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ARTICLE

Circular economy approach to facilitate the transition of the port cities into self-sustainable energy ports—a case study in Copenhagen-Malmö Port (CMP)

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Abstract

Sustainability has recently been one of the main focuses of developments in society and industry. In port cities, sustainable relation between ports and ships is one of the emerging factors of developments. Under the city-port umbrella, there are rarely mechanisms for ports sustainability independent from their cities. In the last years, the increasing negative externalities of the ships, in particular waste and emissions, have been among the priorities of the European ports. To address these issues, solutions like the circular economy in EU port cities has gained significant attention. This paper investigates the application of a waste-to-clean energy model for the Copenhagen-Malmö Port, as a case study. The innovative state-of-art model introduced in this research deals with the feasibility of a closed loop, based on the circular economy, to give added value to a large amount of the waste generated from shipping activities in the Copenhagen-Malmö Port. The proposed model includes key elements such as waste management, biogas plant and cold ironing. Two scenarios are compared, first is the current condition and the second one is assumed with the established circular economy model by the port authority. The scenarios are followed by cost-benefit analyses to show the feasibility of the proposed model.

Keywords Circular economy · Ship-port interaction · Waste management · Biogas plant · Cold-ironing

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1 Introduction

Humans are altering the planet at an increasing rate in particularly with significant environmental impacts (Waters et al. 2016). Global impact of human activities resulted in anthropogenic climate change. As a response to these harmful activities, the concept of planetary boundaries is developed, which should not be crossed to have a sustainable natural ecosystem on Earth (Stockholm Resilience Centre 2017). The definition of sustainability means to be 'causing little or no damage to the environment and therefore able to continue for a long time', as per Cambridge Dictionary. To slow down and finally cease the shift from the environmental stable period in Earth's history, the sustainable development approach attracted attention and defined as a 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (World Commission on Environment and Development 1987). In recent decades, sustainable development has been founded on managing economic growth/prosperity, while sharing the benefits also in a co-evolutionary perspective with the ecosystem.

Port cities as the 'interface' between the cities and the seas are in vulnerable places for climate changes impacts like sea level rise at coasts or flooding at the mouth of (Becker et al. 2011). Seaports have an essential contribution to the globalization and world economy since more than 90% of the world's trade arrive and depart at seaports (World Trade Organization 2010). Port cities are core places: they lead the way in terms of economic strength. According to Girard in 2013, 14 out of the 20 economically strongest cities in the world are port cities (Girard, 2013) are port cities. Port cities are the nodal points connecting countries in a mutual competitive and cooperative process while improving the benefits of their local strategies. Although many drivers to enhance the port sustainability are in the context of 'Command-Control', there are non-legislative drivers such as population growth and increase in fossil fuel price (Ekins and Bradshaw 2015). Indeed, ports are potential places to increase the economic wealth, due to industrial, logistics, fishing and touristic activities. They are the driving forces to introduce new services/activities at seaports.

1.1 Problem statement

Port cities are places of conflict between economy and ecology. Ports city relationships have weakened recently as the port and city disintegrated with less direct economic benefits for cities while lots of environmental impacts due to air, water and land pollution still remain for local communities. So, the common challenge of many port cities is labelled the local-global mismatch. As an example, more than 90% of the indirect economic impacts of the ports of Le Havre are taking place in other regions than the port region itself (Merk and Dang 2013).

Therefore, new models, tools and methods are needed to raise the creativity, resilience and sustainability of the port cities in a win-win perspective. These approaches should reduce the mismatch by transforming differences in complementarities into a synergistic approach. This paper will investigate the application of circular economy approach for port cities, with a focus on the Copenhagen-Malmö Port as a case study. In this respect, this article represents a new port energy framework based on the circular economy modelling to find a solution for ports' energy increasing demands in the light of energy self-sustainability, at Copenhagen-Malmo Port.

2 Transition towards the circular economy in port cities

The recently circular economy has gained significant attention, due to the reduction of negative externalities in a systematic way among different industries and sectors. The circular economy is defined as 'An industrial system that is restorative or regenerative by intention and design. It replaces the end-of-life concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models' (Ellen MacArthur Foundation 2013, p. 7) (See Fig. 1).

Port cities and port areas have a particular development potential combining the port's economic, logistic and industrial activities with the creativity of inhabitants. Ports link international supply chains and are critical to the global economy and trading system. They handle over 80% of world trade and are extremely vulnerable to climate-related impacts, such as flooding at the mouth of rivers, sea-level rise, and storm surges (Acciaro et al. 2013). After the economic crisis in 2008, sustainable long-term development of port areas/cities has been focused based on the following principles:

- the synergy principle between different actors/systems, in particular, the socio-cultural and economic system
- the creativity and innovation principle
- the circularization principle (Girard 2013)

A sustainable port city means the place where the balanced social, economic and environmental values are reached in an efficient way, over the long term. These port cities contribute to closing the flows of material and energy resources through

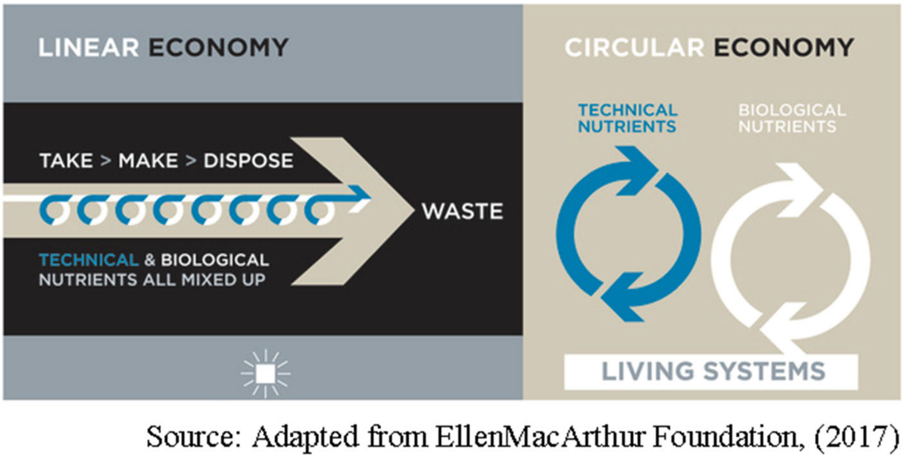


Fig. 1 Circular economy system diagram. Retrieved from the EllenMacArthur Foundation (2017)

circularized processes and synergies between stakeholders and actors. Seaport cities as the gateway of global trade mostly put some added value on all kinds of resources; therefore, it can be simulated for wastes and second-hand products as well. If the seaports are looked at as the ‘crossing-points’ for waste and materials, then it makes sense why the ports are ideal for developing the circular economy (Kyllönen 2017). It is even more profitable to execute these activities in a port area because of industrial parks, clustering activities and megacities in the proximity of ports (Kuipers 2015).

At EU level, principles set by the European strategy for the adopted circular economy package can be a driver for port cities towards sustainable development (Bourguignon 2016). Drivers such as sustainability, public environmental awareness and competitiveness caused the circular economy concept to gain significant attention too. A circular economy strongly supports economic growth and produces job opportunities (European Commission 2017a, b). Seaport cities have always played an important role in the geopolitics of Europe, as 75% of extra-EU goods and 37% of the intra-EU freight traffic are shipped through European ports (European Commission 2016). There is of course literature on EU port cities urban area, while the ones narrowed down to the application of the circular economy in ports are limited. If the ports are looked at as the ‘crossing-points’ for waste types, then it makes sense why the ports are ideal for developing the circular economy (Kyllönen 2017).

A few European ports in recent years have taken serious steps to apply the circular economy approach. The circular strategies of these EU ports like Rotterdam, Amsterdam, Hamburg and Antwerp have similarities, but also some differences due to the profile of the ports. The highest similarity is in moving towards less dependence on fossil fuels by renewables, systematic improvement of energy efficiency and waste management optimization. Another common point is the stakeholders’ involvement in development planning. There are similar challenges like insufficient budget, allocation of sources to transit the linear structure of ports towards circular models and integration of the port development plans into the city municipality plans. All of these ports also to some extent suffer from lack of experts, professional role and validated businesses for new circular models. Furthermore, there is no clear balance in responsibilities and gains between the city urban areas and their port harbour areas. Rotterdam, Amsterdam and Hamburg defined city contact points for circular ideas, activities and customer support. Antwerp has set up a ‘Virtual Knowledge Centre’ for innovative ideas and start-ups (Port of Antwerp 2016a, b, c, d). Every port has a different solution for waste management due to the different types of waste from the industries. In waste management related policies, Antwerp is a leader by a clear ‘zero-ton residual waste’ strategy (Port of Antwerp 2016a, b, c, d). Then similarly, a waste-exchange platform has been used by both Antwerp and Amsterdam ports. Initiatives are applied by the port of Rotterdam to reserve spots for waste companies, and the port of Hamburg to uses recovered materials in road and buildings constructions.

All above-mentioned ports are equipped with the shore power supply to vessels. Hamburg is utilizing an LNG-powered floating power barge for cruise ships whereas land-based facilities in Antwerp are for both seagoing and inland vessels (Hamburg Port Authority 2015). The port of Amsterdam uses shore facilities for inland vessels, at the same time as they are investigating possibilities for shore-based power for cruises as well. In this research, it is necessary to discuss what distinguishes a sustainable port definition from a sustainable city port, since there is no clear boundary to differentiate port's sustainability apart from the urban area and city municipality, particularly in term of energy security. For the purpose of this research, a waste-energy model, structured on the circular economy bio-gradable cycle, is introduced for Copenhagen-Malmö Port (CMP).

3 Methodology

3.1 Data collection

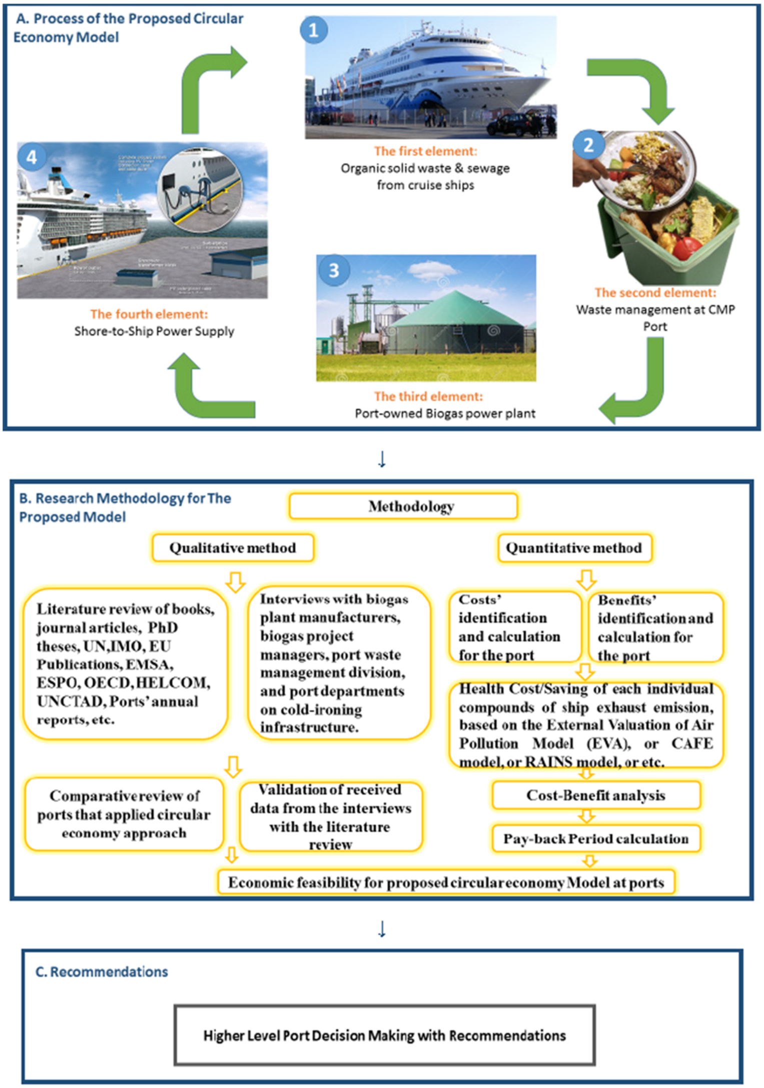
There are fundamentally two data sources for this research: primary data and secondary data. Primary data are the ones collected through interviews. It requires physically collecting the data by meeting persons, over the phone, by email and Skype. The explicit information collected for the research is primary data, while the secondary data is the information collected by others rather than the author (Laycock et al. 2016).

In this study, a combination of both quantitative and qualitative methods has been used to establish and analyse a specific circular economy model for Copenhagen-Malmö Port (CMP). The main part of the qualitative methodology is carried out through two-phase interviews with CMP departments. The first phase is aimed at receiving some general information about CMP environmental and energy policies, while the second phase targeted to access the needed data about the CMP performance and statistics, particularly in 2016.

Both phases of the interviews were to some extent similar to questionnaires and the interviewee answers were recorded. Among three different types of interviews: structured, semi-structured and unstructured. The semi-structured interview has been used in this research. It is due to the reason that in this situation, there were fewer predetermined questions and it is more likely to develop as a 'guided conversation' according to the willingness of the port interviewees (Walsh and Thornes 2011). Furthermore, the Biogas 2020 project in Samsø island of Denmark was contacted to get technical information and price quotation of their biogas project.

In addition, other literature sources like IMO conventions, EU commission publications, European Sea Port Organization (ESPO) reports, and CMP annual reports have been referred to. Data collection and literature review will be followed by a cost-benefit analysis of the circular economy model for Copenhagen-Malmo Port. Figure 2 illustrates a summary of the research methodology for this paper.

The above framework consisted of three main parts in line. Part **a** of the proposed framework illustrates the circular economy model with four main elements of the ship waste management, port ship management, port-owned biogas plant and cold-ironing facility to close the loop in the port. It shows how the organic wastes of the ships could be used to produce electrical power and give it back to the birthed cruise ships. In part **b** of the framework, the research methodology for the proposed model is shown in the block diagram. It describes both quantitative and qualitative methods result in the economic feasibility of the proposed circular economic model at a port. Involvement and cooperation of multiple. Finally, in part **c** is the recommendation which is the higher level port decision-making with recommendations.



Source: Produced by the Author

Fig. 2 Proposed circular economy framework

3.2 Circular economy application at Copenhagen-Malmö Port

3.2.1 The potential of the Copenhagen-Malmö Port for the application of circular economy

The location of the CMP is at the heart of the Øresund Region with almost four million populations. The region is in a transition of fast integration between the Danish and Swedish local areas. The Øresund Region is one of the strategic straits in the world that function as a gateway for Baltic Sea Region with more than 100 million habitants with the rest of the world (Copenhagen-Malmo Port 2012a, b). The unique geographical location of CMP provides economic potentials for investments while posing increasing environmental concerns to the local area.

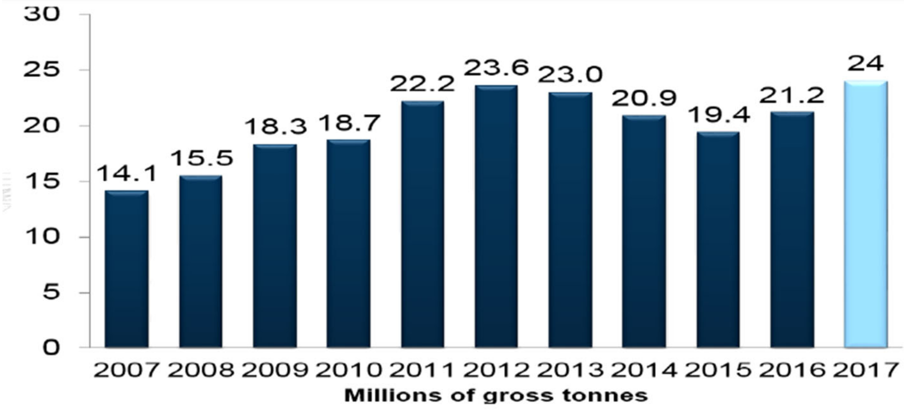
Cruise shipping at CMP—Cruise shipping is in the intersection of the interest of tourism and shipping and Europe is the second biggest cruise market. Based on the number of passengers, Southampton and Copenhagen are the biggest cruise ports in order in Northern Europe (Dayioglu 2010). The cruise industry has generated approximately 2000 jobs in CMP (Copenhagen-Malmo Port 2012a, b). In Copenhagen, there are four cruise terminals locations for up to 10 vessels (Copenhagen-Malmo Port 2017) (see Fig. 3). According to the report of HELCOM, Copenhagen hosted 311 cruise port calls during 2014 (Copenhagen-Malmo Port 2014).

As shown in the Figs. 4 and 5, the cruise activities at CMP in 2012 is close to the year 2017, in terms of the number of passengers and ships' gross tonnage. Copenhagen-Malmo Port is also a major turn-around point for cruise ships where passengers either begin or terminate their trip in the city. It means that the vessels stay longer in the port than if they were just visiting. The season for cruise shipping in Copenhagen-Malmö Port is from early May to late October (Ballini and Bozzo 2015). From 2015, CMP has experienced a rise in the number of passengers with the highest of around 850,000 since 2007 (see Fig. 5).

Environmental regulation can be the main driver for the transition of the industries including the cruise shipping towards the sustainability era. In 2011, the International Maritime Organization (IMO) designated the Baltic Sea as a special area for sewage from passenger ships and it came into force from 2013. The new enforcement amendment as decided on by IMO in 2016 is that by 2021 all IMO registered passenger vessels sailing in the Baltic Sea, as the first region in the world, must discharge all sewage at port reception facilities (PRFs) or treat it with an on-board treatment plant

Source: CMP Port, 2017

Fig. 3 Copenhagen port terminals, location of the Oceankaj cruise terminal for this research. CMP 2017



Source: CMP Port, (2017)

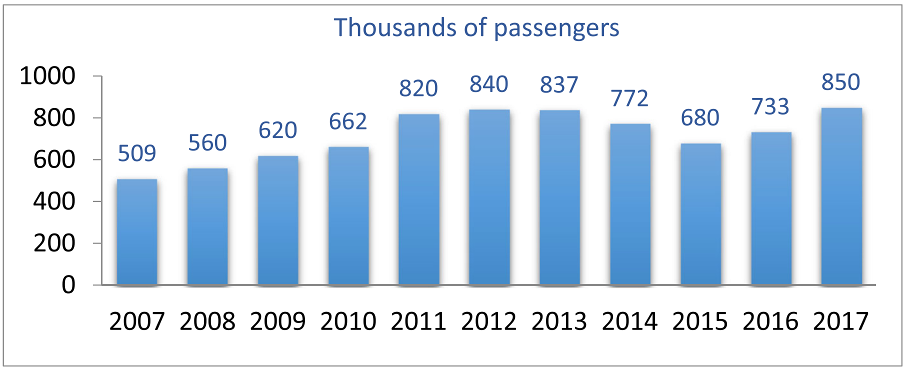
Fig. 4 Total cruise ship gross tonnage visited Copenhagen port in the last 10 years. CMP (2017)

certified to meet stringent special area requirements. For new ships built on or later than 2019, these requirements will apply earlier (HELCOM 2016).

3.2.2 The circular economy model for Copenhagen-Malmö Port

To convert the increasing threats arising from the negative externalities such as air and noise pollutions of cruise shipping at ports into opportunities, a circular model is offered. The proposed model consists of four key elements as illustrated in Fig. 2 and named: ship on-board waste management, port waste management, port-owned biogas power plant and shore-to-ship facility.

The first element of the model is ship on-board waste management. According to the international regulations, MARPOL Annex V of the International Maritime Organization for the prevention of pollution by garbage from ships, onboard collection, separation and storage of all solid organic waste like food waste is regulated, and for the case



Source: CMP Port, (2017)

Fig. 5 The number of cruise passengers at CMP over the last 10 years. CMP (2017) of this study with a focus on the Baltic Sea as a special designated area for garbage disposal (IMO 2017). For this purpose, the organic ship wastes should be collected, separated and stored on board properly to be delivered to the port reception facilities (see Table 1).

Sewage is the drainage and wastes from toilets, urinals and dispensaries which is generally referred to as 'black' water. Grey water is the drainage generated from galley basins, dishwasher, showers, laundry and bath drains (MEPC 2012). According to Annex IV of MARPOL of the IMO, the discharge of sewage into the sea is prohibited, except when the ship has in operation an approved sewage treatment plant at a certain distance from the nearest land (IMO 2017). Under Annex IV of the MARPOL Convention, the Baltic Sea area is a special area and regarding the new amendments to Annex IV by the IMO on 22 April 2016, the sewage treatment system in Baltic sea should meet the nitrogen and phosphorus removal standard when tested for its Certificate of Type Approval by the Administration (IMO 2017). It means that from 2019 onwards, cruise ships and passenger ferries are not permitted to discharge untreated sewage into the Baltic Sea anymore. The regulation will affect new vessels from June 2019 onwards. For those ships currently in service, they would be obliged to meet the requirements by 2021; with an exception of extension until 2023 for direct passages between St. Petersburg and the North Sea (HELCOM 2016).

The second element of the model is the waste-management at CMP. The effectiveness of MARPOL convention depends on the availability of adequate port reception facilities, especially within special areas (IMO 2017), and CMP has a good reputation in providing shore reception facilities to collect and transfer both the organic solid waste and sewage from cruise ships, based on the interviews and annual port reports (CMP 2016).

The third element of the model is a biogas plant which is known as a clean and renewable source of energy (International Gas Union 2015) and can be built in Denmark. Denmark is a leading country in biogas industry where 154 biogas plants were running in 2014 with an annual output of 1.2 TW.h and it was predicted to increase to 4.7 T W.h in 2020 by Danish Energy Agency (IEA Bioenergy 2015). According to the European Biogas Association (2016), EU policy is aimed at using green gaseous fuels while trend indicates a continual growth in this sector.

Table 1 Simplified overview of the discharge provisions of the revised MARPOL Annex V

Type of garbage	Ships outside special areas	Ships within special areas	Offshore platforms and all ships within 500 m of such platforms
Food waste comminuted or ground	Discharge permitted ≥ 3 nm from the nearest land and en route	Discharge permitted ≥ 12 nm from the nearest land and en route	Discharge permitted ≥ 12 nm from the nearest land
Food waste not comminuted or ground	Discharge permitted ≥ 12 nm from the nearest land and *en route*	Discharge prohibited	Discharge prohibited

Recaptured and reproduced from the IMO (2017)

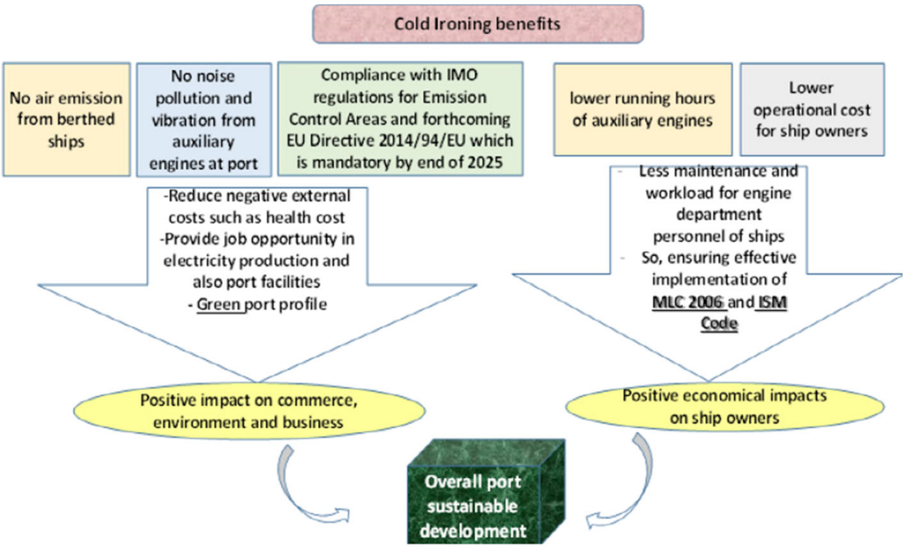
The fourth element of the model is the shore-to-ship power supply, known as cold-ironing. It is defined as the process of providing shore electrical power to berthed vessels while their auxiliary engines are turned off. In this method, the operational and maintenance costs of auxiliary engines will be reduced. Based on the research carried out by (Ericsson and Fazlagic in 2008), the air emission by auxiliary engines which are even using 0.1% low sulphur content fuel is still higher than the mixed fuel used in the EU power plants to produce the same electrical power. The model for the case study includes three cruise berths of Ocean Quay in CMP. Figure 6 presents the main advantages of applying cold ironing. However, the main barrier to applying this technology pertains to the investment cost in port. Figure 6 shows the related benefits of the application of cold ironing at ports.

Having conducted an investigation by Ballini (2013a, b) and also the CMP feasibility study of cold ironing for Copenhagen Ocean quay (Oceankej) cruise terminal, three berths required cold-ironing installation.

4 Circular economy scenario for Copenhagen-Malmö Port

In this section, two scenarios will be considered for the proposed circular model. Costs and benefits of both scenarios are analysed. The first scenario is the current condition of Copenhagen-Malmö Port while the second scenario is based on the circular model.

Scenario 1 Applying no circular economy model, i.e. the current status of the CMP



Source: Reproduced and recaptured from literature by author

Fig. 6 The main drivers for the application of cold ironing in EU cruise terminals. Reproduced and recaptured from literature by author

Scenario 2 Applying a circular model using organic solid and sewage wastes from berthed ships, the port buildings, city household, and agriculture.

The methodology of the cost-benefit side of the establishment of such a model is the calculation of four related costs and four related benefits for both scenarios. Principally, a cost-benefit analysis replicates vital motivations or obstacles that affect the port authority's decision making to choose such a model. Furthermore, the cost-benefit analysis is followed by a payback. The summarised costs and benefits are listed in Table 2.

4.1 Cost analysis

Assumptions: The rate of exchange assumed 1 USD = 0.837952EUR, 1 USD = 6.6 RMB and 1 USD = 1 USD = 6.23 DKK, based on average value during September 2017 (CNN Money 2017).

4.1.1 Cost of ship-originated waste management at CMP cruise terminals

Extracted from interviews with the CMP cruise department, the following fees received about waste management costs at CMP in 2016 (see Table 3). The first part is the waste-collection service costs specifically for cruise terminals. The second part represents the total waste-service costs in all terminals.

For scenario 2, based on the literature review and feasibility studies for CMP, electrical power for the Oceankej terminals is 18 MW (21 MV.A) (Ballini 2013a, b). The amount of input waste for a large biogas plant with such an electrical output is considered 1650 tons/day. As per interview with the Samsø biogas2020 project manager in Denmark, the input of biomasses from farms is almost free, and there might be a minor gate fee for some societal waste. This is a common practice in most biogas plants in Denmark as stated in interviews. Therefore, there will be no payment for 1650 tons/day feedstock to plant in scenario 2. Additionally, the cost of collecting the waste for scenario 2 is regarded as a part of the operational cost of a biogas plant in the costs' subsection 2. The biogas plant operational cost will include the collection and transferring costs of the waste. Therefore:

For scenario 1: The overall waste collection at the cruise terminal is € 519,642.

Table 2 Summarized costs and benefits

Costs	Ship-generated waste management cost in CMP	Capital and operational costs of biogas plant	Capital and operational cost of Cold-ironing installation at Oceankej-Copenhagen	Externality cost of berthed cruise ships in Copenhagen
Benefits	Saving from cutting negative externality	Saving from electrical power sale to ships	Saving from waste collection in port area	Saving from sale of produced fertilizer

Table 3 Waste management costs in CMP

Waste management costs in CMP during 2016	In Danish krone (DKK)	Euro (€)
Sewage/sludge in cruise terminals	1.500.000	201,414
Dry garbage in cruise terminals	2,370,000	318,234
Total waste management costs in cruise terminals	3,870,000	519,642
Sewage/sludge in all terminals	4,350,000	584,100
Dry garbage in all terminals	3,370,000	452,510
Total waste management cost in all terminals	7,720,000	1,036,600

Provided by CMP (2017)

For scenario 2: The waste collection at all terminals is zero.

4.2 Cost of biogas power plant

For scenario 1, there is no biogas plant owned by the port currently. The CMP was interviewed for the amount of waste received from 308 visiting cruise and ferry ships in 2016 (see Table 4). In scenario 2, a large amount of biomass feedstock from different sources like ships, agriculture, animal manure and household waste is considered, to produce 18 MW electrical power. The maximum electricity demand of the cruise ships as discussed by Ballini in 2013 is 16 MW. The biogas plant is assumed to be an 18 MW since 10% of the produced electricity will be consumed for the operation of the pumps, brewers and injectors in the biogas plant itself (Naskeo Environnement 2017).

For scenario 2, biogas of 36 MW, which is under construction in Denmark with an approximate capital cost of €10,750,000, is referenced, through interviews with the project manager of Biogas2020, in Samsø Municipality. Therefore, the installation cost of the 18 MW plant in scenario 2 is considered €5,375,855 (see Table 4). Annual operational and maintenance (O&M) cost is assumed 4% (International Renewable Energy Agency 2012) (see Table 5).

Therefore, the overall costs for the establishment of different capacity biogas power plants are summarized below:

For scenario 1: The total of the biogas power plant is zero.
For scenario 2: The total of the biogas power plant is €5,590,889.

Table 4 Cruise ship–originated waste in CMP

Type of ship-originated waste in CMP	Amount of waste (m^3) or (ton)
Organic solid waste including food waste and combustible materials	1086 tons
Black water (sewage)	7377 m^3
Grey water (sewage)	10,742 m^3

Provided by CMP (2017)

Table 5 Costs of different capacity of biogas plants for all scenarios

	Biogas power plant	CAPEX of biogas plant	Annual OPEX of biogas plant	Generator rated/max power	CAPEX of the matched Generator with CHP €	Annual OPEX of generator	Overall cost
Scenario 3	–	€5,375,855	€215,034	18 MW (21 MV.A)	–	–	€5,590,889

Assumption: to convert Volt-Ampere to Watt, cosφ = 0.85

4.2.1 Cost of cold-ironing installation at CMP Oceankaj terminal

It was assumed that about 60% of cruise vessels calling on the CMP are equipped with cold-ironing facilities to use shore power rather than electricity from the auxiliary engines of ships. The 60% assumption was chosen since all the visiting cruise ships are not built or retrofitted with cold-ironing equipment (Ballini 2013a, b). The overall capital cost of founding a shore-to-ship power supply utility in three berths of the Oceankaj cruise terminal for the port of Copenhagen, under a study by Ballini (2013a, b) was assessed to €36,866,548. Annual maintenance costs for the shore power facility itself are expected to amount to 0.8% of the construction costs per year according to the report of Copenhagen-Malmo Port (2015a, b), which equals €2,956,800 in scenario 2.

For scenario 1: The total cost cold-ironing installation is 0.
For scenario 2: The total cost cold-ironing installation is € 36,960,000.

4.2.2 External cost of cruise ships berthing in Copenhagen

Within economics, the externality is described as a cost or a benefit which is not reflected in prices, in that it is incurred by a party who was not involved as either a buyer or seller of the goods or services causing the cost or the benefit. Therefore, the cost of an externality is the external cost (Ballini 2013a, b). In cruise shipping, external costs include the social cost (primarily health cost) of mostly atmospheric pollution (Ballini 2013a, b).

In Copenhagen-Malmö Port, the ships are obliged to consume maximum sulphur content of 0.1% fuel or apply equivalent measure like a scrubber. Therefore, emission from this low sulphur fuel is a baseline for analysing the benefits of converting ships to use cold ironing. Using shore-to-ship electricity exempts ships from having to meet the 0.1% sulphur fuel requirement under the IMO regulations in MARPOL Annex VI for sulphur emission areas (SECA). Therefore, in scenario 1, substantial external health costs due to the socio-economic impact of hazardous emissions from AE of cruise ships are posed to the local people. The externality cost, in this case, is € 5,384,086 per year (Ballini 2013a, b) (see Table 6).

To calculate the external health costs of SO2, NOx, VOC and PM exhaust emissions from cruise ships hoteling in Copenhagen, this case study uses application of EVA (Economic Valuation of Air pollution) which is developed by the Aarhus University in

Table 6 Summarized costs for different scenarios

	Cost of ship-originated waste management at CMP cruise terminal-OPEX (€)	Cost of biogas power plant + generator-CAPEX (€)	Annual maintenance and operation cost of biogas power plant + generator–OPEX (€)	Cost of initial cold-ironing installation at CMP Oceankej–CAPEX (€)	Annual maintenance and operation cost of cold-ironing infrastructure–OPEX (€)	Annual externality cost of cruise ships berthed in Copenhagen consuming 0.1% sulphur or 60% ships using cold ironing with Nordic energy mix-OPEX (€)	Total cost (€)
Scenario 1	€519,642	€0	€0	€0	€0	€4,944,578	€5,464,220
Scenario 2	€0	€5,590,889	€223,636	€36,960,000	€2,956,800	€2,417,338	€44,968,227

Denmark. The EVA modelling system is based on an impact pathway chain and can be applied to estimate population-level exposure to air pollution from specific sources (via atmospheric transport and chemistry) and thus calculate the subsequent external health costs related to the specific source of pollution (Ballini and Bozzo 2015).

In scenario 2, the produced electricity in the biogas plant is supplied to the cruise ships via land-based cold-ironing installation at Oceankaj terminals to cover 60% of the total cruise visits in Copenhagen. Therefore, the annual external health cost for scenario 2 is the summation of externality costs of 60% vessels using cold ironing in berth plus the rest which is 40% using the A.E-generated electricity with 0.1% sulphur fuel. As the externality cost of 60% of the vessels using shore power (Nordic Energy Mix) is €263,702 and externality cost of 40% of the vessels using AE power (0.1%sulphur) is €2153,634, therefore:

Total externality cost of applying cold ironing for 60% of cruise vessels (in scenario 2)

$$= \sum_{i=1}^{i=n} 1E.\text{cost of }60\%\text{vessels using shore power} + \text{E.cost of }40\%\text{vessels using AE power}$$

$$= €\ 263,702 + €\ 2,153,634 = €\ 2,417,338$$

For scenario 1: The total externality cost is €5,384,086.
For scenario 2: The total externality cost is €2,417,338.

A summarized table of costs is generated, calculating the outgoing cash flow (see Table 6). The costs in all of the sections are the combination of capital costs and annual operational costs. The total costs of scenario 1 are low while scenario 2 has the highest expenditure due to the initial installation costs of both large-scale biogas plant and land-based cold ironing.

4.3 Benefit analysis

In this section, the four benefits, as listed in Table 8, related to the establishment of the circular model in CMP will be discussed and calculated. In the following sections, each of the savings will be discussed and analysed for the model in Copenhagen-Malmö Port.

4.3.1 Savings from cutting negative externality costs

For scenario 1, since there is no cold-ironing installation, the benefits of cutting externality cost will be zero, unlike the case in scenario 2 where 60% of cruise ships visiting Copenhagen are provided with shore power in Oceankaj terminals. Thus, there will be a reduction of externality cost for 60% of cruise ships at Copenhagen.

Annual total savings if 60% of vessels use cold ironing = [externality cost of 60% vessels using AE power consuming 0.1%sulphur] − [Externality cost of 60% vessels using shore power]

According to Ballini (2013a, b), the externality cost of 60% ships using AE power consuming 0.1% sulphur fuel is €3,230,452 and the externality cost of 60% vessels using shore power (Nordic energy mix) equals €263,704. Therefore, annual total

$$\text{savings if 60\% vessels are using shore power} = €3,230,452 - €263,704 = €2,966,748.$$

For scenario 1: The annual saving is 0
For scenario 2: The annual saving is € 2,966,748

4.3.2 Savings from electrical power sale to ships

Electricity cost charged from the city grid to port net is obtained from interviews with the CMP, as illustrated in Table 7. Each KWh without taxation is 58.18 øre (a currency unit worth one-hundredth of a Danish krone) while for sale taxation is included in the final price of 149.18 øre in 2017. This price can be used for electricity sale to the cruise ships in Copenhagen. According to Ballini (2013a, b), overall energy demand for cruise ships is 31 ,674 MWh/year. This data is used to calculate the electricity sale to only 60% of the cruise vessels which are assumed to use shore-power in the Oceankaj terminal in Copenhagen.

$$\text{Required electricity to 60\% visiting cruise ships} = 31,674 \text{ MWh/season} \times 60\% = 19,004 \text{ MWh/season}.$$

$$\begin{aligned}\text{Annual profit of electricity sale to 60\% visiting cruise ships}\\ &= 19,004\ MWh \times 149.18 \text{Øre/KW.h}\\ &= 28,350,167 \text{Øre} = 28,350,167 \text{ DKK}\\ &= €3,810,719\end{aligned}.$$

Table 7 The price of electricity charge from the city grid to port

Calculation of electricity costs 1 KWh			
1/100 DKK/kWh			
	2016	2017	2018*
Market price Energi Danmark	24.00	23.00	22.00
Net cost, local grid (estimated)	11.0	11.00	12.00
Net cost, energinet.dk	8.33	8.43	8.53
Public service obligations (PSO) tariff–phased out by 2022	23.40	15.75	12.75
Total net cost	66.73	58.18	55.28
Electricity tax exclusive of minimum tax	88.10	90.60	91.60
Electricity tax–minimum tax	0.40	0.40	0.40
Total gross excl. VAT	155.23	149.18	147.28
Elimination of electricity tax is currently being considered.			
Local grids are being studied to identify cost-cutting initiatives			

Provided by CMP through interviews (2017)

For scenario 1, since there is no shore-to-ship infrastructure at the Oceankaj; therefore, there will be no electricity sale to the cruise ships. Therefore:

For scenario 1: The annual saving is 0.
For scenario 2: The annual saving is €3,810,719.

4.3.3 Savings from the waste collection in the port area

To provide feedstock for the biogas plant, it is assumed that no more solid organic waste is collected from port area and transported to municipality incineration plant. Hence, there will be no extra charge for this waste management, and the collection cost has already been included in the annual operation and maintenance (O&M) cost of a biogas plant (Naskeo Environnement 2017). Therefore, the savings from the waste management at CMP cruise terminals is equal to the cut in costs of waste collection in the cruise terminals. The cost data was provided by the CMP during interviews as per cost subsection 1. For scenario 2, saving of waste management from all passenger and cargo terminals is assumed.

For scenario 1: The annual saving is 0
For scenario 2: The annual saving is € 1,036,600

4.3.4 Savings from selling the produced fertilizer to the agriculture industry

During biogas production from waste material, some amounts of compressed organic waste are left over. As per interview with the Puxin Company, for each case of the solid and liquid waste materials that are fed to the biogas plant, the produced solid and liquid fertilizer will be approximately half of the input amount. However, the company stated that the amount of solid fertilizer is dependent on the percentage of the water content of the feedstock. The fertilizers can be presented in the market for sale. According to Italian Biogas Association, each ton of digestate equals €13.34. This can be used to calculate the earnings from sale of digestate to the market (European Biogas Association 2017). For scenario 2, the same reference as in cost subsection 1 is used. The biogas plant with an approximate output of 36 MW is under construction in Denmark. As stated by the project manager of Biogas2020, in Samsø Municipality, the solid feedstock will be 120 tons/day. Therefore, the approximate 60 tons/day of feedstock is required for the model in CMP with output of 30 tons/day fertilizer. Therefore, there will be no production of fertilizer for scenario 1 while for scenario2:

Savings from sale of fertilizer = [annual fertilizer in ton] × €13.34 = [30 × 365] × €13.34 = € 4,002,000

Table 8 shows the summarized benefits for circular economy model and current condition of the port.

Table 8 Summarized benefits

	Annual saving from cutting negative externality costs	Annual saving from electrical power sale to ships	Annual savings from waste collection in port area	Annual saving from selling the produced fertilizer	Annual total benefit
Scenario 1	€0	€0	€0	€0	€0
Scenario 2	€2,966,749	€3,810,719	€1,036,600	€4,002,000	€11,816,067

5 Cost-benefit analysis and discussion on the results

To calculate the time to repay the investment for the establishment of the proposed circular economy model in scenario 2, pay-back (Table 9) is provided which include both capital costs of installation of the biogas plant and cold ironing. Four annual saving items arising from the proposed circular economy model contributes to repay the total investments in a model lifetime of 25 years (Vasiliki et al. 2012). In scenario 2, there will be a year of payback between the 5th and the 10th year that shows the feasibility of the proposed model. The dynamic approach of benefits and costs, in scenario 2 with recovery year, should be considered over years.

Because of the fact that the same amount of a credit can have different values depending on when the investment takes place, the net present value (NPV) is used to calculate profit by subtracting the present values (PV) of outgoing cash flows (costs) from the present values of incoming cash flows (benefits) over a period of time. According to literature, the interest rate of 8% is considered for NPV calculations (Energypedia 2017) and defined as follows:

$$\mathrm{NPV} = \sum_{t=1}^{n} \frac{B_t - C_t}{(1+k)^t}$$

NPV	net present value
C_t	costs in year t
B_t	benefits in year t
k	discount in year t
t	number of years from the present
n	total number of the year of the analysis period

$$\text{For the 6th year NPV} = \textstyle\sum_1^6 \frac{70896402-76085922}{(1+0.08)^6} = \frac{-5189520}{1.586} = -272,080\ \text{EUR}$$

$$\text{For the 7th year NPV} = \textstyle\sum_1^7 \frac{82712469-81675094}{(1+0.08)^7} = \frac{1037375}{1.713} + = +605,589\ \text{EUR}$$

Based on the above NPV calculations, the 7th year is the beginning of recovery of the investment. A cost-benefit analysis of the installation of the model for scenario 2 yielded positive net present values (NPV) at the prevailing discount rate of 8%. The

Table 9 Cost benefit for scenario 2

	1st year	5th year	10th year	15th year	20th year	25th year
Annual costs of waste management in terminals	0	0	0	0	0	0
Costs of biogas power plant installation (€) CAPEX	€5,590,889	€5,590,889	€5,590,889	€5,590,889	€5,590,889	€5,590,889
Annual O&M cost of biogas power plant (€) OPEX	€215,034	€1,075,170	€2,150,340	€3,225,510	€4,300,680	€5,375,850
Cost of gold-ironing installation at CMP (€) CAPEX	€36,960,000	36,960,000	€36,960,000	€36,960,000	€36,960,000	€36,960,000
Annual O%M cost of cold-ironing installation at CMP (€) –OPEX	€2,956,800	€14,784,000	€29,568,000	€44,352,000	€59,136,000	€73,920,000
Annual externality cost of ships at berth	€2,417,338	€12,086,690	€24,173,380	€36,260,070	€48,346,760	€60,433,450
Total cost	€48,140,061	€70,496,749	€98,442,609	€126,388,469	€154,334,329	€182,280,189
Annual saving from cutting negative externality cost	€2,966,748	€14,833,740	€29,667,480	€44,501,220	€59,334,960	€74,168,700
Annual saving from electricity sale (with taxation) to ships	€3,810,719	€19,053,595	€38,107,190	€57,160,785	€76,214,380	€95,267,975
Annual saving from waste management in port area	€1,036,600	€5,183,000	€10,366,000	€15,549,000	€20,732,000	€25,915,000
Annual saving from sale of produced fertilizer to the agriculture industry	€4,002,000	€20,010,000	€40,020,000	€60,030,000	€80,040,000	€100,050,000
Total benefits	€11,816,067	€59,080,335	€118,160,670	€177,241,005	€236,321,340	€295,401,675
Payback = benefit-cost	−€36,323,994	−€11,416,414	€19,718,061	€50,852,536	€81,987,011	€113,121,486

results demonstrate that the establishment of the model for scenario 2 is capital intensive. However, the total cost is viable with a payback period (PBP) of 7 years.

The maritime and port industries like other sectors have the potential to benefit from application of circular economy approach to decrease the negative externalities, to boost economic growth and enhance competitiveness. The circular model of this research focused on 'waste-to-clean energy', in line with Goal 7 of the UN Sustainable Development agenda, to provide clean and affordable energy for all. In the literature review, some port cities in Le Havre region, which have already adopted circular economy in their development strategies, have been analysed. The remarkable similarity of them was found in the transition towards less dependence on fossil fuel and import of raw materials. Furthermore, their energy policies are underpinned by renewables. The novelty highlighted refers to the point that it is the first investigation with a focus on the application of a circular economy model in the port area independent from the municipality development plans. This paper is aimed at assessing the feasibility of the implementation of a circular economy approach at CMP. By application of qualitative and quantitative methods on the data from primarily CMP and literature, the cost-benefit analysis conducted for the proposed model scenario. In addition, the payback time of initial investment of the model is calculated to be more close to reality. In scenario 2, a positive net present value (NPV) showed the recovery of investment, at the prevailing discount rate of 8% in 7 years. It means that CMP will have economic benefits. Additionally, the model offers significant reduction in air pollution besides securing the port energy demand.

6 Conclusion and recommendation

The maritime and port industries have substantial potential to benefit from the application of circular economy businesses not only to decrease the negative externalities but also to boost economic growth and enhance competitiveness. The principle of the proposed circular model of this research is to utilize resource yields by circulating ship-originated waste to use at the highest utility in the biological cycle. The proposed circular model includes involvement of cooperation of multi-stakeholders. In the second scenario, by using some household and agriculture wastes by the port-owned plant, the workload on the municipality in waste management will be reduced. The proposed circular economy framework can be generalized to be applied to any other port in the world with the same modelled waste management. Mostly, the seaports with the similar geopolitics are located on high-traffic shipping routes with high ship-originated waste handling; like Bandar Abbas in the Strait of Hurmuz in the Persian Gulf, and Singapore in Malacca Strait. This approach can offer a unique opportunity to the CMP to use its anchorage area as a place for waste reception from all types of vessels which are not even going to be berthed at CMP.

For further studies, it is recommended to develop the proposed circular economy of this paper to other types of ship-originated wastes such as sludge and dirty oil. Furthermore, multi-criteria analysis can be pursued in addition to cost-benefit analysis.

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