A Swappable Battery to Reduce Emissions of Ships

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Abstract. Waterborne transport emissions represent around 13% of the overall EU greenhouse gas emissions from the transport sector and the push for reducing carbon emissions is a top priority for the next decade in the shipping industry. The project 'Current Direct', funded by the EU Horizon 2020 initiative, contributes to the direction of decarbonization and addresses the challenges by designing an innovative and optimized Lithium-Ion battery system. Current Direct aims to develop a containerized energy storage system which enables easy swapping operations to provide a zero-emission source of energy for vessels' propulsion and auxiliary power. The concept of having a module energy system introduces the need to have a commonly adopted standard interface irrespective of the ship and supporting shoreside infrastructure. Current Direct will be targeting inland waterway & short sea shipping as the conventionally propelled or hybrid vessels in these sectors provide a high degree of applicability for swappable battery energy storage systems. The cloud-based Energy as a Service platform developed under Current Direct will pave the way for a sustainable battery swapping business model ensuring the end-users have the clean energy needed, when they need it, at a competitive price comparable to today's fossil fuels. The platform will primarily tackle the optimal charging and discharging scheduling of the batteries, manage the battery supply planning of the vessels, manage the battery fleet deployment between the swapping stations, and incorporate recognized practices of revenue management. This will provide end-users and stakeholders with sustainable swapping services through the EaaS network. The standardization of this innovative model for swappable energy is also being considered through the development of a unified certification methodology that covers to the containerized battery design, operation, routine verifications, and the ship's suitability for utilizing such a power source for main propulsion and auxiliary onboard systems.

Keywords. Environment Protection, GHG, Inland WaterWays, Short Sea Shipping, Lithium Ion Battery, Energy-as-a-Service, Route Planning, Battery Charging Infrastructure, Safety, Cyber Security, Swappable Container, Risk Management, Risk Based Certification, Standardization, Power generation, Power conversion, Energy storage.

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1. Introduction

1.1. The GHG Challenge and the EU Goal

The transport sector contributes almost a quarter of Europe's greenhouse gas (GHG) emissions and when compared to other sectors, such as agriculture or energy, and is the only sector where emissions are higher than those of 1990. Within this sector, the waterborne transport industry emissions represent around 13%. Under a business-as-usual scenario it is expected that these could increase between 50% and 250% by 2050, undermining the goals of the EU and those captured in the Paris Agreement and International Maritime Organization (IMO) which aim to significantly reduce GHG emissions during this period. Regulations descending from these concerns have driven exploration of various propulsion alternatives, ranging from replacing heavy fuel oil with gas alternative fuels to all-electric propulsion.

Each of these approaches is greatly abetted using energy storage, and the most efficient means of rechargeable energy storage available today is the lithium-ion battery. Large-scale adoption and implementation of batteries for waterborne transport is mainly limited by the high costs of battery systems and their electrical integration. Investments into supporting shore side infrastructure for charging is also often necessary to support vessel operations. Lastly, there is a relatively small market, when compared to automotive or grid storage, for the maritime battery industry and thus a lack of drivers for battery cell producers to adapt their products to be optimized for the market along with an inability to benefit from the economies of scale. The combination of these challenges ultimately leads to a higher capital expenditure (CAPEX) for vessel owners and a barrier for entry to adopt cleaner propulsion technologies.

1.2. The EU Project.

Current Direct aims to address these challenges and achieve the EU goals of reducing GHG in the waterborne transport sector through the development of a swappable battery energy storage container that operates on an Energy-as-a-Service (EaaS) platform. To realize these objectives the project will develop innovations across all levels in the value chain. Starting at the component level Current Direct is developing an innovative lithium-ion cell optimized for waterborne transport using novel additive manufacturing techniques to enable consistent cost reduction, increased performance, and flexible production capabilities when compared to conventional techniques. A distributed BMS, referred to as a Single Cell Supervisor (SCS), will be developed under the project to enable granular data management while eliminating the need for wire harness through use of power line communication. A composite material will also be developed under the project that aims to combine thermal and mechanical properties into a single component. The combination of these innovations will be integrated into a pack design to further reduce material and manufacturing costs. Current Direct will optimize the implementation of these innovations with the development of an Energy-as-a-Service (EaaS) platform underpinned by a physics-based battery model to further reduce the barrier for entry and increase market adoption. To support the commercialization of the EaaS ecosystem Current Direct will also develop standardized interfaces for the container to support both onshore and vessel operations. Finally, a harmonized battery certification methodology to validate and verify safety will be proposed aiming to reduce time to market to increase competitiveness. Current Direct will revolutionize the waterborne transport industry through energy storage innovations at the cell, pack, integration, and operational levels to create a clean energy ecosystem for the benefit of Europe.

2. The Current Direct swappable container design

With the introduction of a swappable battery energy storage the Current Direct project aims to increase the number of vessels using batteries as the primary means of energy powering the vessels. The swappable solution will enable vessel electrification an easier implementation when compared to fixed installations and will support an increase of retrofit and newbuild installations within European waterways. The swappable battery energy storage will be installed in movable 20-foot equivalent standard ISO containers.

The batteries inside the containers will be charged at dedicated charging stations on shore side. There will be multiple strategic locations for charging the batteries along the inland waterway and coastal shipping transport network. The containers will be handled by means of cranes between the shore and vessel.

The typical power demand on inland waterway vessels using the service of swappable battery energy storage is between 200kW to 1,000kW. The variation in power demand will ultimately require different scenario combinations on the frequency of swapping and the quantity of containers onboard the vessels. These combinations will be analyzed and considered as part of the vessel voyage energy plan.

2.1. The AC/DC decision.

To understand the benefits and drawbacks with both AC power and DC power solution a spider diagram was developed to analyze the five different main categories:

1. Operational Aspects; 2. Mechanical, machinery & electrical aspects; 3. Integration; 4. Structural Aspects; 5. Economical Aspects

Overall, the DC Power option provides the highest number of advantages to the project with only very few / minor disadvantages, as following:

- Maximize Energy Density in a Battery Energy Storage Container.
- Minimum fault occurrence frequency inside the Battery Energy Storage Container due to limited number of main components.
- Adaptability to different power levels through the Battery Energy Storage Container.
- Bi-directional connectivity to support the connection point on shore side.
- Lower build cost/kWh for the Battery Energy Storage Container

2.2. Simplified Block diagram

The block diagram below shows the standard mechanical, electrical and physical interfaces between battery container and vessel. The same interfaces exist between the container and charging station onshore.

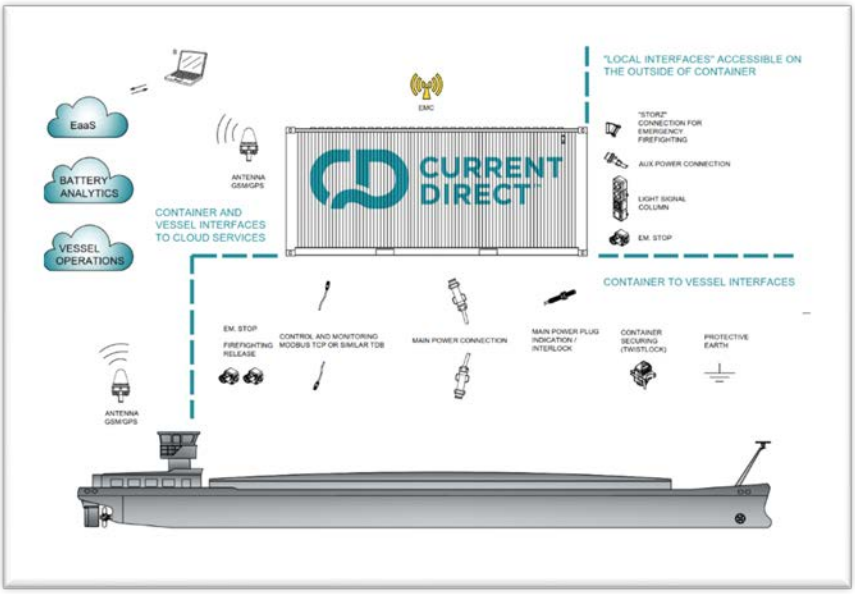

Figure 1. Interfaces between battery container and vessel.

2.3. Inland Water Transports (IWT) ships applicability study result

In the inland waterways study, the IVR database was used as reference. The IVR database contains 8199 vessels, which is over 80% of all vessels operating in Rhine region. Most of the deficiencies consist of dry cargo vessels, approximately 75% are included in database.

This report puts a limit at 10% deadweight for the maximum amount of battery containers for any vessel considered. Based on that, a total of 6259 vessels may be applicable for Current Direct Service. Detailed breakdown for the different vessel types can be seen in Table 1 below.

The 10% deadweight is a boundary condition, chosen based on the assumption that the energy provided by the Current Direct container would replace that same deadweight taken by bunkering capacity. Further verification of this with respect to the individual vessels may be needed.

Vessel Type	Amount when considering DW	
All Vessels	8199	
Totals	6259	76,3 %
Passenger Vessel	802	69,6 %
Tanker Vessel	1297	84,2 %
Dry Cargo Vessel	3908	93,2 %
Tugs	147	14,5 %
Push	92	32,7 %
Other Vessel	13	65,0 %

Table 1: Number of suitable vessels for battery containers when considering the limit of 10% deadweight.

2.4. . Short sea shipping applicability study

A similar ship applicability study as completed for of the IWT vessels is under development for the applicable short sea vessels. There is no equivalent database as the IVR for the short sea fleet so a slightly different approach will be used.

Marine traffic is used to gather shipping routes, speed profiles and vessel characteristics. Based on the collected data, four vessel types are identified as the most common operating in the coastal sector: Passenger vessels, RoRo/Passenger vessels, General Cargo vessels and Oil/Chemical Tankers.

Power profiles will be developed for five vessels of each type and applicability for the Current Direct swappable container solution will be determined.

3. The Current Direct Energy as a Service (EaaS)

3.1. Overview

Energy-as-a-Service is a business model, which directly relates the cost of the battery to its usage. The goal is to create a system which re-energises electric vessels by swapping their depleted batteries with fully charged batteries in store and charges their depleted batteries locally with optimised charging operations.

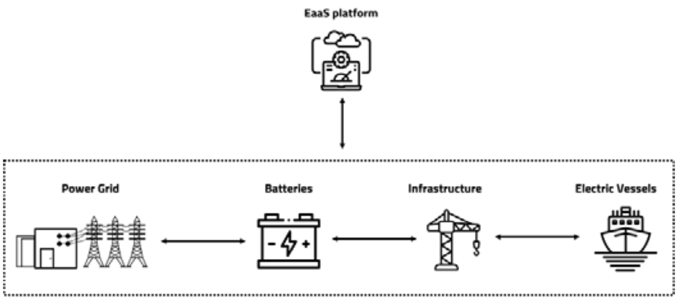

Figure 2 Illustration of the EaaS structure

Such a complex structure requires the deployment of a monitoring system that processes information, decides, and provides directions. As a consequence, the cloud based EaaS platform is being developed. This type of platform comprises of the built-in control unit and the web platform.

The control unit is responsible for the optimisation of the entire logistic process. It aims to tackle the optimal energy transfer of the batteries (when to recharge/reserve batteries), manage the battery fleet between the electric vessels and the EaaS stations, and incorporate recognised practises of revenue management (pricing optimisation and service fee calculation). All the above are developed to ensure that the end-users have the energy needed, when they need it, at a competitive price, comparable to today's fossil fuels. EaaS platform is the system under which connects all the functionalities needed for the continuous operation of the battery swapping network.

The web platform is the visualised environment of the EaaS network, which allows the users to review information on demand and to interact with the functional components of the EaaS platform. Each user, depending on its type, will have different privileges and access to different data and operations of the platform.

3.2. Functionalities

In this section, the core functionalities of the EaaS platform are presented. Specifically, these functionalities are:

- *Initial infrastructure planning*: to support the deployment of the infrastructure of the EaaS network, the infrastructure planning algorithm will be created. This algorithm outputs the optimal locations that the EaaS network's stations should be placed, along with the corresponding number of chargers that each one should install, and the batteries that each one will need. The infrastructure will be deployed in such a way that will provide high QoS to the end-users, while at the same time, it will minimise the cost of the initial deployment.
- *Infrastructure replanning*: the hard infrastructure of the EaaS network will be recalculated when specific events occur (e.g., vessel addition into the EaaS network). The purpose of this algorithm is to provide the necessary output regarding the expansion of the infrastructure to adapt when the circumstances demand it.
- *Fleet management*: the EaaS network is an entity which is expected to change dynamically, depending on the vessel movement and emergencies. The purpose of the fleet management algorithm is to provide instructions regarding the optimal relocation of the batteries to cover the demand and to ensure the unhindered operation of the EaaS network.
- *Route planning*: in order to minimise the cost imposed on the end-users for the battery swapping services and the utilisation of the EaaS network, the route planning algorithm will be introduced. This algorithm's output is the location of the intermediate stops that each vessel needs to make along its route to be re-energised.
- *Charging scheduling*: to enhance the efficiency of the system, it is important that the batteries will exploit the low prices imposed by the electricity provider to charge and avoid charging operations when the prices are high. For this purpose, the charging scheduling algorithm creates the charging schedule of each battery, based on the EaaS network's battery demand. This algorithm allow the EaaS network to maintain high QoS, while minimizing the total charging cost at the same time.
- *Service fee calculation:* a PPU pricing model has been implemented for the service fee calculation. This fee is the total service fee that each vessel should pay for the battery swapping service and the utilisation of the EaaS network. Ultimately, it comprises of the electricity costs (i.e., due to power purchased from the grid), the batteries' SoH degradation costs and fixed costs (i.e., operating and construction costs derived from CapEx and OpEx analysis). This cost is imposed to the vessel each time it completes a battery swapping operation.

4. Regulatory framework standardization

4.1. Scope for Standardization and Standard Certification.

The innovative solution of having the source of power for a ship contained in a container that could be replaced with easy and quick operation, leads to the need to standardize the container itself and its interface facilities. An industry-agreed regulatory framework would allow different manufacturers to supply standardized swappable containerized battery to the market.

Standardizing the design is focused on an ISO container having the appropriate robustness to safely contain a heavy load (the Li-ion battery, ancillaries for electric and thermal protection, HVAC, thermal protection and fire fighting ancillaries, communication equipment) and the geometrical characteristics needed to connect (and disconnect) it to the ship's structures and keep the position when the ship is sailing subject to seagoing environmental stresses.

The Li-ion battery are largely regulated by International Standards, Classification Societies and some Flag Administrations issued additional prescriptions for the safe use of such equipment [1]. There are industry initiatives [2] within the maritime community having as an objective the standardization of the Lithium Battery requirements, and other EU-funded projects [3] [4] explored the development of high-performance Li-ion cells and the application of such storage equipment in the maritime industry.

On a side of the design requirements, there shall be a set of standardized testing procedures and acceptance criteria, to complete the assurance process of the whole containerized battery system and a process ensuring that the characteristics of the system remain within acceptable limits until the end of life. Such a process is well consolidated for the ship's structures, machinery and safety equipment permanently installed onboard and is based on continuous surveys carried out by the Classification Societies and the Flag Administrations but is missing for equipment that are removable and replaceable (swappable) from the ships and provide essential services for the ship.

The challenge with the standardized certification process is approached in a way that – in principle – could be extended to other containerized equipment, intended to provide 'essential systems' (*) to the ships, e.g. containerized fuel vessels, containerized fuel cells with reformers, etc. This certification process will be based on a combination of selected requirements from existing Regulatory Frameworks and the outcomes from an appropriate Risk Management process.

4.2. Considerations on existing regulatory framework.

Existing requirements for structures, electric equipment, lithium battery and fire safety systems have been collected from the existing applicable Regulatory Framework.

The Ship Rules from Lloyd's Register, DNV-GL and ABS have been considered as the basement together with the International Electrotechnical Commission Standards [5] [6]. The Li-ion Battery requirements have been collected from the above Ship Rules and Standards and additional product certification specifications for marine applications have been considered [7].

As there is a strong focus on the application of Current Direct project within the Inland Waterways sector, the project also considered the existing requirements of the *Comité Européen Pour L'élaboration De Standards Dans Le Domaine De La Navigation*

Intérieure (CESNI) [8]. From this European Commission, the project considered the latest issue of the technical Requirements for Inland Navigation Vessels.

4.3. Risk Based Certification methodology.

The concept of swappable battery container – and similarly any concept of essential service when they are not permanent part of the ship, i.e. swappable – is considered as *innovative* in respect of the technology consolidated in the maritime transportation sector and this makes a challenge to identify the appropriate scale of the assurance.

Innovative technologies and ideas are promoted by both the Class Societies and the Flag Administrations, provided they are based on safe engineering and can be proved as providing a level of risk acceptable for the safety of personnel and navigation and in respect of the environmental protection. In line with these goals, the Standardized Certification process is supported by Risk Based Studies (Risk Management), reflecting the approach [10] [11] [12] consolidated in the maritime sector to innovative solutions and considering that safety, sustainability and security will remain the top priorities for the Class Society and the Flag Administration.

The Lloyd's Register Risk Based Certification [13] process has been identified as the tool to implement the activities of Risk Management by risks identification and mitigation. The areas of risks managed include the cyber risks [14] associated to the container as an asset, with particular focus to the Energy as a Service (EaaS) and the whole container monitoring, control and safety systems.

(*) Essential systems are those necessary for the propulsion and safety of the ship (see LR Rules and Regulations for the Classification of Ships, Part 6, Chapter 2, 1.6)

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