# CRUISE SHIP TOURISM -

# A LCA ANALYSIS

Morten Simonsen

Western Norway Research Institution,

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# Content

## Introduction

In this paper we have used an analytical approach called triangulation [1]. It can be separated into two parts, method triangulation and data triangulation. The overall idea is to produce several estimates for the same phenomenon or observandum, i.e. cruise ships' fuel consumption at sea or in port. If several estimates for the same observandum agree to a reasonable degree we have more confidence in all of them. If they disagree substantially we have reason to question the underlying assumptions or calculations. This should lead to a more thorough inspection of each of them.

We can distinguish between method triangulation and data triangulation. In method triangulation we employ different methods to arrive at different estimates of the same phenomenon. Two examples from LCA analysis may be a top-down approach and a bottom-up approach. The first one tries to arrive at estimates on a more detailed level from macro-data at aggregated levels. The second one starts at a detailed level and try to aggregate estimates to higher levels. If different methods arrive at estimates that are reasonable consistent, coherent and continuous the estimates will be considered strengthened. By consistent we mean that estimates do not change when small variations in assumptions or preconditions occur. When i.e. analyzing transport systems we must require that the different systems have the same borders, that they are defined consistently. By coherent me mean that phenomena that are related theoretically also fit together empirically and by continuous we mean that estimates for the same phenomenon at different times do not differ substantially.

The two forms of triangulation are complementary. Method triangulation concerns the validity of the analysis. Do our empirical definitions fit in with the theoretical ones and how generalizable are our estimates to a larger context? Data triangulation concerns the measurement practice or reliability of the estimates. Is there reason to believe that some calculation errors are present, i.e. when converting from British Thermal Units to joule or from miles pr gallon to litre per km?

Triangulation also concerns verifiability of estimates. If several estimates are well documented it is easier for other researchers to do the same calculations and check the results. Documentation should include what method is used to arrive at the estimates as well as underlying assumptions for calculations, i.e. specification of what fuel is assumed when analyzing fuel consumption as well as what emission factor is applied for that specific fuel.

## Energy chain analysis

We will analyze the environmental impact of cruise ship tourism by estimating a cruise ship's energy consumption and emissions of climate gases during its different life stages. Each of these stages can be considered to be a energy chain. This implies that energy is consumed in different amounts for different purposes at different life stages. The crucial point is that this energy must be produced before it is consumed, and the production of energy also requires energy. Energy then is the basic input at all stages and all emissions are related to the amount and type of energy consumed for a specific purpose at a specific life stage.

We call the energy consumed for a specific purpose, i.e. propulsion of a cruise ship, for end energy. The energy required for the production of this end energy, with their related emissions, should be an integral part of the end energy estimate itself. This means that all end energy consumption should be

[1] Triangulation (social science), http://en.wikipedia.org/wiki/Triangulation_(social_science)

considered to be the last part of a chain of intertwining energy consumption and production. At the beginning of the chain is the energy source that is converted into some useful end energy carrier. The extraction of the energy source, its conversion into useful energy, all these steps also requires energy consumption and emissions. The energy applied in each of these steps is also a energy chain with its specific conversion from energy source to energy carrier. Therefore, an estimate of a specific energy consumption should mirror these web of energy chains leading up to it.

We will mainly use estimates obtained from a German LCA database called ProBas. The database presents estimate for a specific energy carrier, i.e. diesel in Germany 2005, as an energy chain. Each estimate consists of the direct energy available as well as the indirect energy consumed further down the chain or upstream in order to produce the final end energy. The same is true for embedded energy in i.e. materials like steel or aluminium. Energy estimates for production of these materials includes indirect estimates of energy consumption further down the chain, i.e. to extract and fabricate raw materials, as well as direct energy consumption in the final production of the material in question.

## Propulsion - direct energy chain

According to Carnival Corporation, their cruise ships in 2008 used 0,1148 kg fuel pr ALB-km or available lower berth km [2]. An ALB-km is equivalent to two passengers pr km. We will consider ALB-km and passenger-km to be identical terms.

Walnum [3] quotes an emission factor from Carnival publications of 3,117 kg $CO_2$ pr kg fuel for heavy fuel oil (HFO). Environment Canada uses an emission factor of 3,124 kg pr litre for heavy fuel oil [4]. Since its density is 0,98 kg/litre [5] this corresponds to 3,188 kg $CO_2$ pr kg fuel. Cruise ships also use marine diesel oil (MDO) and marine gasoline oil (MGO). According to Walnum, referring to documentation from Carnival cruise company, use of MDO and MGO amounts to 4% of total fuel use. We therefore discard these fuels in these calculations and concentrate on heavy fuel oil. Using Walnum's emission factor pr kg fuel heavy fuel oil we get 357,8 gram $CO_2$ per passenger-km.

In order to estimate the fuel consumption pr km for the cruise ship at sea we have to make assumptions about number of passengers onboard the ship pr km. According to Walnum (2011), a total of 78 cruise ships arrived in Bergen, Norway, from March to September 2010. They carried a total of 291 887 passengers. On average, each ship therefore carried 3742 passengers. Using this number, we can use Equation 1 to estimate fuel consumption in kg pr km. With the numbers above, we get 429,6 kg or 438,4 litre pr km.

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[2] Walnum, H.J. (2011): *Energy use and CO2 emissions from cruise ships - A discussion of methodological issues*, Western Norway Research Institution, Note 2/2011, page 5,http://www.vestforsk.no/filearchive/vf-notat-2-2011-cruise.pdf

[3] ibid., Page 5

[4] Table 4, http://www.ec.gc.ca/ges-ghg/default.asp?lang=En&n=AC2B7641-1

[5] Toutain, J.E.W, Taarneby, G., Selvig, E.,*Energiforbruk og utslipp til luft fra innenlandsk transport*, Statistisk Sentralbyrå, Rapport 2998/49, Table 2.1 http://www.ssb.no/a/publikasjoner/pdf/rapp_200849/rapp_200849.pdf

Equation 1 Fuel consumption pr km

$$\frac{Fuel-kg}{km}=\frac{Fuel-kg}{passenger-km}*\frac{passenger-km}{km}$$

A good practice is to assess estimates by triangulation, a method by which we collect identical estimates for the same phenomenon or attribute. If several estimates agree within a reasonable range we may get a larger confidence in each of them. If we find an unreasonable disagreement this is a reason to question the underlying assumptions of the different estimates.

Carnival Corporation have 20 cruise ships that are build before or in 2008 [6]. These ships had a capacity of 2722 passengers on average. This gives 312,5 kg heavy fuel oil pr km or 318,9 litre pr km with the fuel consumption pr passenger-km estimated above. Again, these estimates are based on passenger capacity and not the actual number of passengers on board.

We can assess our estimates of fuel consumption by using information about the cruise ship QE2. According to "How Cruise Ships Work" the cruise ship QE2 consumes 380 tons of fuel per day when it is travelling at a speed of 28,5 knots and is fully loaded with fuel for a 12 days roundtrip. This speed corresponds to 37 km pr hour. If we assume the ship travels 24 hours without spending time in port we have 15,8 tons of fuel per hour for a distance of 37 km. This corresponds to 428 kg fuel pr km. Assuming a density of 0,98 for heavy fuel oil we get 437 litre pr km. QE2 can take 1777 passengers [7]. This gives 0,241 kg fuel per passenger-km using passenger capacity and not actual passenger load factor.

The estimate for QE2 is an estimate for an individual ship while the other estimate presented above is an average for ships belonging to Carnival Corporation in 2008. The QE2 is an older ship originally built as an ocean liner [8] in the late 1960's. QE2 has 70 327 gross tonnes (which actually is a measure of volume and not weight). The 20 ships used by Carnival Corporation in 2008 had an average size of 88 435 GT. It is therefore reasonable that the fuel consumption and emission estimates for QE2 should be larger given that it is an older ship with a larger GT to passenger ratio.

## Energy use and emissions in port

Figure 1 shows gallon consumed per hour in port for cruise ships visiting Skagway, Alaska, summer season 2008. The numbers are obtained from Graw & Faure, 2008 [9]. According to the report, cruise ships in port operates in "hotel mode" whereby most of the power generated is used for heat, hot water and air condition. This is contrary to operations in open sea where most of the ships' energy use is related to propulsion.

The required electricity for ships in port are generally produced by diesel generators. These mostly run on Intermediate Fuel Oil (IFO). Gas turbines can also be used, but these are more expensive to

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[6] Wikipedia: http://en.wikipedia.org/wiki/Carnival_Cruise_Lines One of their cruise ships, Carnival Freedom, is built in 2008, presumably that ship was not in service that year.

[7] See http://en.wikipedia.org/wiki/Queen_Elizabeth_2

[8] See http://en.wikipedia.org/wiki/Queen_Elizabeth_2

[9] Graw, R., Faure, A.: *Air Pollution Emission Inventory For 2008 Tourism Season Klondike Gold Rush National Heritage Park, Skagway, Alaska*. Alaska Department Of Environmental Conservation, Division of Water, Cruise Program, February 2008, see http://dec.alaska.gov/water/cruise_ships/pdfs/Skagway2008_Final_Emissions_Report.pdf

operate. Auxilliary boilers are also used while ships are in port in order to generate steam and hot water. The report registered the electricity needed to operate cruise ships in hotel mode while in port. It also registered the amount of fuel in gallons consumed per hour while in port [10]. The electricity needed for hotel mode in one hour is not identical to number of gallons consumed during the same time span. This is probably due to the fact that the ship needs electricity for more than the hotel functions. Emergency systems must be avaliable, pumps, lifts, restaurants, shops and leisure facilities need lightning in addition to hotel rooms and cooling must be available for the ships' food storage.

**Figure 1 Gallons per hour in port**

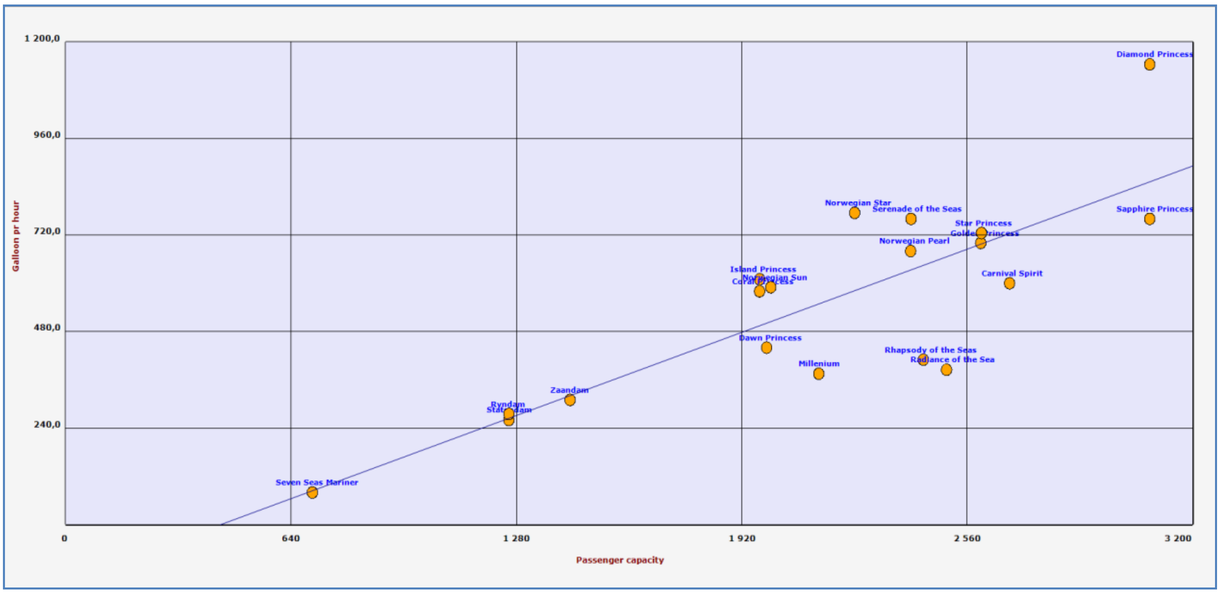



Figure 1 shows that gallons consumed in port is. The figure indicates that fuel consumption is a function of the ships' size measured in passenger capacity. All data are obtained from Graw & Faure, except from some passenger capacities that are obtained from Wikipedia. The fitted regression line suggests that an increase in capacity of 100 passengers would result in 32,3 more gallons per hour. Still, there are marked differences between ships of about the same size. This indicates that passanger capacity alone is not sufficient to explain the differences in fuel consumption.

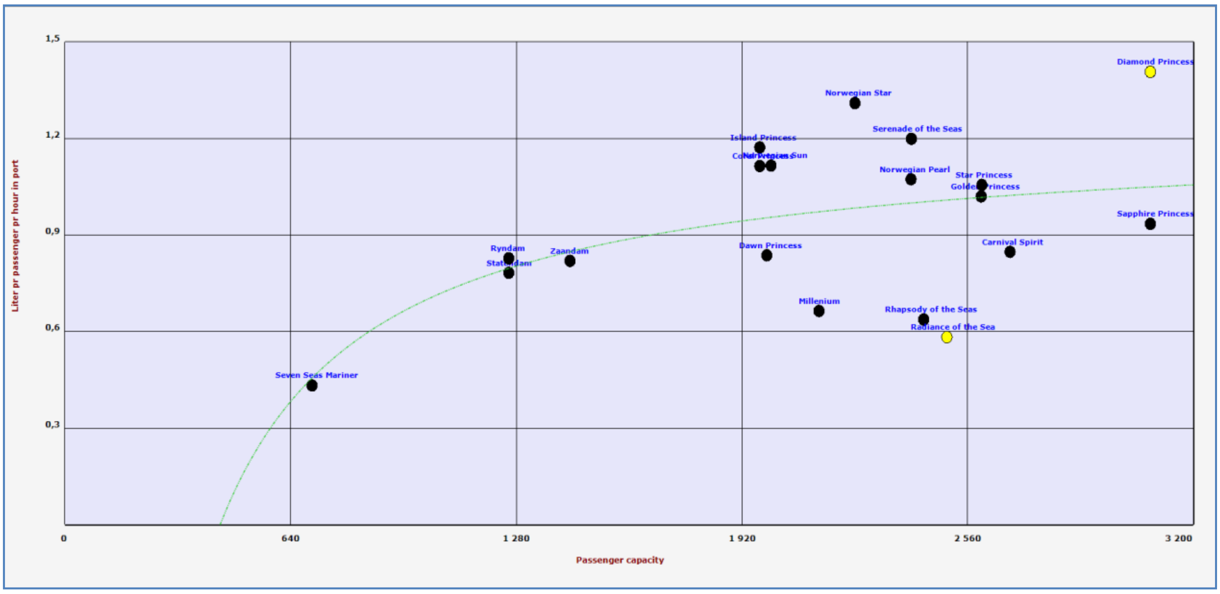
Figure 2 shows litre pr passenger pr hour consumed while in port in Skagway, Alaska [11] as a function of passenger capacity. The figure shows increasing deviations from the fitted regression line as passenger capacity increases. This indicates again that number of passengers is a poor indicator of fuel consumption in port. We also note that the bigger ships do not have less energy consumption pr passenger than smaller ships measured by passenger capacity. Consequently, there is no economies of scale for the bigger ships.

However, the figure shows som interesting differences between ships of roughly the same passenger capacity. This is especially true for the ships "Radiance of the Seas" and "Diamond Princess", marked with yellow in the figure. The first ship is powered by a gas turbine [12] while the last one is powered by

[10] ibid., Figure 4.
[11] Graw & Faure
[12] http://en.wikipedia.org/wiki/MS_Radiance_of_the_Seas

conventional diesel generators. The proulsion system may be a detemining factor for fuel consumption while in port.

**Figure 2 Fuel consumption in litre pr passenger pr hour in port**




There are also som striking differences between the ships "Diamond Princess" and "Golden Princess" from the same company. According to the Skagway report, the first ship uses 2 diesel engines in port while the second one uses one engine. Also, the hotel load for the first ship is 1 MW larger than the second one even if the first ship's passenger capacity is only 80 passenger more than the second one. If the two ships stay 12 hours in port, this means the first one is using 12 000 kWh more electricty for the hotel load than the second one.

This discussion indicates two conclusions: Firstly, the ships' propulsion systems do matter for fuel consumption while in port. Secondly, hotel design for individual ships should matter for the required hotel electricity load while residing in port.

Passenger capacity may be a bad indicator of ships' size. It may be that bigger ships can fit more passengers pr weight unit or pr volume unit. Then weight or volume should be a better indicator of the ships' size than passenger capacity.

Cruise ships are often measured in gross tonnes. This measure is not a weight measurement contrary to its name. It is rather a volume measurement since grosse tonnes are an indicator of the ships' available storage capacity or "overall internal volume" [13] . Figure 3 shows the relationship between ships gross tonnes and passenger per gross tonne. The registrations are for the ships docked in Skagway, 2008. The figure shows that bigger ships do not accomodate more passenger pr volume unit or pr gross tonne. Cruise ships with a gross tonnage of 75 000 have the same number of passenger pr gross tonne as ships with up to 120 000 gross tonnes. One explanation for may be that bigger ships have more and bigger shops, more leisure facilities and bigger cinemeas, theatres etc. So the tendency for bigger ships to accomodate more passengers would be counter-balanced by a tendency towards more and bigger facilities for the extra amount of passengers.

[13] Wikipedia, Gross tonnage, http://en.wikipedia.org/wiki/Gross_tonnage

Figure 3 Gross tonnes vs passenger pr gross tonnes

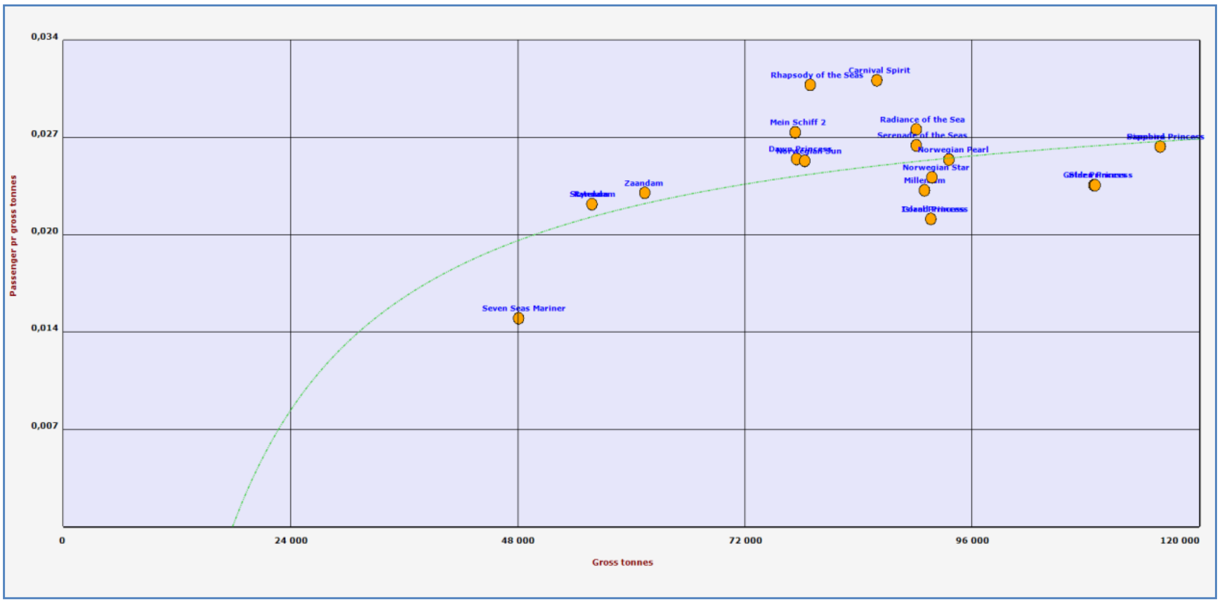



Figure 4 Gross tonnes vs hotel load in kW pr passenger

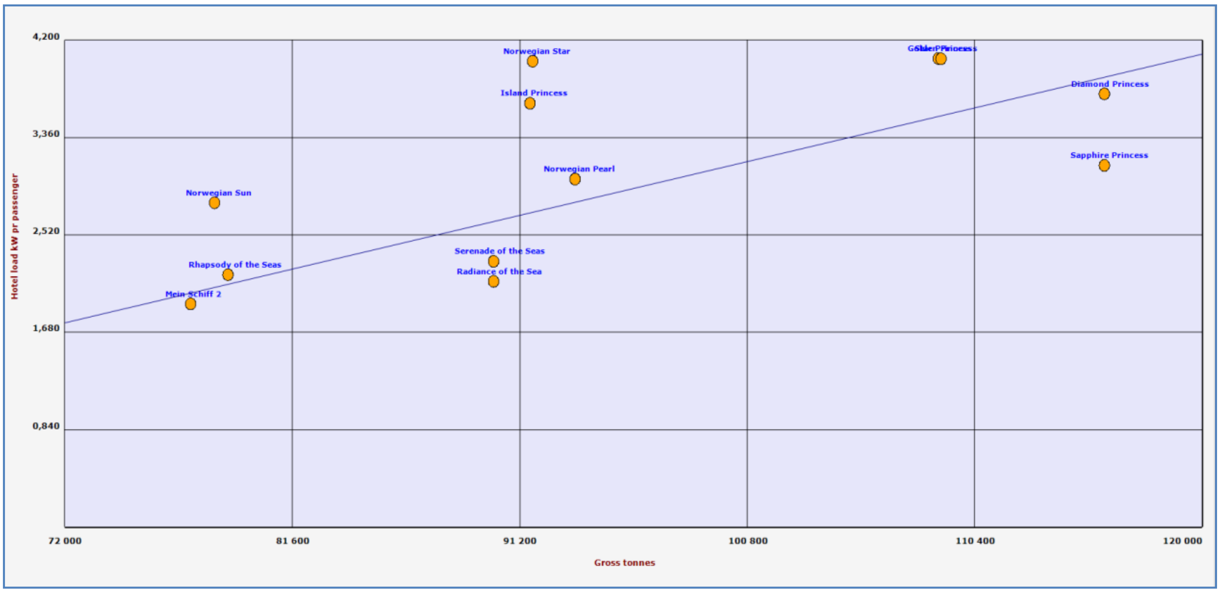



Figure 4 shows that bigger ships measured by gross tonnes have a larger hotel load pr passenger while docked in port. So even if we only look at hotel load in port, bigger ships use more energy pr passenger than small ships. The advantage of bigger ships then is not economies of scale, an ability to fit more passengers pr volume unit, but rather more attractions for the accomodated passengers.

How much energy does a cruise ship use while in port? If we look only at hotel load, Table 1 shows the energy use for three hypotethical cruise ships in port. The calculations are based on the data from Skagway 2008 with regression lines fitted in figures above. The table shows that the biggest cruise ships consume about 130 000 kWh for a port stay of 12 hours.

Table 1 only show energy use for  the hotel load. Ships also need energy use for other functions as mentioned above such as emergency systems, lifts, lightning, dispensing gray and black water etc.

**Table 1 Energy consumption while in port**

| | A | B | C |
|---|---|---|---|
| Gross tonnes | 75000 | 100000 | 120000 |
| Load pr passenger | 2,3 | 3,3 | 4,0 |
| Passengers | 2000 | 2500 | 2700 |
| Load kW | 4 594 | 8 167 | 10 915 |
| Hours in port | 12 | 12 | 12 |
| Energy use kWh | 55 129 | 98 002 | 130 977 |

**Figure 5 Gross tonnes vs energy use in litre pr passenger pr hour**

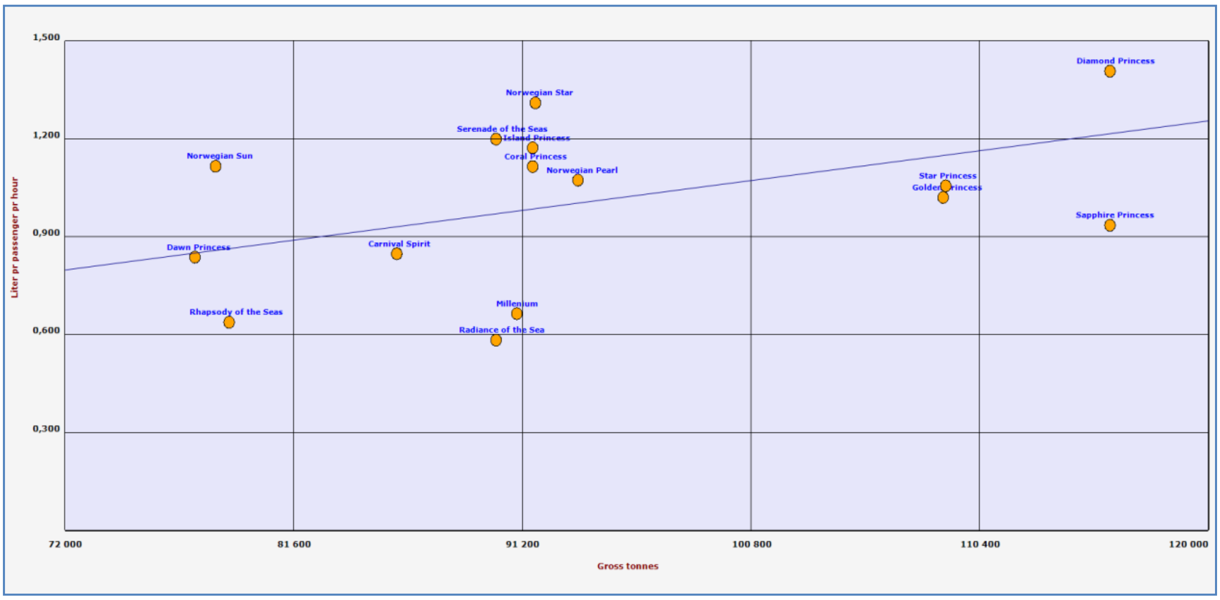



**Table 2 Energy consumption in port for total ship functions**

| | | A | B | C | Remark |
|---|---|---|---|---|---|
| Gross tonnes | A | 75000 | 100000 | 120000 | |
| Litres pr passenger pr hour | B | 0,83 | 1,06 | 1,26 | From Figure 2 |
| Passengers | C | 2000 | 2500 | 2700 | |
| Litres pr hour | D=B*C | 1 654 | 2 662 | 3 389 | |
| Hours in port | E | 12 | 12 | 12 | |
| Litres in port | F=E*E | 19 843 | 31 944 | 40 668 | |
| MJ pr litre HFO [14] | G | 39,8 | 39,8 | 39,8 | |
| kWh in port | H=(F*G)/3,6 | 219 374 | 353 155 | 449 608 | 1 MJ=3,6 kWh |

[14] Toutain, J.E.W., Taarneby, G., Selvig, E.: *Energiforbruk og utslipp til luft fra innenlandsk transport*, SSB-Rapport 2008/49, Oslo 2008, Table 2.1, Page 15, http://www.ssb.no/a/publikasjoner/pdf/rapp_200849/rapp_200849.pdf

Figure 5 shows energy use in litres pr passenger pr hour vs cruise ships' gross tonnes. This is equivalent to Figure 2 except we use gross tonnes instead of passenger capacity as a measurement of ships' size. Based on Figure 5 we can construct Table 2Table 1 which shows total energy use for all cruise ships' functions while in port, not only for hotel functions. We use the same three hypothetical cruise ships as in Table 1. All in all, the biggest ships use slightly more than 449 000 kWh for 12 hours in port. The increase in energy use is about 320 000 kWh for 12 hours when we include all functions for the biggest ships.

Figure 6 shows emissions of NOx in kg pr hour for cruise ships in Skagway, 2008, while in port. The emissions are a function of the hotel load in MW. The figure shows the emissions relative to the ships' size measured in gross tonnes.

Figure 6 Emissions of NOx pr hour in port


Table 3 shows emissions of NOx pr hour for our three hypothetical ships. Roughly, an increase in gross tonnes of 10 000 yields an increase in NOx emissions of 17 kg pr hour.

Table 3 NOx emissions pr hour for different cruise ships

| | A | B | C |
|---|---|---|---|
| Gross tonnes | 75 000 | 100 000 | 120 000 |
| kg NOx pr hour | 54,4 | 169,0 | 204,4 |

# Production of cruise ships - indirect energy chain

## Lightweight estimation

In order to obtain an estimate of energy use and emissions related to production of cruise ships we need to know the material composition of them. The first step towards this material analysis is to obtain an estimate of cruise ships' own weight. In naval terminology, this is referred to as the ship's lightweight [15]. This is the weight of the ship without fuel in tanks, water in ballast tanks, passengers,

[15] Foreship, Some Important Naval Architectural terms, see http://www.foreship.com/documents/fs-naterms.pdf

crew and their luggage load. These weight items make up the deadweight of the ship [16]. Together, the lightweight and the deadweight make up a ship's displacement weight. This section proposes a method to estimate cruise ships' lightweight based on known attributes such as gross tonnes.

From different web sites we have obtained deadweight for some cruise ships. For the same ships we have also obtained ship's length, breadth and draft. The last attribute is the height from the waterline to the hull's keel. When the ship is fully loaded the waterline marks where the ship is floating in the water. The ship's length is measured as length between perpendiculars. This is defined as "the distance between rudder shaft and the point where the bow stem enters water at design draft" [17]. The breadth is measured as moulded breadth which is defined as "the vessel breadth without the shell plating" [18].

When the attributes length between perpendiculars (LPP), breadth and draught are known we can calculate the ships displacement weight as follows:

**Equation 2 Calculation of displacement weight**

$$displacement\_weight = LPP * breadth * draught * seawater\_density * block\_coefficient$$

In Equation 2, seawater density is 1,025 tonne/$m^3$ . The block coefficient is a factor which describes how much of the ship's rectangular volume defined by its length, breadth and draft is actually filled up given the ship's design. The block coefficient describes the "fullness of the hull" [19].

We have obtained the required information in order to calculate the displacement weight for a set if cruise ships. Data sources are the classification society Det Norske Veritas [20] where applicable or the web site shipspotting.com which tracks ships and give basic information about each one of them. The last source is used where Det Norske Veritas is not used as classification authority for the relevant ship. For each ship we have also registered its deadweight and its gross tonnes. The ship's lightweight is defined as

**Equation 3 Calculation of lightweight**

$$lightweight = displacemen\_weight - deadweight$$

When we know the displacement weight and the deadweight we can calculate lightweight according to Equation 3. This is done in Table 17. In order to obtain the displacement weight we need an estimate of the block coefficient. We have chosen to use a known block coefficient for an actual ship, the Norwegian Gem. We know its length between perpendiculars, the breadth and the draught [21]. We can therefore find the bloc coefficient as follows:

[16] ibid.
[17] ibid.
[18] ibid.
[19] ibid.
[20] See http://en.wikipedia.org/wiki/Det_Norske_Veritas
[21] Det Norske Veritas, https://exchange.dnv.com/exchange/main.aspx?extool=vessel&subview=dimensions&vesselid=26557

Equation 4 Estimating block coefficient

$$block\_coefficient = \frac{displacement\_weight}{LPP * breadth * draugth * seawater\_density}$$

We also know the deadweight [22] and the lightweight [23] for this ship. We can therefore calculate the displacement weight and use it in the equation above to estimate the actual block coefficient used. The estimated block coefficient for Norwegian Gem is 0,71 [24] and we will use this block coefficient to estimate the displacement weight for other cruise ships when we know their length between perpendiculars, breadth and draught. This information is available from the classification company Det Norske Veritas(if the ship is classified by this company) or from web sites like shipspotting.com or vesselfinder.com. We have used average available ratio of length between perpendiculars to overall length to find the former from the latter if the former is unknown.

It is of special interest to estimate the ratio of lightweight to gross tonnes since the last attribute is easily obtained. From the ratio we can therefore estimate the ship's lightweight from its gross tonnes without knowing the ship's length, breadth, draft or block coefficient. The gross tonne value is readily available from many web sites since this is the attribute used to calculate ships' port dues [25].

Figure 7 Lightweight as proportion of gross tonnes by gross tonnes

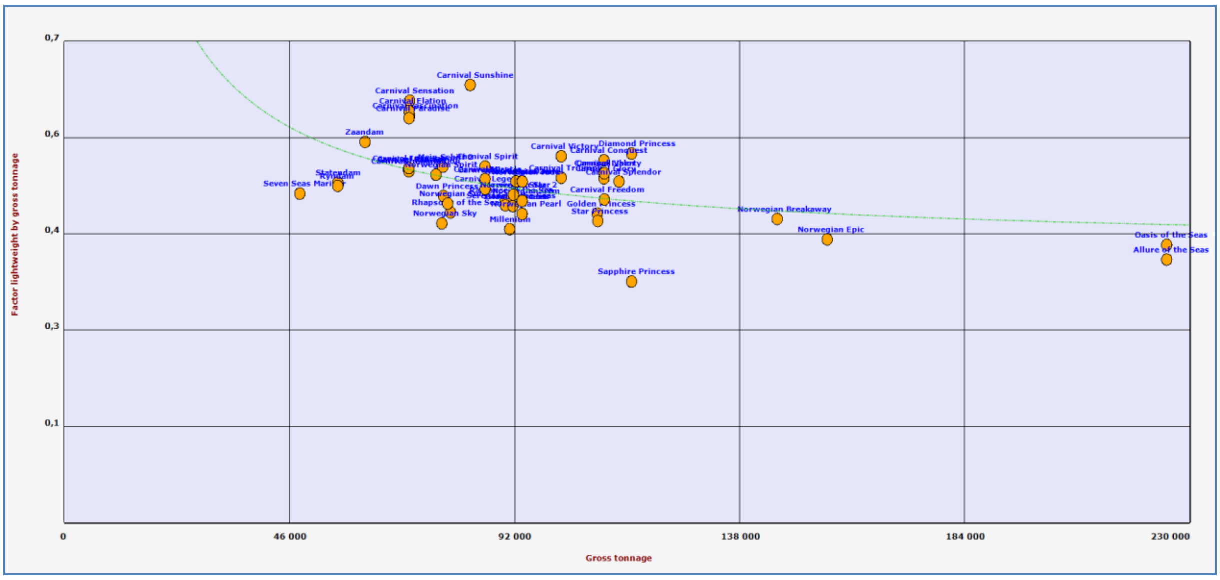



Figure 7 shows lightweight as a proportion of gross tonnes versus gross tonnes for 51 cruise ships. The lightweight is calculated for each ship according to Equation 3 above. We have fitted an inverse regression line which captures the underlying trend, the proportion seems to decrease to a threshold value as gross tonnage increases. This indicates that there is a lower absolute value for the lightweight's proportion of total gross tonnes.

[22] ibid.
[23] Evegren, F., Hertzberg,T., Rahm, M.: *LASS-C; Lightweight construction of a cruise vessel,* SP-Report 2011:12, Table 3-2, Page 15, http://s-lass.com/en/Documents/Rapporter/SPreport_2011_12[1]-Cruise%20vessel.pdf
[24] See also Cruise Industry News, Quaterly Magazine Winter 2003-2004: "Smooth sailing is also ensured by QM2's block coefficient which is 0.61 compared to 0.73 for most cruise ships. "
http://www.cruiseindustrynews.com/cruise-magazine/feature-magazine-articles/67-articles/15.html
[25] Wikipedia, http://en.wikipedia.org/wiki/Gross_tonnage

Table 4 shows lightweight calculations for our three hypothetical cruise ships based on the fitted regression line in Figure 7.

Table 4 Lightweight calculations

| | A | B | C |
|---|---|---|---|
| Gross tonnes | 75 000 | 100 000 | 120 000 |
| Factor | 0,50 | 0,47 | 0,46 |
| Lightweight | 37 446 | 47 239 | 55 073 |

Figure 8 Gross tonnes pr passenger vs passenger capacity

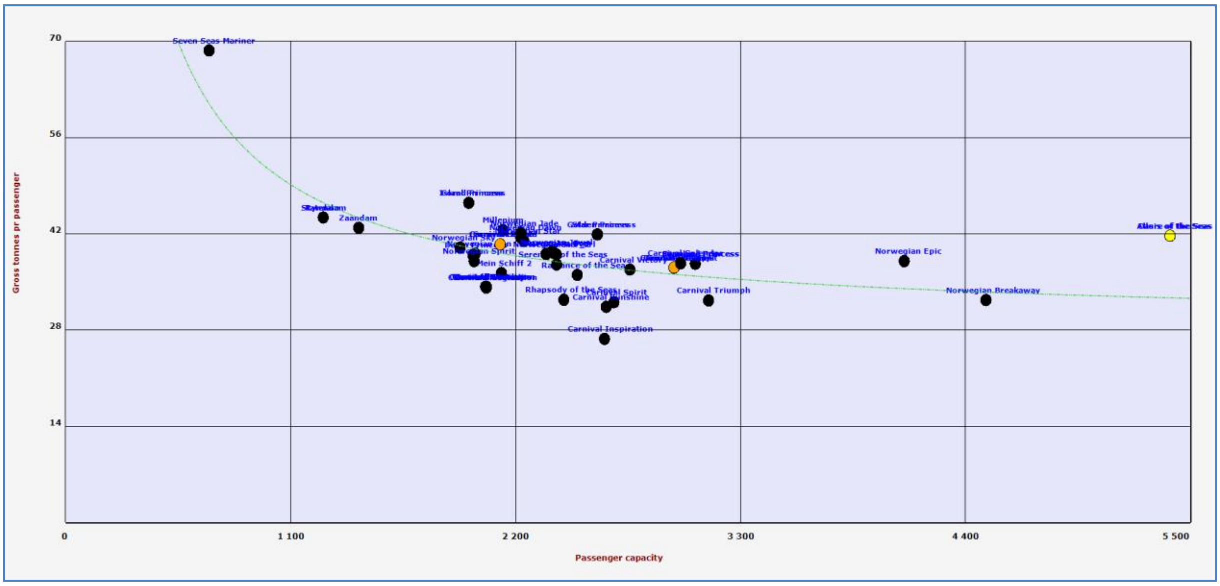



Figure 8 shows passenger pr gross tonnes vs passenger capacity. Gross tonnage is really a measurement of the ships' internal volume. The figure shows that the smallest ships have the biggest volume pr passenger. Another way to put it is that bigger ships have better utilization of their internal volume than smaller ships. The figure also shows that the effect of better utilization is strongest when passenger capacity is increased from 1000 to 2000. After that the effect is diminishing. There is a tendency for the two biggest cruise ships (Allure of the Seas and Oasis of the Seas, two overlapping points marked with yellow) to increase their gross tonnage pr passenger compared to the ships that comes next measured by gross tonnage. This may indicate that these cruise ships have more volume for shops, restaurants and entertainment facilities pr passenger then cruise ships with the second largest gross tonnes.

Table 5 Gross tonnes vs passenger capacity

| | A | B | C |
|---|---|---|---|
| Passenger capacity | 1000 | 2000 | 3000 |
| Gross pr pass | 51,2 | 39,8 | 36,1 |
| Gross tonnes | 51 196 | 79 689 | 108 182 |
| Factor | 0,55 | 0,49 | 0,47 |
| Lightweight | 28 122 | 39 283 | 50 444 |

Table 5 shows three hypothetical ships with three different passenger capacities and their calculated gross tonnes according to the regression line shown in Figure 8. The table shows that an increase from 1000 to 2000 passenger capacity will decrease gross tonnage pr passenger with 11 gross tonnes while a similar increase from 2000 to 3000 passengers implies a similar decrease of 4 gross tonnes. As already mentioned, the increase in utilization of gross tonnes is greatest when the passenger capacity is smallest. The table also shows that for every increase in passenger capacity of a thousand passengers the gross tonnage increases with the same amount, roughly 28 500 tonnes.

We have also included an estimation of the lightweight factor and the lightweight itself for ships in Table 5. The estimates are produced by using the regression coefficients from Figure 7.

## Material distribution

We have now established a method to estimate cruise ships' lightweight based on either gross tonnes or indirectly through passenger capacity. In order to arrive at an estimate for energy use and emissions related to production of cruise ships we need estimates of the material distribution of cruise ships.

We will build an estimate of material distribution based on two reports related to the S-LÄSS project which is a project initiated by the Swedish network of Lightweight constructions at sea [26]. One of the projects is an LCA analysis [27] of use of light weight composite material in a cruise ship's superstructure. This is the part of the ship that is above the waterline. The hull is the part below the waterline. The LCA-analysis is based on the cruise ship Norwegian Gem.

The other project is an analysis of using fibre-reinforced polymers, also a composite material, in the superstructure of the same ship, Norwegian Gem [28]. Both projects analyze the use of lightweight composite materials in the superstructure above deck 11.

The Norwegian Gem has a gross tonnage of 93 530 and a deadweight of 10 000 tonnes [29]. Length between perpendiculars is 263,5 meter, breadth is 32,2 meter and its draught is 8,625 meter [30]. According to Hou, the passenger capacity is 2 394 in cabins with double occupancy and the crew amounts to 1 101 persons [31]. According to Evegren et al., the ship has 15 decks [32] and the lightweight of the ship is 43 150 tonnes [33].

The decks above deck 11 have a total weight of 5 200 tonnes. Of this, 2 050 tonnes are for steel structures and 310 tonnes for aluminium structures. The outfitting of these decks amounts to 2 840 tonnes, of this 1 090 tonnes are for public spaces inside, such as restaurants, pools, library, fitness

[26] http://s-lass.com/en/about/Sidor/default.aspx
[27] Hou, Q.: *Life-Cycle Assessment of Cruising Ship Superstructure*, Master Thesis in Sustainable Development, Uppsala University, Sweden, May 2011, http://uu.diva-portal.org/smash/get/diva2:451090/FULLTEXT01
[28] Evegren, F., Hertzberg, T., Rahm, M.: LASS-C; Lightweight Construction Of A Cruise Vessel, SP-Report 2011:12, Technical Research Institute of Sweden, 2011, http://s-lass.com/en/Documents/Rapporter/SPreport_2011_12[1]-Cruise%20vessel.pdf
[29] Det Norske Veritas, https://exchange.dnv.com/Exchange/Main.aspx?EXTool=Vessel&VesselID=26557
[30] ibid.
[31] Hou, page 17.
[32] Evegren et al., page 4.
[33] ibid., Table 3-2, page 15.

centre, tennis court etc. This weight is not split on materials, but presumably the materials are wood for doors and roofs, mineral wool for insulation, glass etc.

According to Evegren et al. the total glass weight for the front part of decks 13-15 is 23,8 kg. The authors claim that 5,3 kg of glass can be saved by using laminated glass. This saving makes up 22,3% of the original glass weight. Further, the authors claim that if the same weight saving procedure would be applied to all glass on decks above deck 11 the total saving would be 19 tonnes [34]. Assuming that the weight saving amounts to the same proportion of total glass weight we arrive at an estimate of 85,3 tonnes of glass for decks above deck 11. The total savings for all decks at the ship if laminated glass would substitute for ordinary glass would be 41 tonnes, this gives an estimate of 184 tonnes of glass for all decks at the whole ship.

Hou [35] claims that there are 50 tonnes of mineral wool on the decks above deck 11 on Norwegian Gem. This figure is estimated by using SimaPro database.

The ESAB Welding and Cutting Journal claims that the steel hull of the cruise ship Oasis of the Seas weighs 45 000 tonnes [36]. The cruise ship is the world's largest with a length between perpendiculars of 329,887 meter, a breadth of 47 meter and a draught of 9,3 meter. Combined with the density of salt water (1,025 kg for each litre of sea water) and a block coefficient of 0,71 this gives a displacement weight of 104 726 tonnes. Its deadweight is 15 000 tonnes which yields a lightweight (ship's own weight) of about 89 700 tonnes. The ship's steel hull weight therefore amounts to almost exactly 50% of the ship's total weight. This again means that the superstructure also weighs 45 000 tonnes.

There are obvious problems with using the material distribution for the decks above deck 11 as representative for the whole superstructure of Norwegian Gem. The main objection is that the lower decks have more passenger cabins while the upper decks have more public spaces such as restaurants, bars, tennis courts, library etc. This will obviously have an impact on the material distribution. Still, we do not have a more representative material distribution for the lower decks. Using this distribution, Table 6 presents an estimate for the material distribution for Norwegian Gem. The distribution is split on hull and superstructure. As can be seen from the table, we can account for about half of the superstructure weight and all of the hull's weight.

**Table 6 Material distribution for superstructure Norwegian Gem**

| | |
|---|---|
| Lightweight tonnes, actual value | 43 150 |
| Steel hull weight in tonnes, estimate | 21 641 |
| Superstructure weight in tonnes, estimate | 21 509 |
| Superstructure steel structure weight tonnes, estimate | 8 480 |
| Superstructure aluminium structure weight tonnes, estimate | 1 282 |
| Glass weight tonnes, estimate | 353 |
| Mineral wool tonnes, estimate | 207 |
| Materials accounted for superstructure, estimate | 10 322 |

[34] ibid., page 11

[35] Hou, page 32.

[36] Svetsaren, ESAB Welding and Cutting Journal Vol. 65, NO. 1, 2010, page 26:"The steel plate weight of the hull is around 45,000 tons." http://www.esab.com/global/en/news/upload/svetsaren-1_2010.pdf

## Embedded energy and emissions

How much energy is embedded in the materials used to build a cruise ship? We will use energy use factors and emissions factor for different materials to provide an estimate for total energy use and total emissions of climate gases for building a cruise ship. We will use the cruise ship Norwegian Gem as our reference ship.

The energy use and emission factors are discussed in Simonsen [37], [38]. They are taken from the German online LCA-database ProBas [39], but for each factor chosen several alternative estimates have been considered. This process of triangulation, collecting several estimates for the same process and reviewing them against each other, is the underlying method applied in the selection of the factors. By applying a mutual examination of estimates, strength and weaknesses for each of them are more readily uncovered.

The estimates include process energy and related emissions from raw material excavation and fabrication, transport to production plant and processing at plant. The estimates therefore contain all embedded energy and related emissions in the final product [40].

ProBas has estimates for 2005 and 2010. Since the building of Norwegian Gem started in 2006 we have used factors from 2005 since these are at least as old as the ship. Since Norwegian Gem was built at Meyer Werft in Papenburg, Germany, we use estimates for production of materials in Germany with German electricity mix. Since Germany import materials we have used estimates for mixed production where available [41].

For steel, we have used an estimate for hot rolled steel. This estimate is used both for hull and for superstructure. We have assumed that cold rolled steel plates are too thin to be used in a cruise ship. Hot rolled steel plates are in any case made from hot rolled ones [42]. For glass, we have used an estimate that does not use any recycling of glass. For steel, it is assumed that about a third of the raw materials needed comes from the EAF [43] production method where some 97% of the input comes

[37] Simonsen, M.: *Metal Production*, Vestlandsforsking April 2009, http://vfp1.vestforsk.no/sip/EnergiTransport/pdf/Felles/MetalProduction.pdf

[38] Simonsen, M.: *Energibruksfaktorer og utslippsfaktorer for ulike metaller*, Vestlandsforsking June 2009, http://vfp1.vestforsk.no/sip/EnergiTransport/pdf/Felles/EnergibruksfaktorerOgUtslippsfaktorer.pdf

[39] ProBas is a cooperation project between the Federal Agency for Environment and Ôko-Institut, a research institute in Freiburg, Germany, see http://www.probas.umweltbundesamt.de/php/index.php

[40] From ProBas documentation: "Bei Ökobilanzen für Produkte – zum Beispiel für Getränkeverpackungen – wird der gesamte Lebensweg des Produktes betrachtet. Von der Wiege bis zur Bahre - also von der Herstellung über die Nutzung bis zur Entsorgung des Produktes - werden die Umweltauswirkungen erfasst. Dabei werden nicht nur die Umweltauswirkungen des eigentlichen Herstellungsprozesses berücksichtigt, sondern auch die Herstellung der Vorprodukte, teilweise sogar der Hilfs- und Betriebsstoffe, der Energieerzeugung sowie die Förderung und Bereitstellung der Rohstoffe. Einbezogen werden auch alle Transporte." http://www.probas.umweltbundesamt.de/download/uba_bewertungsmethode.pdf

[41] For i.e. aluminium: "Es geht hervor, daß im Jahr 1994 die Primäraluminiumproduktion der Bundesrepublik (ca. 0,5 Mio t) nur ein Drittel des inländischen Verbrauchs (ca. 1,5 Mio t) abdeckte. Die Statistik zeigt ferner, daß die Direktimporte der BRD von Primäraluminium auf mehrere Dutzend Länder verteilt sind". http://www.probas.umweltbundesamt.de/php/themen.php?&prozessid={4D141B2B-80FB-4324-BCC8-EFA0D3F8F406}&id=9915334656&step=4&search=&show_comment=1

[42] http://www.cargohandbook.com/index.php/Steel_sheet_in_coils

[43] Electric arc furnace

from smelting of scrap iron. This means that for any kg produced steel in Germany in 2005, about 195 g came from recycled steel [44].

For aluminium, we have produced a weighted estimate composed from two ProBas estimates. The first estimate is from production of primary aluminium [45] in Germany 2005 which is given a weight of 0,68. The second estimate [46] is for aluminium produced from old scrap aluminium which is given a weight of 0,32. The weights represent world average percentages of production of primary and recycled aluminium in 2007 [47]. Norsk Hydro assumes that the 20-25% of the demand for aluminium can be supplied by recycled aluminium [48].

The energy consumption and emissions related to glass production is obtained from ProBas [49]. The glass production is based on the float production process. No recycling of glass is included in the estimate [50]. The estimate for rock wool is also obtained from ProBas [51]. This estimate includes use of material waste from the production and recycled material [52]. The estimate fits well with another LCA-study of production of rock wool [53].

PVC is used both in cabin doors [54] and in toilets [55]. According to product details, we cannot say exact how much of the materials for doors and toilets are PVC. In doors the material is used as door leaf with a rock wool core and steel frames. In toilets PVC is used in pipes and covers. We have assumed that 50% of the weight for doors and toilets are made up of PVC. We acknowledge that this is a guess, but it's the best we can do given that we know PVC is widely used as a material but we do not know exact how much of it is used where. Rockwool accounts for much of the volume in i.e. doors, though this material does not weigh much. We therefore consider 50% weight proportion for PVC to be a conservative estimate.

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[44] Simonsen, M.: Metal production, http://vfp1.vestforsk.no/sip/EnergiTransport/pdf/Felles/MetalProduction.pdf , page 7

[45] MetallAluminium-Import-mix-DE-2005

[46] MetallAluminium-DE-sekundär-2005

[47] International luminium Institue, *Global Aluminium Recycling*, London 2009, page 8-9: "Refiners and remelters play vital roles for the downstream industry; in 2007 they produced close to 18 million tonnes of recycled aluminium from old and traded new scrap including ingots for casting, rolling and extrusion and pellets for the deoxidation of steel. This compares with in excess of 38 million tonnes of primary aluminium produced in the same year." http://www.world-aluminium.org/media/filer_public/2013/01/15/fl0000181.pdf

[48] http://www.hydro.com/en/About-aluminium/Aluminium-life-cycle/Recycling/

[49] ProBas - Details: Steine-ErdenGlas-flach-DE-2005

[50] "Die Rohstoffzusammensetzung beim Flachglas muß sehr genau und konstant sein, da das Verfahren gegen Abweichungen sehr empfindlich ist. Dadurch kann auch kein Recycling-Glas eingesetzt werden. Lediglich ein geringer Anteil des im Werk anfallenden Glasbruches und der Reststoffe kann wieder in den Prozeß eingebracht werden." , ibid.

[51] In German mineral wool is Steinwolle, Steine-ErdenSteinwolle-DE-200

52 "Neben den Primärrohstoffen werden auch Mineralien über Recyclingmaterial eingebracht. Dabei handelt es sich sowohl um interne Abfälle aus der Zerfaserung als auch um div. Wollabfälle von Baustellen und produktionsinterne Stäube. Diese werden zusammen mit Zusatzsteinen (Felsbrocken/Kies) in Zement eingebunden als Briketts in den Prozeß eingebracht", ibid.

[53] Flury, K., Frischknecht, R.: *Life Cycle Assessment of Rock Wool Insulation,* ESU-Services, June 2012, http://www.esu-services.ch/fileadmin/download/Rockwool_v2.2_2012.pdf

[54] Navaliber, http://www.navaliber.com/dl/FichaNavaliberPT.pdf

[55] Technical data, http://www.evac.com/sites/default/files/attachments/00_Inshine_910_toilets.pdf . According to CruiseCritic.co.uk the toilet Evac 900 is used on Royal Caribbeans' Independence of The Seas. We have used the product description for Evac 910, see http://www.cruisecritic.co.uk/articles.cfm?ID=405

We have used the product description for the door Navaliber 2NB-15 hinged door[56]. It is 1900 mm high and 750 mm wide. It weighs 40 kg pr m2. With 1,425 m2 we get a total weight of 57 kg. According to the Meyer Werft, there are 4500 doors on a typical cruise ship[57]. If each door weighs 57 kg we get a total of 256,5 tonnes of material for doors. Assuming 50% of this is PVC we get 128 tonnes of PVC for doors.

EVAC-toilets are used in the Royal Caribbean's cruise ship Independence of the Seas[58]. The toilet weight for an EVAC 9210 toilet is given as roughly 24 kg (net weight)[59]. Norwegian Gem has 1197 cabins. With one toilet in each cabin we get 28,7 tonnes for all toilets. Again assuming 50% of this is PVC we get 14,4 tonnes of PVC for toilets. Adding PVC in doors and toilets together we get a total of 142,4 tonnes of PVC. We have used the PVC estimate based on the suspension polymerisation process.

With these assumptions, we can account for 10 464 tonnes of Norwegian Gem's superstructure weight. This is almost 49% of the total superstructure weight.

None of the materials analysed here have relevant co-products that should be considered in the production process. Some iron is produced as a by-product during production of mineral wool, but the amount of it is so insignificant that it is not further considered in this analysis[60].

**Table 7 Energy use factors for materials MJ pr kg**

| Material | MJ pr kg |
|---|---|
| Steel, hot rolled | 20,54 |
| Aluminium | 123,81 |
| Glass | 11,91 |
| Mineral wool | 14,48 |
| PVC | 20,64 |

Table 7 shows energy use factors for the different materials. Table 8 shows $CO_{2e}$[61] emission factors for the same materials. For process energy we will use information from Meyer Werft, Germany which built the Norwegian Gem. In their sustainability report for 2010, the ship yard claims that they use 180 kWh of process energy in form of electricity for each grosse tonne[62] built in 2006. They also use 12,71 $m^3$ of natural gas for each gross tonne in 2006. We have used numbers for 2006 since the Norwegian Gem was built at the ship yard during 2006-07. There is 10,3 kWh in each $m^3$ of natural

[56] http://www.navaliber.com/dl/FichaNavaliberPT.pdf
[57] http://www.meyerwerft.de/de/meyerwerft_de/service/publikationen/publikationen_detailseite_1319.jsp
[58] http://www.cruisecritic.co.uk/articles.cfm?ID=405
[59] http://www.evac.com/sites/default/files/attachments/00_Inshine_910_toilets.pdf
[60] " Allokation: Als Nebenprodukte der Steinwollen-Herstellung fallen in geringen Mengen an Eisen und Granulat. Sie werden in dieser Studie nicht als Koppelprodukte betrachtet. Weder bei der Betrachtung physischer Parameter der Allokation noch bei der Betrachtung ökonomischer Parameter ergibt sich eine Signifikanz der Nebenprodukte. Daher wird keine Allokation zwischen den Steinwolle-Matten und den angesprochenen Nebenprodukten vorgenommen.", ibid.
[61] $CO_{2e}$=$CO_2$- equivalents, the mix of climate gases weighted together according to the Kyoto Protocol.
[62] Nachhaltigkeitsbericht 2010, Meyer Werft, page 21, http://www.meyerwerft.de/de/meyerwerft_de/service/publikationen/publikationen_detailseite_1216.jsp

gas [63]. Consequently, the ship yard used 130,9 kWh of natural gas for each gross tonnes built. This gives a total of 311 kWh pr gross tonnes in process energy. With 93 500 gross tonnes it requires 104 653,3 GWh of process energy to build Norwegian Gem.

**Table 8 Emissions factors, emission of CO2-equivalents kg pr kg**

| Material | kg pr kg |
|---|---|
| Steel | 1,54 |
| Aluminium | 13,27 |
| Glass | 1,12 |
| Mineral wool | 1,05 |
| PVC | 2,17 |

**Table 9 Total energy embedded in materials**

| | GWh |
|---|---|
| Steel | 171,87 |
| Aluminium | 44,10 |
| Glass | 1,17 |
| Mineral wool | 0,83 |
| PVC | 0,818 |
| Sum | 218,79 |

There are different $CO_2$ emission factors for electricity and natural gas. We have used an estimate from Probas for German electricity mix in 2005 with an emission factor of 0,167 kg $CO_2$ for each MJ (0,05 kg $CO_2$/kWh) consumed [64]. For natural gas, we have used an estimate for a small gas-driven thermal power station. We therefore assume that most of the gas is used for heating buildings at the ship yard. The emission factor for natural gas used in a thermal power plant is 0,13 kg $CO_2$ pr MJ (0,04 kg $CO_2$/kWh). Since Norwegian Gem has 93 500 gross tonnes, total emissions of $CO_2$ from use of process energy are 780,4 tonnes for electricity and 445 tonnes for natural gas or 1225,4 tonnes together.

**Table 10 Total emissions of $CO_2$ embedded in materials**

| | |
|---|---|
| Steel | 46 385,5 |
| Aluminium | 17 013,0 |
| Glass | 395,5 |
| Mineral wool | 217,2 |
| PVC | 309,5 |
| | |
| Sum | 64 320,6 |

[63] http://www.guenstiger-tarif.de/gas_umrechnung.html
[64] ProBas - Details: El-KW-Park-DE-2005

Table 9 shows total energy embedded in materials. Table 10 shows total emissions of tonnes $CO_2$ embedded in materials. Both tables are produced by using the energy use factor and the emissions factors for each material and then multiply with the total amount of that material used in building the Norwegian Gem. All in all, about 219 GWh is embedded in materials with a total emission of a little over 64 000 tonnes of $CO_2$-equivalents.

**Table 11 Total energy used for building Norwegian Gem**

| Source | GWh |
|---|---|
| Embedded energy | 218,79 |
| Process Energy | 29,07 |
| Sum | 247,9 |
| Energy pr tonne lightweight # | 0,0057 |

# Based on Norwegian Gem

**Table 12 Total emissions of tonnes of $CO_2$-equivalents**

| Source | tonnes of $CO_2$-equivalents |
|---|---|
| Embedded in materials | 64320,6 |
| Process energy | 1225,4 |
| | |
| Sum | 65546,0 |
| Emissions pr tonne lightweight # | 1,5 |

# Based on Norwegian Gem

Table 11 shows total energy used for building Norwegian Gem. All in all, 247 GWh is required both for extracting, producing and transporting materials as well as energy used to process the materials at the ship yard. Energy embedded in materials accounts for 88% of total energy use. Table 12 shows the total emissions of tonnes of CO2-equivalents for building the ship. The biggest contribution comes from extracting and producing materials which accounts for over 98% of total emissions.

In order to arrive at an estimate for energy and emissions from building the ship Norwegian Gem per passenger-km we need an assumption about the ship's load factor. According to Walnum, ships from Carnival had an occupancy rate of 105,7% in 2008 [65]. Since a cabin can accommodate more than 2 passengers an occupancy rate of more than 100% is possible. The same occupancy rate for ships from Royal Caribbean Cruise Lines was 104,5% that same year. We do not know the exact occupancy rate for Norwegian ships, we therefore take the average of the two occupancy rates quoted. This gives an occupancy rate of 105,1%.

Further, we need an estimate of daily sailing distance. According to Hou, the Norwegian Gem has a cruising peed of [66] 25 knots or 46,3 km per hour. According to the same study, the ship spends 77% of its total trip time cruising in open sea. The rest is spent in port. This translates to a total of 270

[65] Walnum, H.J.: *Energy use and CO2-emissions from cruise ships*. Vestlandsforsking-note, 2/2011, page 4-5 http://www.vestforsk.no/filearchive/vf-notat-2-2011-cruise.pdf
[66] Hou, Q.: *Life Cycle Assessment of Cruising Ship Superstructure*, page 16, http://uu.diva-portal.org/smash/get/diva2:451090/FULLTEXT01

days per year cruising, excluding time in port [67]. The assumed lifetime of the ship is 25 years [68]. This gives a total of 754 888 586 passenger kilometres per year and a total of 18 872 214 656 passenger kilometres over the the assumed lifetime.

**Table 13 Energy use and emissions of CO2-equivalents pr passenger-km for building Norwegian Gem**

| | | |
|---|---|---|
| Passenger capacity, number of | A | 2 394 |
| ALB Occupancy rate,% | B | 105,1 |
| Average cruising speed, km/hour | C | 46,3 |
| Days of year in operation, excluding time in port | D | 270 |
| Hours pr day cruising at sea, excluding time in port | E | 24 |
| Passenger-km pr year | F=A*B*C*D*E | 754 888 586 |
| Lifetime, years | G | 25 |
| Passenger-km lifetime | H=F*G | 18 872 214 656 |
| Total energy use for building the ship, GWh | I | 248 |
| Total emissions of $CO_2$-equiv. for building the ship, tonnes | J | 65546,0 |
| kWh pr passenger-km, energy for production of ship | $K=(I*10^{6})/H$ | 0,0131 |
| MJ pr passenger -km | L=K*3,6 | 0,047 |
| kg $CO_2$-equivalents pr passenger-km for production of ship | $M=(J*10^{3})/H$ | 0,0035 |

Table 13 shows energy use in kWh and emissions of kg $CO_2$-equivalents pr passenger kilometre related to building Norwegian Gem. In total, the energy use is 0,047 MJ pr passenger kilometre while the emissions are 0,0035 kg $CO_2$-equivalents pr passenger kilometre.

Based on energy use and emissions of $CO_2$-equivalents pr tonne lightweight for Norwegian Gem we can produce an estimate both for energy required for production and their related emissions of $CO_2$-equivalents for each ship used in the regression analysis above. These calculations are shown in the appendix.

## Fuel production

This section will address the following questions: How much energy does it require to produce diesel for cruise ships' electricity generators? And how large are the emissions from this added energy consumption required for propulsion?

So far we have analyzed the energy requirements and the implied emissions from building the ship. This section will analyse the corresponding energy use and emissions related to produce the cruise ship's fuel. The ship in question is the Norwegian Gem.

ProBas has an estimate for production of 1 TJ of electricity from a thermal power plant fuelled with heavy fuel oil [69]. The power plant has a NOx catalyst and there is no allocation for heat produced in the same process. The estimate is therefore a gross estimate for the power produced.

[67] ibid., page 34.
[68] ibid., page21.
[69] Details: Öl-schwer-BHKW-gross-SCR-DE-2005/brutto (Endenergie)

This estimate includes the energy consumed all along the production chain for this electricity. In other words, it includes the indirect energy required to produce the heavy fuel oil fuel as well as the direct energy used to generate electricity.

All in all, it takes 1,14 TJ of energy to produce 1 TJ of electricity with a generator fuelled by heavy fuel oil. This means that the energy efficiency is 88%, the rest of the energy content in the fuel is lost as heat during electricity production. The loss multiplier of 1,13 covers energy used for extraction of oil, transport to refineries, processing oil to heavy fuel oil at refinery and distributing the final product.

In comparison, it takes 3,5 TJ of energy to produce 1 TJ of energy with a generator running on diesel. Diesel has a higher energy content pr kg than heavy fuel oil but the energy required to produce the fuel is much higher compared pr produced energy unit.

According to Walnum (2011) [70] the fuel consumption for Carnival ships in 2008 was 0,1148 kg pr ALB-km [71]. We will use ALB-km as equivalent with passenger-km. It must be emphasized that this is based on passenger capacity and not actual load factor. This load factor may be lower or higher than 100% since some cabins can accommodate more than two passengers. We don't know the actual load factor and use passenger-capacity as a proxy for number of passengers pr km. We also consider the energy use pr passenger-km for Carnival ships to be valid for the cruise ship Norwegian Gem.

According to the Central Bureau of Statistics, Norway, heavy fuel oil has an energy content of 40,6 MJ pr kg [72] with a density of 0,98 kg/litre. This gives 4,7 MJ pr passenger-km. We will call this net direct propulsion energy. Using a car analogy we can call this energy Tank-to-Wheel.

With a loss multiplier of 1,14, we find that the total energy use for propulsion is 5,3 MJ pr passenger-km when we take energy required to produce heavy fuel oil into consideration. We will call this gross direct propulsion energy. Using the same car analogy we can call this Well-to-Tank energy. The energy required to produce net direct propulsion energy is then 0,6 MJ pr passenger-km for Norwegian Gem.

The ProBas estimate uses an emission factor of 3,197 gram $CO_2$-equivalents pr litre heavy fuel oil [73]. For comparison, according to Environment Canada, a website run by the Government of Canada [74], heavy fuel oil has an emission factor of 3,124 gram $CO_2$ pr litre when used to generate electricity. This factor only comprises emissions of $CO_2$, not $CO_2$-equivalents. Most of the emissions from combusting heavy fuel oil comes from $CO_2$, according to Environment Canada the emissions of methane ($CH_4$) from burning one litre of heavy fuel oil is 0,034 gram which is 0,001% of the emissions

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[70] Walnum, H.J. (2011): *Energy use and CO2 emissions from cruise ships — A discussion of methodological issues,* Western Norway Research Institution, Note 2/2011, page 5, http://www.vestforsk.no/notater/energy-use-and-co2-emissions-from-cruise-ships-a-discussion-of-methodological-issues

[71] ALB=Available lower berth.

[72] Toutain, J.E.W., Taarneby, G., Selvig, E.: *Energiforbruk og utslipp til luft fra innenlandsk transport*, SSB-Rapport 2008/49, Oslo 2008, Table 2.1, Page 15, http://www.ssb.no/a/publikasjoner/pdf/rapp_200849/rapp_200849.pdf

[73] The emissions are 80 355 kg for 1 TJ of electricity production with heavy fuel oil. These are only direct emissions, not including emissions upstream (or "Vorkette" in German). This is equivalent to 0,0804 kg pr MJ. Since there are 40,6 MJ in a kg of heavy fuel oil with a density of 0,98 this means 3,197 kg CO 2 from one litre of heavy fuel oil.

[74] http://www.ec.gc.ca/ges-ghg/default.asp?lang=En&n=AC2B7641-1

of $CO_2$ (3124 gram). The corresponding figure for $N_2O$ is 0,002%. The estimates from ProBas and the Canadian Environment Agency therefore fit well together.

The emissions of $CO_2$ from direct propulsion energy is then estimated to 374,5 gram pr passenger-km. Previously, we have estimated 357,8 gram pr passenger-km using data from the Walnum (2011). In the following, we will use the ProBas estimate.

This is without the added energy required to produce the fuel that emits the $CO_2$. According to the ProBas estimate, producing i TJ of electricity from heavy fuel oil emits 11442 kg of $CO_2$-equivalents. These are emissions up to but not including production of electricity in the generator. This is equal to 11,4 gram pr MJ of heavy fuel oil. We have already estimated that we need 0,6 MJ pr passenger-km in added energy consumption to accommodate the production of the fuel. This means an additional 7,3 gram $CO_2$-equivalents or passenger-km. Adding this to the 374,5 gram of $CO_{2-}$ equivalents for propulsion we estimated above we get 381,8 gram $CO_{2-}$ equivalents pr passenger-km.

## Summary

Table 14 shows the gross energy required for propulsion and for building the ship Norwegian Gem in MJ pr passenger-km. Gross energy for propulsion is the energy required for propulsion plus energy required to produce the fuel that is burnt for that propulsion. Table 15 shows emissions of gram CO2-equivalents for the same processes.

Table 14 Energy use in MJ pr passenger-km for propulsion and from building the ship

| Source | MJ pr passenger-km |
|---|---:|
| Propulsion | 4,7 |
| Producing fuel for propulsion | 0,6 |
| Gross energy for propulsion | 5,3 |
| Building the ship | 0,047 |

Table 15 Emissions of CO2-equivalents for propulsion and from building the ship

| Source | gram CO2-equivalents pr passenger-km |
|---|---:|
| Propulsion | 374,5 |
| Producing fuel for propulsion | 7,3 |
| Gross energy for propulsion | 381,8 |
| Building the ship | 3,5 |

## Alternative fuels

We will look at two alternative strategies for mitigating the environmental impact from cruise tourism. One is making use of lighter materials for cruise ships' superstructure, thereby reducing the

ships' own weight. The other is using renewable fuels instead of fossil fuel. We will look at biodiesel as an alternative fuel to heavy fuel oil for cruise ships' power generators.

## Reducing ship's lightweight with composite materials

Hou [75] has analyzed the application of fibre-reinforced plastic as structural material in Norwegian Gem's superstructure above deck 11. Fibre-reinforced plastic is also called composite sandwich materials. This composition consists of a core which often is a polymer, a large molecule with repeating subunits which are called monomers. Polymers can be natural or synthetic. Plastic is a synthetic polymer [76]. According to Hou, potential core materials sandwich composites are PVC foam, balsa wood cores or cellular material cores [77]. The core material is attached to a skin material which can be glass or carbon fibre reinforced laminates [78]. Composite materials can substitute structural materials in a cruise ships' superstructure. The core material absorbs shear forces generated by loads carried by the ship and distribute these forces over a larger area [79]. Composite sandwich materials have high strength and stiffness while being much lighter than alternative structural materials. According to Umair (2006), structures made of composite materials are 30-40% lighter than aluminium [80].

According to Hou, replacing traditional structural materials in the upper five decks at Norwegian Gem will save 1160 tonnes. However, the steel hull needs to be strengthened accordingly which is a weight increase of 400 tonnes. The net saving from applying composite materials is then close to 800 tonnes. This means the ship can carry the same amount of passengers with a lower weight, thereby saving fuel. Alternatively, the ship can be fitted with extra cabins to compensate for the weight loss. This means that the cruise ship will have approximately the same own weight after using composite sandwich materials but with a larger passenger carrying capacity.

A Swedish study concluded the saved weight can accommodate 86 extra passenger cabins plus an extra 350 $m^2$ of public spaces [81]. Thus, the new designed Norwegian Gem will have a lightweight of 43 130 tonnes which is 20 tonnes less than the ship's actual lightweight but with increased passenger capacity and higher income potential for the ship's owners. This also means that the same assumed fuel consumption (since the lightweight is roughly the same) can be distributed on more passengers pr km thereby reducing the environmental impact pr passenger-km.

Table 16 shows the environmental impact of adding new passenger capacity to Norwegian Gem and distributing fuel consumption and emissions of $CO_2$ from propulsion on the increased production of passenger-km.

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[75] Hou, Q.: *Life-Cycle Assessment of Cruising Ship Superstructure*, Master Thesis in Sustainable Development, Uppsala University, Sweden, May 2011, http://uu.diva-portal.org/smash/get/diva2:451090/FULLTEXT01

[76] Wikipedia: Polymer, http://en.wikipedia.org/wiki/Polymer

[77] Hou, page 8, paragraph 2.5.

[78] Umair, S.: *Environmental Impacts of Fiber Composite Materials*, Swedish Royal Institue Of Technology, Stockholm 2006, page 21, http://www.infra.kth.se/fms/pdf/Life_Cycle_Assessment_of_Fiber_Composite_Materials2.pdf

[79] composite-superstructure.com: *LÄSS offers more benefits for passenger ship designers,* http://composite-superstructure.com/pst_csc_article.pdf

[80] Umair (2006), page 13.

[81] Evegren, F., Hertzberg, T., Rahm, M.: LASS-C; Lightweight Construction Of A Cruise Vessel, SP-Report 2011:12, Technical Research Institute of Sweden, 2011, page 15, http://s-lass.com/en/Documents/Rapporter/SPreport_2011_12[1]-Cruise%20vessel.pdf

Table 16 Environmental impact for Norwegian Gem with added passenger capacity

| | | |
|---|---|---|
| Old passenger capacity | A | 2 394 |
| Fuel consumption kg pr passenger-km old passenger capacity | B | 0,1148 |
| Extra cabins accommodated by weight saving due to composite material | C | 86 |
| Extra passengers, assuming 2 passenger pr cabin | D=C*2 | 172 |
| Total new passenger capacity | E=A+D | 2 566 |
| Fuel consumption, kg pr km old passenger capacity | F=B*A | 274,8 |
| Fuel consumption kg pr passenger-km new passenger capacity | G=F/E | 0,1071 |
| Energy content 1 kg heavy fuel oil | H | 40,6 |
| MJ pr passenger-km (net propulsion energy) | I=G*H | 4,3 |
| MJ pr passenger-km saved with composite materials | J=(B-G)*H | 0,31 |
| Emission gram $CO_2$-equivalents pr passenger-km old capacity (net propulsion energy) | K | 374,5 |
| Emission gram $CO_2$-equivalents pr km | L=K*A | 896 613 |
| Emission gram $CO_2$-equivalents pr passenger-km new capacity | M=L/E | 349 |
| Passenger-km pr year old weight | N | 718 257 456 |
| New passenger-km pr year | O | 769 861 584 |

## Alternative fuel: Biodiesel

Using biodiesel as a substitute for heavy fuel oil could be another strategy for mitigating emissions of $CO_2$. We assume that biodiesel can substitute heavy fuel oil without any modifications in the propulsion system.

According to Hammond et al [82] claims that 1 ha will yield 452 litre of biodiesel from vegetable oil. The same yield for biodiesel from jatropha as feedstock is 1870 litre. The Norwegian Gem requires 280,4 litre pr km with a passenger capacity of 2 394, a consumption of 0,1148 kg fuel pr passenger-km and a density of 0,98 kg pr litre for heavy fuel oil. This implies 1 ha could produce biodiesel from vegetable oil enough to keep Norwegian Gem cruising for 1,6 km or almost exactly one English mile. Norwegian Gem has a cruising distance of 46,3 km an hour and 1111,2 km pr day at open sea. According to Hou, Norwegian Gem spends 270 days at open sea during a year [83]. The rest of the year is spent in port. Total sailing distance pr year is therefore 300 024 km with a total fuel consumption of 84,1 million litre heavy fuel oil. It would take 186 148 ha of cultivated land to produce this amount of biodiesel.

As a comparison, the total cultivated area of Norway is 1 million ha [84]. This implies that 18,5% of the total cultivated area of Norway had to be dedicated to produce biodiesel just for one cruise ship. Or, the total cultivated area of Norway could produce biodiesel for 5 cruise ships. These calculations show that use of biofuel as a substitute for heavy fuel oil in cruise ships is totally unrealistic.

[82] Hammond, GP, Seth, SM.: Carbon and environmental footprinting of global biofuel production. Appl. Energy (2013), http://www.sciencedirect.com/science/article/pii/S0306261913000172
[83] Hou, page 34.
[84] Norges Bondelag: Fakta om situasjonen for dyrka og dyrkbar mark i Norge

# Appendix

Table 17 List of cruise ships used in lightweight calculations

| | Length | Breadth | Draft | Displace-ment weight | Dead-weight | Light-weight (estimate) | Prod-uction energy GWh (estimate) | Production emissions CO2-equiv. tonne (estimate) |
|---|---|---|---|---|---|---|---|---|
| Seven Seas Mariner | 187,0 | 28,8 | 7 | 27 380 | 4 700 | 22 680 | 130 | 34 452 |
| Carnival Spirit | 258,5 | 34,0 | 8 | 51 064 | 7 200 | 43 864 | 252 | 66 631 |
| Millenium | 260,3 | 32,0 | 8,3 | 50 204 | 11 928 | 38 276 | 41 | 10 877 |
| Rhapsody of the Seas | 235,0 | 32,2 | 7,92 | 43 527 | 8439 | 35 088 | 220 | 58 143 |
| Radiance of the Sea | 263,5 | 32,2 | 8,5 | 52 380 | 10 759 | 41 621 | 202 | 53 299 |
| Serenade of the Seas | 266,2 | 32,2 | 8,5 | 52 922 | 11 936 | 40 986 | 239 | 63 223 |
| Dawn Princess | 231,0 | 32,0 | 8,3 | 44 569 | 8 293 | 36 276 | 235 | 62 259 |
| Sapphire Princess | 254,9 | 36,0 | 8,2 | 54 661 | 14 601 | 40 060 | 208 | 55 104 |
| Golden Princess | 254,9 | 36,0 | 8,5 | 56 660 | 8 418 | 48 242 | 230 | 60 851 |
| Diamond Princess | 254,9 | 50,0 | 8,2 | 75 917 | 14 601 | 61 316 | 277 | 73 281 |
| Island Princess | 260,3 | 32,0 | 8,2 | 49 599 | 8 015 | 41 584 | 352 | 93 141 |
| Star Princess | 254,9 | 36,0 | 8,7 | 57 993 | 10 852 | 47 141 | 239 | 63 168 |
| Coral Princess | 260,3 | 32,0 | 8,2 | 49 599 | 8 015 | 41 584 | 271 | 71 609 |
| Statendam | 194,8 | 32,0 | 7,7 | 34 852 | 7 637 | 27 215 | 239 | 63 168 |
| Zaandam | 210,7 | 32,0 | 8,1 | 39 662 | 6 150 | 33 512 | 156 | 41 340 |
| Ryndam | 194,8 | 32,0 | 7,6 | 34 399 | 7 447 | 26 952 | 192 | 50 906 |
| Norwegian Pearl | 264,8 | 32,2 | 8,3 | 51 400 | 10 000 | 41 400 | 155 | 40 941 |
| Norwegian Star | 264,0 | 32,2 | 8,2 | 50 627 | 7 500 | 43 127 | 238 | 62 887 |
| Norwegian Sun | 223,1 | 32,3 | 8,217 | 42 929 | 7 100 | 35 829 | 248 | 65 511 |
| Mein Schiff 2 | 233,7 | 34,0 | 8,5 | 49 053 | 9 600 | 39 453 | 206 | 54 426 |
| Carnival Fantasy | 230,2 | 32,0 | 8 | 42 794 | 7 200 | 35 594 | 204 | 54 068 |
| Carnival Ecstasy | 230,2 | 32,0 | 8 | 42 794 | 7 200 | 35 594 | 204 | 54 068 |
| Carnival Sensation | 231,0 | 36,0 | 8,2 | 49 536 | 6 870 | 42 666 | 245 | 64 811 |
| Carnival Fascination | 231,0 | 36,0 | 8 | 48 328 | 7 180 | 41 148 | 236 | 62 505 |
| Carnival Imagination | 229,3 | 32,0 | 8 | 42 629 | 7 180 | 35 449 | 204 | 53 848 |
| Carnival Inspiration | 231,0 | 32,0 | 8 | 42 958 | 7 180 | 35 778 | 206 | 54 348 |
| Carnival Elation | 231,0 | 37,0 | 7,9 | 49 049 | 7 498 | 41 551 | 239 | 63 118 |
| Carnival Paradise | 231,0 | 36,0 | 7,9 | 47 724 | 6 894 | 40 830 | 235 | 62 022 |
| Carnival Sunshine | 240,8 | 42,0 | 8,6 | 63 166 | 11 142 | 52 024 | 299 | 79 025 |
| Carnival Triumph | 241,7 | 42,0 | 8,3 | 61 186 | 10 984 | 50 202 | 288 | 76 259 |
| Carnival Victory | 241,7 | 44,0 | 8,3 | 64 100 | 10 774 | 53 326 | 306 | 81 004 |
| Carnival Pride | 259,4 | 32,0 | 8,2 | 49 431 | 7 200 | 42 231 | 243 | 64 149 |
| Carnival Legend | 259,4 | 32,0 | 8 | 48 225 | 7 089 | 41 136 | 236 | 62 487 |
| Carnival Miracle | 259,4 | 32,0 | 8,2 | 49 431 | 7 089 | 42 342 | 243 | 64 318 |
| Carnival Conquest | 256,7 | 44,0 | 8,2 | 67 271 | 10 000 | 57 271 | 329 | 86 997 |
| Carnival Glory | 255,8 | 43,0 | 8,2 | 65 516 | 11 100 | 54 416 | 313 | 82 659 |
| Carnival Valor | 258,5 | 44,0 | 8,3 | 68 561 | 13 294 | 55 267 | 317 | 83 952 |
| Carnival Liberty | 258,5 | 44,0 | 8,3 | 68 561 | 13 294 | 55 267 | 317 | 83 952 |
| Carnival Freedom | 255,8 | 42,0 | 8,2 | 63 992 | 12 870 | 51 122 | 294 | 77 656 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Carnival Splendor | 256,7 | 44,0 | 8,2 | 67 271 | 11 843 | 55 428 | 318 | 84 197 |
| Norwegian Gem | 263,5 | 32,2 | 8,625 | 53 150 | 10 000 | 43 150 | 248 | 65 546 |
| Norwegian Sky | 223,1 | 32,3 | 8,017 | 41 884 | 8 800 | 33 084 | 190 | 50 256 |
| Norwegian Spirit | 235,6 | 32,2 | 8,421 | 46 398 | 8 530 | 37 868 | 218 | 57 523 |
| Norwegian Star | 264,0 | 32,2 | 8,2 | 50 627 | 7 500 | 43 127 | 248 | 65 511 |
| Norwegian Dawn | 264,8 | 32,2 | 8,5 | 52 638 | 7 500 | 45 138 | 259 | 68 566 |
| Norwegian Jewel | 264,8 | 32,2 | 8,6 | 53 257 | 7 500 | 45 757 | 263 | 69 507 |
| Norwegian Jade | 264,8 | 32,2 | 8,6 | 53 257 | 7 500 | 45 757 | 263 | 69 507 |
| Norwegian Epic | 288,8 | 40,6 | 8,7 | 74 161 | 10 850 | 63 311 | 364 | 96 172 |
| Norwegian Breakaway | 300,1 | 39,7 | 8,6 | 74 420 | 11 000 | 63 420 | 364 | 96 337 |
| Oasis of the Seas | 329,9 | 47,0 | 9,3 | 104 726 | 15 000 | 89 726 | 515 | 136 296 |
| Allure of the Seas | 330,0 | 47,0 | 9,3 | 104 746 | 19 750 | 84 996 | 488 | 129 111 |

**Table 18 List of cruise ships in Skagway 2008**

| | Fuel consumption | | Auxilliary boiler | | Hotel load | NOx |
|---|---|---|---|---|---|---|
| Name | gallons/hour | Litre/hour | mt/hour | Fuel type | MW | lbs/hour |
| Seven Seas Mariner | 80 | 302,8 | | | | |
| Carnival Spirit | 600 | 2271,2 | | | | |
| Empress of the North | 40 | 151,4 | | | | |
| Millenium | 375 | 1419,5 | | | | |
| Rhapsody of the Seas | 410 | 1552,0 | 1,5 | HFO | 5,3 | |
| Radiance of the Sea | 385 | 1457,4 | 2,9 | MGO | 5,3 | |
| Serenade of the Seas | 760 | 2876,9 | 2,6 | IFO | 5,5 | 80,0 |
| Dawn Princess | 440 | 1665,6 | | | | |
| Sapphire Princess | 760 | 2876,9 | 2,3 | IFO | 9,6 | 271,0 |
| Golden Princess | 700 | 2649,8 | 2,5 | | 10,5 | 277,5 |
| Diamond Princess | 1144 | 4330,5 | 4,1 | IFO | 11,5 | 314,0 |
| Island Princess | 610 | 2309,1 | 2,3 | IFO | 7,2 | 208,0 |
| Star Princess | 725 | 2744,4 | 2,3 | IFO | 10,5 | 277,5 |
| Coral Princess | 580 | 2195,5 | | | | |
| Statendam | 260 | 984,2 | | | | |
| Zaandam | 310 | 1173,5 | | | | |
| Ryndam | 275 | 1041,0 | | | | |
| Norwegian Pearl | 680 | 2574,1 | 2,5 | IFO | 7,2 | 176,2 |
| Norwegian Star | 775 | 2933,7 | 2,7 | IFO | 9,0 | 238,0 |
| Norwegian Sun | 590 | 2233,4 | 2,1 | IFO | 5,6 | 182,0 |
| Mein Schiff 2 | | | 1,3 | IFO 380 | 4,1 | |

## References

Walnum, H.J.: *Energy use and CO2 emissions from cruise ships — A discussion of methodological issues,* Western Norway Research Institution, VF-notat 2-2011, http://www.vestforsk.no/notater/energy-use-and-co2-emissions-from-cruise-ships-a-discussion-of-methodological-issues

How cruise ships work, http://adventure.howstuffworks.com/cruise-ship.htm

The electric cruise ship, http://www.edn.com/electronics-news/4341136/The-electric-cruise-ship

QE2: From the desk of the chief engineer, http://www.qe2.org.uk/engine.html

Graw, R. (US Forest Service), Faure, A (Alaska Department of Environmental Conservation) A Study for Alaska Department Of Environmental Conservation, *Air Pollution Inventory For 2008 Tourism Season*, http://www.dec.alaska.gov/water/cruise_ships/pdfs/Skagway2008_Final_Emissions_Report.pdf

Toutain, J.E.W, Taarneby, G., Selvig, E.,*Energiforbruk og utslipp til luft fra innenlandsk transport*, Statistisk Sentralbyrå, Rapport 2998/49. http://www.ssb.no/emner/01/03/10/rapp_200849/rapp_200849.pdf