0 s}{H}\right) + \frac{Hs}{EA}$$

$$= \frac{H}{w_0}\ ln\left\{\frac{w_0 s}{H} + \sqrt{\left(\frac{w_0 s}{H}\right)^2 + 1}\right\} + \frac{Hs}{EA} \tag{3.22}$$

$$= \frac{H}{w_0} \, ln\left\{\tan\varphi + \frac{1}{\cos\varphi}\right\} + \frac{Hs}{EA}$$

The stretched length of the cable can be found by considering the relation between the stretched coordinate, p_s *and the unstretched coordinate, s:*

$$dp_s = ds(1+\varepsilon) \qquad (3.23)$$

ε *is the axial strain in the cable, given as:*

$$\varepsilon = \left[\frac{1}{E}\,\frac{T}{A} + 2\mu p\right] \qquad (3.24)$$

Here $p = -\rho g z$ *is the hydrostatic pressure at the actual position of the cable. T is the physical tension in the cable. According to (Triantafyllou 1990), the Poisson's ratio,* μ *is approximately* $\frac{1}{3}$ *for metallic cables while synthetic cables it is close to* $\frac{1}{2}$*. For all practical purposes the effect of the hydrostatic pressure on the strain is minor. It is therefore convenient to assume* $\mu = \frac{1}{2}$ *independent of material. I.e. the strain is assumed given as:*

$$\begin{aligned} \varepsilon &= \frac{1}{E}\left(\frac{1}{A} + p\right) \\ &= \frac{1}{EA}(T + pA) \qquad (3.25) \\ &= \frac{T_E}{EA} \end{aligned}$$

I.e. we may use the *effective tension,* T_E *in computing the strain of the cable. It should be noted that this result is a consequence of putting* $\mu = \frac{1}{2}$*. In general (for instance for risers and pipelines with external pressure) one must be very careful and distinguish between physical tension, (causing axial stress) and the effective tension entering the equations for static and dynamic equilibrium of the cable. Some further discussion on the effective tension is given in Chapter 7.*

The stretched length can, according to (Triantafyllou 1990) be written as:

$$L_s = L + \frac{1}{EAw_0}\left\{V\sqrt{H^2+V^2} + H^2\, ln\left[\frac{V}{H} + \sqrt{1+\left(\frac{V}{H}\right)^2}\right]\right\} \qquad (3.26)$$

The above elastic equations are not straight forward to use as they involve iterations to solve. However, for a taut horizontal towing cable it is possible to obtain some simple approximate solutions.

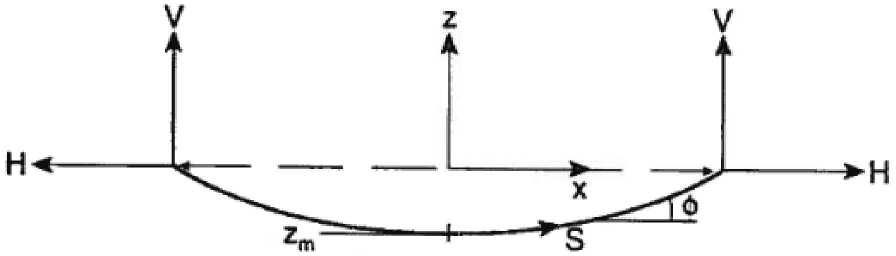


Figure 3.21: **Geometry of a horizontal towing line and symbols used in the analysis**

Figure 23: Geometry of a horizontal towing line and symbols used in the analysis (Nielsen 2006)

Further in the book, it is assumed that the towing force is large compared to the weight of the cable. But for the concept it is rather assumed that the weight of the cable itself provides the highest tension on it. By this it is meant that when the whole cable is spooled out and the ferry is docked at the opposite quay, the highest tension is provided on the cable from its own weight. And under transit spooling out is done in a higher velocity than what the ferry travels with such that towing force is negligible. However, the cable may experience more tension under ferry drift, but the system should be designed such that under ferry drift the cable tension is slackened. That means that for a given amount of tension experienced on the braking system, it will start to slack the tension and thus feed out more cable in accordance with the drift speed and tension. This implies that the storage unit is located onboard the ferry. But in reality when the storage unit is located on shore, tension from dragging the cable after the ferry during transit should be taken into account, i.e. *"We assume the towing force to be large compared to the weight of the cable, i.e. δ = (H/(wL)>> 1"* (Nielsen 2006). The same yields for onboard storage when the ferry sails back and spools the cable in. The book further states for the towing calculations (Nielsen 2006):

We invoke the following general approximations which are valid for any small quantity δ << 1:

$$\sqrt{1+\delta} \approx 1+\frac{\delta}{2} \qquad (3.27)$$

$$ln\left[\delta+\sqrt{1+\delta^2}\right] \approx \delta-\frac{\delta^3}{6} \qquad (3.28)$$

The equations for the horizontal and vertical coordinates may be written as:

$$x \simeq \left(1+\frac{H}{EA}\right)s-\frac{1}{6}\left(\frac{w_0}{H}\right)^2 s^3 \tag{3.29}$$

$$z \simeq z_m+\frac{w_0 s^2}{H}\left(1+\frac{H}{EA}\right) \tag{3.30}$$

With

$$z_m=-\frac{w_0 L^2}{8H}\left(1+\frac{H}{EA}\right) \tag{3.31}$$

From these approximations we realize that the horizontal stretched coordinate may be approximated by linear stretching of the strait cable minus a third order correction for the catenary effect. From (3.30) we observe that the towing cable may be approximated by a parabola. The sag of the cable (-z_m) has a correction due to the elastic elongation of the cable. The last term in equation (3.31) is frequently ignored. (3.29 – 3.31) are quite accurate even if $w_0 L/H$ is not very small. According to Triantafyllou reasonable results are obtained if $w_0 L/H$ is less than 1, i.e. -$z_m/l < 1/8$.

In addition, the effects of propeller race may affect the cable and should be taken into account. The propeller creates turbulent flow around the cable, given that the ferry only has one propeller in each end. The book of Marine Operations provide a set of formulas for calculating the effects of the propeller race on the cable/pipeline (Nielsen 2006). It is assumed that the ferry will have two thrusters mirrored around the centerline on each end. The cable will enter the hull between two of them at one end, reducing the effect of propeller race and the risk of propeller interactions. However, in this thesis the propeller race effect calculations have not been included due to the limiting time frame.

7.1.5.2 Mooring calculations – bottom configuration:

For the bottom configuration there are a number of parameters that affect the tension calculations of the cable. The picture is very wide with different forces acting on the cable, requiring advanced force and tension analyses.

In order to view the bottom configuration it has to be assumed that the seabed is flattened in a “street” such that the risk of damage to the cable due to interactions with sharp edges and rocks is reduced. Further, for onboard storage, it is assumed that the cable feeding and spooling goes faster than the ferry transit, such that the cable is able to sink to the bottom with as little stretch as possible to avoid high tensions from dragging. The cable is spooled in faster than the ferry sails such that interaction with the hull or propulsors is avoided. But spooling in will give some dragging/towing force on the cable which would need to be taken into account.

The cable is most likely to form an s-curve between the ferry and the seabed, as seen in figure 24. The steeper the curve is the more bending stress the cable will experience at the touch down point (TDP), i.e. maximum curvature where the cable lands on the bottom.

Since the ferry is moving relatively fast it is assumed that the cable will experience some dragging/towing force. Here, these forces will give frictional forces between the seabed and the cable, and drag-force in the water. The drag forces depend on the cables’ horizontal speed, which varies along the cable between the surface en the TDP. This means that at TDP the speed is approximately zero and at the surface it has the same speed as the ferry.

In addition, the operation can be thought of as a lifting- and lowering-operation, where the cable is the object lifted and lowered. In that the ferry is under transit, the cable will experience “current” (i.e. drag forces) giving a situation where the cable is curved. In a normal lifting/lowering operation, the vessel is usually not moving in order to place an object on the bottom at an accurate position, e.g. a subsea installation. However, in a still position lifting operation, currents may cause drag forces on the hauling cable/wire, giving curvature on the cable and the lifting object. From this, similarities in the operations (concept cable laying and lifting operation) are seen. DNV provides a set of formulas for marine operations like under water lifting operations in their recommended practices. In the recommended practices it is stated that for such deep water lifting operations the following effects/parameters must be taken into account (DNV 2014):

- *stretched length of cable due to cable own weight and weight of lifted object*
- *horizontal offset due to current where the current velocity may be time-dependent and its magnitude and direction may vary with water depth*
- *dynamics of lifted object due to wave induced motion of crane tip on vessel*
- *methods for controlling vertical motion of lifted object.*

The formulas are for deep water operations, but in general they describe forces beneath the wave zone and down to the seabed. However, it is assumed that the formulas can be used in the concept configuration because of the similarities. Since the forces and different calculation formulas which may be applicable for the bottom configuration are additional and overlapping, the wide range of calculations is better fit for designated software. In designated software the mentioned effects can be taken into consideration and implemented, such that the cable strength can be determined sufficiently and dimensioning of the cable armor is done thereafter. One such software can be RIFLEX developed by MARINTEK, which *"is an efficient program system for hydrodynamic and structural analysis of slender marine structures"*, and can be used for mooring lines, flexible risers, umbilicals, etc. (SINTEF 2011). Due to the limited amount of time in the thesis the software will not be used for dynamical cable strength dimensioning. Therefore, a simplification is made where the operation is seen as a static mooring analysis with an additional horizontal force from drag during cable laying. In order to use catenary equations for mooring, it is assumed that the cable is in a J-lay configuration as illustrated in figure 24.

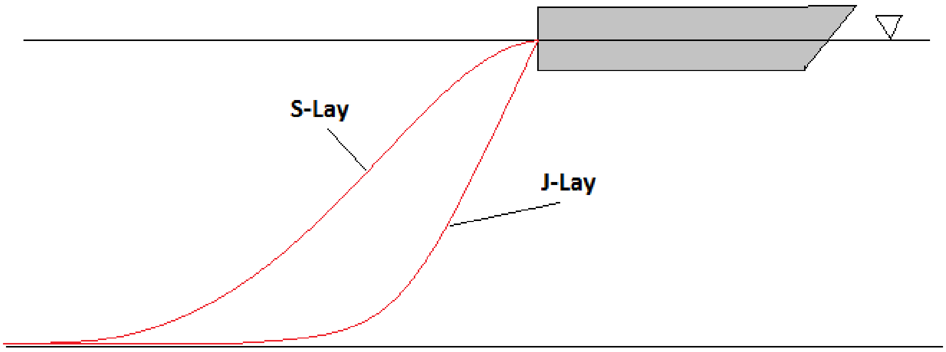


Figure 24: J-lay and S-lay illustration

In the lecture note compendium of Offshore Pipeline Technology by Svein Sævik used in lectures for the NTNU-course TMR 4120 Underwater Technology, the catenary equation is presented for installation of pipelines (Sævik 2013). The formulas are assumed applicable for the concept because of the similarities in laying. The catenary equations are derived and presented as follows (Sævik 2013):

$$T_{eff} = \int_{A_p} \sigma_p dA_p - \int_{A_i} p_i dA_i + \int_{A_e} p_e dA_i = T_p - p_i A_i + p_e A_e \tag{5.2}$$

5.2.2 The catenary equation

Consider an infinitesimal element carried by tension forces alone and with no consideration of buoyancy effects, see Figure 5.8(a) positioned at coordinate point y as illustrated in Figure 5.8(b), then by equilibrium at position y:

$$dT_p = w_p \sin\theta ds = w_p dy \tag{5.3}$$

Further, by integration on both sides:

$$T_p = w_p y + T_{p0} \tag{5.4}$$

where T_{p0} is the pipe wall tension at the origin positioned at the seabed touchdown point (TDP). Then by direct application of Eq. 5.2 at the coordinate point y we get:

$$\begin{aligned} T_{eff} &= T_{p0} + w_p y + p_e A_e \\ &= T_{p0} + w_p y + \rho_w g(d-y)A_e \\ &= T_{p0} + \rho_w g d A_e + \left(w_p - \rho_w g A_e\right)y \qquad (5.5) \\ &= T_{eff0} + w_s y \\ T &= T_0 + w_s y \end{aligned}$$

where T and T_0 hereafter will refer to the effective tension values.

The catenary equations based on neglecting the bending stiffness effect. This means that it will represent an approximate solution, even for J-configurations, overestimating the curvature at TDP. By only including tension and gravity forces as in Figure 5.9, equilibrium yields:

$$Td\theta = w_s \cos\theta \, ds$$

$$T = w_s \cos\theta \frac{ds}{d\theta} \tag{5.6}$$

Further, by differentiation on both sides of Eq. 5.5 with respect to the length coordinate s:

$$\frac{dT}{ds} = w_s \frac{dy}{ds}$$

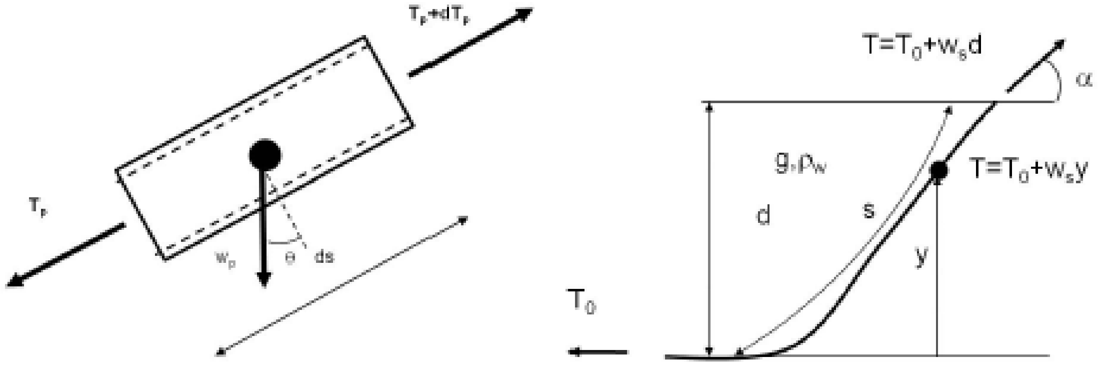
$$dT = w_s \sin\theta \, ds \tag{5.7}$$

By dividing Eq. 5.7 with Eq. 5.6 and integrating on both sides, we get:

$$\frac{dT}{T} = \frac{\sin\theta}{\cos\theta} d\theta$$

$$lnT = -\ln\cos\theta + C \tag{5.8}$$

$$T = T_0 \frac{\cos\theta_0}{\cos\theta}$$



(a) Infitesimal pipe element exluding buoyancy forces

(b) Global catenary geometry

Figure 5.8: Effective tension along catenary

Figure 25: Effective tension along catenary(Sævik 2013)

where θ_0 *represents slope of the seabed at TDP. If one assume* $\theta_0 = 0$ *at* $s = 0$ *then:*

$$T = \frac{T_0}{\cos\theta} \tag{5.9}$$

Further from Eq. 5.9 and Eq. 5.6 and introducing the top angle α located at $s = s^*$ *and* $y = d$ *as new parameters.*

$$ds = \frac{T d\theta}{w_s \cos\theta}$$

$$s = \frac{T_0}{w_s} \tan\theta + C \tag{5.10}$$

$$\tan\theta = \frac{w_s}{T_0} s$$

$$\tan\alpha = \frac{w_s}{T_0} s^*$$

We also have by using Eq. 5.5 and Eq. 5.10:

$$dy = \sin\theta \, ds$$

$$= \frac{T_0 \sin\theta}{w_s \cos\theta^2} d\theta$$

$$y = \frac{T_0}{w_s \cos\theta} + C \tag{5.11}$$

$$d = \frac{T_0}{w_s}\left(\frac{1}{\cos\alpha} - 1\right)$$

By application of Eq. 5.10 and Eq. 5.11, the catenary length s^* can be expressed in terms of the wated depth d, the submerged weight w_s and the horizontal bottom tension

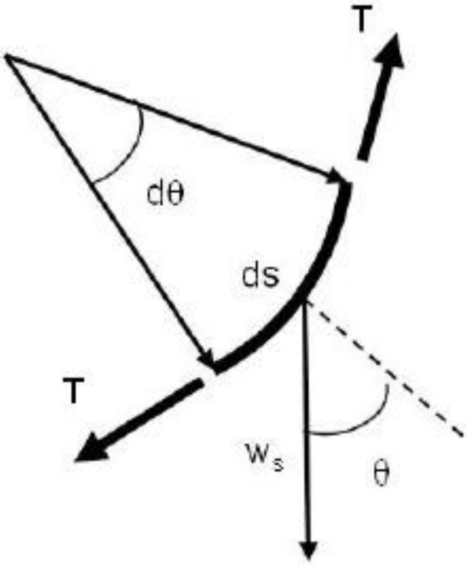


Figure 5.9: Infintesimal catenary segment - only tension - no bending stiffness

Figure 26: Infinitesimal catenary segment - only tension - no bending stiffness (Sævik 2013)

T_0 as:

$$s^* = \sqrt{d^2 + 2\frac{dT_0}{w_s}} \tag{5.12}$$

The curvature along the catenary is further found by application of Eq. 5.9 and Eq. 5.6 as:

$$\frac{d\theta}{ds} = \frac{w_s}{T_0}\cos\theta^2 \tag{5.13}$$

having its maximum value at TDP.

The horizontal length from TDP to the top connection point, the socalled layback x^*can further be found by utilizing the above as:

$$dx = \cos\theta\, ds$$

$$= \frac{T_0}{w_s \cos\theta} d\theta$$

$$x = \frac{T_0}{w_s} ln\left(\frac{1}{\cos\theta} + \tan\theta\right) \tag{5.14}$$

$$x^* = \frac{T_0}{w_s} ln\left(1 + \frac{w_s d}{T_0} + \sqrt{\left(1 + \frac{w_s d}{T_0}\right)^2 - 1}\right)$$

5.2.3 Minimum horizontal radius

One important routing and installation criterion is the minimum horizontal radius of curvature that can be obtained on the seabed. This is found by simple transverse equilibrium in the horizontal plane using the available transverse force μw_s instead of $w_s \cos\theta$ in Figure 5.9:

$$R_{min} = \frac{T_0}{\mu w_s} \tag{5.15}$$

These formulas are derived for pipes with inner and outer walls and different pressure inside and outside, with tension in the pipe wall. However, it is assumed that by disregard the inner values in the formulas, they can relatively easily be made to fit for cable calculations.

As mentioned, the cable will experience drag force along the curve length. In figure 27 it is displayed how the flow velocity on the cable is assumed between the surface and the seabed. By deriving Morison's equation (Faltinsen 1990) we can find the drag force over the cable curve length.

Morison's equation:

$$F_D = \frac{1}{2}\rho C_d D u|u|$$

F_D is the drag force [*N*]

ρ is the density of the fluid (i.e. sea water) $[kg/m^3]$

C_d is the drag coefficient of the cable (between 1.0 – 1.3 according to (ToolBox))

D is the diameter of the cable $[m^2]$

u is the flow velocity [*m/s*]

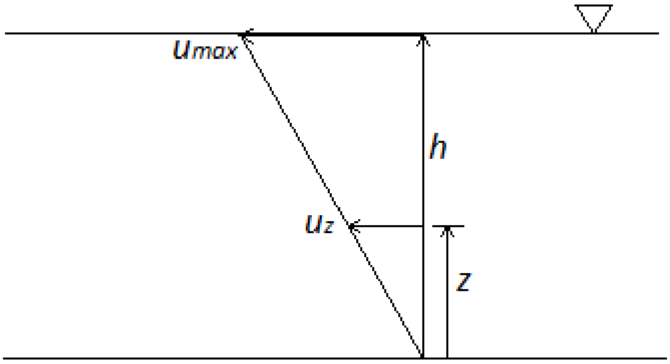


Figure 27: Assumed velocity profile of drag force on the cable

For a point *z* on the cable (figure 27) the drag force is then:

$$F_{D_z}(z) = \int_0^h \frac{1}{2}\rho C_d D u_z^2 dz$$

The flow velocity at point *x* is:

$$u(z) = u_{max}\frac{z}{h}$$

The drag force along the curve length:

$$F_{D_{tot}} = \int_0^h \frac{1}{2}\rho C_d D u_{max}^2 \left(\frac{z}{h}\right)^2 dz$$

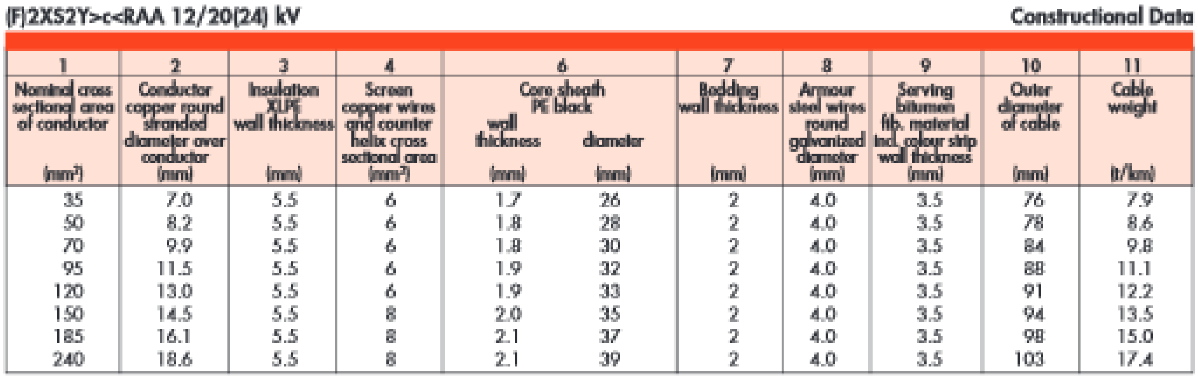
$$= \frac{1}{2}\rho C_d D u_{max}^2 \frac{1}{h^2}\int_0^h z^2 dz$$

The drag force is horizontal and will add to the horizontal component of the cable tension found by the catenary equations.

7.1.6 Cable dimensions and strength

There are many cable manufactures over the world delivering cable solutions of many varieties. One cable manufacture is the French company Nexans which is represented in 40 nations, and has 6 offices in Norway, forming Nexans Norway (Nexans 2013). Among other cable types, they deliver submarine medium voltage cables and overhead lines (which are of interest in this project).

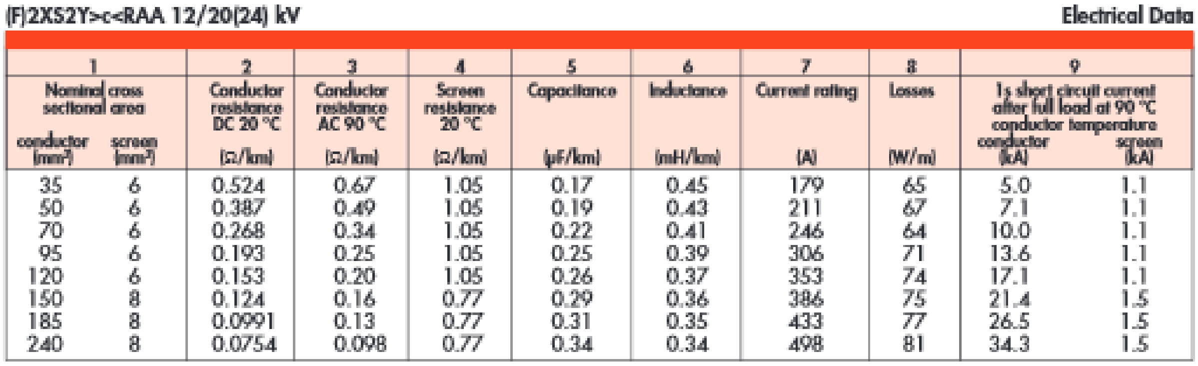
Nexans state that: *"Submarine cables are used to link islands, between platforms, submarine installations, across fjords and over the sea for hundreds of kilometres"* (Nexans 2013). The submarine medium voltage cables are delivered for voltages between 6 – 525 kilovolts with varying layer configurations and dimensions, i.e. of conductor cross sectional area, insulation, armor, etc. Below, in table 3 it is displayed a section from Nexans' Submarine Power Cables brochure with varying cable sizes for voltages between 12 – 20(24) kV (Nexans 2014).



(F)2XS2Y>c<RAA 12/20(24) kV

Constructional Data

1	2	3	4	6		7	8	9	10	11
Nominal cross sectional area of conductor	Conductor copper round stranded diameter over conductor	Insulation XLPE wall thickness	Screen copper wires and counter helix cross sectional area	Core sheath PE black		Bedding wall thickness	Armour steel wires round galvanized diameter	Serving bitumen fib. material incl. colour strip wall thickness	Outer diameter of cable	Cable weight
				wall thickness	diameter					
(mm²)	(mm)	(mm)	(mm²)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(t/km)
35	7.0	5.5	6	1.7	26	2	4.0	3.5	76	7.9
50	8.2	5.5	6	1.8	28	2	4.0	3.5	78	8.6
70	9.9	5.5	6	1.8	30	2	4.0	3.5	84	9.8
95	11.5	5.5	6	1.9	32	2	4.0	3.5	88	11.1
120	13.0	5.5	6	1.9	33	2	4.0	3.5	91	12.2
150	14.5	5.5	8	2.0	35	2	4.0	3.5	94	13.5
185	16.1	5.5	8	2.1	37	2	4.0	3.5	98	15.0
240	18.6	5.5	8	2.1	39	2	4.0	3.5	103	17.4



(F)2XS2Y>c<RAA 12/20(24) kV

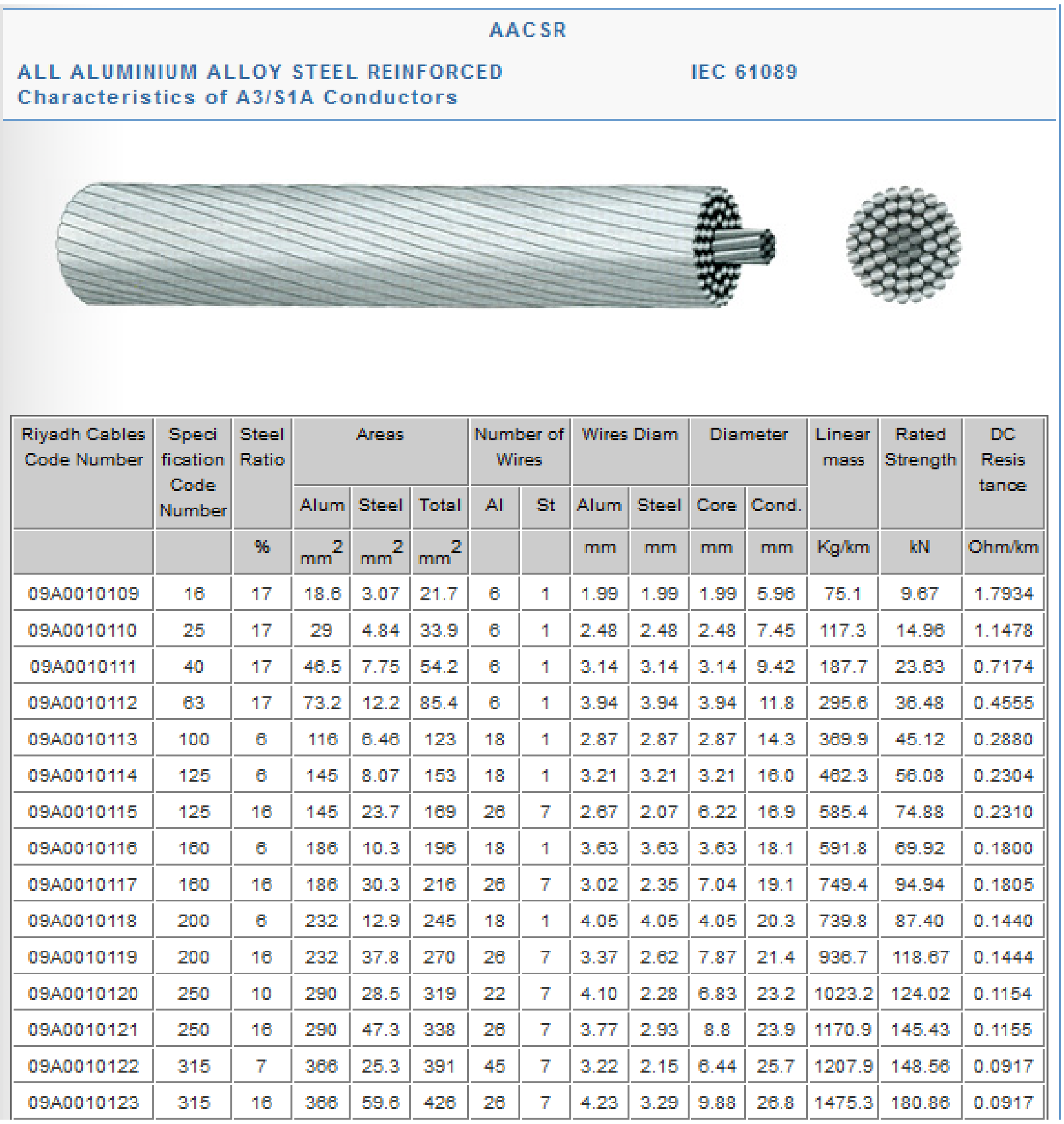
Electrical Data

1		2	3	4	5	6	7	8	9	
Nominal cross sectional area		Conductor resistance DC 20 °C	Conductor resistance AC 90 °C	Screen resistance 20 °C	Capacitance	Inductance	Current rating	Losses	1s short circuit current after full load at 90 °C conductor temperature	
conductor (mm²)	screen (mm²)	(Ω/km)	(Ω/km)	(Ω/km)	(µF/km)	(mH/km)	(A)	(W/m)	conductor (kA)	screen (kA)
35	6	0.524	0.67	1.05	0.17	0.45	179	65	5.0	1.1
50	6	0.387	0.49	1.05	0.19	0.43	211	67	7.1	1.1
70	6	0.268	0.34	1.05	0.22	0.41	246	64	10.0	1.1
95	6	0.193	0.25	1.05	0.25	0.39	306	71	13.6	1.1
120	6	0.153	0.20	1.05	0.26	0.37	353	74	17.1	1.1
150	8	0.124	0.16	0.77	0.29	0.36	386	75	21.4	1.5
185	8	0.0991	0.13	0.77	0.31	0.35	433	77	26.5	1.5
240	8	0.0754	0.098	0.77	0.34	0.34	498	81	34.3	1.5

Table 3: Nexans cables with XLPE insulation for voltages between 6 – 10(12) kV uses (Nexans 2013)

Further, Nexans provides different overhead line cables with a range of dimensions with either copper or aluminum conductors (Nexans 2014). It is also possible to get steal reinforced aluminum cables to give higher tensile strength. For the air stretched alternative for the concept, steal reinforced aluminum cables are preferred. This is because aluminum weighs less than copper and is cheaper to buy, and because aluminum has less tensile strength than copper, a steel reinforcement is a good option to increase the strength. However, aluminum cables will have larger cross sectional area than a copper cable in order to provide the same amount of conductivity, but the weight is less (Pryor, Schlobohm et al. 2008).

The strongest overhead cable Nexans provide on their web page (Nexans 2014) has a minimum breaking load of 130kN with a diameter of 39,24mm, an approximate weight of 2,525kg/m and a resistance of 0,0317Ohm/km at 20°C. It is assumed that this cable will be insufficient for the concept ferry. So in order to satisfy the high strength requirements and power delivery, the cable would need to be designed and engineered sufficiently with a high tensile steel core and enough amount of aluminum conductor. Riyadh Cables Group of Companies is another overhead cable manufacturer which delivers various types of cables, for instance power lines (Companies 2008). On their web page tables of different cable types with varying dimensions and configurations are listed, a table section is displayed in table 4. One cable that may be relevant for the ferry concept is a steel reinforced all aluminum alloy cable with strength of approximately 530kN, a weight of 4,428kg/m with a resistance of 0,0258Ohm/km. Calculations and iterations are needed to determine if this cable is satisfying.



AACSR

ALL ALUMINIUM ALLOY STEEL REINFORCED IEC 61089
Characteristics of A3/S1A Conductors

Riyadh Cables Code Number	Specification Code Number	Steel Ratio	Areas			Number of Wires		Wires Diam		Diameter		Linear mass	Rated Strength	DC Resistance
			Alum	Steel	Total	Al	St	Alum	Steel	Core	Cond.			
		%	mm^2	mm^2	mm^2			mm	mm	mm	mm	Kg/km	kN	Ohm/km
09A0010109	16	17	18.6	3.07	21.7	6	1	1.99	1.99	1.99	5.96	75.1	9.67	1.7934
09A0010110	25	17	29	4.84	33.9	6	1	2.48	2.48	2.48	7.45	117.3	14.96	1.1478
09A0010111	40	17	46.5	7.75	54.2	6	1	3.14	3.14	3.14	9.42	187.7	23.63	0.7174
09A0010112	63	17	73.2	12.2	85.4	6	1	3.94	3.94	3.94	11.8	295.6	36.48	0.4555
09A0010113	100	6	116	6.46	123	18	1	2.87	2.87	2.87	14.3	369.9	45.12	0.2880
09A0010114	125	6	145	8.07	153	18	1	3.21	3.21	3.21	16.0	462.3	56.08	0.2304
09A0010115	125	16	145	23.7	169	26	7	2.67	2.07	6.22	16.9	585.4	74.88	0.2310
09A0010116	160	6	186	10.3	196	18	1	3.63	3.63	3.63	18.1	591.8	69.92	0.1800
09A0010117	160	16	186	30.3	216	26	7	3.02	2.35	7.04	19.1	749.4	94.94	0.1805
09A0010118	200	6	232	12.9	245	18	1	4.05	4.05	4.05	20.3	739.8	87.40	0.1440
09A0010119	200	16	232	37.8	270	26	7	3.37	2.62	7.87	21.4	936.7	118.67	0.1444
09A0010120	250	10	290	28.5	319	22	7	4.10	2.28	6.83	23.2	1023.2	124.02	0.1154
09A0010121	250	16	290	47.3	338	26	7	3.77	2.93	8.8	23.9	1170.9	145.43	0.1155
09A0010122	315	7	366	25.3	391	45	7	3.22	2.15	6.44	25.7	1207.9	148.56	0.0917
09A0010123	315	16	366	59.6	426	26	7	4.23	3.29	9.88	26.8	1475.3	180.86	0.0917

Table 4: Overhead cables from Riyadh Cable Group of Companies (Companies 2008)

It is evident that calculations are required for both the water cables and overhead cables in order to determine which cable sizes are needed, in terms of electric conductor dimensions, armor strength and weight.

7.1.7 Discussion of strength

In this thesis it is most likely the submerged power transfer configuration that will be best suitable for the ferry concept. This is because the cable is long enough to avoid sudden jerks during transit due to drifting or environmental forces, and the conductor diameter and weight is less than for the bottom configuration (a lower voltage is needed for power transfer). In addition, the seabed would have to be straightened in order for the bottom configuration to be applicable, to avoid being damaged by rocks and other bottom formations. Straightening the seabed can be very expensive depending on the bottom formations and the water depths. Also, friction from a straightened seabed may eventually damage the cable and thus possibly cause blackout and emergency situations. If however the submerged cable configuration experiences seabed interactions due to drifting, blackout etc., it should be strong enough and hold until the ferry can restore power or start up the emergency power source.

For the air stretched configuration it is assumed that the allowable deviation (i.e. drift) from the “street” is less than for either of the water configurations. Here, the cables are stretched over the route between- and fixed to support masts on either side, giving less room for drifting. In addition, the trolley arms have limited length and strength, as well as upward pressure for ensuring conductor connection during varying weather and transit situations. In order for the air stretched configuration to work, the trolley arms need comprehensive engineering with safety in mind, i.e. factors such as arm strength, upward pressure, arm lengths, etc. The cable strength is also important considering the risk of electrocution of the ferry if the cable is damaged or fractured. Another factor that needs to be taken into account is the height between the cable stretch and the water surface, this relates to crossing traffic (i.e. tall vessels and high masts).

Due to the arguments mentioned, the limiting time frame and the lack of designated software it is rather conducted static strength calculations for towing. The calculations are conducted in accordance with the book of Marine Operations, with the assumption that the largest tension on the cable is experienced when the full length is fed out and comes from its weight. This assumption is rather simplified since the cable will experience additional tension contributions. For instance, there will be a tension contribution from the thrust flow/propeller race (the cable will get a horizontal tension contributions over a certain length), and from environmental forces such as wave-, current-, and wind forces on the ferry and the cable. When spooling cable in, it will experience some towing forces due to the handling speed. However, in the calculations this is disregarded and the simplification of just the cable weight applies tension, is made. Obviously, this assumption does not apply in a real life situation.

In the simplified calculations, an iteration process is needed since the strength required depends on the cable weight, and the cable weight will increase with the armor adding.

7.1.8 Calculations

Since short route ferries have relatively low power requirements, it is assumed that the power needed on the concept ferry is within 4MW with a main bus voltage of 690volt. In consultation with Øystein Tvedt (Tvedt 2014) and Lars Øyvind Moen (Moen 2014) at Nexsans Norway, it has been stated that the voltage through the cable needs to be increased significantly in order to reduce the cross sectional area and thus the weight of the cable. Because, the lower the voltage through the cable is, the higher the current will be. And the higher current, the larger cross sectional area is required due to conductor resistance. In the consultation it has been recommended a voltage over the cable length of up to 24kV such that the conductor diameter is low and thus the weight (Tvedt 2014). For high voltages, the power loss is low due to the low currents, and therefore the conductor cross sectional area will be less. In order to have such high cable voltages, there must be installed a large converter or transformer onboard the ferry in order to reduce the voltage such that the correct power is delivered on the main bus and thus the main switchboard (690Volt).

According to Lars Øyvind Moen, dimensioning of power cables are based on estimated maximum conductor temperature for a given phase current (Moen 2014). Typically maximum 90°C for high voltage phases, i.e. voltage ≥ 7.2kV, and 70°C for low voltage phases, i.e. ≤ 3kV. However, there are difficulties dimensioning the conductors based on length and power demand (Tvedt 2014). But it was stated that for a power demand of 1MW over a cable length of 750m and a voltage of 3kV, the cross sectional area would be at least 3x95mm^2.

In that it is difficult to dimension the cable size, i.e. conductor dimension, it has been performed strength calculations for a number of XLPE (Cross-Linked PolyEthyline) insulated 24KV cables with varying sizes and specifications. The cables provided by Nexans in their brochure of Submarine Power Cables (Nexans 2013), as presented in table 3 are used. The calculations are performed according to the static strength calculations for towing with the assumption that the cable is unstretched. This is however not a correct approximation since the cable will experience some stretching due to its own weight as well as from towing forces. The assumption is made due to the requirements of modulus of elasticity for the cable. This is very difficult to find as the cable is composed of several material components in layers with different properties. So the modulus of elasticity for the cable is a combination of these materials' modulus of elasticity's, and finding the combined one is therefore hard, since the cable will have to be customized for the concept with respect to strength, heat transfer and weight.

The following submerged configuration calculations are performed for four cable sizes with four cable lengths and for four curve depths (as shown in table 5). The horizontal and axial tensions on the cable are calculated at the surface crossing (i.e. the height at the end *z* is as close to zero as possible – approximation is found using a goal-seek function in Excel which alter the variables such that the a cell becomes as close to the wanted value as possible). However, the tension will be a little higher since the tension point is in the ferry somewhat above the surface. For the length above the surface, the tension depends on for instance the weight in air, etc. But the contribution is regarded so small that it is negligible in this context. The results for various cable tensions, horizontal H and axial T, are presented in the tables 6-9.

Cable depth zm:	**Cable lengths x:**	**XLPE 24kV Cable alternatives:**			
-40 m	2000 m	A (mm2):	d (m):	w (kg/m):	w0 (kg/m):
-50 m	3000 m	120	0,091	12,2	5,5335208
-60 m	4500 m	150	0,094	13,5	6,3867274
-70 m	6000 m	185	0,098	15	7,2684619
		240	0,103	17,4	8,8594037

Table 5: Depths, lengths and cable dimensions

Cable depth zm:	-40 m					
Cable weight (kg/m):			5,53352	6,38673	7,26846	8,85940
	Cable lengths:					
	2000 m	**z end (m):**	0,00001	0,00004	0,00004	0,00023
		H (N):	69205,85	79876,56	90904,09	110800,92
		T (N):	69427,19	80132,03	91194,83	111155,29
	3000 m	**z end (m):**	0,00009	0,00001	0,00022	0,00009
		H (N):	155666,78	179669,23	204472,78	249229,20
		T (N):	155888,12	179924,70	204763,52	249583,58
	4500 m	**z end (m):**	0,00010	0,00007	0,00000	0,00017
		H (N):	350204,15	466513,06	604206,00	897632,36
		T (N):	350425,49	466734,40	604427,34	897853,70
	6000 m	**z end (m):**	0,00007	0,00004	0,00004	0,00023
		H (N):	622556,91	718548,77	817749,52	996736,25
		T (N):	622778,25	718804,24	818040,26	997090,63

Table 6: Calculations for 40m water depth

Cable depth zm:	-50 m					
Cable weight (kg/m):			5,53352	6,38673	7,26846	8,85940
	Cable lengths:					
	2000 m	**z end (m):**	0,00001	0,00001	0,00001	0,00001
		H (N):	55381,25	63920,41	72745,09	88667,75
		T (N):	55657,92	64239,75	73108,52	89110,72
	3000 m	**z end (m):**	0,00001	-0,00013	0,00001	0,00002
		H (N):	124550,27	143754,93	163600,91	199410,29
		T (N):	124826,95	144074,26	163964,33	199853,26
	4500 m	**z end (m):**	0,00001	0,00003	0,00028	0,00030
		H (N):	280180,52	373227,52	483378,74	718121,23
		T (N):	280457,20	373504,20	483655,41	718397,91
	6000 m	**z end (m):**	0,00001	-0,00013	0,00001	0,00002
		H (N):	498062,85	574860,17	654222,05	797419,83
		T (N):	498339,53	575179,50	654585,47	797862,80

Table 7: Calculations for 50m water depth

Cable depth zm:	-60 m				
Cable weight (kg/m):		5,53352	6,38673	7,26846	8,85940
Cable lengths:					
2000 m	**z end (m):**	-0,00027	0,00013	0,00000	0,00004
	H (N):	46168,11	53286,36	60643,07	73916,74
	T (N):	46500,12	53669,56	61079,17	74448,30
3000 m	**z end (m):**	-0,00028	0,00013	0,00000	0,00004
	H (N):	103809,29	119814,69	136356,29	166202,23
	T (N):	104141,30	120197,89	136792,40	166733,80
4500 m	**z end (m):**	-0,00029	-0,00003	0,00004	0,00000
	H (N):	233501,83	311040,16	402834,50	598454,81
	T (N):	233833,84	311372,17	403166,51	598786,82
6000 m	**z end (m):**	-0,00029	0,00013	0,00000	0,00004
	H (N):	415071,37	479067,34	545207,35	664543,44
	T (N):	415403,38	479450,55	467848,49	665075,00

Table 8: Calculations for 60 m water depth

Cable depth zm:	-70 m				
Cable weight (kg/m):		5,53352	6,38673	7,26846	8,85940
Cable lengths:					
2000 m	**z end (m):**	-0,00001	-0,00079	0,00050	-0,00032
	H (N):	39589,55	45694,31	52001,80	63384,84
	T (N):	39976,89	46141,38	52510,59	64004,99
3000 m	**z end (m):**	-0,00001	-0,00082	0,00050	-0,00033
	H (N):	88996,08	102719,46	116898,43	142487,18
	T (N):	89383,43	103166,53	117407,23	143107,34
4500 m	**z end (m):**	-0,00001	0,00026	-0,00002	0,00001
	H (N):	200160,62	266621,83	345304,13	512978,31
	T (N):	200547,97	267009,18	345691,48	513365,66
6000 m	**z end (m):**	-0,00001	-0,00084	0,00050	-0,00033
	H (N):	355790,94	410654,73	467339,70	569639,14
	T (N):	356178,29	411101,79	467848,49	570259,29

Table 9: Calculations for 70m water depth

From the tables it is seen that the largest cable with the longest length (6000m) and deepest submerge (-70m) provides the largest tension of approximately 570,3kN. Calculations for some additional lengths between 1500-6000m are presented in Appendix C. The tension results are given in Newton's, but can be converted to tonnes by using Newton's second law. It states that force is mass multiplied by acceleration, i.e. $F = m \cdot a$. Because only gravitational loads are considered, the following relation holds true: $1kg = 9{,}81N = \frac{1}{1000} tonnes$ which gives $\frac{1}{9810} tonnes/N$. The converted tension is thus $tonnes = \frac{Newton}{1000kg/t * 9{,}81m/s^2}$.

The results are not very accurate due to the assumptions made. However, they provide a good approximation for dimensioning the cable handling equipment.

7.2 Cable handling

For the three water power transfer configurations and storage onboard, the cable will enter the hull at the bow or stern of the ferry. It enters as mentioned in the concept explanation through a guider hole which is comparable to a recessed anchor hole on ships. The hole is placed above the water line, but below the loading ramp hatch and positioned such that thrust flow on the cable is minimized from the propeller(s), e.g. with two parallel propellers the hole would be placed in the middle on the centerline. A protruding guider may be required in order to expand the distance for cable hull entrance such that propeller race is further reduced. The protruding guider must however not interfere with the quay under docking sequences or the loading ramp. This gives that the protrusion must be limited. After entering the ferry hull, the cable is guided in a cable tray towards a braking system. The braking system's mission is to apply constant tension on the cable when spooling the cable out, in order to keep the cable from racing out during transit. After the brake, the cable is further guided into a retractor whose task is to spool or retract the cable in under transit. The retractor applies constant speed in such way that the risk of sailing over the cable or interaction with the propeller(s) is absent. Now, after the retractor the cable goes through a guider arm which will lay the cable onto the storage unit in a spiral matter. So the cable handling consists of cable trays, a brake, a retractor and a guider arm.

The concept has many similarities with cable- and pipe laying vessels with laying and retrieval operations, as well as storage. The main difference in the concept is that the cable is feed out and spooled in very frequently. While in cable- and pipe-laying operations, the cable or pipe is laid to lay for longer periods and retrieved for either inspection and repair, moving or decommissioning. The concept ferry can borrow technology and components from cable laying vessels, such as storage units like drum spool or basket carousel, guider arms, cable trays, and tensioners and haulers. But these may need reengineering for the concept in order to provide good operational speed and low weight.

7.2.1 Brake unit

Tensioners functions as brakes by applying tension to the cable. They come with either wheel pairs or belts with varying capacity, and are called respectively *linear cable engines* and *linear tracked cable engine* (Axelsson 2008). Linear cable engines (LCE) have vertical opposed rubber wheels that hydraulically presses against the cable to apply tension (see figure 28). Pressing the cable with the wheels creates friction which holds the cable. However, wet cable and marine growth may cause it to slip. Therefore, linear tracked cable engines (TCE) may be a better alternative (see figure 29). Here, the tracks/belts have a larger contact surface creating larger friction and can thus handle larger and heavier cables. However, LCEs have a higher speed capacity than TCEs and can thus handle smaller cables faster and it weighs less, making it more suitable for the concept ferry. Marine growth is not a big problem as the cable will constantly be spooled. However, it will be wet. A solution for drying the cable before entering the LCE can be either a brush or compressed air blown through nozzles.

Figure 28: 12-18 Pair Linear Cable Engine (Ltd 2007)

Figure 29: Tracked Cable Engine (System 2013)

Fraser Hydraulic Power Ltd manufactures both tracked cable engines and linear cable engines of varying sizes. For instance they manufacture LCEs like the one shown in figure 28. This particular one has between 12-18 opposing wheels that provide tension between 10-15 tonnes, and can operate at a maximum speed of 6 knots (Ltd 2007). On their web page, they also present three tracked cable engine types with respectively 5, 10 and 15 tonnes cable handling tension (Ltd 2007), see figure 30. The 10tonnes tensioner has a maximum speed of 40m/min (i.e. ca. 1.3knots), and the 15tonnes tensioner has a maximum speed of 1200m/hour (i.e. ca. 0.65knots) and weighs 8.2tonnes.

RIG G41 RIG G42 RIG 56

Figure 30: Tracked cable engines/tensioners. 5, 10 and 15 tonnes respectively (Ltd 2007)

Another LCE provider is National Oilwell Varco (NOV 2014). They deliver for instance LCEs with 8 and 20 tonnes hold back tension seen in figure 31 and 32. The specifications for the two are listed below in table 10 and 11.

Figure 31: LCE 8tonnes - National Oilwell Varco (NOV 2014)

Specifications

Model: 8-LCE-SSFR-250-HS

- Weight: 12.2mT
- Drive: Hydraulic
- SWL:
  8mT, pulling
  10mT, breaking

Performance, pick up mode:

- 1.5mT, 250m/min (8.0 knots)
- 8.0mT, 55m/min (1.8 knots)
- Max speed: 280 m/min (9.0 knots)

Performance, hold back mode:

- 3.0mT, 170m/min (5.5 knots)
- 8.0mT, 75m/min (2.4 knots)
- Max speed: 310m/min (10 knots)
- Tubular diameter: max 150mm
- Repeater diameter: max 400mm
- Min. setting in CT mode = 100kg
- (2 wheel-pair engaged)

Table 10: LCE 8tonnes - National Oilwell Varco (NOV 2014)

Figure 32: LCE 20tonnes - National Oilwell Varco (NOV 2014)

Specifications

Model: 20-LCE-SSFR-625-HS

- Weight: 30mT
- Drive: Hydraulic
- SWL:
  20mT, pulling
  25mT, breaking

Performance, pick up mode:

- 10.0mT, 224m/min (7.2 knots)
- 20.0mT, 107m/min (3.4 knots)
- Max speed: 280m/min (9.0 knots)

Performance, hold back mode:

- 10.0mT, 270m/min (8.7 knots)
- 20.0mT, 130m/min (4.2 knots)
- Max speed: 310m/min (10 knots)
- Tubular diameter: max 150mm
- Repeater diameter: max 400mm
- Min. setting in CT mode = 100kg
- (2 wheel-pair engaged)

Table 11: LCE 20tonnes - National Oilwell Varco (NOV 2014)

From the specifications, it is seen that for the 8tonne LCE the maximum tension (hold back force) is operated at 2.4knots, but it can reach a maximum operation speed of 10knots. The 20tonne LCE provides maximum tension at an operational speed of 3.4knots. Maximum operational speed is 9knots.

7.2.2 Retraction unit

For retraction it can either be used a winch or a cable drum engine (CDE). CDEs are constructed as a capstan type machine with a drum on which the cable winds a few rounds around (Axelsson 2008). Either a winch or a CDE will have to work together with the tensioner, such that the strain is distributed. They must work together in order to reduce the unit weights and sizes. Otherwise, the cable handling speed will be low. Figure 33 shows an offshore cable winch and figure 34 displays an cable drum engine.

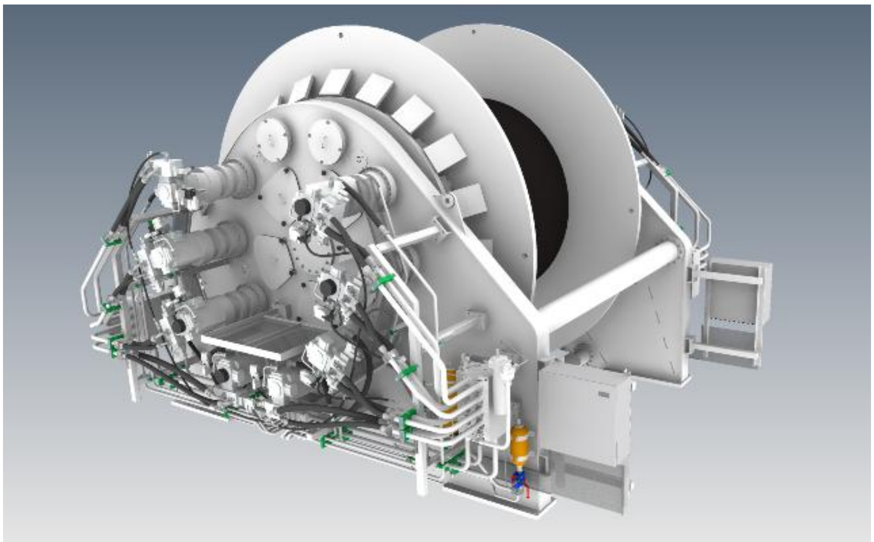


Figure 33: Offshore subsea winch (GROUP 2013)

Figure 34: Cable Drum Engine (NOV 2014)

The companies Parkburn (Parkburn 2014) and National Oilwell Varco (NOV) (NOV 2014) offers a set of cable drum engines each. NOV provides three types of CDEs on their web page with varying specifications (NOV 2014). For instance, the smallest that NOV offers (see figure 34) weighs 19tonnes and can pick up (i.e. retract) and hold back with a tension of 15tonnes at a speed of 1.5knots. With a speed of 8 knots, it can retract cable with a tension of 2tonnes and hold back with a tension of 1tonne. The middle sized CDE that National Oilwell Varco offers, weighs 32tonnes and can pick up and hold back a maximum force of 25tonnes at 0.8knots, and 1tonne at 8knots. The third CDE weighing 37tonnes can pick up and hold back a maximum force of 40tonnes at 1knot and 1tonne at 8knots. In the specifications of the

CDEs, it is stated that each has the ability to operate at a maximum speed of 10knots. Based on these specifications, it is implied that a CDE can be applicable for the ferry concept as a retraction unit.

It is seen that both the retraction unit and the tensioner have the ability to handle cable tension, i.e. both hold back and retraction. Thus, they can work together to handle the tension the cable provides under spooling in and out. However, they may need custom engineering to meet the concept requirements.

7.2.3 Guidance system

As for the guidance system, current technology is assumed applicable. Guiding the cable from the hull entry to the storage unit through the brake and the retractor will be relatively easy with the use of cable trays and rollers. It is important that the cable avoids interaction with other equipment within the hull. This can be solved with routing/guiding the cable around the items. However, curved guidance may cause angular tension on for instance the brake and/or retractor. Also, reeling onto or of the storage unit should be in a tangential matter in order to reduce the angular tension on the guider arm, i.e. the arm is set in line with the guidance towards the storage unit. For the basket carousel this is not the case as the guider arm will move horizontally. This must be taken into consideration when designing the layout of the handling system.

Parkburn provides custom guidance systems which they design and produce according to space available and weight limitations (Parkburn 2014). Figure 35 and 36 shows components configurations which a guidance system can contain, i.e. cable trays and rollers. For the ferry concept it may be preferred to use a combination of rollers and smooth steel supports as the cable is spooled in and out frequently and relatively fast. It is anyway important that good maintenance routines are assessed with lubrication of bearings and rollers. The guidance system should be designed with respect to space limitations, cable dimension and reel speed. In addition it is preferred that the system is constructed with strong lightweight materials such that weight is reduced without affecting the life cycle of the system.

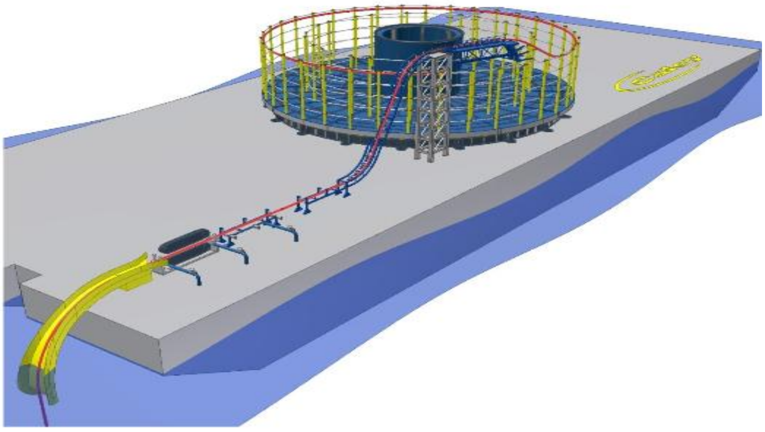


Figure 35: Cable tray guidance system illustration (McPherson 2012)

Figure 36: Roller guidance system example (System 2013)

7.2.4 Guider arm

The guider arms mission is to load and unload the cable onto and of the storage unit. The arm guides the cable by moving vertically for the drum spool option, and horizontally for the basket carousel option, such that the cable is loaded and unloaded in a spiral matter in order to avoid tangling. Parkburn provides loading arms for both drum spools and basket carousels (manipulator arms), but also loading arms for static tank storage (offshore-technology.com 2014). Current technology used in offshore cable laying vessels can be applicable for the ferry concept, but may need reengineering in that the required velocity for handling may be higher. I.e. the arm must move vertically/horizontally relatively fast if the ferry is to operate with a transit speed of around 10 knots, (it is important that the guider arm must move in a specific speed such that the cable doesn't get tangled on the storage unit). In addition, there is a space and weight limitation onboard the ferry which needs to be taken into account during design and engineering of the guider arm.

Figure 37 displays a large scale drum spool being loaded by a loading arm mechanism. This loading arm consists of several rollers placed after each other on articulated frames, (similar to a spine). The end frame is attached to a hydraulic hoist which moves up and down, thus guiding the cable onto and off the drum spool. Such a mechanism may be applicable for the concept.

Figure 37: Cable laying machinery – guider arm (Systems 2013)

7.2.5 Storage

As mentioned, storage of cable could either be within a drum spool or a basket carousel onboard the ferry or on shore, if one of the water power-transfer configurations are chosen. Illustrations of the storage units in mind for the concept are shown in figure 8 and 9 in chapter 3.1.1. The size of the storage unit will depend on operational distance and what cable configuration is selected for the location, with factors like cable bend radius, outer diameter, weight and length. In addition, the size of the ferry will restrict the space available for the storage unit, i.e. breadth and deck height, as well as rooms and compartments within the hull. Also, there are weight limitations which gives restrictions to what amount of cable (and weight of the handling equipment) the ferry can carry in order not to reduce its payload, i.e. the number of passengers and cars it can transport. This gives data for sizing the storage unit in terms height, column diameter and disc diameter, as well as strength required in the unit and hydraulic turntable engine size and capacity (i.e. the hydraulic engine turning the storage unit). Current technology may be applicable, but custom engineering may be required in terms of the limiting factors mentioned, (turn speed is a factor that can be difficult to address in terms of hydraulic pressure for large weights).

Below, formulas for dimensioning the size of the storage unit are derived:

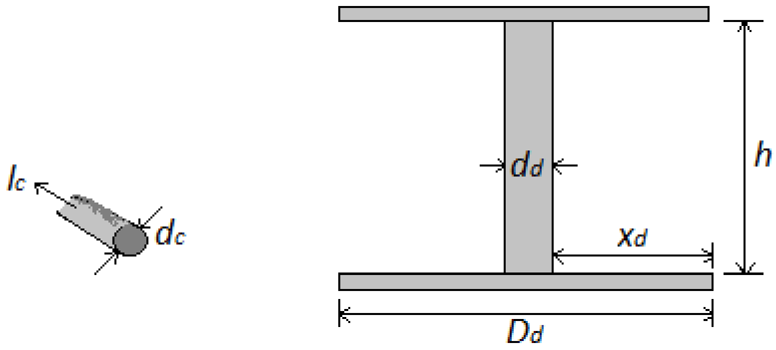


Figure 38: Drum spool dimensions

The volume of the cable, (cubic meters, m^3):

$$V_c = l_c \cdot \frac{\pi d_c^2}{4}$$

The disc area on the drum spool, (square meters, m^2):

$$A_d = \frac{\pi (D_d - d_d)^2}{4}$$

The height of the drum spool column, (meters, m):

$$h = \frac{V_c}{A_d}$$

The distance between the column and the edge of the disc:

$$x_d = \frac{D_d - d_d}{2}$$

The number of rounds/coils of cable the drum spool can have:

$$s = \frac{x_d}{d_c} \cdot h$$

D_d is the diameter of the drum spool's disc, (meters, m).

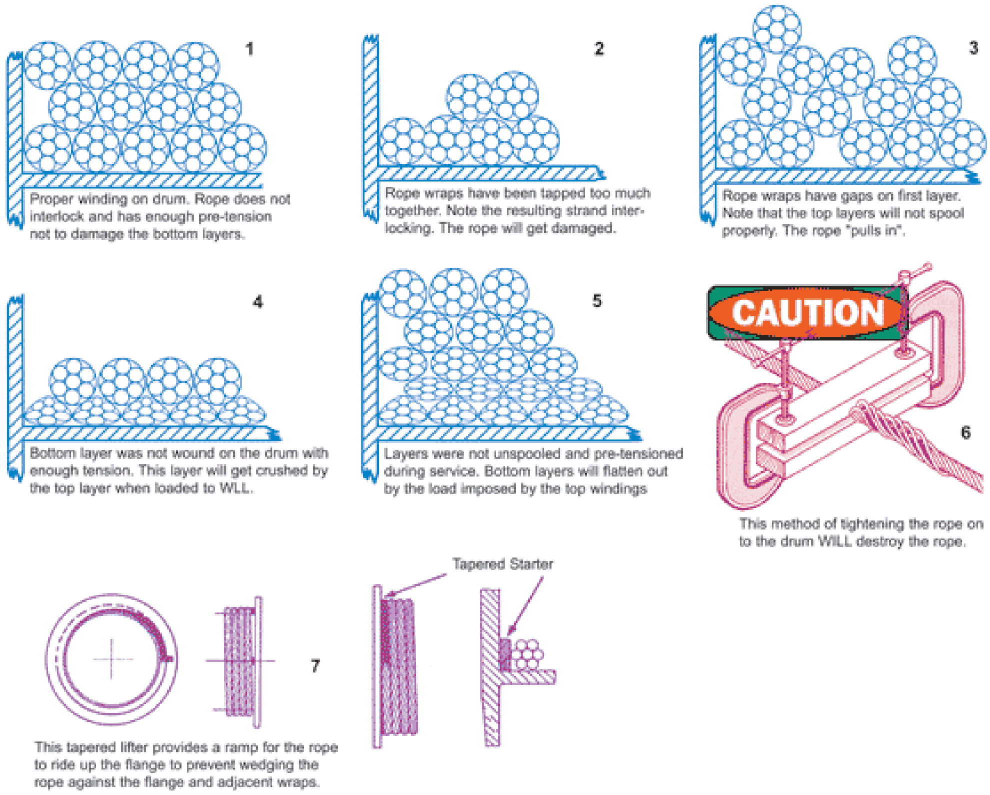
d_d is the diameter of the drum spool column, (meters, m).

d_c is the diameter of the cable, (meters, m).

l_c is the length of the cable, (meters, m).

The drum spool size is dimensioned after the volume of all the cable which will be stored on it and the limitations of width and height of the storage compartment it will be located, (the height of the discs are not taken into account since their height is very low compared to the column height). The volume available for cable storage on the drum spool is assumed to be equal to the volume of cable that will be stored on it, i.e. $V_{drum} = V_{cable}$.

The calculations of the number of rounds/coils the drum spool can have is rather conservative as the packing/stacking of cable is not assumed to be linear with one cable directly on top of the other, but rather in between exploiting the room available. So, the calculation will be slightly wrong as the number of windings will some places be larger and some places less than if the packing was conservative. However, the calculations will provide good estimates for the total number of windings. Figure 39, point 1 displays how the windings are assumed to be on the drum spool. The figure is based on rope winding, but the winding configuration is assumed to yield for the power cable as well. From the figure, point 4 and 5, it is seen that the bottom layers (horizontal on disc) will have to carry the weight from the layers above. This may damage the bottom layers. Pre-tensioning the cable is thus a possibility. However, since the cable is constantly spooled in and fed out, it is assumed that pre-tension is not needed in that degree.



Proper winding on drum. Rope does not interlock and has enough pre-tension not to damage the bottom layers.

Rope wraps have been tapped too much together. Note the resulting strand inter-locking. The rope will get damaged.

Rope wraps have gaps on first layer. Note that the top layers will not spool properly. The rope "pulls in".

Bottom layer was not wound on the drum with enough tension. This layer will get crushed by the top layer when loaded to WLL.

Layers were not unspooled and pre-tensioned during service. Bottom layers will flatten out by the load imposed by the top windings

This method of tightening the rope on to the drum WILL destroy the rope.

This tapered lifter provides a ramp for the rope to ride up the flange to prevent wedging the rope against the flange and adjacent wraps.

Figure 39: Cable winding layer configurations (Slingmax 2014)

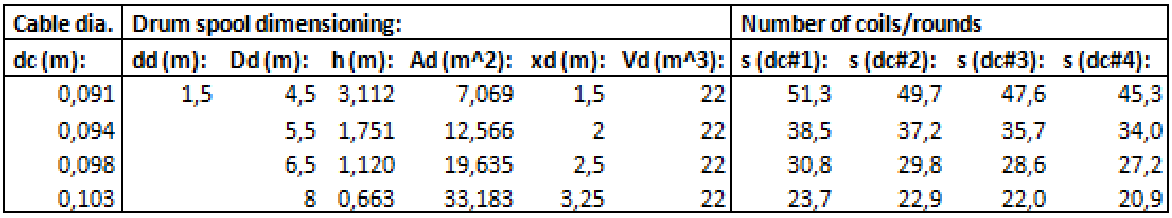
Using the four cables presented in table 5 in chapter 7.1.8 and the calculation formulas derived above, calculations have been conducted for cable volume and weight. Restrictions in the ferry influence the drum spool size greatly by the height and breadth of the compartment, as well as weight limitations regarding payload. Cable volume and weight calculations for the four cables are presented in table 12. However, the total length of the cable is not regarded, i.e. only the stretch in the water is considered. The part within the ferry trough the cable handling system is disregarded as the length is small compared the overall length – the water stretch.

Cable diameter dc (m):		0,091	0,094	0,098	0,103
Cable lengths lc (m):					
1500	**Vc (m^3):**	9,755823	10,409667	11,31445	12,49843
	w0c (kg):	8300,281	9580,0911	10902,69	13289,11
2000	**Vc (m^3):**	13,00776	13,879556	15,08593	16,66458
	w0c (kg):	11067,04	12773,455	14536,92	17718,81
2500	**Vc (m^3):**	16,25971	17,349445	18,85741	20,83072
	w0c (kg):	13833,8	15966,818	18171,15	22148,51
3000	**Vc (m^3):**	19,51165	20,819335	22,62889	24,99687
	w0c (kg):	16600,56	19160,182	21805,39	26578,21
3500	**Vc (m^3):**	22,76359	24,289224	26,40037	29,16301
	w0c (kg):	19367,32	22353,546	25439,62	31007,91
4000	**Vc (m^3):**	26,01553	27,759113	30,17186	33,32916
	w0c (kg):	22134,08	25546,909	29073,85	35437,61
4500	**Vc (m^3):**	29,26747	31,229002	33,94334	37,4953
	w0c (kg):	24900,84	28740,273	32708,08	39867,32
5000	**Vc (m^3):**	32,51941	34,698891	37,71482	41,66145
	w0c (kg):	27667,6	31933,637	36342,31	44297,02
5500	**Vc (m^3):**	35,77135	38,16878	41,4863	45,82759
	w0c (kg):	30434,36	35127,001	39976,54	48726,72
6000	**Vc (m^3):**	39,02329	41,638669	45,25778	49,99373
	w0c (kg):	33201,12	38320,364	43610,77	53156,42

Table 12: Cable volume and weights

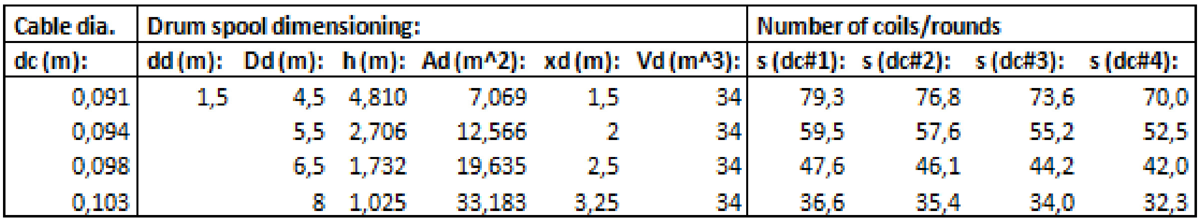
It is seen that the largest cable volume is approximately 50m^3 for the longest and largest cable at the deepest depth. This cable weighs then approximately 53,1tonnes.

For the four cables alternatives presented in table 5 in chapter 7.1.8, the drum spool size has been calculated for the cable volumes of 22m^3, 34m^3 and 43m^3 with a drum spool column diameter of 1,5m (which is a chosen limit set for cable bending) and four limiting disc diameters. The goal-seek function in Excel as explained for the strength calculations have been used for the cable volumes. The results are presented in the tables 13, 14 and 15:



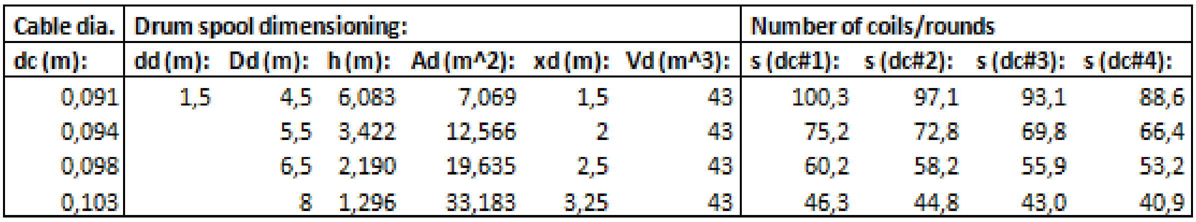
Cable dia.	Drum spool dimensioning:						Number of coils/rounds			
dc (m):	dd (m):	Dd (m):	h (m):	Ad (m^2):	xd (m):	Vd (m^3):	s (dc#1):	s (dc#2):	s (dc#3):	s (dc#4):
0,091	1,5	4,5	3,112	7,069	1,5	22	51,3	49,7	47,6	45,3
0,094		5,5	1,751	12,566	2	22	38,5	37,2	35,7	34,0
0,098		6,5	1,120	19,635	2,5	22	30,8	29,8	28,6	27,2
0,103		8	0,663	33,183	3,25	22	23,7	22,9	22,0	20,9

Table 13: Drum spool dimensions for cable volume of 22m3



Cable dia.	Drum spool dimensioning:						Number of coils/rounds			
dc (m):	dd (m):	Dd (m):	h (m):	Ad (m^2):	xd (m):	Vd (m^3):	s (dc#1):	s (dc#2):	s (dc#3):	s (dc#4):
0,091	1,5	4,5	4,810	7,069	1,5	34	79,3	76,8	73,6	70,0
0,094		5,5	2,706	12,566	2	34	59,5	57,6	55,2	52,5
0,098		6,5	1,732	19,635	2,5	34	47,6	46,1	44,2	42,0
0,103		8	1,025	33,183	3,25	34	36,6	35,4	34,0	32,3

Table 14: Drum spool dimensions for cable volume of 34m^3



Cable dia.	Drum spool dimensioning:						Number of coils/rounds			
dc (m):	dd (m):	Dd (m):	h (m):	Ad (m^2):	xd (m):	Vd (m^3):	s (dc#1):	s (dc#2):	s (dc#3):	s (dc#4):
0,091	1,5	4,5	6,083	7,069	1,5	43	100,3	97,1	93,1	88,6
0,094		5,5	3,422	12,566	2	43	75,2	72,8	69,8	66,4
0,098		6,5	2,190	19,635	2,5	43	60,2	58,2	55,9	53,2
0,103		8	1,296	33,183	3,25	43	46,3	44,8	43,0	40,9

Table 15: Drum spool dimensions for cable volume of 43m^3

7.3 Ship systems

In a conventional diesel electric solution, monitoring and managing of the engines, generators, thrusters etc., is performed through the control room. For the concept ferry it is assumed that through a control room, monitoring and managing of the cable handling equipment is carried out. But in order for the different cable handling and storage equipment to work together, a management system is required. Such a system should assign and manage the components in collaboration with transit speed, and various environmental forces from wind, waves and currents. This means that the brake, the retractor, the guider arm and the storage unit, are linked such that the cable is handled (i.e. spool in and fed out) in accordance with the ferry transit. Computer programs has to be developed such that constant analyses and calculations can be performed onboard for cable tension, laying and retraction speed, slacking and tensioning, etc. The system should then address adjustments to the cable handling systems immediately. For instance, the system should assure that the tension on the cable is kept within the given limits along with the curvature (e.g. for the towing configuration the cable must not touch the seabed as this may cause damage), and that the spooling and retraction occurs according to the changes in the ferry speed. If the tension on the cable reaches a given limit, the system should give slack to the cable such that it won't get damaged or broken off if the ferry starts to drift. Further, the system should address the cable handling in emergency situations like blackout and drifting, in such a way that the ferry can restore power, or by emergency power get back to shore.

BPP-Cables has developed systems and programs for cable handling, laying and recovery analyses for the offshore industry (BPP-Cables 2014). The methodologies and software is developed with analyses and calculations for cable handling. Here, the system is intended for cable laying vessels. The system contains for instance calculations for catenary with bottom slack (i.e. no bottom tension), calculations for catenary with bottom tension, analyses for changes in slack and tension (repeater launch), track deviation and cable recovery analyses, etc. So it is reasonable to assume that such programs for cable handling can be customized and designed for the concept ferry for the different power transfer configurations.

7.4 Emergency power solution – Battery pack vs. Genset

For a battery emergency power supply system, the engineering shall follow DNV's regulations for Electric Installations (DNV 2013). But as battery systems are constantly under development such systems could have additional and varying specifications, which the classification society will have to consider from case to case. However, for battery power sources DNV requires that a number of documentations are present on board at all times, for instance operational manuals, and systematic maintenance and function testing plan, etc. (DNV 2013). Documentations which states that the capacity is sufficient in order to handle the emergency loads, without the need of recharging within the given time frame of emergency power operation must also be present.

Since the battery technology is constantly under development, regulations will develop and one will have battery packages with varying specifications. Different manufactures provide solutions with varying specifications within energy density, size and weight, charging time, lifecycle and cost, etc. Currently, the most promising technology is rechargeable lithium-ion batteries which have high energy density and cell voltage, as well as high life cycles before maintenance and replacement is needed. The ZERO-report lists some advantages and disadvantages regarding lithium-ion batteries (Opdal 2010):

Advantages:

- High energy density
- High cell voltage, resulting in fewer cells per battery
- Low self-discharge
- No or little memory effect
- Low maintenance need

Disadvantages:

- Safety and stability, i.e. sensitive to overcharging which may result in release of chemical gases and flammable electrolyte solvent vapors
- Requirements for substantial surveillance systems to control charging and discharging
- Costly production, but expected more reasonable by the years
- Ageing even if not in use

In addition, batteries come in small dimensions, enabling engineers to distribute and build the battery packs around the ship structure using void spaces. This gives good weight distribution and thus a stable vessel. Stacking batteries on top off each other is also good, but may restrict the positioning of the batteries and require better cooling systems.

High costs and life cycle limitations give reasons to consider a genset solution as ferries are expected to have long operational periods and lifecycles. A genset is relatively cheap both in purchase and production, in addition to its low maintenance costs. Diesel gensets are considered to be reliable, to have low lifecycle costs, to be efficient, easy to install, and to be operationally flexible (high load ranges), as well as providing high electrical performance (Iverson 2007). But gensets come with varying dimensions and weights, which restricts their positioning. This also gives stability calculation restrictions for the vessel. However, the technology is constantly developing following given regulations (Tier II and III).

Manufacturers are pushing the engine efficiency higher with more environmental friendly and emissions in mind, for instance through more power from smaller volume and weight.

Measures to improve efficiency as mentioned in chapter 5.2 are implemented in the development of gensets. In order to have fully functioning genset at all times, in case of an emergency, it has to be driven and maintained every now and then on an interval basis, such that fuel injectors and -pumps have circulation and the cylinders are lubricated. Maintenance should follow manufacture recommendation and regulations, (equivalent to service booklets for cars). The diesel fuel has to be changed occasionally as it becomes bad when storing over longer periods. Reaction with air gives sediment in the tanks, which can block fuel filters and choke the engine. Combustion of these sediments may cause carbon and soot blockages of injectors and piston heads. (Limited 2002) This may lead to wear and damage to injectors and pumps before expected lifecycle, causing engine failure and reduced equipment reliability.

The selection of emergency power source must be contemplated and analyzed for the specific route and ferry, whether it is a new build or a conversion of a current ferry. Momentums for the decision are costs and lifecycle, maintenance and reliability, weight and stability calculations.

7.4.1 Fuel cells

An alternative to both battery packs and gensets for power generation is fuel cells. Fuel cells produce electricity by converting hydrogen and oxygen into water (without emissions of NO_x, SO_x and particle matter (PM)) by an electrochemical reaction between an anode or a cathode and an electrolyte membrane (DNV, Ludvigsen et al. 2012). The process is similar to batteries but here “fuel” and air is continuously supplied. Figure 40 illustrates the process principle of a fuel cell.

There are a number of different types of fuel cell technologies with varying fuels and electrolyte membranes. FuelCellToday presents some technologies (FuelCellToday):

- PEMFC – proton exchange membrane fuel cell
- DMFC – direct methanol fuel cell

- SOFC – Solid oxide fuel cell
- AFC – Alkaline fuel cell
- MCFC – molten carbonate fuel cell
- PAFC – phosphoric acid fuel cell

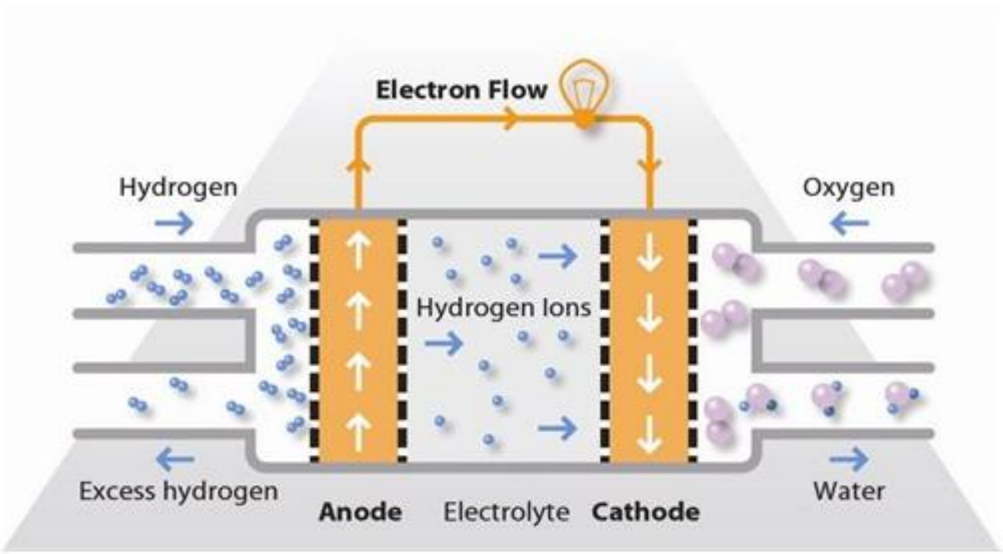


Figure 40: Principle of a fuel cell (FuelCellToday)

However, separation of pure hydrogen gas requires much energy, and if this energy comes from a gas, oil or coal power plants, the environmental footprint for fuel cells is present with regards to CO_2.

DNV has written a report on research and innovation for fuel cells for ships. This report explains some advantages and challenges with fuel cell technologies. Some of the advantages and challenges are presented here (DNV, Ludvigsen et al. 2012):

The technology for fuel cells today gives relatively high efficiency and low energy loss trough heat, compared to conventional gensets. However, the heat loss can be somewhat recovered in combining the fuel cell with for instance a steam turbine, or in a ship produce hot water or as hydronic heating on board. Fuel cells have little moving parts, which results in less noise, vibration and maintenance requirements.

Fuel cell technology can be arranged in modules which can be placed separately if space is issued, giving reductions in risk of failure. However, there are some challenges to the technology. Fuel cells require fuel in form of hydrogen, or other fuels that can be reformed into hydrogen and CO before entering the fuel cell or within the fuel cell. LNG or methanol can be used. Either fuel are currently not common because of the limiting distribution network. But, LNG is somewhat distributed in some harbors along the Norwegian coast. The costs of fuel cells are relatively large per kW compared to combustion engines. This may be because of the small prevalence and few large scale installations of fuel cells. But in the future, production costs may be reduced. Another challenge is the lifecycle of the fuel cells. Fuel cell stacks must be replaced regularly. Operation time have not reached 40000 hours, as expected, without “suffering from significant performance degradation”(DNV, Ludvigsen et al. 2012). It is said that fuel cell stacks need to be replaced every 5 years, and the rest of the plant has a lifecycle of 20 years. In addition, the total installation size and volume of fuel cell power packs per kW varies, but conventional gensets are smaller per kW in comparison.

The technology has been developed until recently for special purposes such as submarines and outer space exploration, but research and development has proven that fuel cells work in large scale as well. FellowSHIP developed and made a fuel cell power pack unit of 330kW, which were installed and tested on the supply vessel Viking Lady(FellowSHIP 2011). The fuel cell operated more than 7000 hours. This shows that in the future, fossil fuel engines may be faced out for power generation on ships. Given that the separation of hydrogen gas for fuel cells comes from renewable energy, the environmental footprint is reduced or even absent.

A fuel cell power pack can be an alternative as emergency power source on board the concept ferry, but investment costs and lifecycle analyses are needed with careful consideration of alternatives in respect to regulations.

8 Solution

The best suitable concept solution for power transfer is regarded as submerging and "towing" the cable, with drum spool storage onboard or on shore. The solution is regarded most possible since current cable technology limits the floating capability and tension requirements for the surface floating configuration (i.e. the outer diameter will be very large and the cable weight will be large as of the armor), in addition to that straitening of the seabed is considered very expensive for the bottom configuration. The air stretched configuration is disregarded because of the risks involved, for instance the little drift abilities and the connectivity between the ferry and the cables (i.e. the ferry has little room for drifting as the connector arm length is limited, and environmental forces may affect the connection between the connector arm and the cables), even though it may be less expensive than others.

One solution for onboard storage with a retractor winch and a linear tracked cable engine as brake unit is illustrated in the figures 41, 42 and 43. Here it is also shown a cable tray guidance system, a guider arm (i.e. two rollers moving vertically with the cable between them), and a drum spool for storage. It can also be seen a switchboard example in the background. It is however assumed that a linear cable engine is better suitable than a linear tracked engine as tensioner, because of the cable handling speed requirement. This also yields for the retraction unit where the cable drum engine is assumed more suitable than a winch.

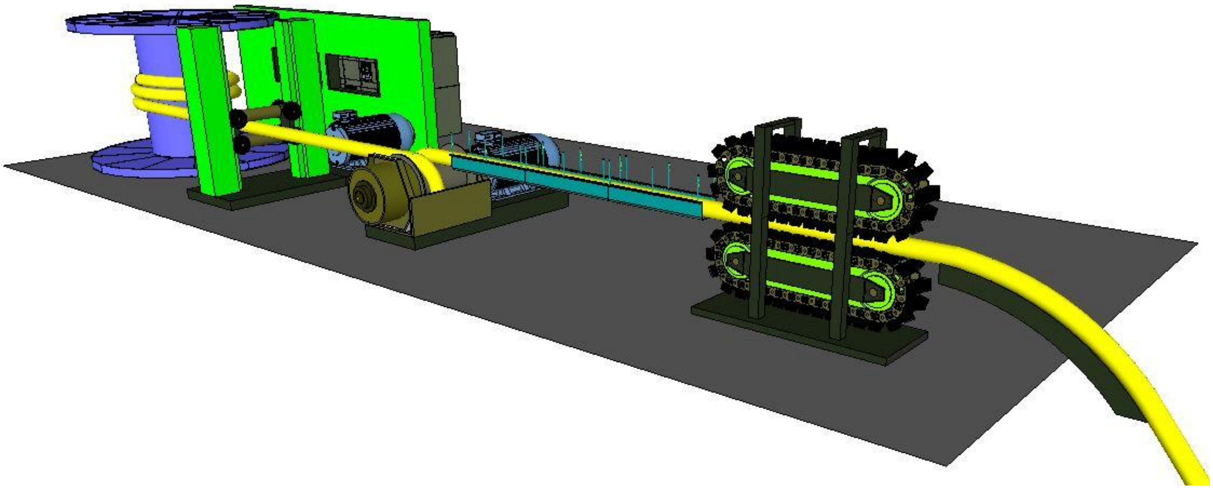


Figure 41: Concept illustration #1

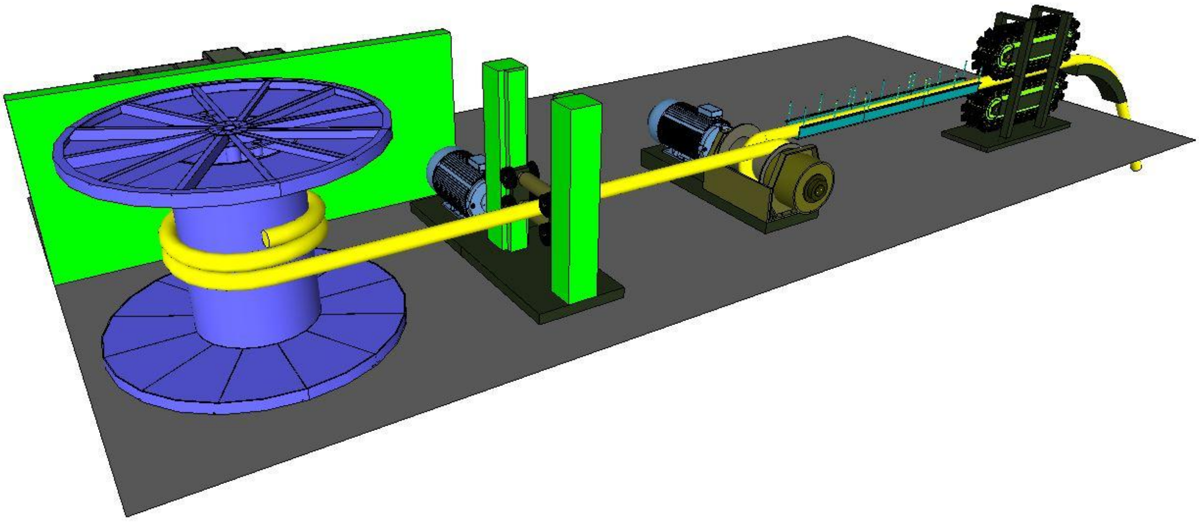


Figure 42: Concept illustration #2

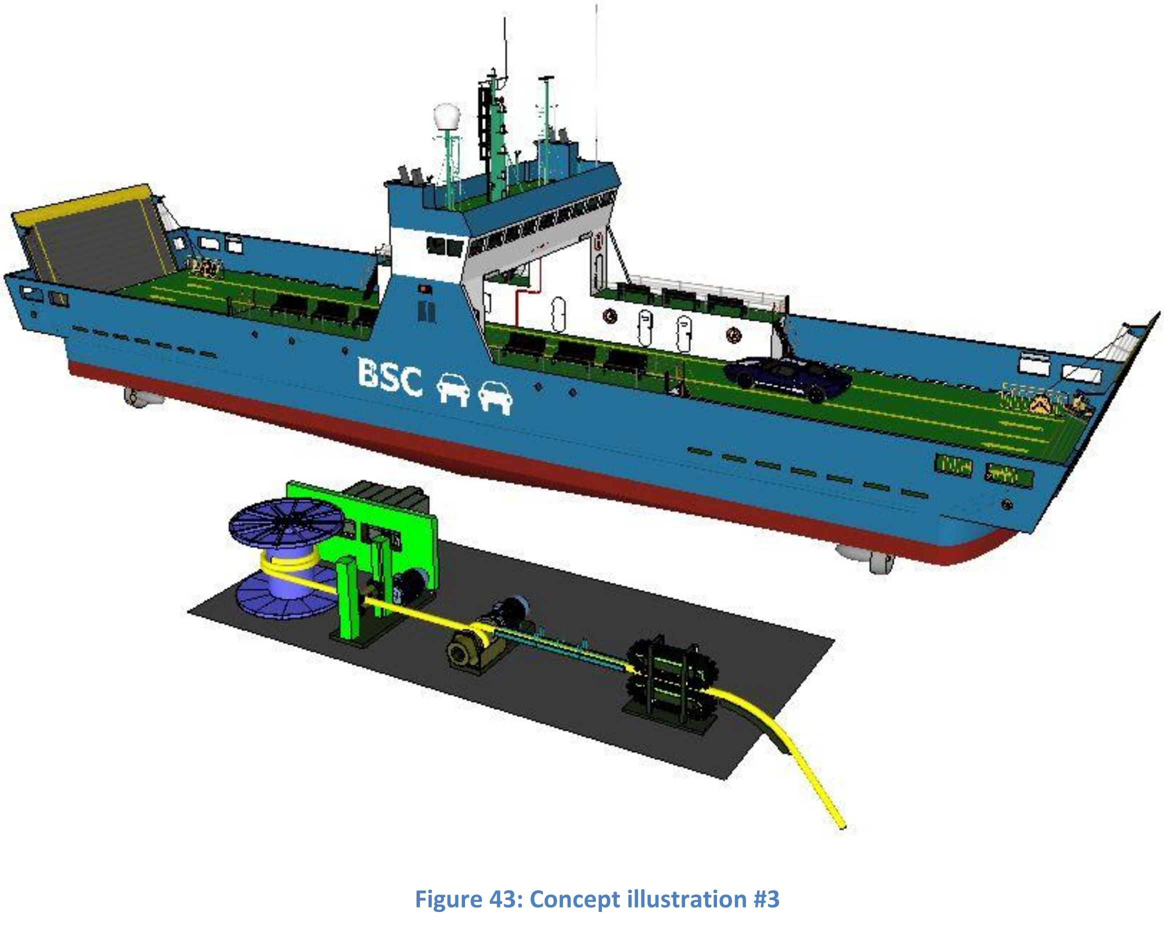


Figure 43: Concept illustration #3

9 Diesel- and LNG-electric vs. concept

So why should the electric concept be chosen over a diesel-/LNG-electric genset solution? The genset solution is well known, relatively easy to install and maintain, and fairly efficient. The technology is constantly developing and becoming cheaper to build. The efficiencies are increasing and size and weight is reduced. So decisions should be made regarding weight, size, efficiencies, costs and future environmental legislations.

9.1 Volume and weights

How much space do the respective solutions require? For a genset solution, it is required space for the engine and the generator, for which the size depends on delivered power (kW). Further, it is required space for exhaust pipes and exhaust cleaning units, in addition to fuel and lube oil tanks. It is assumed that the propulsion motor and axles are the same for both the concept and a genset solution. For the concept solution, the space requirements are based on the storage unit, the guider arm, retractor and brake units, as well as guidance system (cable trays). For the concept ferry, the genset solution and associated equipment's spaces are enabled for the cable handling equipment, including the space taken up by fuel and lube oil tanks.

9.1.1 Concept equipment

As mentioned, the drum spool dimensions are determined by cable length, thickness and hull limitations. In chapter 7.2.5, it has been calculated a few drum spool sizes for storing cable volumes of 22m^3, 34m^3 and 43m^3. This has been done for a set of chosen limiting hull factors. In addition, in table 12 it is displayed the cable volume and weights for given lengths and cable dimensions, where the average cable weight is approximately 26.3tonnes.

Further, it has been assessed some cable tensioners and retraction units. The largest tracked cable engine with 15tonnes tension provided by Fraser Hydraulic Power Ltd weighs 8.2tonnes, and has the following dimensions: height 3.1m, width 2.4m and length 4.6m, giving an installation volume of 34.2m^3 (Ltd 2007). The linear cable engines presented by National Oilwell Varco (NOV 2014) weighs respectively 8.8, 12.2 and 30 tonnes. The 8.8tonnes LCE however, is assumed to have insufficient capacity for the concept, as it only has a holdback force (tension) of 4tonnes. In table 10 and 11, specifications for the 12.2tonnes and 30tonnes LCEs are presented, but their dimensions are unfortunately not displayed. Neither the cable drum engines provided by National Oilwell Varco have dimensions listed. However, their weights are respectively 19, 32 and 37 tonnes (NOV 2014).

Weights and volumes of the cable guidance systems, like cable trays and guider arm, are rather small compared to the cable handling equipment assessed above. It can be assumed that the sizes are determined after the cable dimensions. This means that the breadth and height of the cable trays are determined based on the cable outer diameter. The guider arm arrangement will have the same height as the cable drum spool, since the cable will be laid over the whole column height. The size of the arm is determined, similarly as the guidance system, based on the cable outer diameter. So the guidance system consists of tubular frames and rollers positioned in intervals. Their dimension and weight are based on the materials selected, interval distances and the cable diameter and weight.

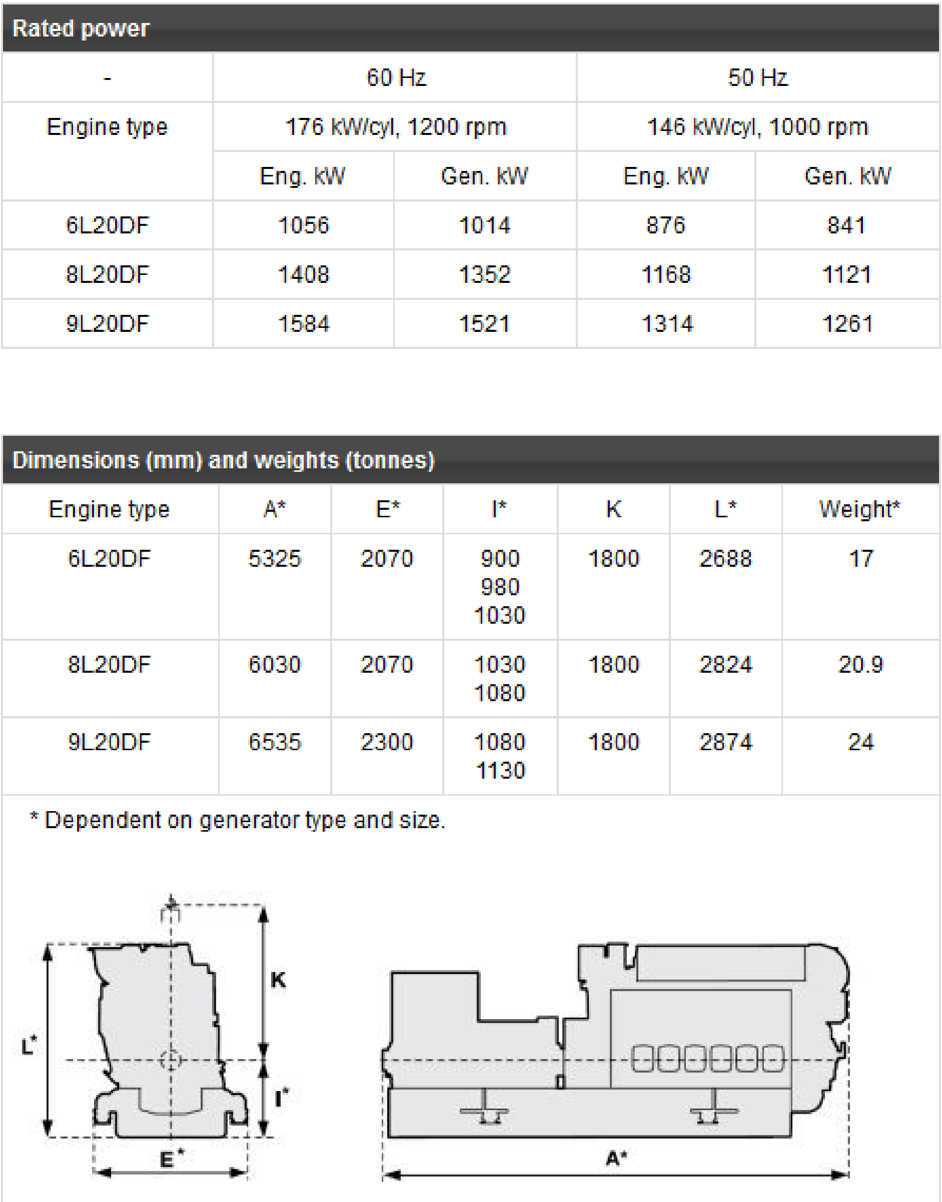
9.1.2 Genset solution

The size and weight of genset varies with the power output. Known genset and marine engine manufactures are Wärtsilä and Caterpillar. For instance, Caterpillar delivers both diesel and gas gensets and marine engines with varying power output (Caterpillar 2014). One example of a gas genset is the CG170-12 showed in figure 41 (Caterpillar 2014). It delivers 1200kW of maximum continuous rating power with an efficiency of 43.7%. It has the following dimensions: length of 4.66m, width of 1.81m and a height of 2.21m, giving an installation volume of 18.64m^3. The generator set's dry weight is 11.7tonnes.

Figure 44: Caterpillar CG170-12 (Caterpillar 2014)

Another example is the diesel genset 20DF by Wärtsilä shown in figure 45 (Wärtsilä 2014). It satisfies the Tier II emission standard and can be delivered with 6, 8 or 9 cylinders, giving respectively 1014, 1352 and 1521 kW of rated power through the generator. Specifications for the genset are showed in table 16.

Figure 45: Wärtsilä generating set (Wärtsilä 2014)



Rated power

-	60 Hz		50 Hz	
Engine type	176 kW/cyl, 1200 rpm		146 kW/cyl, 1000 rpm	
	Eng. kW	Gen. kW	Eng. kW	Gen. kW
6L20DF	1056	1014	876	841
8L20DF	1408	1352	1168	1121
9L20DF	1584	1521	1314	1261

Dimensions (mm) and weights (tonnes)

Engine type	A*	E*	I*	K	L*	Weight*
6L20DF	5325	2070	900 980 1030	1800	2688	17
8L20DF	6030	2070	1030 1080	1800	2824	20.9
9L20DF	6535	2300	1080 1130	1800	2874	24

* Dependent on generator type and size.

Table 16: Wärtsilä 20DF generating set (Wärtsilä 2014)

Now, these gensets require fuel. Wärtsilä construct various engines which can operate on a range of fuels such as heavy fuel oil, diesel and natural gas (Wärtsilä 2014). The size of the fuel tanks are determined by the range the vessel is designed to operate before refueling, and the fuel consumption of the engine(s). One engine example is the Wärtsilä 20DF genset which has a Brake Specific Energy Consumption BSEC of 8510kJ/kWh (Wärtsilä 2014). A ferry operating a short route will have the ability to refuel quite often compared to a long distance tanker. Therefore, the fuel tanks are not that large. However, it is not usual to refuel every day. For instance, the Whatcom Chief ferry operating the ca 900m route between

Gooseberry Point and Lummi Island in Washington USA, has a refueling rate of every 14 days (Washington 2014). This ferry has approximately 39 departures every day and a capacity of 100 passengers and 20 cars.

The weights of the different fuels are also an issue with regards to payload. The specific fuel weights are termed as weight per volume. Heavy fuel oil has a specific weight of 930kg/m^3, diesel (grade 2) has 849kg/m^3, and natural gas has between 0.7 – 0.9 kg/m^3 (depending on the gas composition, i.e. methane level) (Toolbox 2014).

The natural gas is liquefied or compressed and stored on tubular tanks. An example of LNG storage tanks is shown in figure 47. These tanks have one disadvantage in that they don't exploit the space within the hull very efficient, giving large voids. This, in addition to that the gas consumption is somewhat higher than a diesel engine, it is implied that the refueling rate is somewhat more frequent.

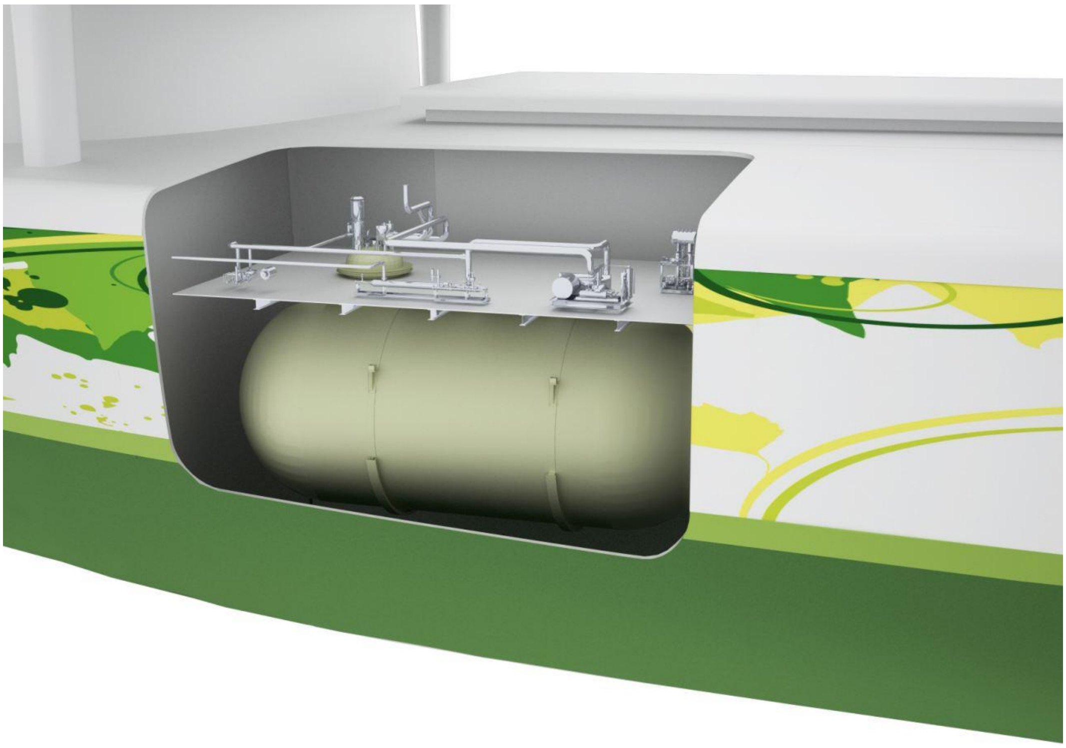


Figure 46: Ship LNG fuel tank (News 2012)

9.2 Costs

When designing a power system for a ferry, there are a number of factors that affect the costs. Which power plant and associated equipment should be bought, what are the installation costs, and how does it perform – operational costs (fuel consumption and maintenance costs)? It all depends on the ferry's functions and specifications (as described in chapter 2.1 and 6), e.g. the hull shape and its performance in different environmental conditions, and its ability to cope with different environmental loads. Every vessel project is unique, where specifications and component compositions differ. For instance during a series production, the technology may change as the time passes, where one vessel is built at a time. The customer may want a different component composition and products from different suppliers in the newer vessels, as he or she sees the technology changes. So, determining the actual total costs of a power system is difficult.

9.2.1 Equipment and system costs

For a diesel- or LNG-electric power system, the costs are related to genset among others purchase, installation costs, fuel consumption regarding engine type and operational loads, maintenance costs and maintenance intervals (oil and filter changes, and overhauls). Also, costs of the equipment needed for the gensets (such as fuel systems and lube oil systems) and control systems are taken into account. In addition, future emission regulations may require more extensive exhaust gas cleaning equipment. An example of a diesel genset is a 1350kW KTA50GS8 Cummins Diesel GenSet. It is retailed for US $249000 – 255000/set at Alibaba.com (Alibaba.com 2014). Another example is a natural gas genset from Jichai with 1000kW, model H16V190ZLT retailed at Alibaba.com for US $385000/piece (assumed that the largest genset has the highest price where it is listed 19 gensets between 8 – 1000kW for a price between US $5000 – 385000/piece) (Alibaba.com 2014).

As for the concept solution, the costs are related to the drum spool, cable tensioner and retractor, guidance system, guider arm, hydraulic systems, and transformers (both on shore and onboard), installation costs of these, and maintenance costs and maintenance intervals. The highest cost for the concept is the cable costs. In consultancy with Øystein Tvedt at Nexans Norway, it was concluded that the cable construction, specifications and the customers' requirements, as well as the length affects the cable price (Tvedt 2014). Nexans don't have a specific price list of their cables, but a couple of examples were given: As a basis for cost estimate, the price for a standard 3x25mm^2 TXRE 24kV cable is taken as approximately 450NOK/m (i.e. US $75.58/m in 28th May 2014 currency), and for a standard 3x95mm^2 TXRE 24kV cable the price is 850NOK/m (i.e. US $142.76/m in 28th May 2014 currency). The 28th May 2014 currency is US $1 = 5.9539NOK (Bank 2014). These prices apply for delivery lengths of per 1000m. So for a cable length of 5km the costs are respectively 2.25million NOK (i.e. US $377903.56 in 28th May 2014 currency) and 4.25million NOK (i.e. US $713817.3 in 28th May 2014 currency). These are standard cables, but for the concept it is assumed that the price will be higher. This since the cable layer configuration and construction must be custom engineered in terms of conductivity, armor and weight, giving a special layer configuration.

The costs of the cable handling equipment (i.e. the drum spool, retractor and tensioner, and guidance system), the hydraulic system and the control system, are assumed to be low compared to the cable costs. Determining the concept costs is hard since price offers are only given to serious customers who contact the different companies, i.e. no official pricelists are available on company web pages. In addition, the companies can special-/custom make the products according to the customers' needs. An example of a land based power grid transformer on Alibab.com is a CNGNA transformer, model S9 S11, which can be designed to transform for instance 24kV to 400V (Alibaba.com 2014). Depending on what transformer specification chosen, the cost varies between US $1000 – 26000/unit. Although a land based transformer is somewhat different from a shipboard transformer, the price range is assumed to be similar or somewhat higher.

9.2.2 Fuel costs

The fuel prices vary from country to country and from year to year. DNV have in their Shipping 2020 report (DNV 2012) looked upon the global fuel price projections from 2010 to 2020, based on information collected from OECD, the International Energy Agency (IEA) and the US Energy Information Administration (EIA). The following graphs as sighted in the Shipping 2020 report, i.e. figure 49, 50 and 51, shows the fuel price projections (i.e. US $/tonne) from 2010 to 2035 for heavy fuel oil (HFO), marine gas oil (MGO) (diesel with low sulfur (Caltex 2011)), and liquefied natural gas (LNG). For each fuel type, there are three graphs. They show estimated high and low price projections, as well as reference price projections.

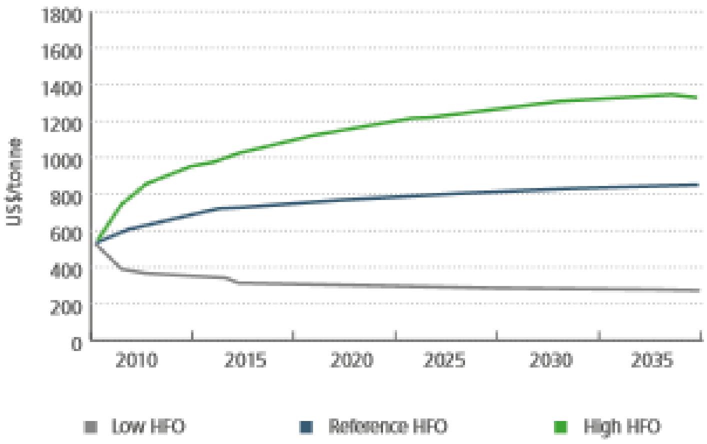


Figure 21: HFO price projections 2010-2035 (real terms).
Source: OECD, IEA, EIA Distillates.

Figure 47: HFO price projections 2010-2035 (DNV 2012)

In April 2014 the international price for HFO was averaged at US $ 620.30/tonne (Insee 2014).

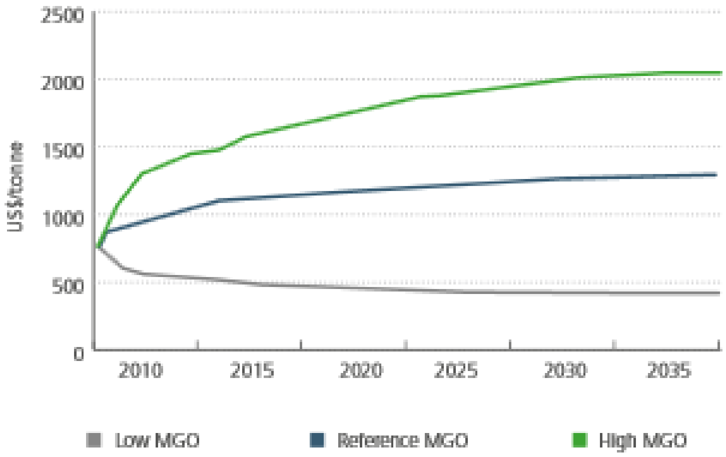


Figure 22: MGO price projections 2010-2035 (real terms).
Source: OECD, IEA, EIA.

Figure 48: MGO price projections 2010-2035 (DNV 2012)

On May 29th 2014 the retailed price of MGO was US $881.50/tonne in Rotterdam (Bunkerworld 2014).

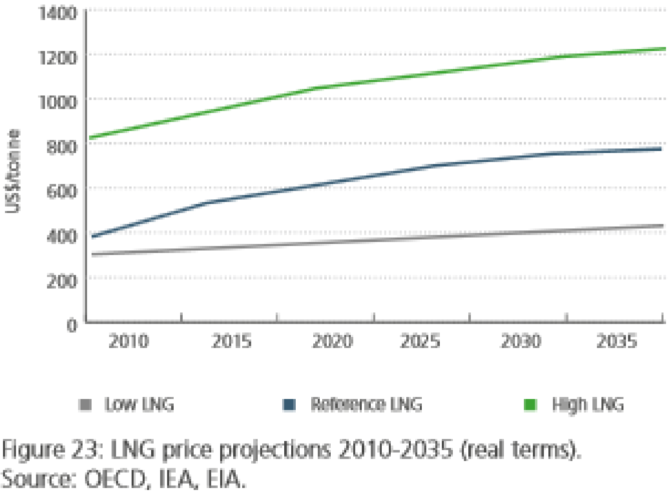


Figure 49: LNG price projections 2010-2035 (DNV 2012)

On April 30th 2014 the import price for natural gas was US \$10.73/MMBtu for the European Union (YCharts 2014). MMBtu is a measure for heat energy in fuels and can be converted into kWh through the relation 1MMBtu = 293.1kWh (Toolbox 2014). This gives that the price was US \$0.0366/kWh.

For comparison, the average electricity price for industrial businesses (i.e. for industry which are not energy intensive) in Norway the 1st quarter of 2014 was 0.284NOK/kWh (i.e. US \$0.0477/kWh in 28th May 2014 currency) (ssb 2014). The electricity price changes throughout the year and from year to year, depending on the market and the supply. In Norway, the main electricity supply comes from hydropower, i.e. water in dams propels large turbines which produce electricity. However, in periods with low water reserves, electricity is imported from Europe (e.g. Sweden, Germany, etc.), where other forms of main electricity production methods are common (e.g. from gas, coal, nuclear, or wind, etc.). The concept is intended to use hydropower as electricity source, giving no emissions to air (emissions from eventual imported energy and production of the concept equipment are disregarded).

From the graphs it can be seen that the price for HFO and LNG is assumed to have rather similar future price range, and that MGO will have a somewhat higher price range. However, due to stricter future emission regulations it is assumed that the use of HFO will be significantly reduced and phased out. It is also seen that the price for LNG and electricity per kWh is currently approximately the same. This may in the future change depending on market and available supply.

It is important to understand that the natural gas price mentioned is what the European Union pays when importing the gas. Pipelines form fields in the North Sea transport the gas to the continent. With LNG (processed natural gas) transportation is done by special ships (larger quantities) or semi-trucks (smaller quantities), giving additional transportation costs. Norway has a couple of land based gas process facilities from which LNG is transported to consumers (e.g. consumers like the LNG powered ferries MF Landegode (Skipsrevyen 2012) and MF Boknafjord (Skipsrevyen 2012), etc). So the LNG price for consumers in Norway may be assumed somewhat different compared to the European Unions' natural gas import price, considering processing and transportation.

10 Case study

In table 1 it is listed 20 Norwegian short ferry routes along the coast, which are somewhat suitable for testing the concept. Some of the routes as they are presented today are better suited then others with regards to route curving and oblique quays. Route curving and oblique quays can make the transit and cable handling difficult without damaging or reducing the operational lifetime of the cable and the handling equipment. Also, the route locations experience different environmental conditions and level of crossing traffic. In order for the different routes to be suitable for the concept, alterations to the quays and their directions are recommended such that they become as straight as possible. The main reason for having oblique quays today is to be able to dock under varying weather conditions. But piers can help reduce the influence, such that strait quays are possible. However, there are a few routes along the coast that don't require much alteration other than installation of a transformer on shore, and eventual cable handling equipment on shore if this configuration is chosen.

10.1 Ferry of interest

One route which may be applicable for the concept is the route between Kvellandstrand and Launes in Vest-Agder County. The location of the route can be seen in figure 54. This is a route of approximately 1.3km and is operated by the M/F Hidraferja, shown in figure 52. This ferry is 49.8m long, 13.70m wide and has a capacity of 38 cars and 130 passengers (Maritime). The ferry has two Volvo TAMD 162C engines with 375kW of power, one on each end directly connected through shafts to Schottel STP 330 thrusters (Dyrli 2014). An illustration of the engine and thruster arrangement onboard M/F Hidraferja can be seen in figure 53.

Figure 50: M/F Hidraferja (Maritime)

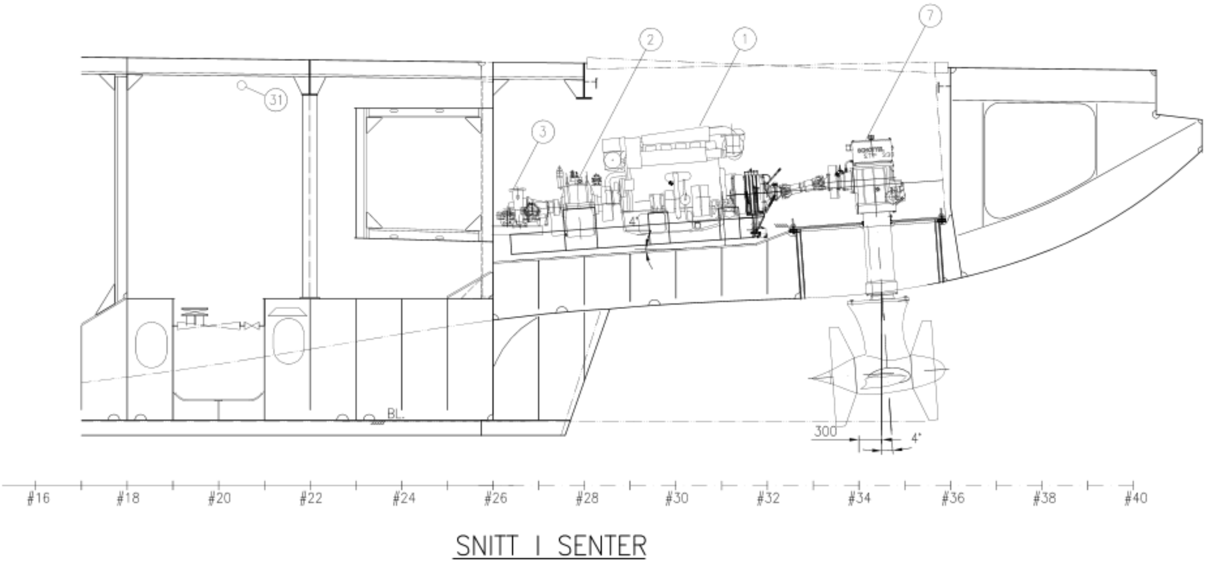
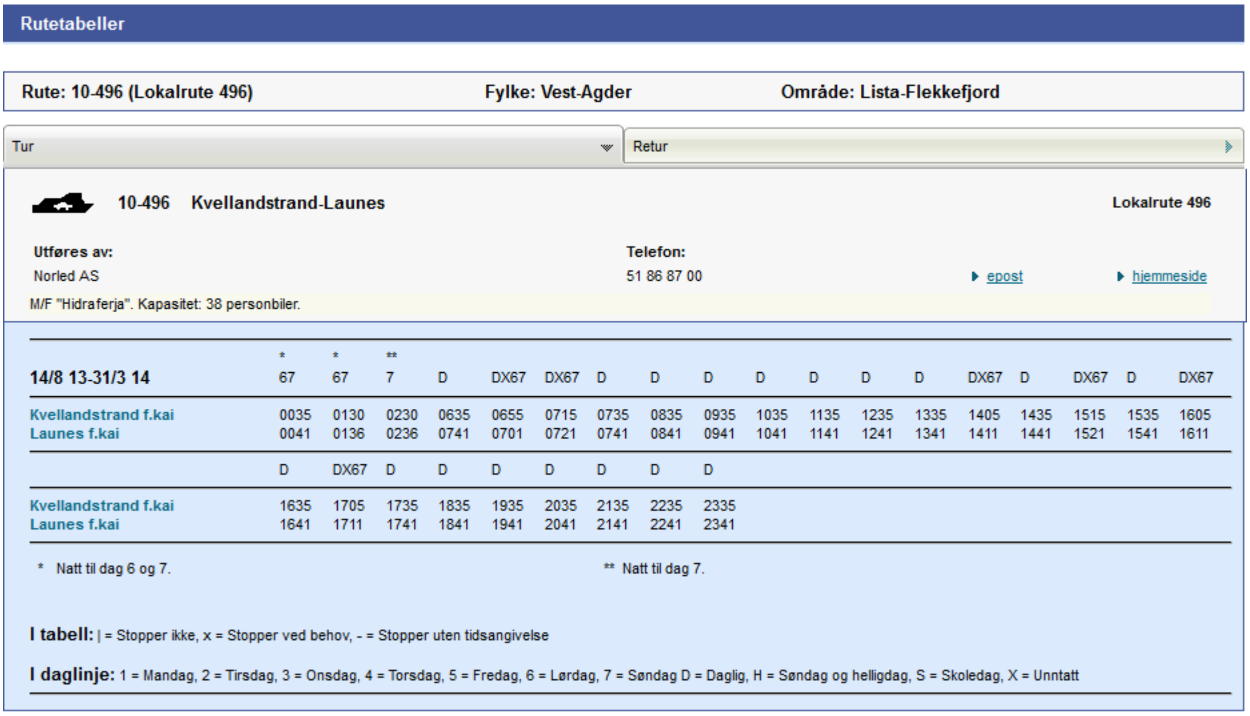


Figure 51: Engine and thruster arrangement onboard M/F Hidraferja (Dyrli 2014)

As of the section arrangement drawing above, it can be seen that the engines can be replaced with electric motors for thruster driving.

10.1.1 The Kvellanstrand – Launes ferry route

The ferry has 24 daily departures in addition to a few extra night routes in the weekends, as can be seen in the route table below (Rutebok 2008). The route is operated all year, and based on the route table each transit takes approximately 6 minutes including loading and offloading. The ferry transports annually 126880 vehicles between the main land and the island Hidra (StatensVegvesen 2013).



Rutetabeller

Rute: 10-496 (Lokalrute 496) **Fylke: Vest-Agder** **Område: Lista-Flekkefjord**

10-496 Kvellandstrand-Launes **Lokalrute 496**

Utføres av:
Norled AS

Telefon:
51 86 87 00

M/F "Hidraferja". Kapasitet: 38 personbiler.

14/8 13-31/3 14	* 67	* 67	** 7	D	DX67	DX67	D	D	D	D	D	D	D	DX67	D	DX67	D	DX67
Kvellandstrand f.kai	0035	0130	0230	0635	0655	0715	0735	0835	0935	1035	1135	1235	1335	1405	1435	1515	1535	1605
Launes f.kai	0041	0136	0236	0741	0701	0721	0741	0841	0941	1041	1141	1241	1341	1411	1441	1521	1541	1611

	D	DX67	D	D	D	D	D	D	D
Kvellandstrand f.kai	1635	1705	1735	1835	1935	2035	2135	2235	2335
Launes f.kai	1641	1711	1741	1841	1941	2041	2141	2241	2341

* Natt til dag 6 og 7.

** Natt til dag 7.

I tabell: | = Stopper ikke, x = Stopper ved behov, - = Stopper uten tidsangivelse

I daglinje: 1 = Mandag, 2 = Tirsdag, 3 = Onsdag, 4 = Torsdag, 5 = Fredag, 6 = Lørdag, 7 = Søndag D = Daglig, H = Søndag og helligdag, S = Skoledag, X = Unntatt

Table 17: Kvellandstrand – Launes route table (Rutebok 2008)

Figure 52: Kvellandstrand – Launes ferry route location (Google 2014)

Figure 55 shows a closer map view of the route's location with the blue line marking the transit, and figure 56 shows a sea map of the route.

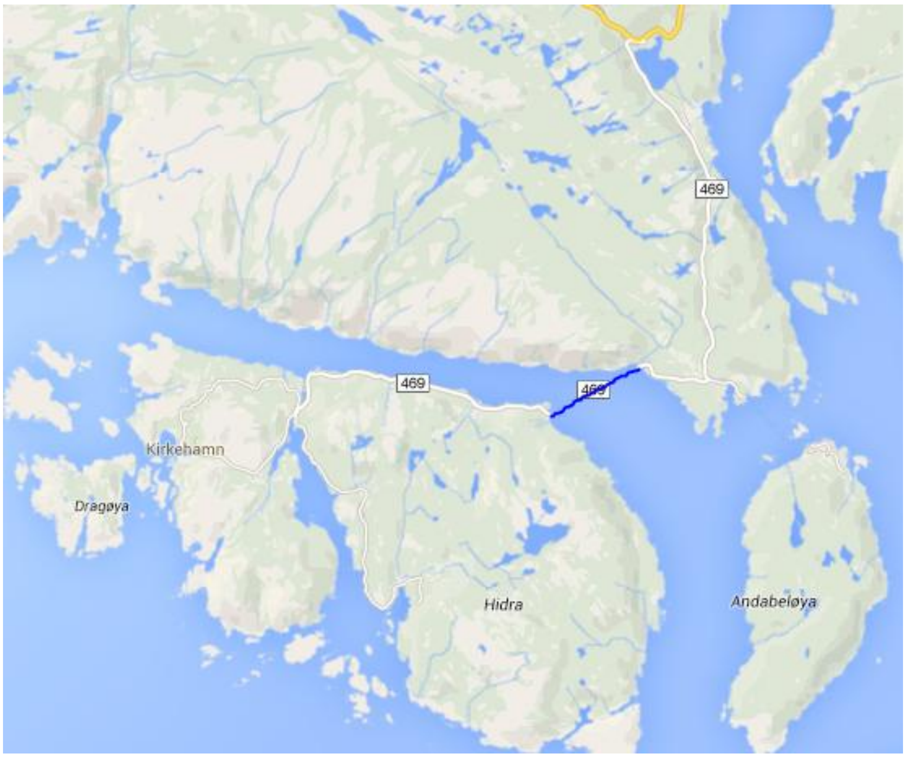


Figure 53: Map of the Kvellandstrand – Launes route location (Google 2014)

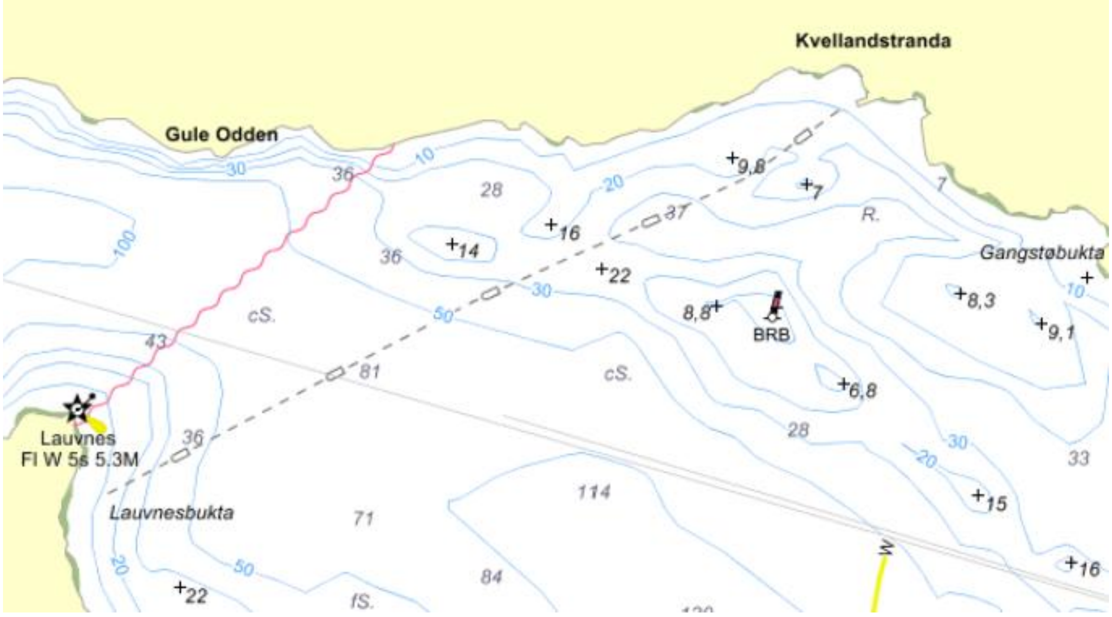


Figure 54: Sea map over the Kvellandstrand – Launes route (Gulesider 2014)

The sea map in figure 56 shows the water depths over the route transit. Close to shore on both sides, it can be seen that the bottom slopes are fairly steep. The deepest part on the route is 81m.

In figure 55 it is seen that the route crosses a strait, the Hidrasundet. The strait may channel westerly weather in the North Sea in towards the transit route. There is not much crossing traffic in the strait, but some pleasure boats traffic the strait during the summer months. Larger ships are not usually sailing here because of the relatively shallow waters in the Risholmsundet by Andabeløy (see figure 57) towards Storfjorden. Storfjorden is the seaward approach to Flekkefjord, so larger vessels sail here. However, there is a fish farm located in the Hidrasundet strait west of the ferry route. Wellboats and feeding boats are regularly sailing from between the fish farm and Abelsnes harbor, thus crossing the ferry route. The Abelsnes harbor is established as an international harbor with weekly voyages to Rotterdam, and is a harbor for container traffic between Kristiansand and Stavanger (Larsen and Eie 2012). However, traffic to Abelsnes harbor mainly sails through Strandfjorden between Andabeløya and Hidra (figure 55), and does not affect the ferry route in Hidrasundet greatly.

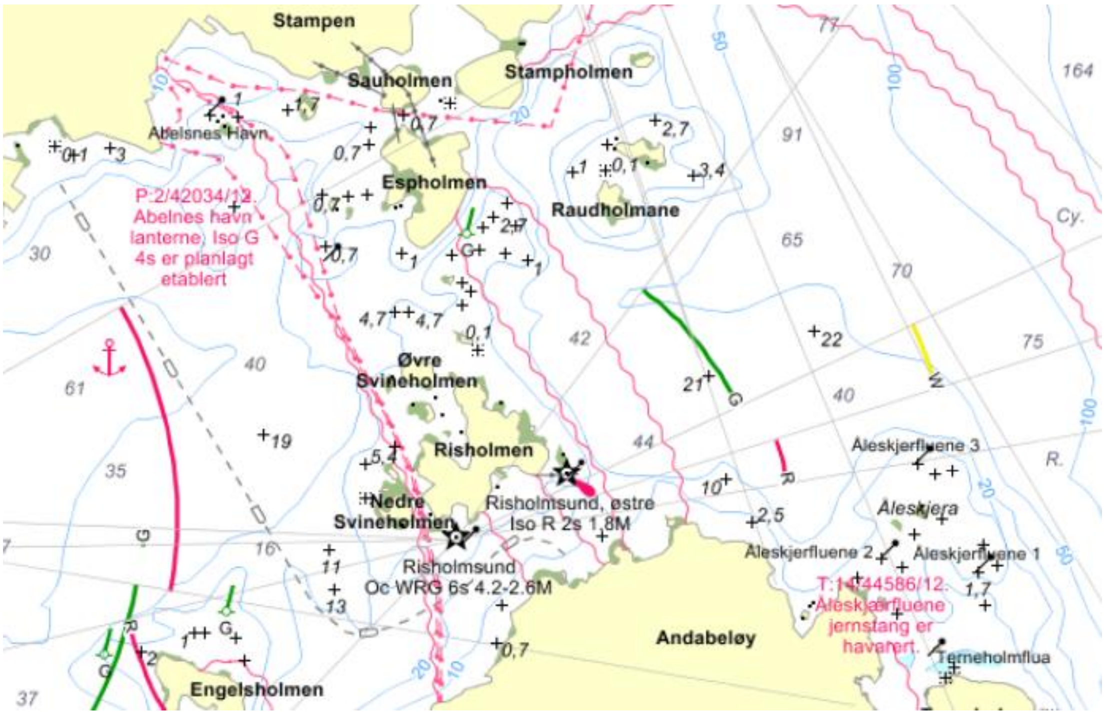


Figure 55: Sea map of Risholmsundet (Gulesider 2014)

10.2 Concept implementation

As there is some crossing traffic and unknown sea bottom formations at the route, it is assumed that the concept solution best suited for the strait is the submerged cable configuration. Not only does it reduce the risk of interactions with crossing traffic, it also removes the need for bottom straitening. Weaves have less effect on the cable tension, but strong currents may have larger influence. The reason that the air stretched concept configuration is not chosen is that the allowable drift will be too small considering the weather affects, as well as the possibility that high masts on crossing traffic may interact with the cable. Since the submerged cable is relatively long, the allowable ferry drift is larger.

Now the question is whether to store the cable onboard or on shore. This depends on the space and weight enabled onboard the ferry. For instance, as seen in the General Arrangement drawings in the following figures, there is a fair amount of space available onboard the ferry, i.e. dry tanks which can be enabled for implementation of the concept with onboard storage. In addition, it is assumed that some space in the engine rooms can be enabled as well, since the electric motors replacing them will be somewhat smaller in size. The two Volvo TAMD 162C engines onboard M/F Hidraferja have the following dimensions (AB 2000):

Dry weight: 1740kg

Length: 2430mm

Breadth: 920mm

Height: 1540mm

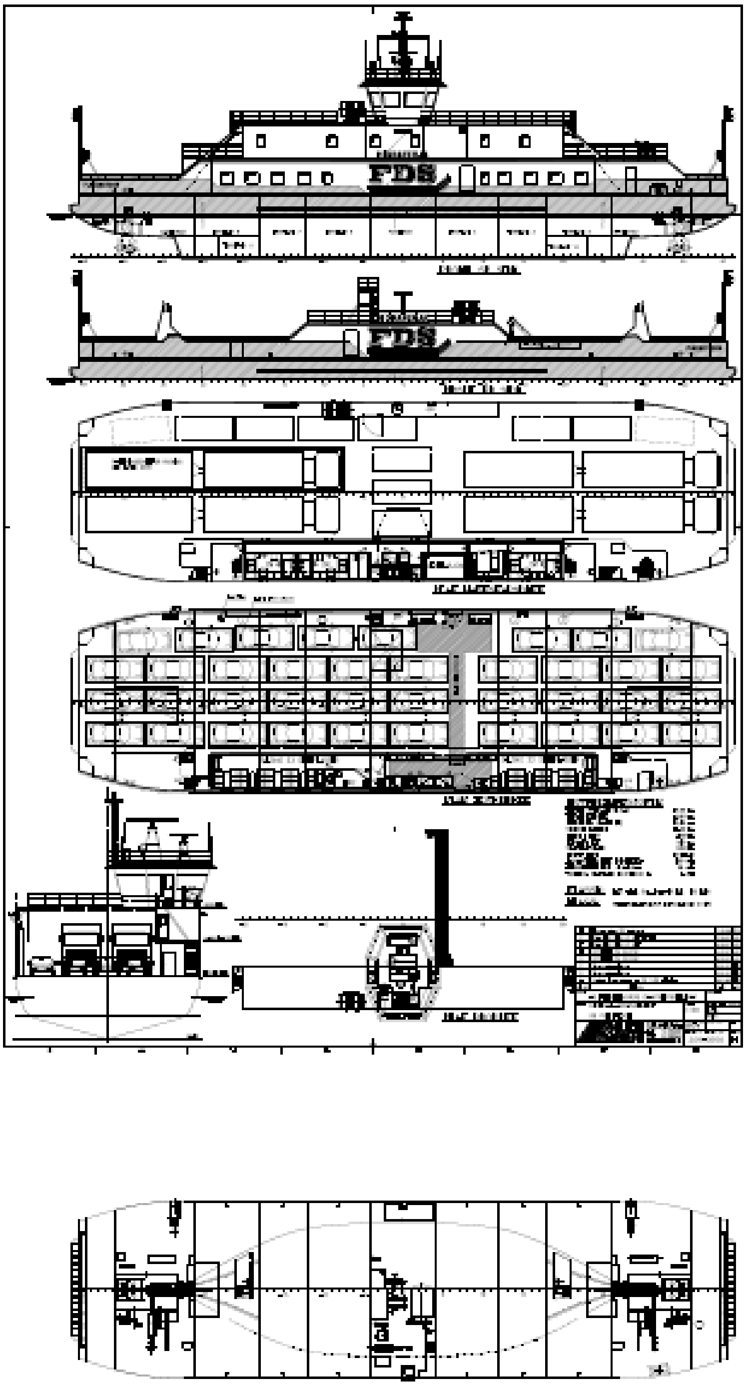


Figure 56: General arrangement drawing of the M/F Hidraferja (Dyrli 2014)

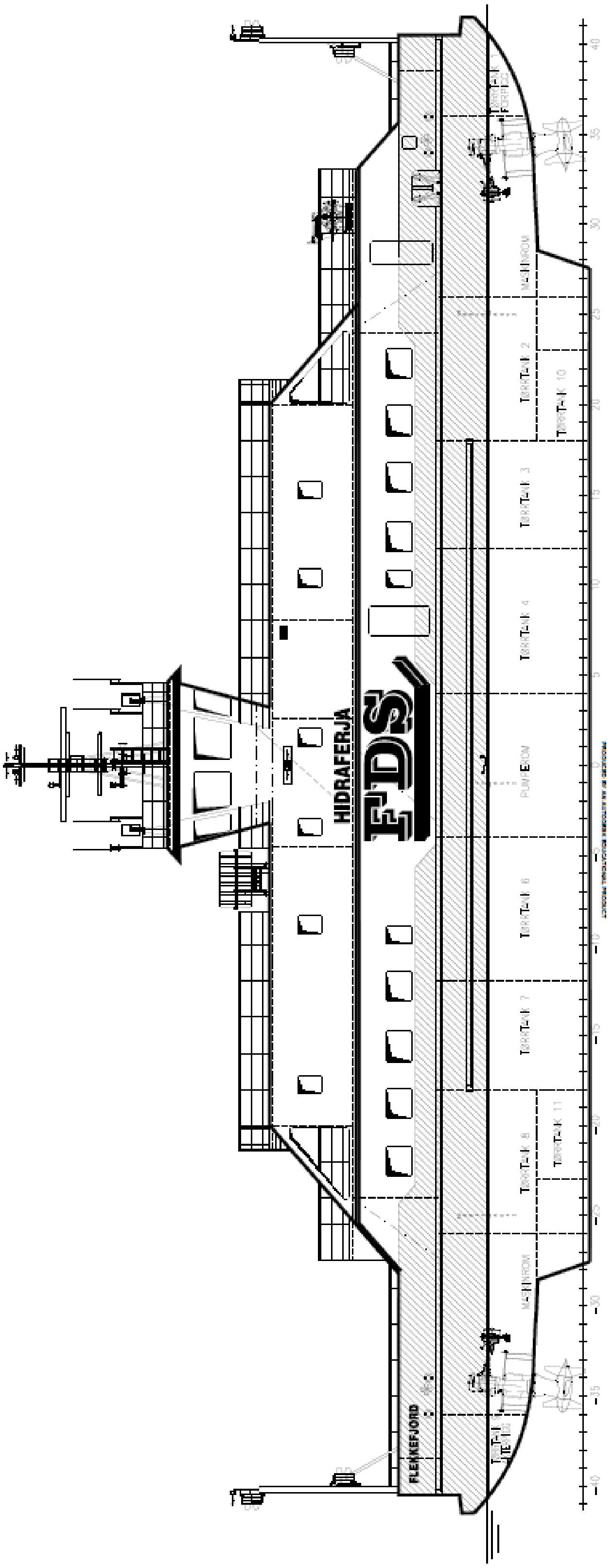


Figure 57: Starboard side profile of the M/F Hidraferja (Dyrli 2014)

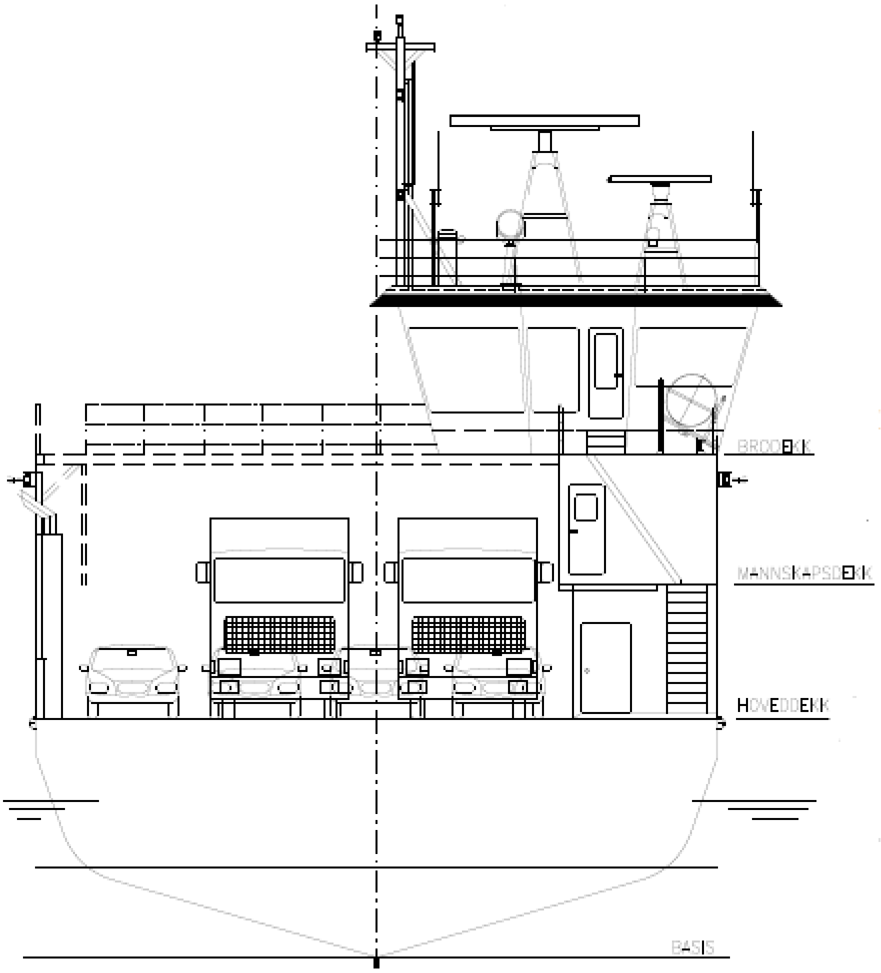


Figure 58: Sectional view with deck divisions of the M/F Hidraferja (Dyrli 2014)

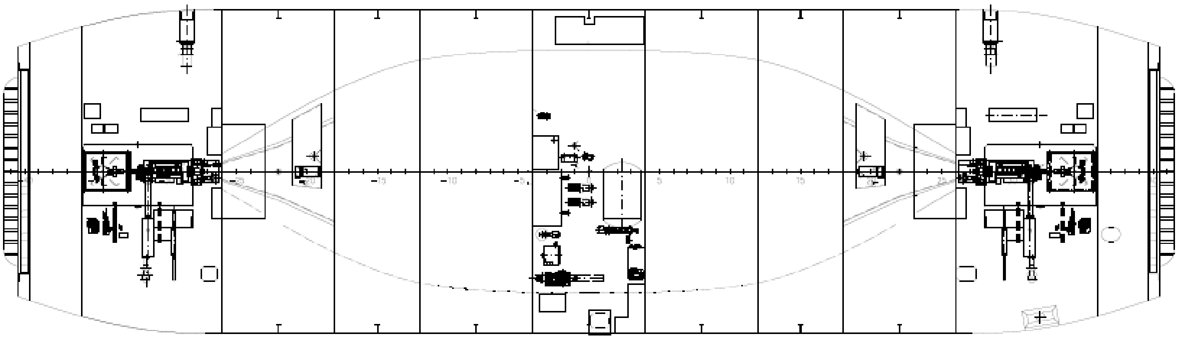


Figure 59: Machine rooms and tank divisions of the M/F Hidraferja (Dyrli 2014)

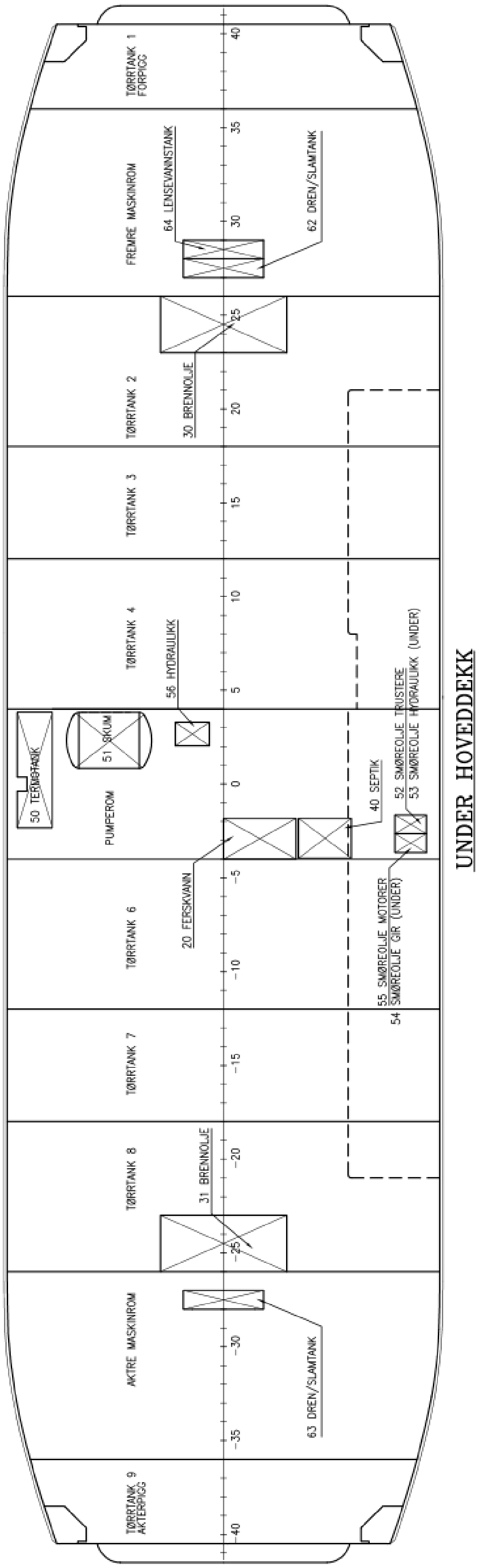
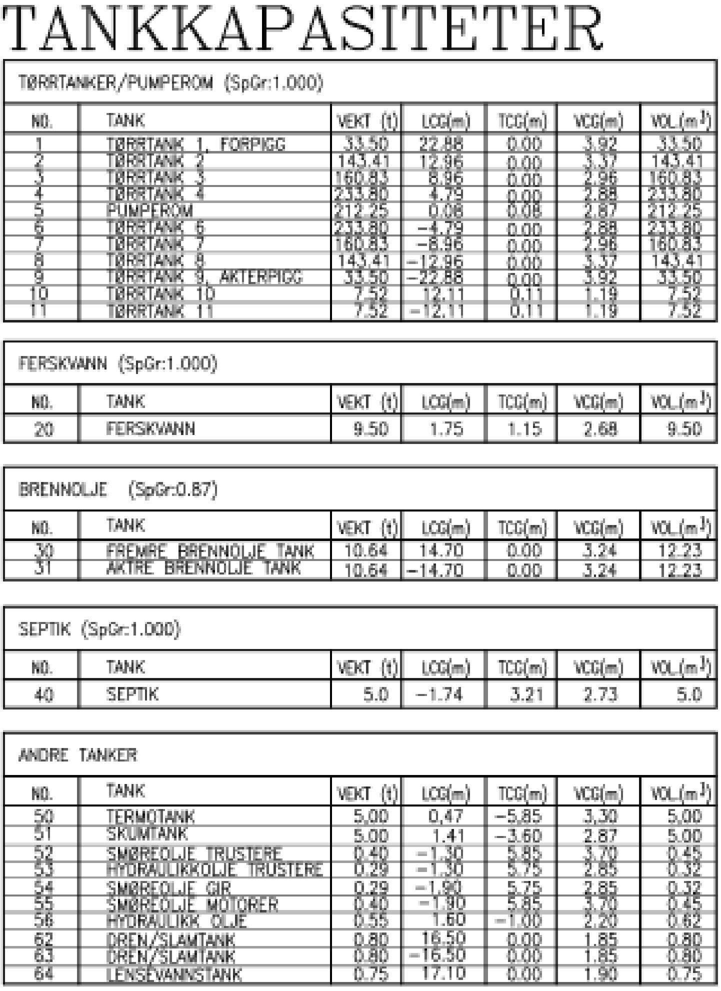


Figure 60: Tank arrangement drawing of M/F Hidraferja (Dyrli 2014)



TANKKAPASITETER

TØRRTANKER/PUMPEROM (SpGr:1.000)

NO.	TANK	VEKT (t)	LCG(m)	TCG(m)	VCG(m)	VOL.(m^3)
1	TØRRTANK 1, FORPIGG	33.50	22.88	0.00	3.92	33.50
2	TØRRTANK 2	143.41	12.96	0.00	3.37	143.41
3	TØRRTANK 3	160.83	8.96	0.00	2.96	160.83
4	TØRRTANK 4	233.80	4.79	0.00	2.88	233.80
5	PUMPEROM	212.25	0.08	0.08	2.87	212.25
6	TØRRTANK 6	233.80	−4.79	0.00	2.88	233.80
7	TØRRTANK 7	160.83	−8.96	0.00	2.96	160.83
8	TØRRTANK 8	143.41	−12.96	0.00	3.37	143.41
9	TØRRTANK 9, AKTERPIGG	33.50	−22.88	0.00	3.92	33.50
10	TØRRTANK 10	7.52	12.11	0.11	1.19	7.52
11	TØRRTANK 11	7.52	−12.11	0.11	1.19	7.52

FERSKVANN (SpGr:1.000)

NO.	TANK	VEKT (t)	LCG(m)	TCG(m)	VCG(m)	VOL.(m^3)
20	FERSKVANN	9.50	1.75	1.15	2.68	9.50

BRENNOLJE (SpGr:0.87)

NO.	TANK	VEKT (t)	LCG(m)	TCG(m)	VCG(m)	VOL.(m^3)
30	FREMRE BRENNOLJE TANK	10.64	14.70	0.00	3.24	12.23
31	AKTRE BRENNOLJE TANK	10.64	−14.70	0.00	3.24	12.23

SEPTIK (SpGr:1.000)

NO.	TANK	VEKT (t)	LCG(m)	TCG(m)	VCG(m)	VOL.(m^3)
40	SEPTIK	5.0	−1.74	3.21	2.73	5.0

ANDRE TANKER

NO.	TANK	VEKT (t)	LCG(m)	TCG(m)	VCG(m)	VOL.(m^3)
50	TERMOTANK	5.00	0,47	−5.85	3.30	5.00
51	SKUMTANK	5.00	1.41	−3.60	2.87	5.00
52	SMØREOLJE TRUSTERE	0.40	−1.30	5.85	3.70	0.45
53	HYDRAULIKKOLJE TRUSTERE	0.29	−1.30	5.75	2.85	0.32
54	SMØREOLJE GIR	0.29	−1.90	5.75	2.85	0.32
55	SMØREOLJE MOTORER	0.40	−1.90	5.85	3.70	0.45
56	HYDRAULIKK OLJE	0.55	1.60	−1.00	2.20	0.62
62	DREN/SLAMTANK	0.80	16.50	0.00	1.85	0.80
63	DREN/SLAMTANK	0.80	−16.50	0.00	1.85	0.80
64	LENSEVANNSTANK	0.75	17.10	0.00	1.90	0.75

Table 18: Tank capacities from the tank arrangement drawing for M/F Hidraferja (Dyrli 2014)

The engines will be replaced with less space requiring electric motors. But, the current layout with the thrusters placed on the centerline is rather unsuitable for the concept. In order to avoid interactions between the thruster and the cable, it should be installed an additional thruster at the cable entrance end. The hull would need rework such that the thrusters are installed symmetrically around the centerline with sufficient distance from the cable hull entrance, which would be on the centerline. By installing two thrusters on each end, the capacity of each thruster can be reduced, i.e. the capacity of the previous thrusters can be divided between two smaller thrusters and electric motors. This will increase the weight somewhat compared to the current system.

From figure 61, it can be seen that there is a pump room located at the midship, with several dry tanks around (which mission is to provide buoyancy for the ferry). And in figure 62 the tank arrangement can be seen, with the location of the fuel and lube oil tanks. For the concept implementation, the fuel tanks are removed along with the engine lube oil tanks. However, the thruster- and hydraulic lube oil tanks will remain, and possibly increase in size due to increased hydraulic capacity requirements for the concept. The hull below the main deck would need substantial rework in order to achieve implementation of the concept: the pump room needs to be relocated, and the machine rooms must be rearranged. Also, structural supports and foundations for the cable handling equipment, the pump, the electro motors and thrusters will have to be made.

10.2.1 Concept calculations for M/F Hidraferja

In that the breadth of the ferry hull is 13.70m, the drum spool can be somewhat large. It is assumed that it can have an outer diameter of 9m, giving a space of 2.35m on each side to allow inspections and passage. The route length is approximately 1.3km and the water depth is 81m. For simplicity, it can be assumed that an additional length of approximately 200m can be added on the cable, such that it can hang above the seabed and the ferry can have a reasonable drift range, thus giving a cable length of 1500m. Based on the previously derived formulas in chapter 7.2.5 for cable length, weight and drum spool size, the following has been found for the four cable dimensions given in table 5 (in chapter 7.1.8):

Cable diameter dc (m):		0,091	0,094	0,098	0,103
Cable lengths lc (m):					
1500	**Vc (m^3):**	9,76	10,41	11,31	12,50
	w0c (kg):	8300,28	9580,09	10902,69	13289,11

Table 19: Cable volume and weight for 1500m of the four cable dimensions

Drum spool dimensioning:						**Number of spools:**				
dc (m):	**dd (m):**	**Dd (m):**	**h (m):**	**Ad (m^2):**	**Vd (m^3):**	**xd (m):**	**s (dc#1):**	**s (dc#2):**	**s (dc#3):**	**s (dc#4):**
0,091	1,5	9	0,22	44,18	9,76	3,75	9,1	8,8	8,5	8,0
0,094	1,5	9	0,24	44,18	10,41	3,75	9,7	9,4	9,0	8,6
0,098	1,5	9	0,26	44,18	11,31	3,75	10,5	10,2	9,8	9,3
0,103	1,5	9	0,28	44,18	12,5	3,75	11,7	11,3	10,8	10,3

Table 20: Dimensions and number of coils for 1500m cable on a 9m diameter drum spool

It can be seen that if the drum spool diameter is 9m, the height varies between 0.22m and 0.28m. This is very low compared to the height of the deck, considering the engine heights. To have such a low drum spool has both advantages and disadvantages. The center of gravity is positioned low, but inspection of the cable is difficult. In addition, cooling the cable can be difficult, i.e. the heat must travel through more cable windings. The cooling issue may be solved by water cooling the drum spool discs and the column. By reducing the drum spool diameter and increasing the column height, better cooling and inspection abilities of the cable can be achieved. But the center of gravity will be somewhat higher. Below, results from drum spool diameters of 7m, 5m and 3m are presented.

Drum spool dimensioning:						Number of spools:				
dc (m):	dd (m):	Dd (m):	h (m):	Ad (m^2):	Vd (m^3):	xd (m):	s (dc#1):	s (dc#2):	s (dc#3):	s (dc#4):
0,091	1,5	7	0,41	23,76	9,76	2,75	12,4	12,0	11,5	11,0
0,094	1,5	7	0,44	23,76	10,41	2,75	13,2	12,8	12,3	11,7
0,098	1,5	7	0,48	23,76	11,31	2,75	14,4	13,9	13,4	12,7
0,103	1,5	7	0,53	23,76	12,5	2,75	15,9	15,4	14,8	14,0

Table 21: Dimensions and number of coils for 1500m cable on a 7m diameter drum spool

Drum spool dimensioning:						Number of spools:				
dc (m):	dd (m):	Dd (m):	h (m):	Ad (m^2):	Vd (m^3):	xd (m):	s (dc#1):	s (dc#2):	s (dc#3):	s (dc#4):
0,091	1,5	5	1,01	9,62	9,76	1,75	19,5	18,9	18,1	17,2
0,094	1,5	5	1,08	9,62	10,41	1,75	20,8	20,1	19,3	18,4
0,098	1,5	5	1,18	9,62	11,31	1,75	22,6	21,9	21,0	20,0
0,103	1,5	5	1,30	9,62	12,5	1,75	25,0	24,2	23,2	22,1

Table 22: Dimensions and number of coils for 1500m cable on a 5m diameter drum spool

Drum spool dimensioning:						Number of spools:				
dc (m):	dd (m):	Dd (m):	h (m):	Ad (m^2):	Vd (m^3):	xd (m):	s (dc#1):	s (dc#2):	s (dc#3):	s (dc#4):
0,091	1,5	3	5,52	1,77	9,76	0,75	45,5	44,1	42,3	40,2
0,094	1,5	3	5,89	1,77	10,41	0,75	48,6	47,0	45,1	42,9
0,098	1,5	3	6,40	1,77	11,31	0,75	52,7	51,1	49,0	46,6
0,103	1,5	3	7,07	1,77	12,5	0,75	58,3	56,4	54,1	51,5

Table 23: Dimensions and number of coils for 1500m cable on a 3m diameter drum spool

The 7m diameter drum spool has still a rather low column, i.e. between 0.41m and 0.53m. For heat transfer, the 5m diameter drum spool is better. But still, the cooling could be better. By further reducing the diameter to 3m, it is seen that the column height exceeds 5m which will give issues with the deck height. Therefore, dimensions for a 4m diameter drum spool are calculated below.

Drum spool dimensioning:						**Number of spools:**				
dc (m):	**dd (m):**	**Dd (m):**	**h (m):**	**Ad (m^2):**	**Vd (m^3):**	**xd (m):**	**s (dc#1):**	**s (dc#2):**	**s (dc#3):**	**s (dc#4):**
0,091	1,5	4	1,99	4,91	9,76	1,25	27,3	26,4	25,4	24,1
0,094	1,5	4	2,12	4,91	10,41	1,25	29,1	28,2	27,0	25,7
0,098	1,5	4	2,30	4,91	11,31	1,25	31,6	30,6	29,4	28,0
0,103	1,5	4	2,55	4,91	12,5	1,25	35,0	33,9	32,5	30,9

Table 24: Dimensions and number of coils for 1500m cable on a 3m diameter drum spool

These results are more reasonable with a column height ranging between 1.99m and 2.55m. This gives relatively good inspection abilities and cooling, and issues with deck height are regarded as non-problematic.

The M/F Hidraferja has two 1740kg engines and a fuel capacity of total 21.28tonnes as seen the tank capacity table, i.e. table 18. The engines and the fuel tanks are removed enabling 23.02tonnes for the concept. For simplicity, it can be assumed that the thrusters and electric motors combined weigh the same as the engines, i.e. 2*1740kg, giving that the remaining weight available for the concept equipment comes from the removal of the fuel tanks. However, this assumption is not accurate as the combined weight of the motors and thrusters will exceed the engine weights, even though the thruster sizes are reduced.

Table 19 displays the cable weight and volume for the concept. But since the cable handling equipment must be somewhat custom engineered, their weight and dimension contributions for the concept are unknown. However, based on the tension calculations for 1500m cable length with a hanging depth of 70m (see the results in table 25), it can be assumed that the 8tonnes linear cable engine (LCE) seen in figure 31 and table 10 (chapter 7.2.1) can be utilized. This can be assumed since the highest cable tension calculated for the 1500m cable length is approximately 3.7tonnes (converted from 36319.01N using Newton's second law). Though the lighter 4tonnes linear cable engine could be used here, it is considered insufficient because of the additional tensions disregarded in the calculations, for instance from towing forces and environmental forces.

Cable depth zm:	-70 m					
Cable weight (kg/m):			5,53352	6,38673	7,26846	8,85940
	Cable length:					
	1500 m	**z end (m):**	-0,00001	-0,00076	0,00049	-0,00031
		H (N):	22297,16	25735,40	29287,85	35698,86
		T (N):	22684,51	26182,47	29796,64	36319,01

Table 25: Cable tensions for 1500m length

So, with the cable and the tensioner the concept weight has reached approximately 20.5tonnes for the smallest cable and 25.5tonnes for the largest cable. The total concept weight will further increase as of the retraction unit, the guidance system and guider arm. In addition, the concept will take more space than the engines and fuel tanks, thus reducing the void space. The buoyancy of the ferry will thus be somewhat reduced because of the additional weight and void space reduction.

10.2.2 Applicability for the M/F Hidraferja

The applicability of the concept for the M/F Hidraferja can be discussed as the space available onboard is considered sufficient, based on the tank arrangement drawing and the general arrangement drawing. However, the concept weight will be somewhat larger than the current power solution. This will affect the payload capacity of the ferry in terms of the number of vehicles and passengers it can carry. In addition, the costs of implementing the concept should be considered for the applicability. This means the costs are related to engineering of hull rework, engineering of the cable and cable handling equipment, costs of the hull rework and equipment installation, and the purchase costs of the cable handling equipment as well as the cable. The costs should be compared to alternative power solutions (such as LNG, LNG hybrids and battery packs) and future emission regulations.

There is however planned a ferry free crossing of the Hidra strait between the island Hidra and the main land. The solution planned is an underwater tunnel (Vegvesen 2013), but a submerged pipe bridge is also considered (Løvland 2013). This plan of a ferry free crossing, gives that implementation of the concept onboard the M/F Hidraferja is considered inapplicable. This because the ferry will be taken out of service when the tunnel or bridge is finished, and that the engineering and development of the concept is assumed to take a few years. The concept would thus have somewhat little lifetime for operation on this route.

11 Discussion

By bringing the concept to life, there are several parameters and points that need to be considered and assessed. Four power transfer configurations have been looked upon, these are air stretched cables, surface floating towed cable, submerged towed cable and bottom laid cable. For the three water power transfer configurations (bottom, submerged and surface floating), cable handling equipment are required, such as a storage unit, a retractor, a tensioner and a guidance systems. And for the air stretched power transfer configuration, a power recovery system is needed. Here, a trolley arm system similar to what trolley buses have is considered. The trolley arms will provide upward pressure onto the cable to ensure conductor contact. Either power transfer configuration requires electrical transformers, both on shore and onboard, such that the power from the land grid can be delivered to the ferry and transformed to low voltage for onboard consumers.

The four configurations assessed all have limitations. For instance, the air stretched configuration will limit the ferry's ability to drift. The ferry is limited to operate in a relatively narrow street, due to the trolley arms' length and the tight cable stretch. It will be required three air stretched cables because of the three phase power requirement on board the ferry. This gives that there must be three trolley arms.

The cables would need to be engineered with regards to strength and weight, since the tension they may experience is assumed to be larger than what the cable weight itself will give, e.g. tension from ferry drifting. This may result in high cable costs in terms of engineering and material. Further, there is a risk that the connection between the trolley arms and the cables may experience disconnection due to environmental effects, e.g. from waves or current which may force the ferry into a heave motion or to drift out of the transit street. If a trolley arm is disconnected, the ferry will experience a blackout situation. Therefore, the trolley arm connection system would have to be custom engineered. In addition, if the cable gets fractured for instance due to high tensions from ferry drifting, there is a risk of short circuits and electrification of the trolley arms and the ferry itself. The air stretched configuration is thus regarded as less feasible due to these risks.

For onboard storage of the three water power transfer configurations, there are limitations onboard the ferry in terms of space and weight. For a new build it is simpler to implement the concept as the hull can be designed around the different equipment, i.e. their locations can be optimized with regards to weight and stability calculations. But for a conversion, the concept components must replace previous equipment such as diesel engines and generators, fuel and lube oil tanks, etc., and be located in their absence, i.e. they must exploit the enabled space and available voids. New weight and stability calculations are required as the equipment components' weights and sizes may affect the stability of the ferry and its payload. It is preferred that the components are located such that the center of gravity is as close to initial as possible, or in a new build low at the midship and centerline. In addition, it is important to understand that for stability calculations, the center of gravity will shift during the transit as the cable is spooled in and fed out. This gives requirements to the ballast system such that the ferry remains stable during the whole transit. The drum spool is the heaviest concept component when it is fully loaded, but it may be lighter than other equipment components when the cable is fed out. Since none of the cable handling equipment are implemented onboard when the land based storage configuration is chosen, stability will have to be restored by the use of ballast and perhaps increased payload (given that the engines and tanks are removed and a lighter emergency power sources is implemented – perhaps battery packs).

For onboard storage, it is required a management software system for coordinating the cable handling systems and thus handling the cable. The cable is constantly deployed and retracted, and affected by tension from its own weight, towing- and environmental forces. So, the management system must coordinate the cable handling system such that the cable is spooled in and out according to the transit speed and the tensions applied. Such a system should also be the case for storage on shore, but this will give some changes to the specifications, e.g. signals with ferry behavior information must be sent to the control system on shore such that the cable handling equipment are managed and adjusted accordingly.

When it comes to designing and engineering the cable handling equipment, there are some challenges that need to be taken into consideration. Current technology may have trouble reaching the desired requirements in terms of cable tension, cable handling speed, and component weight and size. So manufacturers would therefore need to design and engineer the cable handling equipment according to the route and ferry specifications, i.e. with focus on cable dimension, ferry operational speed and the applied cable tension. This gives indications to the capacity of the hydraulic system which powers the cable handling equipment.

The floating cable configuration will give the shortest cable, but it will be the heaviest and thickest. This is because of the substantial amount of armor required to cope with the tension from sudden jerks (i.e. the ferry can be forced back and forth due to environmental forces, especially during a blackout situation), from towing forces and from ferry drift. And the cable will be thick since it will require a large floating cap in order to float the heavy weight from the armor and the conductors. This is the least manageable power transfer configuration since it requires larger storage space and larger cable handling equipment. The cable handling equipment will increase in weight and size because of the cable dimension and the tension, and larger weight and space requirements give reduction in the ferry's payload, i.e. the number of vehicles and passengers the ferry can transport.

The bottom configuration will result in the longest cable since the cable will follow the sea bottom and its contours. The cable will have the thickest conductor diameters in order to provide sufficient amount of power to the ferry, but the armor requirements are very low compared to the floating configuration, giving less outer diameter and weight per meter. Therefore it is assumed that the cable costs are less. However, in order to ensure that cable damage is avoided, the seabed may require straitening, i.e. rocks, sharp edges and cliffs must be straightened such that if the ferry drifts and drags the cable, the cable will not get fractured or damaged by such. Straitening can be conducted by blasting and mass filling (e.g. crushed rocks and gravel). The cost of straitening the seabed is estimated from bottom formation and contours, and water depth, and is assumed to be very expensive compared to the cable costs.

For the submerged configuration, the cable outer diameter will be somewhat thicker than the bottom configuration since it requires more armor, but the conductor diameter will be less since the length is shorter. Since the cable is shorter, the ferry drift abilities will be less, resulting in higher requirements to the armor. It is however assumed that the cable weight per meter is approximately in the same range as the bottom configuration, but the cable cost is assumed to be somewhat higher because of the additional armor. The submerged towing cable configuration is assumed to be the most feasible transfer solution as the ferry will have reasonable ability to drift, the cable dimensions and weight are assumed to be relatively low, and the cable tension is less than for the floating configuration. In addition, there is less risk of cable damage due to bottom formation and crossing traffic interactions.

It has been derived two forms of cable tension calculations, i.e. towing calculations and mooring calculations. It was assumed that mooring calculations where applicable for the bottom configuration and that towing calculations where applicable for the other three configurations. However, the use of towing calculations for the floating configuration is considered rather conservative in that the cable floats and doesn't hang in a curve formation. Therefore it is rather difficult to estimate the cable strength with towing calculations. For the air stretched configuration however, the cable strength will depend on different considerations than the submerged towing configuration (i.e. the cable hangs in the air and tension is vertically dominant), and thus the formulas would need adaption in order to apply.

For the bottom configuration, there are several similarities with offshore cable laying operations. Spooling in and out could therefore be seen as a cable laying operation, either S-lay or J-lay. Dynamic mooring calculations can be used for this "laying operation" and conducted using designated software like RIFLEX. However, due to the limiting timeframe, dedicated software has not been applied for cable strength calculations. A simplification has been made and the derived formulas presented are static catenary equations. In addition, it has been assumed that the cable will experience some drag forces due to spooling in and out according to operational transit speed. Therefore, Morison's equation has been derived in order to estimate additional horizontal tension.

The derived towing calculation formulas are also static, due to the limiting timeframe. However, there will be dynamic effects on the cable form waves, current and from the ferry's operational speed and motions. Effects from propeller race should also be taken into account. With dedicated software, the strength calculations would be more accurate. However, the iterated static towing calculations performed for the submerged cable configuration, gives a good estimate on the cable armor requirements.

The drum spool sizes calculated are based on the cable dimensions used in the towing calculations. They are not accurate since the actual cable dimensions, with armor and conductor diameter according to route length and power requirements is unknown. The cable will have to be custom engineered. But the calculations give good indications on size and weight.

As for the dimensioning of the cable handling equipment, i.e. the retractor unit and tensioner, they must be custom designed and engineered with focus on low weight and size, with high tension and handling speed capacities. Current available cable handling equipment used on offshore cable laying vessels are capable of reaching the concept ferry's desired operational speed of around 10knots. However, their sizes and weights are regarded as high, which will result in reductions of ferry payload. In addition, their tension capacities are currently low compared to the heaviest cable weight and strength calculations conducted for the concept. Design and engineering of retractor units and tensioners should therefore focus on low weights and sizes, as well as high tension and operational speed capacities.

It has also been looked upon competing power sources such as diesel- and LNG-gensets, hybrids, and battery packs. Technology within these are constantly developing towards better efficiencies and future emission regulations, as the world society's focus on the environment and global warming is increased. Size, weight and costs have been assessed compared to the cable ferry concept components. Among others, the power demand onboard and the route length determines the power source sizes, weights and costs. With today's cable handling equipment and cable technology, the sizes and weights are larger than competing power sources, such as for instance gensets. Further, the cable composition will vary depending on the route and the strength requirements, and the cable will be the most expensive component in the concept. The total costs of the concept solution have been found to exceed competing technology, e.g. LNG-gensets, in purchase, but current electricity and LNG prices have been found to be comparable. As for operational costs, except from fuel costs, regular maintenance must be performed. For gensets the most expensive maintenance cost is overhauling the engines where pistons, bearings and seals are replaced. For the concept, the cable will be exposed for fatigue since it is constantly spooled in and out. After a given operational period, the cable will therefore have to be replaced. As the cable is found to be more expensive than a new genset, the concept is regarded economically infeasible with today’s technology. However, physically the concept can be feasible, given that the required specifications of the cable handling equipment are met, i.e. in terms of weight, size, and tension and operational speed capacities.

Lastly, it has been conducted a case study for the M/F Hidraferja and the route between Kvellandstrand and Launes. It has been performed static towing calculations according to the route length for a set of given cable dimensions, and drum spool dimensions for these. Based on the ferry’s specifications, there is sufficient space available for concept implementation onboard, but the concept weight will somewhat exceed the initial power source, i.e. the engines and fuel tanks. The buoyancy of the ferry will be reduced as a consequence of concept implementation, due to the additional weight and reduced dry tank volume (i.e. the void spaces). This will result in reduced payload for the ferry.

12 Conclusion

Of the four cable transfer configurations assessed in the thesis, the submerged towing configuration and the bottom configuration are the most physically feasible solutions. These solutions give the least cable tension and weights, as well as the good ferry drift abilities. However, the bottom configuration is more expensive due to seabed straitening and cable handling equipment specifications. The equipment will have larger operational speed in order to handle more cable in the same time frame, such that cable damages from bottom friction and propeller interactions are prevented. Even though the cable costs are assumed to be higher in terms of armor requirements for the submerged towing configuration, it is assumed to be more economical than the bottom configuration.

Further, the cable handling equipment and the storage unit can either be situated onboard the ferry or on shore. Storage on shore requires that signals of ferry behavior are sent to the on shore management system such that the cable is handled accordingly, resulting in a somewhat more expensive cable. With current cable handling equipment technologies, their sizes and weights will exceed available competing power sources, such as diesel- and LNG-gensets with fuel tanks, hybrids and battery packs. So for onboard storage in a conversion, the equipment will replace these with somewhat larger space requirements and weight (depending on route length and power requirement). As the weights and sizes are larger than for competing power solutions, the ferry's buoyancy and void space is reduced, thus affecting the stability. This gives reduction in payload, i.e. the number of vehicles and passengers the ferry can transport. The component locations should therefore be optimized such that the stability is as close to initial as possible. With a new build, the ferry can be designed around the components such that given stability and payload requirements are met. This may however result in increased ferry size. The construction of a new build is planned in detail, where the structures and foundations supporting the components are implemented under construction. For a conversion, fuel tanks and gensets will have to be removed, and the hull would need substantial rework with new construction of hull structure and foundations. In addition, installation of the components would require space, provided by cutouts in the hull or in worst case separation of the superstructure from the hull.

Current cable handling equipment used on offshore cable laying vessels have sufficient tension handling capacities, but their low operational speed, and large weights and sizes makes them rather insufficient for the concept. Therefore, development of the equipment technologies is needed, with focus on reducing the weight and size, as well as increasing the operational speed and tension capacities.

In addition, the cable will have to be custom designed and engineered, in terms of low weight and high strength, simultaneously with good conductivity. It is also important that fatigue is taken into consideration to ensure high operational life time of the cable. The cable must as well have durable outer coating, i.e. jacket, to ensure that the risks of damages are reduced. Damages may come from for instance bottom friction and interactions with the seabed formations. Further research in cable technology and composition is needed. The cable must be designed and engineered with basis on strength calculations. The strength calculations derived in this thesis are considered insufficient and not accurate as they are static and don’t take all acting forces into account. Dedicated software where dynamic loads, forces and operational details can be implemented is required to get more accurate results.

Physically, the concept may be feasible given that the cable handling equipment and cable technologies are developed to fit the requirements, i.e. weight, size, tension and handling speed. But with today’s technology, the concept is unpractical in terms of reaching the requirements. In an economically view, the concept is more expensive than a genset solution, where the cable is the most expensive component, i.e. the cable cost exceeds the cost of a genset. As for operational costs, industrial electricity prices are somewhat comparable with current LNG prices. For maintenance, the largest costs for gensets are major overhauling where pistons, bearings and seals are replaced. For the concept, maintenance costs of the cable handling equipment are relative cheap, but the cable itself will only have so long operational lifetime due to fatigue. As the cable is constantly spooled in and out, it would need to be replaced within a certain amount of time. So currently, with today’s competing power source solutions, the concept is found not to be economically feasible. However, in the future, emission regulations may give the concept an opportunity.

13 Suggestions for further work

As the cable strength calculations are static and not very accurate, there should be conducted dynamic calculations with dedicated software where environmental conditions and affecting forces can be implemented. The cable composition should be optimized and engineered with focus on low weight and dimension, and high strength, as well as high conductivity. For cable handling equipment, such as tensioner and retractor units, the technology should be developed in terms of reduction in weight and size, while the operational tension and handling speed is increased. Further, the concept components locations onboard the ferry should be optimized, and stability calculations should be conducted in accordance with their locations, sizes and weights. In addition, the hull structure and foundations will have to be engineered in order to cope with the weights and tensions applied from the concept.

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Appendix

A. Overview of Norwegian ferry routes along the coast

Østfold County

Skjærshalden - Hvalerøyene

Vestfold County

Svelvik - Verket i Hurum
Horten - Moss
Brevik - Sandøya - Bjørkøya
Kragerø - Stabbestad
Kragerø - Tåtøy
Kragerø - Skåtøyroa
Kragerø - Bærø - Langøy
Kragerø - Jomfruland

The Agder Counties

Launes/Hitra - Kvellandstrand
Abelnes - Andabeløy

Rogaland County

Fogn - Judaberg - Nedstrand - Jelsa
Hjelmeland - Nesvik - Ombo
Mekjarvik - Kvitsøy
Oanes - Lavvik
Sand - Ropeid
Stavanger - Tau
Mortavika - Arsvågen

Hordaland County

Fedje - Sævrøy
Fjeldberg - Sydnes - Utbjoa - Skjersholmane
Gjermundshamn - Nordhuglo - Hodnanes
Jondal - Tørvikbugd
Kinsarvik - Utne - Kvanndal
Langevåg - Buavåg
Leirvåg - Sløvåg - Skipavik
Skersholmane - Ranavik
Skånevik - Matre - Utåker
Husavik - Sandvikvåg
Halhjem - Sandvikvåg
Våge - Halhjem
Venjaneset - Hatvik
Hufthammar - Krokeide

Klokkarvik - Hjellestad
Valestrand - Breistein
Duesund - Masfjordnes

Sogn and Fjordane County

Fodnes - Mannheller
Kaupanger - Frønningen
Hella - Vangsnes - Dragsvik
Ortnevik - Måren - Nordeide
Lavik - Oppedal
Rysjedalsvika - Rutteland - Krakkhella
Daløy - Haldorsneset
Askvoll - Gervik - Fure
Askvoll - Værlandet
Oldervik - Måløy
Stårheim - Isane
Lota - Anda
Solvorn - Ornes
Barmsund - Barmen

Møre and Romsdal County

Folkestad - Volda
Volda - Lauvstad
Larsnes - Åram - Voksa - Kvamsøya
Årvika - Koparneset
Hareid- Sulesund
Skjeltene - Lepsøya - Haramsøy
Eidsdal - Linge
Stranda - Liabygda
Lekneset - Sæbø - Trandal- Standal
Festøya - Solavågen
Hundeidvika - Festøya
Sykkylven - Magerholm
Brattvåg - Dryna - Fjørtofta - Harøya
Molde - Sekken
Molde - Vestnes
Åfarsnes - Selsnes
Aukra - Hollingsholmen
Småge - Orta - Sandøya - Finnøya - Ona
Solhomlen - Mordalsvågen
Kvanne - Rykjem
Halsa - Kanestraum
Seivika - Tømmervåg
Arasvika - Henneset
Edøya - Sandvika

The Trøndelag Counties

- Flakk - Rørvik
- Dyrøy (Setra) - Mausund - Sula
- Garten - Storfosna - Leksa - Værnes
- Vakset - Brekstad
- Levanger - Ytterøy (Hokstad)
- Dypfest - Tarva
- Seierstad - Ølhammaren
- Hofles - Geisnes - Lund
- Skei (Leka) - Gutvik
- Borgann - Ramstadlandet

Nordland County

- Vennesund - Holm
- Horn - Andalsvåg
- Horn - Ingerøy (Vega) - Tjøtta
- Brønnøysund (Hestøya) - Suaren
- Tjøtta - Forvik
- Mosjøen - Hundåla - Sund - Dagsvik
- Søvik - Austbø - Herøy - Brasøy
- Sandesjøen - Bjørn (Dønna) - Løkta
- Solfjellsjøen - Vandre
- Nesna - Nesnaøyene
- Stokkvågen - Træna
- Leirvik - Hemnesberget
- Kilboghamn - Jektvik
- Rødøy - Rødøyene
- Forøy - Ågskardet
- Ørnes - Vassdalsvik - Meløysund - Bolga - Støtt
- Sund - Horsdal - Sørarnøy
- Bodø - Værøy - Røst - Moskenes
- Festvåg - Misten
- Svolvær - Skutvik via Skrova
- Drag - Kjøpsvik
- Bognes - Skarberget
- Bognes - Lødingen
- Digermulen - Finnvik
- Hanøy - Kaljord
- Fiskebøl - Melbu
- Andenes - Gryllefjord

Troms County

- Stangnes - Sørrollnes
- Stornes - Bjørnerå
- Grøytøy - Sandsøy - Bjarkøy
- Refsnes - Flesnes

Stornes - Skrolsvik sommer
Brensholmen - Botnhamn sommer
Belsvik - Vengsøy
Lyngseidet - Olderdalen
Svensby - Breivikedet
Mikkelvik - Bromnes
Hansnes - Karlsøy - Vannøy
Rotsund - Havnnes - Uløybukt
Storstein - Nikkelby - Lauksundskaret
Hansnes - Reinsøy

Finnmark County

Øksfjord - Bersfjord - Sør-Tverrfjord
Hasvik - Øksfjord
Øksfjord - Tverrfjord
Korsfjorden - Nyvoll
Akkarfjord - Kjerringholmen
Havøysund - Måsøy - Rolvsøy - Ingøy - Hammerfest - Honningsvåg

B. Emergency power services Table C1 DNV

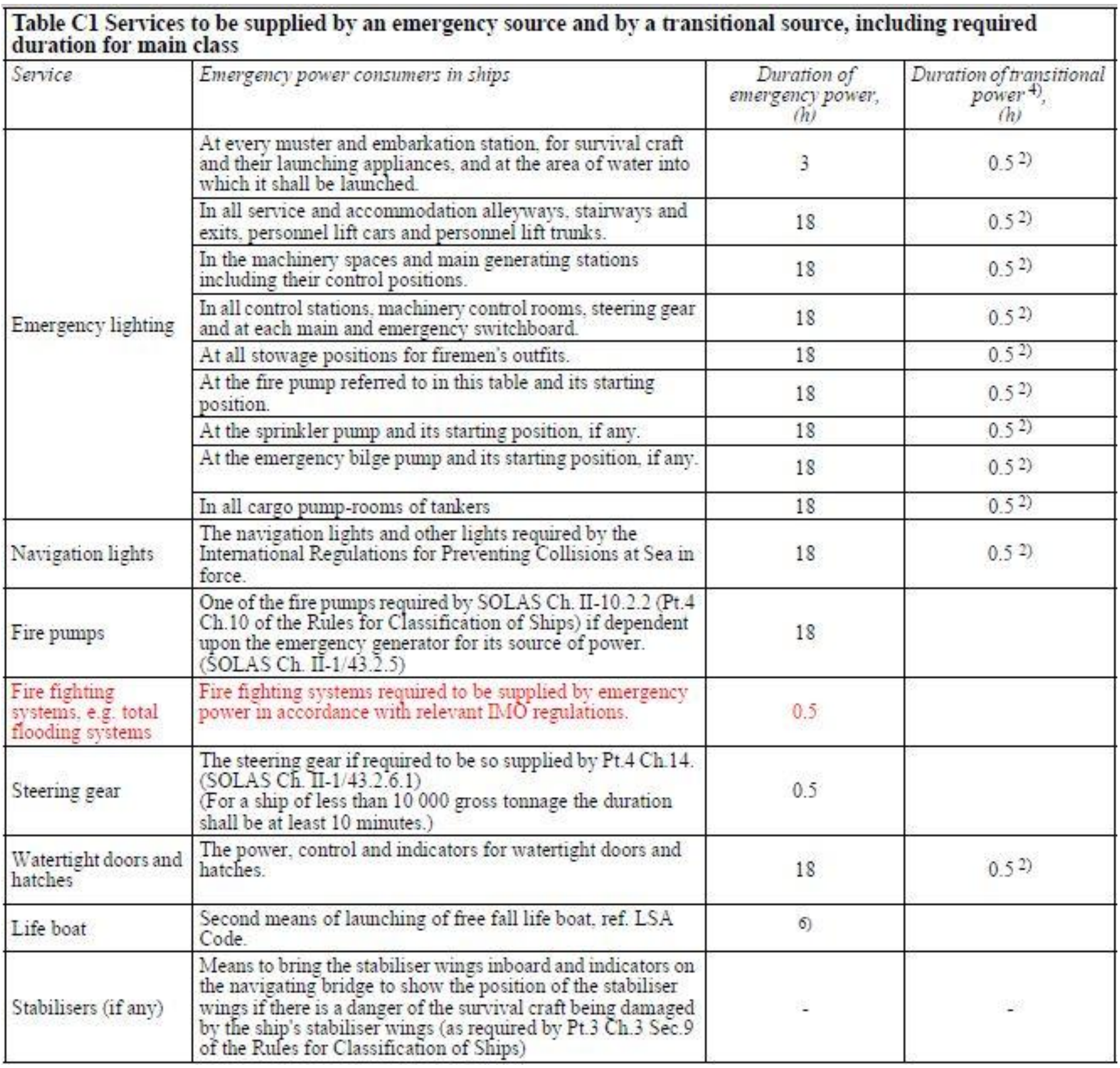

Table C1 Services to be supplied by an emergency source and by a transitional source, including required duration for main class

Service	*Emergency power consumers in ships*	*Duration of emergency power, (h)*	*Duration of transitional power [4], (h)*
Emergency lighting	At every muster and embarkation station, for survival craft and their launching appliances, and at the area of water into which it shall be launched.	3	0.5 [2]
	In all service and accommodation alleyways, stairways and exits, personnel lift cars and personnel lift trunks.	18	0.5 [2]
	In the machinery spaces and main generating stations including their control positions.	18	0.5 [2]
	In all control stations, machinery control rooms, steering gear and at each main and emergency switchboard.	18	0.5 [2]
	At all stowage positions for firemen's outfits.	18	0.5 [2]
	At the fire pump referred to in this table and its starting position.	18	0.5 [2]
	At the sprinkler pump and its starting position, if any.	18	0.5 [2]
	At the emergency bilge pump and its starting position, if any.	18	0.5 [2]
	In all cargo pump-rooms of tankers	18	0.5 [2]
Navigation lights	The navigation lights and other lights required by the International Regulations for Preventing Collisions at Sea in force.	18	0.5 [2]
Fire pumps	One of the fire pumps required by SOLAS Ch. II-10.2.2 (Pt.4 Ch.10 of the Rules for Classification of Ships) if dependent upon the emergency generator for its source of power. (SOLAS Ch. II-1/43.2.5)	18	
Fire fighting systems, e.g. total flooding systems	Fire fighting systems required to be supplied by emergency power in accordance with relevant IMO regulations.	0.5	
Steering gear	The steering gear if required to be so supplied by Pt.4 Ch.14. (SOLAS Ch. II-1/43.2.6.1) (For a ship of less than 10 000 gross tonnage the duration shall be at least 10 minutes.)	0.5	
Watertight doors and hatches	The power, control and indicators for watertight doors and hatches.	18	0.5 [2]
Life boat	Second means of launching of free fall life boat, ref. LSA Code.	[6]	
Stabilisers (if any)	Means to bring the stabiliser wings inboard and indicators on the navigating bridge to show the position of the stabiliser wings if there is a danger of the survival craft being damaged by the ship's stabiliser wings (as required by Pt.3 Ch.3 Sec.9 of the Rules for Classification of Ships)	-	-

Table 26: DNV's Table C1 – part 1 (DNV 2013)

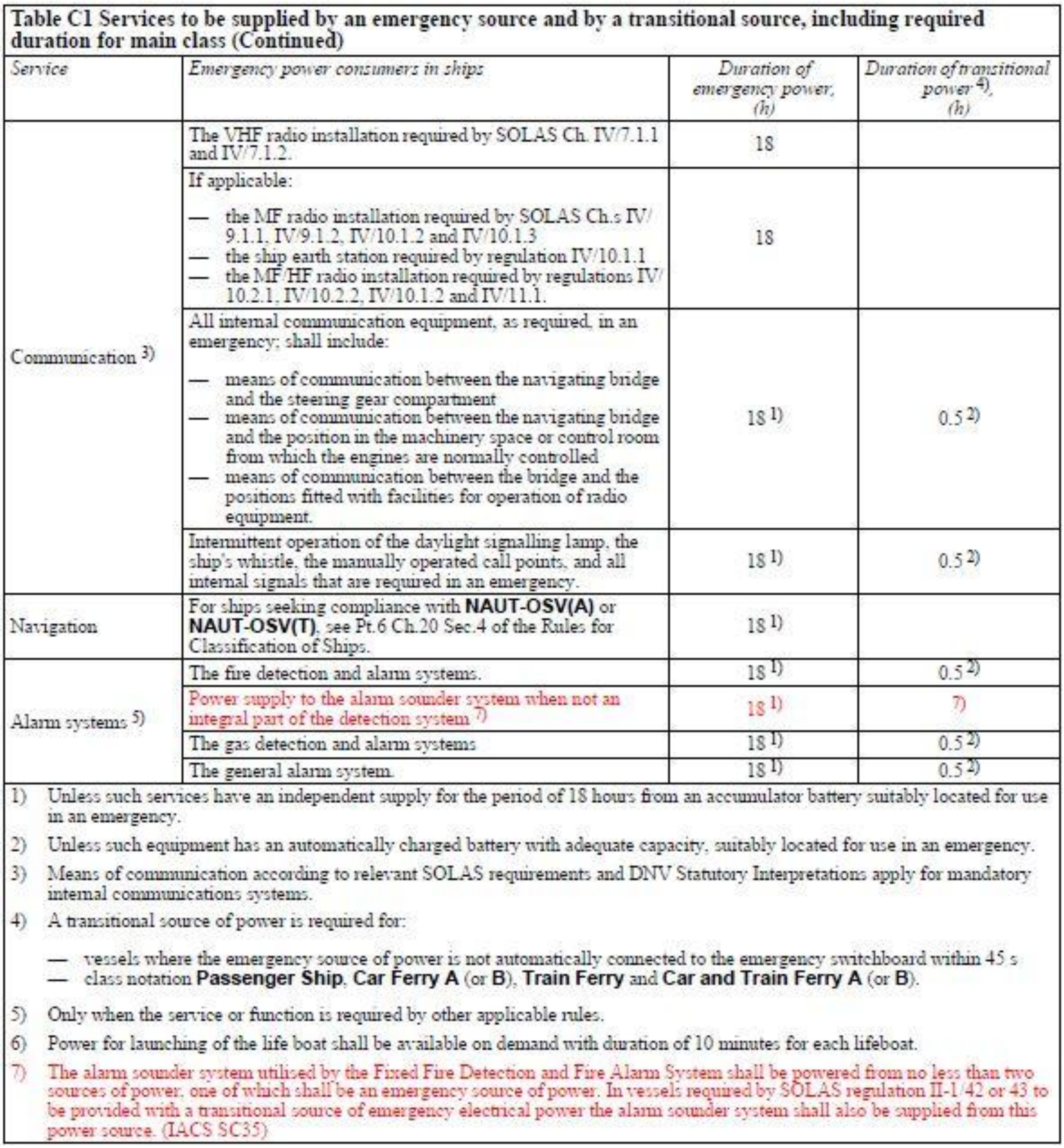

Table C1 Services to be supplied by an emergency source and by a transitional source, including required duration for main class (Continued)

Service	*Emergency power consumers in ships*	*Duration of emergency power, (h)*	*Duration of transitional power 4), (h)*
Communication 3)	The VHF radio installation required by SOLAS Ch. IV/7.1.1 and IV/7.1.2.	18	
	If applicable: — the MF radio installation required by SOLAS Ch.s IV/ 9.1.1, IV/9.1.2, IV/10.1.2 and IV/10.1.3 — the ship earth station required by regulation IV/10.1.1 — the MF/HF radio installation required by regulations IV/ 10.2.1, IV/10.2.2, IV/10.1.2 and IV/11.1.	18	
	All internal communication equipment, as required, in an emergency; shall include: — means of communication between the navigating bridge and the steering gear compartment — means of communication between the navigating bridge and the position in the machinery space or control room from which the engines are normally controlled — means of communication between the bridge and the positions fitted with facilities for operation of radio equipment.	18 1)	0.5 2)
	Intermittent operation of the daylight signalling lamp, the ship's whistle, the manually operated call points, and all internal signals that are required in an emergency.	18 1)	0.5 2)
Navigation	For ships seeking compliance with **NAUT-OSV(A)** or **NAUT-OSV(T)**, see Pt.6 Ch.20 Sec.4 of the Rules for Classification of Ships.	18 1)	
Alarm systems 5)	The fire detection and alarm systems.	18 1)	0.5 2)
	Power supply to the alarm sounder system when not an integral part of the detection system 7)	18 1)	7)
	The gas detection and alarm systems	18 1)	0.5 2)
	The general alarm system.	18 1)	0.5 2)

1) Unless such services have an independent supply for the period of 18 hours from an accumulator battery suitably located for use in an emergency.

2) Unless such equipment has an automatically charged battery with adequate capacity, suitably located for use in an emergency.

3) Means of communication according to relevant SOLAS requirements and DNV Statutory Interpretations apply for mandatory internal communications systems.

4) A transitional source of power is required for:

- vessels where the emergency source of power is not automatically connected to the emergency switchboard within 45 s
- class notation **Passenger Ship**, **Car Ferry A** (or **B**), **Train Ferry** and **Car and Train Ferry A** (or **B**).

5) Only when the service or function is required by other applicable rules.

6) Power for launching of the life boat shall be available on demand with duration of 10 minutes for each lifeboat.

7) The alarm sounder system utilised by the Fixed Fire Detection and Fire Alarm System shall be powered from no less than two sources of power, one of which shall be an emergency source of power. In vessels required by SOLAS regulation II-1/42 or 43 to be provided with a transitional source of emergency electrical power the alarm sounder system shall also be supplied from this power source. (IACS SC35)

Table 27: DNV's Table C1 – part 2 (DNV 2013)

Red text represents DNV's latest changes to the table in the revised rule set from July 2013.

C. Cable strength calculations

XLPE 24kV Cable alternatives:			**Cable submerged weights:**			**Cable lengths x:**		**Cable depth zm:**	
A (mm2):	d (m):	w (kg/m):				1500	m	-40	m
120	0,091	12,2	ρsw=	1025	kg/m3	2000	m	-50	m
150	0,094	13,5				2500	m	-60	m
185	0,098	15	w0=	5,5335208	kg/m	3000	m	-70	m
240	0,103	17,4		6,3867274	kg/m	3500	m		
				7,2684619	kg/m	4000	m		
				8,8594037	kg/m	4500	m		
						5000	m		
						5500	m		
						6000	m		

Table 28: Cable parameters for cable strenght calculations

Cable depth zm:	-40 m					
Cable weight (kg/m):			5,53352	6,38673	7,26846	8,85940
	Cable lengths:					
	1500 m	**z end (m):**	0,00000	0,00004	0,00005	0,00023
		H (N):	38944,40	44949,15	51154,70	62351,29
		T (N):	39165,74	45204,62	51445,44	62705,67
	2000 m	**z end (m):**	0,00001	0,00004	0,00004	0,00023
		H (N):	69205,85	79876,56	90904,09	110800,92
		T (N):	69500,76	80207,49	91336,14	110800,92
	2500 m	**z end (m):**	0,00007	0,00007	0,00000	0,00017
		H (N):	108113,25	124783,09	142010,57	173093,51
		T (N):	108334,59	125038,56	142301,31	173447,89
	3000 m	**z end (m):**	0,00009	0,00001	0,00022	0,00009
		H (N):	155666,78	179669,23	204472,78	249229,20
		T (N):	155888,12	179924,70	204763,52	249583,58
	3500 m	**z end (m):**	0,00060	0,00006	0,00082	0,00009
		H (N):	211863,81	244534,12	278288,56	339207,33
		T (N):	212085,16	244789,59	278579,31	339561,71
	4000 m	**z end (m):**	0,00082	0,00002	0,00017	0,00001
		H (N):	276707,27	319378,78	363469,98	443029,17
		T (N):	276928,62	319634,25	363760,72	443383,55
	4500 m	**z end (m):**	0,00010	0,00007	0,00000	0,00017
		H (N):	350204,15	466513,06	604206,00	897632,36
		T (N):	350425,49	466734,40	604427,34	897853,70
	5000 m	**z end (m):**	0,00000	0,00004	0,00004	0,00023
		H (N):	432343,16	499005,21	567896,41	692195,99
		T (N):	432564,50	499260,68	568187,15	692550,37
	5500 m	**z end (m):**	0,00015	0,00004	0,00004	0,00023
		H (N):	523125,61	603787,37	687144,49	837544,75
		T (N):	523346,96	604042,84	687435,22	837899,13
	6000 m	**z end (m):**	0,00007	0,00004	0,00004	0,00023
		H (N):	622556,91	718548,77	817749,52	996736,25
		T (N):	622778,25	718804,24	818040,26	997090,63

Table 29: Cable tension for 40m depth

Cable depth zm:	-50 m					
Cable weight (kg/m):			5,53352	6,38673	7,26846	8,85940
	Cable lengths:					
	1500 m	**z end (m):**	0,00001	-0,00013	0,00001	0,00002
		H (N):	31172,05	35978,53	40945,52	49907,78
		T (N):	31448,73	36297,87	41308,94	50350,75
	2000 m	**z end (m):**	0,00001	-0,00013	0,00001	0,00002
		H (N):	55381,25	63920,59	72745,10	88667,73
		T (N):	55657,92	64239,93	73108,52	89110,70
	2500 m	**z end (m):**	0,00001	-0,00013	0,00000	0,00002
		H (N):	86507,31	99846,05	113630,22	138501,89
		T (N):	86783,99	100165,39	113993,64	138944,86
	3000 m	**z end (m):**	0,00001	-0,00013	0,00001	0,00002
		H (N):	124550,27	143754,93	163600,91	199410,29
		T (N):	124826,95	144074,26	163964,33	199853,26
	3500 m	**z end (m):**	0,00001	-0,00013	0,00001	0,00002
		H (N):	169510,12	195647,23	222657,16	271392,92
		T (N):	169786,80	195966,57	223020,58	271835,89
	4000 m	**z end (m):**	0,00001	-0,00013	0,00001	0,00002
		H (N):	221386,87	255522,96	290798,99	354449,81
		T (N):	221663,55	255842,30	291162,41	354892,78
	4500 m	**z end (m):**	0,00001	0,00003	0,00028	0,00030
		H (N):	280180,52	373227,52	483378,74	718121,23
		T (N):	280457,20	373504,20	483655,41	718397,91
	5000 m	**z end (m):**	0,00001	-0,00013	0,00001	0,00002
		H (N):	345891,07	399224,71	454339,37	553786,32
		T (N):	346167,74	399544,04	454702,79	554229,29
	5500 m	**z end (m):**	0,00001	-0,00013	0,00001	0,00002
		H (N):	418518,51	483050,72	549737,92	670065,95
		T (N):	418795,19	483370,06	550101,34	670508,92
	6000 m	**z end (m):**	0,00001	-0,00013	0,00001	0,00002
		H (N):	498062,85	654222,05	654222,05	797419,83
		T (N):	498339,53	575179,50	654585,47	797862,80

Table 30: Cable tension for 50m depth

Cable depth zm:	-60 m					
Cable weight (kg/m):			5,53352	6,38673	7,26846	8,85940
	Cable lengths:					
	1500 m	**z end (m):**	-0,00026	0,00013	0,00000	0,00004
		H (N):	25993,64	30001,37	34143,36	41616,72
		T (N):	26325,65	30384,57	34579,46	42148,28
	2000 m	**z end (m):**	-0,00027	0,00013	0,00000	0,00004
		H (N):	46168,11	53286,36	60643,07	73916,74
		T (N):	46610,58	53782,85	61291,36	73916,74
	2500 m	**z end (m):**	-0,00028	0,00013	0,00000	0,00004
		H (N):	72106,65	83224,12	94714,03	115445,23
		T (N):	72438,66	83607,32	95150,14	115976,79
	3000 m	**z end (m):**	-0,00028	0,00013	0,00000	0,00004
		H (N):	103809,29	119814,69	136356,29	166202,23
		T (N):	104141,30	120197,89	136792,40	166733,80
	3500 m	**z end (m):**	0,00001	-0,00013	0,00001	0,00002
		H (N):	169510,12	195647,23	222657,16	271392,92
		T (N):	169786,80	195966,57	223020,58	271835,89
	4000 m	**z end (m):**	-0,00028	0,00013	0,00000	0,00004
		H (N):	184506,88	212954,28	242354,73	295401,82
		T (N):	184838,88	213337,48	242790,84	295933,39
	4500 m	**z end (m):**	-0,00029	-0,00003	0,00004	0,00000
		H (N):	233501,83	311040,16	402834,50	598454,81
		T (N):	184838,88	311372,17	403166,51	598786,82
	5000 m	**z end (m):**	-0,00029	0,00013	0,00000	0,00004
		H (N):	288260,90	332705,16	378638,42	461515,55
		T (N):	288592,91	333088,36	379074,52	462047,12
	5500 m	**z end (m):**	-0,00029	0,00013	0,00000	0,00004
		H (N):	348784,08	402559,84	458137,23	558415,22
		T (N):	349116,09	402943,04	458573,34	558946,79
	6000 m	**z end (m):**	-0,00029	0,00013	0,00000	0,00004
		H (N):	415071,37	479067,34	545207,35	664543,44
		T (N):	415403,38	479450,55	545643,46	665075,00

Table 31: Cable tension for 60m depth

Cable depth zm:	-70 m				
Cable weight (kg/m):		5,53352	6,38673	7,26846	8,85940
Cable lengths:					
1500 m	**z end (m):**	-0,00001	-0,00076	0,00049	-0,00031
	H (N):	22297,16	25735,40	29287,85	35698,86
	T (N):	22684,51	26182,47	29796,64	36319,01
2000 m	**z end (m):**	-0,00001	-0,00079	0,00050	-0,00032
	H (N):	39589,55	45694,31	52001,80	63384,84
	T (N):	40105,83	46273,62	52758,30	63384,84
2500 m	**z end (m):**	-0,00001	-0,00081	0,00050	-0,00033
	H (N):	61822,51	71355,65	81205,31	98980,92
	T (N):	62209,85	71802,72	81714,10	99601,08
3000 m	**z end (m):**	-0,00001	-0,00082	0,00050	-0,00033
	H (N):	88996,08	102719,46	116898,43	142487,18
	T (N):	89383,43	103166,53	117407,23	143107,34
3500 m	**z end (m):**	-0,00001	-0,00082	0,00050	-0,00033
	H (N):	121110,29	139785,76	159081,20	193903,64
	T (N):	121497,64	139785,76	159589,99	194523,80
4000 m	**z end (m):**	-0,00001	-0,00083	0,00050	-0,00033
	H (N):	158165,14	182554,55	207753,60	253230,31
	T (N):	158552,48	183001,61	208262,40	253850,46
4500 m	**z end (m):**	-0,00001	0,00026	-0,00002	0,00001
	H (N):	200160,62	266621,83	345304,13	512978,31
	T (N):	200547,97	267009,18	345691,48	513365,66
5000 m	**z end (m):**	-0,00001	-0,00083	0,00050	-0,00033
	H (N):	247096,75	285199,64	324567,35	395614,29
	T (N):	247484,10	285646,70	325076,15	396234,44
5500 m	**z end (m):**	-0,00001	-0,00084	0,00050	-0,00033
	H (N):	298973,52	345075,93	392708,70	478671,60
	T (N):	299360,87	345522,99	393217,49	479291,76
6000 m	**z end (m):**	-0,00001	-0,00084	0,00050	-0,00033
	H (N):	355790,94	410654,73	467339,70	569639,14
	T (N):	356178,29	411101,79	467848,49	570259,29

Table 32: Cable tension for 70m depth