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Energy Efficient Offshore Accommodations

A study on strategies leading to energy savings in offshore accommodations

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by
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Preface

This report is the result of my master thesis for the degree of Master of Science in Maritime Technology at Delft University of Technology. My research was part of a multidisciplinary project together with Lars Hammer, a graduate student Building Technology. It was performed at Keppel Verolme BV under supervision of Mariano Otheguy. The project took place from December 1st, 2016 to September 5th 2016.

This report is written for all engineers and operators interested in the energy consumption of and energy saving strategies in maritime accommodations. The report can be divided in two parts. The first part shows the results of a research on the energy consumption and distribution of offshore accommodations. The second part gives an overview of applicable energy saving strategies and shows the results of a research on the actual yearly savings and payback times.

I would like to express my gratitude to Keppel Verolme BV for giving me a platform to perform this research and providing me with in-house knowledge which was essential for this research. Also, I would like to thank the supervision from TU Delft in particular Robert Hekkenberg for his support and Prof. Hans Hopman and Prof. Ulrich Knaack for participating in my exam committee. I also thank Mariano for supervising and inspiring me in this project and beyond and his willingness to help whenever needed. I would like to thank Lars for the great collaboration, the inspiring insights and good talks we had related and unrelated to the project. Last but not least I would to thank like my parents, friends and family who have been supporting me during my studies.

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Cover photo: Floatel Superior, built at KeppelFELS Shipyard, Singapore. Reprinted from Floatel International, 2016. Retrieved from http://www.floatel.se/fleet/floatel-superior. Copyright by the Floatel International.

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Abstract

Research on energy savings in the maritime industry has focussed mainly on the power configuration and processes on board. Little attention has been paid to the accommodation unit. However, in onshore building technology many strategies have already been applied which results in 'zero-energy' buildings or even buildings that produce more energy than they consume. Two factors are important to assess the profitability of energy savings strategies. Firstly it is essential to know the current energy consumption and determine the actual yearly savings. Secondly, it is essential to know the cost of energy, capital expenditures and savings in operational expenditures.

A base case model is made with DesignBuilder. The technical specifications of the base case model are based on data from actual accommodations on platforms built at Keppel Verolme BV. The model has a capacity of 37 persons on board and a total floor area of 960 m^2. The simulations are based on yearly weather data from the Norwegian North Sea and the Gulf of Mexico. The model shows a total yearly energy consumption of 1013 MWh in the North Sea and 877 MWh in the Gulf of Mexico. On average 54% is used for the heating, ventilation and air-conditioning (HVAC) installation. Other consumers are: 8% for lighting, 8% for laundry, 17% for the galley, 5% for domestic hot water and 5% for auxiliary consumers. Energy is lost in the HVAC installation due to the high number of fresh-air-changes-per-hour and the fixed supply air temperature setpoints.

Eight energy saving strategies are ranked based on the following design criteria with their corresponding weights: potential savings (5), maturity of technology (4), maintenance cost (3), reliability (3), applicability to retrofit (2) and applicability to newbuild (1). The design matrix resulted in the following scores: LED lighting and occupancy sensors 70%, enthalpy wheel 69%, heat pump 65%, demand controlled ventilation 65%, drain water heat recovery 64%, natural ventilation 64%, natural lighting 50% and a bio-gas digester 37%. For LED lighting, enthalpy wheel, demand controlled ventilation, a drain water heat recovery system, and a water sourced heat pump, the yearly savings and payback times are calculated. This is done for newbuild and retrofit and in the North Sea and Gulf of Mexico. The payback time depends on the cost of energy on board. This is calculated to be €0.20 per kWh, comprising of €0.08 for the fuel, €0.11 for transport of fuel and €0.01 for purchase and maintenance of the generator sets. The saving of the total yearly energy consumption and payback time in years are shown in the table 1.

	Newbuild		Retrofit	
	North Sea	Gulf of Mexico	North Sea	Gulf of Mexico
LED lighting and occupancy sensor	3%/ 3	5%/ 3	3%/ 9	5%/ 7
Enthalpy wheel, excl. recirculation	14%/ 0.2	14%/ 0.2	14%/ 0.3	14%/ 0.3
Drain water heat recovery	2%/ 5	2%/ 5	2%/ 14	2%/ 14
Demand controlled ventilation	6%/ 1	25%/ 0.3	6%/ 2	25%/ 0.5
Water sourced heat pump	18%/ 2	17%/ 2	18%/ 2	17%/ 3
All strategies combined	**29%/ 2**	**34%/ 2**	**29%/ 4**	**34%/ 4**

Table 1 Yearly total energy savings [%] and payback times [years]

Compared to the newbuild price of an offshore accommodation unit, the total extra CAPEX for all strategies combined correspond to +4% for newbuild and +7% for retrofit. The results show that strategies concerning the accommodation's HVAC system are the most profitable. Also, the payback times for newbuild are shorter due to the increased installation cost of retrofitting. A big part of the energy is lost due to the requirement of 6 fresh-air-changes-per-hour. It is recommended to investigate the origin of this requirement and possibilities for change. For further research it is recommended to look at the recovery of waste heat from processes on board the platform and to look at feasibility of generating energy from renewable sources such as solar, wind and wave energy.

1 Introduction

This section shows an introduction into the research. First it describes the problem and the motivation for this research. The second part elaborates on the research questions and the sub-questions. It also describes the research method and the scope of the research. The last section introduces the structure of the report.

1.1 Motivation for research

The environment is one of the world's biggest concerns of the moment and sustainability is a widely spread theme in technical developments. CO_2 emissions can be reduced in two ways: reducing the amount of energy consumed or generating energy by using non-fossil energy sources. Many ways to reduce the energy consumption of buildings and houses have already been developed and show satisfying results. Buildings can be 'zero-energy' or can even produce more energy than they consume. An example is the 'Sun Ship' build in 2004 in Germany (Solarsiedlung GmbH). This not only reduces CO_2 emissions but may also reduce costs. The design of offshore accommodations, however, is lagging behind in energy saving strategies compared to onshore building technology.

Crew is needed in offshore environments such as oil fields or offshore windfarms. These people can be transferred every day from the shore by either a ship or a helicopter. Another option is to accommodate the crew on the platform itself or a separate accommodation platform. The choice between these two options is determined by the time needed for the job and the distance from the working location to the shore. Since offshore fields are located farther and farther away from the shore, the demand for offshore accommodations is increasing (O' Connel, 2016). According to the 'World Offshore Accommodation Market Forecast 2015-2020' by Douglas Westwood (Douglas-Westwood, 2016), the demand for offshore accommodation vessels will average almost 42,000 Personnel on board per year. This is an increase of 14% compared to the six-year period before. Since the capacity of the offshore accommodation fleet is increasing, savings in the energy consumption of accommodation units become more relevant. Also, low selling prices of oil are raising the need for cost saving innovations in offshore activities (Offshore Magazine, 2015).

Techniques to save energy used onshore cannot be directly translated to offshore accommodations. The units operate in diffent environments, have to comply with different rules and regulations and operators have different requirements. Since the operation of offshore platforms is costly, downtime has to be avoided as much as possible. Techniques therefore have to be reliable and low-maintenance. The offshore industry also is a volatile business dependent on the oil price. This leads to operators demanding short payback times. It is therefore necessary to keep the capital expenditures (CAPEX) moderate and the operational expenditures (OPEX) as low as possible. In the end, energy saving investments will only be made if they prove to be profitable.

A previous study by Otheguy has shown that energy savings up to 40-50% for a windfarm transformer substation in the North Sea are achievable at an extra upfront cost of approximately 9% of the total cost of the accommodation block (Otheguy, 2014). Energy saving strategies such as double insulation and LED lighting were evaluated seperately. However, the effect of strategies might not be independent which leads to increased or decreased savings when strategies are combined. Therefore it is important to cover the problem with a whole-building approach to compare the various energy saving strategies. Since the cost savings and payback times are important, it is also valuable to be able to run yearly simulations in order to model the actual savings in a year.

1.2 Research questions

The goal of this research is to supply an offshore operator with a profitable package of energy saving strategies that can be applied to an existing accommodation or a newbuild. This goal is achieved by answering the following research question: Which strategies applied to a retrofit and a newbuild lead to savings in the costs of energy consumption by an offshore accommodation unit and what is their expected payback time?

This research question is supported by the following sub questions:

- What is the current energy consumption and its distribution of an offshore accommodation?
- Which energy saving strategies are on hand and are applicable to offshore accommodations?
- What are the costs and savings when the energy saving strategies are applied to the accommodation, separately and combined?

1.2.1 Method

To answer these questions, a base case model is made in DesignBuilder, a software program which is able to run whole-building yearly simulations. With the base case model, the yearly energy consumption and its distribution over the consumer categories are determined. A selection of most promising energy saving strategies is assessed with a design matrix based on relevant design criteria. Selected energy saving strategies are then applied to the base case model to obtain yearly energy savings. Then an evaluation of the CAPEX and maintenance cost is made based on quotations and in-house knowledge of Keppel Verolme BV. The cost of energy on board is estimated to calculate the payback time. Sensitivity studies showed the effect of changes in relevant parameters. The savings and payback times are calculated for each energy saving strategies individually and combined.

The payback time calculations are done for both retrofit and newbuild of accommodations The research is performed for platforms both operating in hot and cold environments. Therefore the Gulf of Mexico (GOM) and the Norwegian North Sea (NS) are used as a case study. The Gulf of Mexico has the most and the North Sea the second most offshore rigs in the region in 2015 (Number of offshore rigs worldwide as of 2015, by region, 2016).

1.2.2 Scope

This research has focussed on the energy consumption of the accommodation unit (as part of a rig or a dedicated platform) from the 'plug'. Low-emission energy production by the generator sets or other systems on board the platform are not taken into consideration. The focus has been on the energy flows in the accommodation unit. A parallel study by Lars Hammer has focussed on the architectural technological aspects of the accommodation, such as the design of the building's envelope. The base case model, which is used as a benchmark, is based on data from existing platforms built at Keppel Verolme BV. The accommodation unit has a capacity of 37 people and a floor area of 960 m^2. All equipment considered for the energy saving strategies are off-the-shelf and commercially available products. It is preferred that these products are designed for marine applications.

1.3 Structure

Chapter two gives an introduction into offshore accommodations. The third chapter describes the construction and details of the base case model. Chapter four elaborates on the energy consumption of the base case model. Chapter five gives an overview of applicable energy savings strategies and ranks them based on design criteria. Then the energy saving strategies are applied to the model, which is described in chapter six. Finally, chapter seven gives a conclusions and recommendations for further research.

2 Offshore Accommodations

The theme of this research is offshore accommodations. Accommodation units are often integrated in an offshore platform. If more capacity is required, accommodation can by supplied by a separate platform. The accommodation block itself is often designed and constructed as a separate unit. This chapter gives an introduction into offshore accommodations. At first an overview of the state-of-the-art in accommodation design is given to know what is the benchmark for this research. The second section briefly discusses the rules and regulations which are applicable to offshore accommodations.

2.1 A brief introduction into offshore accommodations

Accommodation vessels can be of various types: jackups, liftboats, barges, monohulls and semisubmersibles. Floating structures can be either anchored or dynamic positioned. (Douglas-Westwood, 2016) The capacity of accommodation units is expressed in number of beds. These can range from 30 for an integrated accommodation up to 800 for a dedicated accommodation platform.

Figure 1 Floatel Victory, designed and built at Keppel FELS Singapore. Reprinted from Sjöfards Tidningenfrom, by O. Wahl, 2014, Retrieved from sjofartstidningen.se/molndal-moter-goteborg-mexikanska-gulfen. Copyright by the Floatel International.

As noted, accommodations are supporting the offshore industry. The design is therefore subordinate to the main process. The accommodation has to be functional and reliable. Nevertheless the accommodation is responsible for the well-being of the crew on board who are a key-factor in the process. Efforts are being made to make sure that the crew is able to have a comfortable stay and has ways to relax.

Current offshore accommodations may provide the following facilities: cabins, galley, mess, recreational areas, hospital, offices, laundry room, storage areas and workshop facilities.

The design of offshore accommodations is subjected to rules and regulations concerning the climate, construction, health and safety, etc. This topic is elaborated upon later in this report.

2.2 Current energy saving strategies in marine accommodations

'Danish Operators' (2009) performed a study on the feasibility of installing waste-heat recovery systems on the central pre-heating units on offshore platforms in the Danish part of the North Sea. This report concluded that retrofitting the pre-heating unit with a waste-heat recovery system will have a payback time between 53 and 89 years. This concerns platforms with 57 to 95 occupants. It is assumed that for smaller accommodations the pay-back period will be longer. Installing heat-recovery systems in the after heater is not considered in the research since the energy consumption for the after-heaters is only 10% of the total energy consumption. For newbuild platforms, the initial investment costs are assumed to be lower, so the pay-back time will be shorter. (Danish Operators, 2009)

Research has been done on the use of wind turbines to power oil and gas rigs. The electrical load demanded by the entire rig is often supplied by gas turbines. The study by Korpas et al. (2012) showed that 4 times 5MW wind turbines resulted in a 40% wind energy penetration level. (Korpas, Warland, He, & Tande, 2012)

The cruise industry is another maritime industry in which the accommodation plays a significant role in the process. The comfort and experience of the passengers is of great importance in the design of the accommodation spaces. However the ecological footprint nowadays also plays an important role since passengers become more aware and critical of this aspect. Therefore the energy saving strategies not only lead to savings in the cost of energy but also improves the reputation of cruise liners which leads to increased bookings.

The following strategies have already been applied in accommodations on board cruise vessels:

- Lighting: halogen or incandescent lamps are replaced with fluorescent or LED lamps
- High-efficiency appliances
- Window tinting: reduces amount of solar heat transfer
- Reduced water consumption: low-flow shower and tabs, low-flow dishwasher and laundry equipment
- Operational: switching of lighting, air-conditioning and appliances when not in use and installation of automated control systems
- PV panels on top deck
- Solid waste reduction and recycling

2.3 Rules applied to offshore accommodations

The design of offshore accommodations is subject to rules and guidelines. These are defined by international organisations and flag states. In the following section an overview is given of the relevant rules and guidelines for the design of offshore accommodations. This information is relevant to operators who decide to implement energy saving strategies to determine whether these strategies fulfil the rules and regulations.

In practice, the rules and guidelines are dictated by classification societies. Classification societies are recognized by flag states to classify marine structures on behalf of the flag states according its law. The rules and guidelines are derived from conventions and codes made by international organisations such as the International Maritime Organisation (IMO) and the International Labour Organization (ILO). The three major classification societies for the offshore industry are American Bureau of Shipping (ABS), DNV GL, and Lloyd's Register of Shipping. For that reason these societies are subject to further research besides ILO and IMO.

The Maritime Labour Convention (MLC) is a convention held under the International Labour Organisation in 2006. The most relevant document and a guideline for classification societies on accommodation design is the Maritime Labour Convention 2006, Title 3. This document contains regulations on the accommodation's arrangement, dimension, HVAC, recreational areas, mess room, etc.

A second important convention is the International Convention for the Safety of Life at Sea, 1974 (SOLAS). This is a convention by the IMO. It mainly concerns rules and guidelines concerning the safety on-board like fire safety, communication and life-saving appliances. Like the MLC, SOLAS is also used as reference for classification societies.

DNV GL is a merge of two classification societies: Det Norske Veritas and Germanischer Lloyd. The relevant rules for offshore accommodation design given by DNV GL are given in 'Rules for classification – Offshore units – Offshore drilling and support units – Chapter 2 section 4.

The relevant guidelines by the American Bureau of Shipping are stated in 'guide for building and classing of mobile offshore units'. Besides that, ABS has a guide for building in compliance with the ILO Maritime Labour Convention, 2006. If accommodation units want to operate in the water of the Norwegian Continental Shelf some extra rules apply. These are stated in 'Guide for Mobile Offshore Units Operating on the Norwegian Continental Shelf'.

Lloyd's Register's rules for offshore accommodations are stated in 'Rules and regulations for the classification of offshore units' part 3, chapter four. This section contains rules concerning the structure and electrical installation specific to accommodation units. Also some additional rules are discussed in the rest of the document concerning for example strength requirements and fire safety.

A reference used by offshore operators are the NORSOK standards. These standards are developed by the Norwegian petroleum industry to ensure safety, value adding and cost effectiveness. The NORSOK standards are managed by Standards Norway. (NORSOK Standards, 2015) The most relevant standards for offshore accommodation design are the following:

- C-001 Living quarters area
- C-002 Architectural components and equipment
- H-003 Heating, ventilation and air conditioning (HVAC) and sanitary systems

3 Base case model

The base case model is made by using DesignBuilder. It is used to calculate the yearly energy consumption of an accommodation unit and to determine the energy distribution. After that, it is used to calculate the annual savings in kWh of the energy saving strategies. The model in DesignBuilder is able to run dynamic simulations based on hourly weather data and activity data. This improves the accuracy of the results compared to static calculations. Also, the combined effects of the applied strategies can be determined with this model. The input data for the model is based on existing platforms built at Keppel Verolme BV. This chapter describes the set-up of the model and describes the input data.

3.1 DesignBuilder & EnergyPlus

DesignBuilder is simulation software used to assess the energy consumption of buildings. Furthermore, it is used to obtain data such as: carbon emissions, comfort conditions, daylight illuminance and HVAC component sizes (DesignBuilder Software Ltd). The calculations in DesignBuilder are made using the EnergyPlus dynamic simulation engine. This simulation program was developed by the U.S. Department of Energy. EnergyPlus is tested and validated using industry standard methods. (EnergyPlus, 2016)

Creating a model starts with defining the building's geometry. This is done by drawing building blocks. These blocks can then be divided into zones to represent rooms or a group of rooms with similar characteristics. Besides the model's geometry, the following data has to be defined:

- Construction data (material layers, thickness, construction details)
- Openings data (data on windows, doors, vents)
- Lighting data (lighting lay-out, power density)
- Activity data (occupancy, heat gains, domestic hot water, environmental settings)
- HVAC data (Heating, ventilation and air conditioning settings)

This data can be entered by using templates. The data can be changed on all levels in the DesignBuilder hierarchy as shown in figure 2. If no specific changes are made, the data is inherited from the level above.

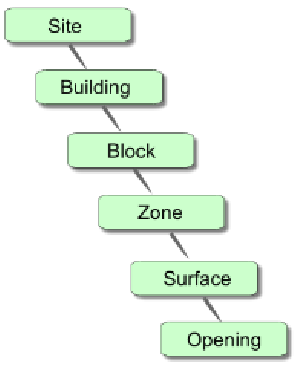


Figure 2 DesignBuilder Hierarchy. Reprinted from DesignBuilder EnergyPlus Simulation Documentation (page 35), by DesignBuilder. Copyright (n.d.) by DesignBuilder Software Ltd.

DesignBuilder uses weather data to calculate the energy consumption. The simulation can be done for hourly up to yearly time periods.

3.2 Case study

The model made in DesignBuilder is based on data from the accommodation units on existing platforms built at Keppel Verolme BV. Keeping the existing accommodations as a guideline for the model, it is aimed to keep the model as universal as possible in order to present a conclusion which is also applicable to other offshore accommodations.

The case study has a capacity of 37 persons on board and has a total floor area of 960 m². The accommodation unit has three decks. Next to cabins, the accommodation contains:

- Gym
- Hospital
- Office areas
- TV-room (smoking and non-smoking)
- Changing room
- Galley
- Mess room
- HVAC room
- Laundry area
- Store
- Corridors and staircases

A figure of the model as created in DesignBuilder is shown in figure 3 including an example of a sun path.

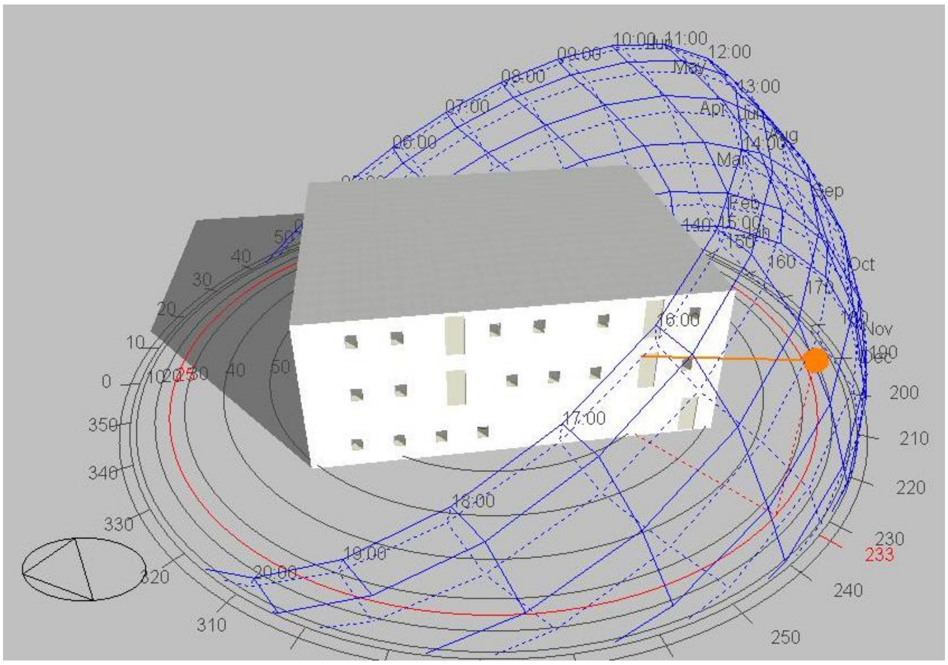


Figure 3 The base case model in DesignBuilder

3.3 Model description

This section describes the input which is used for making the base case model in DesignBuilder. It discusses the arrangement, construction, lighting, activity data, HVAC configuration and the weather data.

3.3.1 Arrangement

The floor areas of the spaces in the model are the same as in the case study, however, rooms with the same characteristics are grouped into zones. This is done for the cabins, offices, HVAC rooms and circulation areas. The cabins are grouped and divided over 8 zones, each representing multiple cabins. The same applies to the circulation areas (corridors and staircases). The dimensions of the accommodation unit are listed in table 2.

Length	20	m
Width	16	m
Deck height	2.90	m
Number of decks	3	
Total floor area	960	m²

Table 2 Main dimensions of model accommodation unit

The arrangement of the zones is similar to the case study, keeping the ratio between zones and circulation areas the same. The floor plans for the decks of the model are shown in figure 4, 5 and 6.

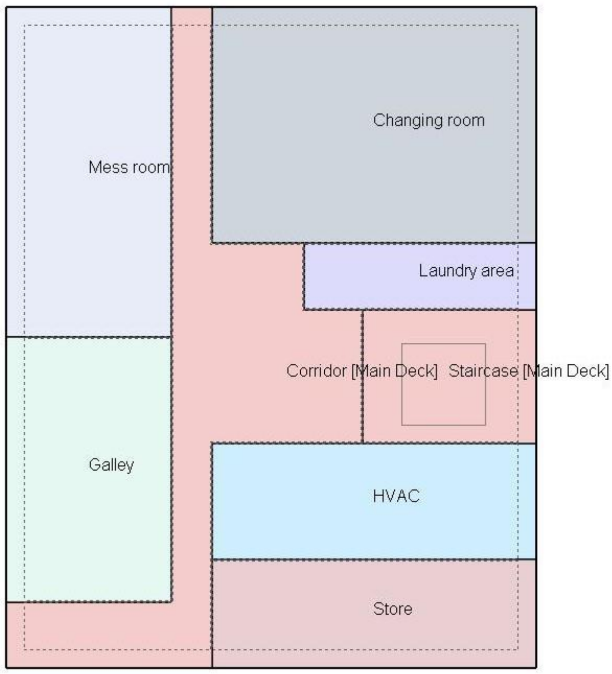


Figure 4 Main deck

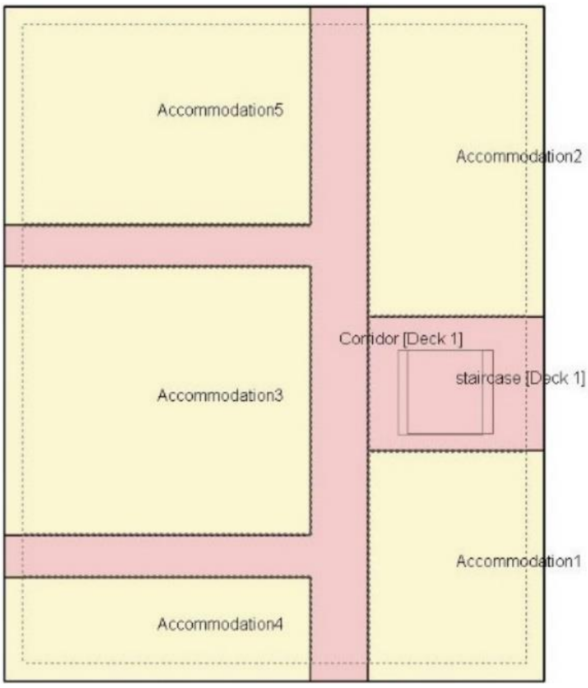


Figure 5 Deck 1

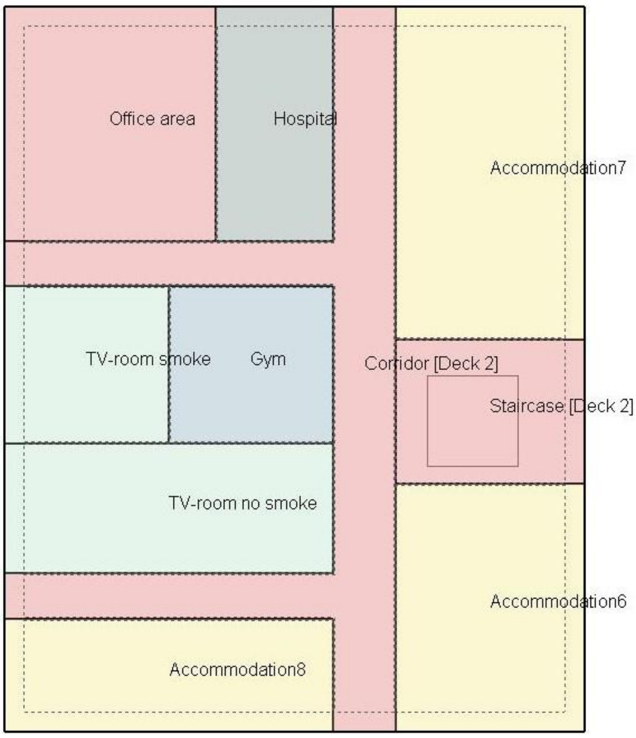


Figure 6 Deck 2

3.3.2 Construction

Construction details are inputted in DesignBuilder by using templates. In these templates all properties of construction elements such as dimensions and materials are described. This section describes the details of the walls, floors, doors and windows.

3.3.2.1 Walls

In this model two types of walls are defined: internal and external walls. The composition of the walls is based on the construction details of the case study. The interior panels are based on technical specifications by Norac AS, a Norwegian manufacturer of interior systems for marine and offshore applications. (NORAC AS, 2016)

The external walls comprise of a layer of steel, insulation, an airgap and inside a NORAC600/25 system panel. The steel stiffeners are also insulated and are therefore not modelled, since they do not function as a thermal bridge. An overview of the material layers and dimensions is shown in table 3. The total thermal resistance (R-value) is calculated by DesignBuilder by adding the r-value of the individual layers.

Layer	Thickness [mm]	Thermal resistance (R-value) [$\frac{m^2K}{W}$]
1 White painted steel	10	
2 Rockwool Marine Slab 55	80	
3 Rockwool Mar. Lamella mat 32	25	
4 Airgap	400	
5 NORAC600/25	25	
Total	**540**	**4.056**

Table 3 External walls

The internals walls comprise of two NORAC600/25 panels and an airgap of 15 mm as described table 4. Multiple cabins have been combined into single zones. However the walls between the cabins have an effect on the thermodynamics and should not be neglected. Therefore, these wall can be modelled as 'internal thermal mass'. The same template as for internal walls is applied to internal thermal mass.

Layer	Thickness [mm]	Thermal resistance [$\frac{m^2K}{W}$]
1 NORAC K-600/25	25	
2 Airgap	15	
3 NORAC K-600/25	25	
Total	**65**	**2.044**

Table 4 Internal walls and Internal Thermal Mass

3.3.2.2 Floors

Floors and ceilings are combined into one construction element. The ceiling consists of NORAC B-600/40 panels. The floor consists of a 10 mm steel plate covered with 40 mm Rockwool. The stiffeners are not modelled. In between is an airgap of 500 mm. The characteristics of the internal floor are shown in table 5.

Layer	Thickness [mm]	Thermal resistance [$\frac{m^2K}{W}$]
1 Rockwool	40	
2 Steel	10	
3 Airgap	500	
4 NORAC B-600/40	40	
Total	**590**	**2.816**

Table 5 Internal Floors

The roof of the accommodation is a boundary between inside and outside and therefore has an extra layer of insulation similar to the external walls. The characteristics of the roof are shown in table 6.

Layer	Thickness [mm]	Thermal resistance [$\frac{m^2K}{W}$]
1 Steel	10	
2 Rockwool Marine Slab 55	80	
3 Rockwool Marine Lamella mat 32	25	
4 Airgap	400	
5 NORAC B-600/40	40	
Total	**555**	**4.829**

Table 6 Roof

The airtightness of the building is set to be 'Excellent' (most airtight setting in DesignBuilder). Exterior walls of offshore accommodations are required to be watertight by the Maritime Labour Convention (American Bureau of Shipping, 2014). There is no infiltration in the model.

3.3.2.3 Doors

Two types of doors are used in the model: internal and external doors. Both are based on technical specifications by NORAC (NORAC AS, 2016). These are shown in table 7 and 8.

Layer	Thickness [mm]	Thermal resistance [$\frac{m^2K}{W}$]
1 White painted steel	1.5	
2 Rockwool	36	
3 White painted steel	1.5	
Total	**39**	**0.916**

Table 7 Internal Doors (NORAC Interior door G007 (B15))

Layer	Thickness [mm]	Thermal resistance [$\frac{m^2K}{W}$]
1 White painted steel	2	
2 Rockwool	60	
3 White painted steel	2	
Total	**64**	**1.427**

Table 8 External Doors (NORAC HB-5000 (A60))

3.3.2.4 Windows

The dimensions for the windows are based on the specifications for an A60 fireproof window by Ship Accommodation Solutions Ltd (Ships' Accommodation Solutions Ltd, 2016). The position of the windows is modelled similar to the case study. The galley for example has no windows. The windows are mounted in a frame of 5 mm steel. The characteristics of the windows and window frames are shown in table 9 and 10 respectively.

Layer	Thickness [mm]	Thermal resistance [$\frac{m^2K}{W}$]
1 Generic Clear glass	15	
2 Air	8	
3 Generic Clear glass	6	
Total	**29**	**0.35**

Table 9 A60 Glass

Layer	Thickness [mm]	Thermal resistance [$\frac{m^2K}{W}$]
1 Steel	5	0.15

Table 10 Window frame

The dimensions of the windows are based on the drawings of the case study. The total number of windows has been counted and divided by the total façade area to determine the window-to-wall ratio. This value is approached by DesignBuilder by discrete steps of the size of a window with fixed width and height. Some windows are later removed manually in zones such as the galley and store where there are no windows. This resulted in a window-to-wall ratio of 4.16%.

Width	550 mm
Height	750 mm
Window spacing	2000 mm
Sill height	800 mm
Frame width	300 mm
Window to wall ratio	4.16%

Table 11 Window Dimensions and Lay-out

3.3.2.5 Lighting

The lighting is based on the lighting layout plan of the case study. All installed lighting has been counted and divided by the total floor area to determine the average normalised power density. The lighting is modelled to be 'surface mount' as show in figure 7. The choice for the lighting system is of influence for the radiant and convective fraction of the heat gain by the lighting.

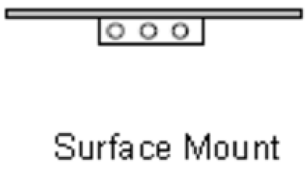


Figure 7 Surface mount lighting. Reprinted from DesignBuilder EnergyPlus Simulation Documentation (page 275), by DesignBuilder. Copyright (n.d.) by DesignBuilder Software Ltd.

The lighting is switched on 24/7 in all zones of the building except for the cabins. The lighting in the cabins is switched on for 6.5% of the time. This is based on the schedules of the crew which is elaborated upon in section 3.3.3.1. A summary of the lighting details is shown in table 12.

Normalised power density	15.95 $[\frac{W}{m^2}]$
Luminaire type	2 – Surface mount
Radiant fraction	0.72
Visible fraction	0.18
Convected fraction	0.10

Table 12 Lighting details

3.3.3 Activity data

The activity data tab in DesignBuilder contains all the information concerning the occupancy, domestic hot water consumption, environmental control setpoints and gains. This data is registered in templates. The following templates are made for this model:

- Cabins
- Mess
- Changing room
- Gym
- Hospital
- Office area
- Recreational rooms
- Galley
- HVAC
- Laundry area
- Store
- Circulation area's

This section elaborates on all the tabs in the activity data template: occupancy, gains, domestic hot water and environmental control.

3.3.3.1 Occupancy

The occupancy of an accommodation is of importance for the metabolic heat gain, use of equipment and lighting. A schedule has been made as a basis for the occupancy of an offshore accommodation. The crew consists of two working groups of 15 people each and two facility groups of three people each. The schedule of a working group and a facility group is shown in appendix I. The shifts have a phase difference of 12 hours. The facility group schedule is planned in such a way that the working hours coincide with the eating hours of the working group.

The schedule determines the allocation of the people in the accommodation. The following assumptions are made to translate the working schedule into the allocation of people, besides the trivial: sleeping is done in the cabins, eating is done in the mess and changing is done in the changing rooms.

- During working hours 12 people are outside the accommodation and 3 are located in the offices.
- During resting hours of the working group the following allocation is maintained:
  - Recreational area (non-smoke): 5 people
  - Recreational area (smoke): 5 people
  - Gym: 2 people
  - Cabins: 3 people
- During resting hours of the facility group the following allocation is maintained:
  - Recreational area (no smoke): 1 person
  - Recreational area (smoke): 1 person
  - Cabins: 1 person
- Working of the facility group is done in the galley and one hours in the laundry area.
- The remaining occupancy is divided over the remaining zones with an average occupancy (independent of time) as follows:
  - HVAC room: 0.05 person
  - Store room: 0.1 person
  - Circulation areas: 0.8 person
  - Hospital: 0.05 person

The platform is assumed to be occupied 7 days per week all year round.

The number of people in a zone is determined in DesignBuilder by the maximum density (people per m^2) and the occupancy factor. These are calculated as followed:

$$Maximum\ density = \frac{Total\ people\ in\ accommodation}{Zone\ floor\ area}$$

$$Occupancy\ factor(t) = \frac{Actual\ amount\ of\ people\ in\ zone}{Total\ people\ in\ accommodation}$$

The occupancy factor is a function of time and therefore defined in DesignBuilder by a schedule.

DesignBuilder further uses the metabolic rate and metabolic factor to determine the metabolic heat gain. The rate depends on the type of activity done by the people. For this value, the standards supplied by DesignBuilder are used. These standard values are based on the ASHREA Handbook of Fundamentals. The metabolic factor reflects the distribution of men, women and children in a building. In this model the metabolic factor is set to 1.00, meaning all men.

3.3.3.2 Gains

The gains tab in the activity data template enables the user to set gains which contribute to the energy consumption of the building and the heat gain. These can be office equipment, lighting, galley appliances, etc. In this model the gains are categorised by lighting and miscellaneous. Lighting has been described earlier in section 3.3.3. All other energy consumers are gathered under miscellaneous. This data is based on the load list of the case study, it contains the power required and usage factor for all consumers on board. This load list was used in the design of the accommodation to design the electrical system. Missing data is completed with standard values supplied by DesignBuilder. An overview of the gains per zone is shown in table 13.

Zone	Miscellaneous Power [W]	$[\frac{\mathrm{W}}{\mathrm{m}^2}]$	Source
Gym	313	24	DesignBuilder standards
Hospital	189	18	DesignBuilder standards
Office area	374	20	DesignBuilder standards
TV-room no smoke	159	13	DesignBuilder standards
TV-room smoke	90	13	DesignBuilder standards
Galley	30,000	862	case study load list
Laundry area	12,000	960	case study load list
Store	7000	288	case study load list

Table 13 Miscellaneous Gains

The equipment of the HVAC system is not modelled by the gains since this energy consumption is calculated by the HVAC module in DesignBuilder. An extra 8 $\frac{W}{m^2}$ is added to each zone to account for the power sockets based on the case study load list.

The heat gain is fragmented by:

- Convected fraction: heat is transferred by movement of air in the spaces.
- Radiant fraction: heat is transferred by thermal radiation (or infrared radiation) and absorbed by surrounding mass in the spaces such as the walls.
- Latent fraction: heat is added to the space as latent heat, keeping the temperature in the space constant.
- Fraction lost: heat lost by any other means and not adding energy to the spaces.

These fractions add up to one. For some zones, the heat gain, which is used for the HVAC design, is given in the design specifications. In that case the 'fraction lost' is set to such a value that the heat gain to the zone corresponds to the heat gain mentioned in the design conditions. All other zones have a radiant fraction of 0.2 and a convected fraction of 0.8.

3.3.3.3 Domestic Hot Water (DHW)

DesignBuilder requires the hot water consumption to be inputted in litre per m² per day for each zone. The rate for the cabins is based on the consumption rates listed below (per person, per day) and later converted to litre per m² per day.

- Shower water 9.5 litre/min, for 8 minutes (Otheguy, 2014)
- Lavatory 4.7 litre (Vitens, 2016)

A consumption rate of 4 litre per m² per day is assigned to the mess room based on the DesignBuilder standards. This represents the washing of hands before eating. The hot water consumption for showering is integrated in the consumption rate for the cabins, therefore the changing room has no consumption rate. The rates are shown in table 14. The temperature setpoints for the water outlet is set to 40 ºC, which is common for showering and washing hands.

Zone	DHW consumption rate [$\frac{L}{m^2 day}$]
Cabins	10
Mess	4

Table 14 DHW Consumption rates

3.3.3.4 Environmental control settings

The environmental control settings determine the setpoints for the temperature and the humidity ratio. These can be set for heating (generally in the winter), cooling (generally in the summer) and set back temperatures (when the building is not occupied). However the platform and its HVAC system are active 24/7, so the setback temperatures are irrelevant.

The humidifying setpoint is set to 30% and the dehumidification setpoint is set to 70%. The temperature setpoints are shown in table 15. The setpoints are based on the design specifications of case study and the ABS Guide for compliance with the ILO Maritime Labour Convention, 2006 (American Bureau of Shipping, 2014).

	Heating [ºC]	Cooling [ºC]
Cabins	20	27
Offices	20	27
Recreational rooms	20	27
Mess	20	27
Changing room	15	30
Circulation areas	15	30
Galley	15	30
Hospital	20	27
Laundry	15	30
HVAC	5	45
Stores	5	25

Table 15 Temperature setpoints

3.3.4 HVAC

The previous sections described the elements which determine the heating and cooling load. This section elaborates on how this load is satisfied. This is done by the heating, ventilation and air conditioning system and a domestic hot water system. Based on the design specifications, four systems are modelled in the base case model:

- Air handling unit 1, serving cabins, offices, circulation areas, recreational rooms
- Air handling unit 2, serving the galley
- Air handling unit 3, serving the HVAC room and the store room
- Domestic Hot Water system

The specifications of the systems and how they are modelled is described in the following sections. If on hand, data is based on the design specifications of the case study. If data is absent, it is autosized by DesignBuilder. In that case DesignBuilder sized the components in order to comply with the needs for the summer and winter design days including a design margin of 1,25.

3.3.4.1 Air handling unit 1

AHU1 is the main unit and serves most of the zones. HVAC systems are modelled in DesignBuilder by connecting zone groups to loops. Loops can be, for example, single duct air loops, hot water loops, chilled water loops, condenser loops, etc. A zone group contains zones with identical HVAC configurations.

Components can be added to the AHU for heating, cooling and humidification. AHU1 has the following components:

- Electric heater
  - Capacity: 120 kW
- DX Cooler
  - Capacity: Autosized
  - Type: single
- Steam humidifier
  - Capacity: Autosized
- Fan section
  - Total fan efficiency: 0.78
  - Pressure rise: 1200 Pa

The AHU has an flow rate of 13865 $\frac{m^3}{hr}$. 40% of the returned air is recirculated. To control the output temperature and humidity levels, DesignBuilder uses setpoint managers. The temperature setpoint managers are set to 'Scheduled' which means that the setpoint temperature for the air handling unit follows a predefined schedule. This is schedule is set to 14 ºC in summer (June until October) and 18 ºC in winter. For humidification and dehumidification, a 'Multi-zone humidity maximum/minimum' setpoint manager is used. The setpoint is then based on the maximum or minimum humidity level in the zones and is calculated in order to maintain the setpoints set in the environmental control settings.

AHU1 is connected to the zone groups by a 'Generic Air Loop'. The system contains four zone groups: with or without reheaters and with or without exhausts. A schematic overview of the system is show in figure 8.

The cabins, offices, mess and recreational spaces have reheaters to adjust the room temperature to personal preferences. Some zones have an own direct exhaust. These are zones with high humidity levels or polluted air, namely the changing room, the smoking recreational area, laundry area and the hospital. In reality the air from these zones is not returned to the air handling unit. However in DesignBuilder, the loop has to be closed in order for the model to work. Therefore, the air input and the exhausted air are set to the same quantity in order to keep the return flow at zero. The airflow rates for these zones are shown in table 16.

Zone	Airflow rate $[\frac{m^3}{hr}]$
Laundry	600
Hospital	285
Smokers room	600
Changing room	1545

Table 16 Airflow exhaust fans

The airflow for the remaining zones is set so that each zone has 6 fresh air changes per hour. This is a minimum according the Maritime Labour Convention (American Bureau of Shipping, 2014). This means that the total number of air changes in the zone is higher since there is an 40% recirculation. All ventilation is done by mechanical means. Natural ventilation (i.e. opening of windows) is not possible in this offshore accommodation.

The reheaters have a capacity of 3000 W per cabin. The zones represent multiple zones. Therefore, a reheater capacity of 300 $\frac{W}{m^2}$ is used. The reheater capacities for each zone are shown in table 17.

Zone	Reheaters capacity [W]
Accommodation 1	8748
Accommodation 2	12027
Accommodation 3	20157
Accommodation 4	6477
Accommodation 5	15102
Accommodation 6	8748
Accommodation 7	12027
Accommodation 8	6477
Office area	9339
TV-room no smoke	9069
TV-room smoke	5115
Mess room	12522

Table 17 Reheaters capacities

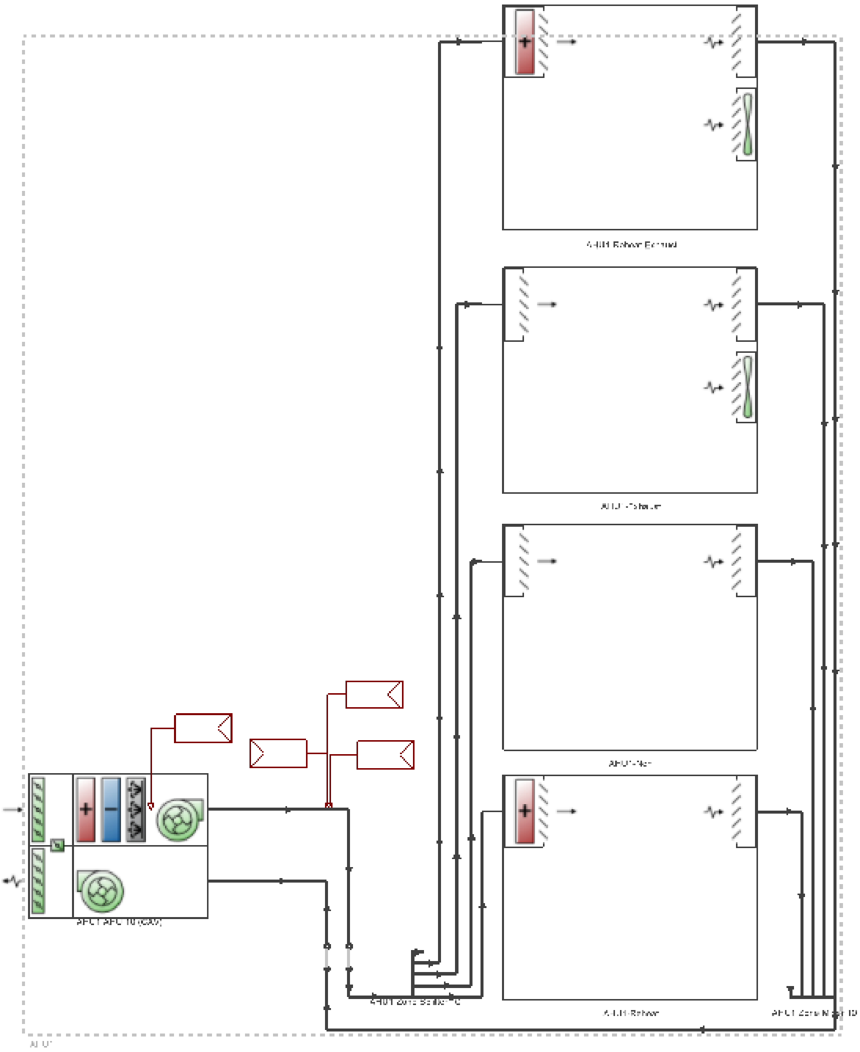


Figure 8 AHU 1

3.3.4.2 Air handling unit 2

AHU2 serves the galley and has the following components:

- Electric heater
    - Capacity: 30 kW
- DX Cooler
    - Capacity: autosized
    - Type: single stage
- Fan and exhaust fan
    - Total fan efficiency: 0.71
    - Pressure rise fan: 800 Pa
    - Pressure rise exhaust fan: 600 Pa

The loop has a flowrate of 3000 $\frac{m^3}{hr}$ and no air is recirculated. The galley itself has no reheater. The setpoint temperature is set to 18 °C throughout the year.

3.3.4.3 Air handling unit 3

AHU3 serves the HVAC and store room and has the following components:

- Electric heater
  - Capacity: 60 kW
- DX Cooler
  - Capacity: autosized
  - Type: single
- Fan and exhaust fan
  - Total fan efficiency: 0.638
  - Pressure rise: 1200 Pa
  - Pressure rise exhaust fan: 600 Pa

The loop has a flowrate of 7000 $\frac{m^3}{hr}$ and no air is recirculated. The rooms itself have no reheaters. The setpoint temperature is set to 15 ºC throughout the year.

3.3.4.4 Domestic Hot Water

The hot water system is modelled by an electric boiler and a DHW Loop. The boiler has a volume of 0.75 m^3 and a heater capacity of 25 kW. The setpoint temperature is set to 65 ºC. This is needed to prevent bacteria growth in the pipe system. The flow rate is determined by the consumption as described in section 0. The temperature of shower water and hot water used for washing hands is set to 40 ºC.

The water supplied to the boiler is supplied from water tanks. The temperature of this water is depends on outside temperatures since the tanks are not conditioned. The water supply temperature is set to 10 ºC for North Sea and 15 ºC for the Gulf of Mexico.

3.3.5 Weather data

DesignBuilder uses yearly weather data to simulate the annual energy consumption. This data contains temperatures (dry-bulb, wet-bulb and dew point), humidity levels, solar irradiance, wind speed and wind direction for a given location. For steady-state heating and cooling calculations and auto sizing, DesignBuilder uses a winter and summer design day, which can be assigned in the weather data file as well.

Two locations are used in this research: the Norwegian part of the North Sea and the Gulf of Mexico, representing a cold and a hot environment. The weather data from the North Sea is based on measurements on the EKOFISK platform. The weather data for the Gulf of Mexico is based on data from a buoy located in the Gulf of Mexico called 'Station 42001'. The data files are obtained from a parallel research by L. Hammer.

A summary of the temperature data for both locations is shown in table 18. Summer months are from April up to and including September.

		North Sea		Gulf of Mexico	
		Summer	Winter	Summer	Winter
Temperature [^{0}C]	Min	2.5	-2.8	20.5	16.6
	Max	20.5	15.2	28.8	27.7
	Average	11.7	5.0	26.2	21.9
Relative humidity [%]	Min	47	40	49	50
	Max	98	101	90	97
	Average	81	80	65	73
Absolute humidity [kg/m^3]	Average	0.008	0.005	0.016	0.013

Table 18 Summary weather data

Note that the relative humidity is the ratio between the actual vapour pressure and the saturation vapour pressure. The absolute humidity ratio, meaning the amount of water per measure of volume, is calculated with the following formulae:

$$AH = \frac{6.112 \cdot e^{\frac{17.62 \cdot T}{T+243.12}} \cdot f(p) \cdot RH}{(273.15 + T) \cdot R_v \cdot 100}$$

$$f(p) = 1.0016 + 3.15 \cdot 10^{-6} p - 0.074 \cdot p^{-1}$$

Where
AH: absolute humidity in kg/m^3
p_{atm}: atmospheric pressure in hPa
T: temperature in ^{0}C
RH: relative humidity in percentage
R_v: specific gas constant for water vapour, 461.5 J/mol K

The results are included in table 18 for the average temperature and relative humidity. It shows that the air in the North Sea contains less moisture than the air in the Gulf of Mexico.

4 Energy use of base case model

The base case model is used to obtain data on energy use which is used as the benchmark for energy saving strategies. This section shows the results for the base case model in both cold (North Sea) and hot (Gulf of Mexico) environments. Firstly, an overview of the yearly energy consumption and the distributions over the consumers is given. The following section elaborates on the heat gains and losses in the accommodation. Finally, a conclusion is given.

4.1 Yearly energy consumption

Table 19 shows a summary of the yearly energy consumption in MWh. The auxiliary energy consumption contains all equipment except for the HVAC, laundry and galley, i.e. computers, power sockets, gym equipment, etc. As a comparison and validation for the model, the results by the research of Otheguy and the design specifications are also shown in table 19, both are calculated for North Sea conditions. Note that 'total HVAC' is the sum of heating, cooling, humidification and fans.

Consumer category	North Sea		Gulf of Mexico		Otheguy	Design Spec.
Heating	*387*	*38%*	*32*	*4%*	*(not specified)*	*(not specified)*
Cooling	*24*	*2%*	*302*	*34%*	*(not specified)*	*(not specified)*
Humidification	*50*	*5%*	*0*	*0%*	*(not specified)*	*(not specified)*
Fans	*114*	*11%*	*114*	*13%*	*(not specified)*	*(not specified)*
Total HVAC	576	57%	449	51%	697	649
Lighting	74	7%	74	8%	96	26[1]
Laundry	74	7%	74	8%	79	74
Galley	159	16%	159	18%	193	188
Aux	79	8%	79	9%	70	139
DHW	52	5%	43	5%	35	*(not specified)*
Total	**1013**	**100%**	**877**	**100%**	**1170**	**1077**

Table 19 Yearly energy consumption in MWh
1 Only lighting in cabins

The results show that the HVAC system is the biggest contributor to the total energy consumption. The consumption of the lighting, laundry, galley and auxiliary equipment are close to the design specifications because the installed power is based on the design specifications. However, the difference in energy consumption is due to a difference in usage. In the model, this is based on the occupancy schedules. In the design specifications this is based on an usage factor. The same applies to the consumption of the HVAC system. In addition, the model is based on actual weather data, whereas the consumption in the design specifications is based on the installed power and a fixed usage factor.

The results for the HVAC energy consumption of Otheguy are estimated by summing up:

- The installed supply and exhaust fan power multiplied by an estimated usage factor
- The installed re-heater power multiplied by an estimated usage factor
- The enthalpy needed to condition the exterior air to interior conditions of temperature and relative humidity, which is calculated by:
  - using a suitable probability distribution of average monthly air temperatures and the corresponding exterior relative humidity
  - putting the enthalpy calculation in the form of power needed and multiply it by the appropriate air recirculation factor.

The difference compared to energy consumption for HVAC as calculated by the model is then caused by the difference in usage factors and the fact that DesignBuilder uses hourly weather data.

The energy consumption for domestic hot water (DHW) is higher than the results by Otheguy. This difference is caused by the fact that in DesignBuilder also the efficiency of the boiler and the water consumption other than shower water is taken into account.

Table 20 shows a comparison of the average total energy consumption per day for the base case accommodation compared to onshore hotels.

Total average energy consumption per day	North Sea/ Gulf of Mexico	Hotels
kWh per m^2	2.89/ 2.50	0.55 to 1.10[1]
kWh per person	75/ 65	46 to 68[2]

Table 20 Comparison offshore accommodation and hotel
[1] For European hotels (Analysis of energy use by European hotels: online surveys and desk research, 2011)
[2] Worldwide (Statistica, 2016)

The consumption rates for offshore accommodations are higher than those of hotels. This has the following possible reasons:

- High number of air-changes-per-hour (elaborated upon in section 4.2)
- 24/7 activity. Whereas in hotels and office buildings, most spaces are unoccupied during night time, in the offshore accommodation day and night shift cause the accommodation to be occupied and active 24 hours a day
- All electric. All systems in the offshore accommodation are electric. Heating and ventilation is done with forced air. However, radiant heating and cooling is more energy efficient. Water is a better transport agent then air. Also it costs less energy to circulate. (Texas University Center for Electromechanics, 2016)
- Occupant density. When comparing hotels to offshore accommodations, hotels have a lower occupant density. Hotel rooms are generally larger than cabins in offshore accommodations.

The distribution of the energy consumption is similar to onshore hotels, as shown in table 21. The energy consumption for DHW in hotels is higher since the hotels considered in this survey also include a pool which need heating.

	Offshore accommodation	Onshore hotel
HVAC	57%	50%
Lighting	7%	10%
Galley	16%	15%
DHW	5%	15%
Other	15%	10%

Table 21 Comparison Offshore accommodation and onshore hotel (based on (Analysis of energy use by European hotels: online surveys and desk research, 2011))

4.2 Heat balance

The biggest contributors to the total energy consumption are the HVAC installations. The installations have to compensate for the heat loss or gain in the accommodation. It is therefore interesting to see how this heat balance is distributed. Figure 9 shows a schematic view of the sensible heat balance of the accommodation as it modelled in DesignBuilder.

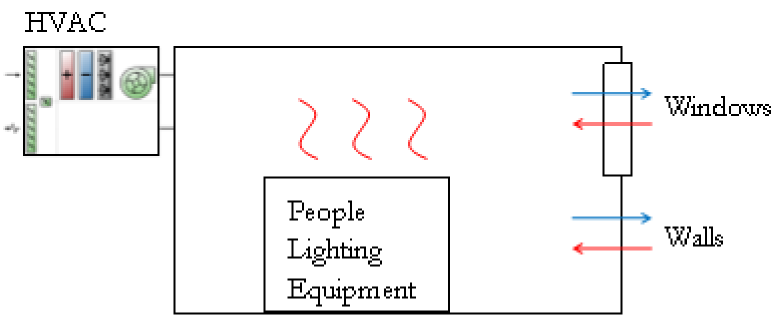


Figure 9 Heat balance of accommodation

The HVAC installation balances the results of the heat addition by people, lighting and equipment and heat transfer trough the building's envelope (walls and windows). Heat transfer trough the walls and windows is the sum of conducted heat transfer and heat gain by solar radiation. Table 22 shows the heat transfers over a week in the summer and winter in kWh for the North Sea and Gulf of Mexico.

	North Sea		Gulf of Mexico	
[kWh]	Winter	Summer	Winter	Summer
Windows	-176	71	96	238
Walls	-852	-324	-246	170
People	311	328	309	328
Lighting	1411	1411	1411	1411
Equipment	1913	1913	1913	1913
HVAC	-2607	-3399	-3484	-4059

Table 22 Weekly heat balance in kWh

The heat gain by lighting, people and equipment is constant. The heat transfer trough the walls is negative as long as the inside temperature is higher than the outside temperature. The heat transfer through the windows in the summer in the North Sea and in the Gulf of Mexico is positive due the solar penetration. Table 22 shows that there is a net cooling effect by the HVAC system. Figure 10 shows a schematic view of the main HVAC installation.

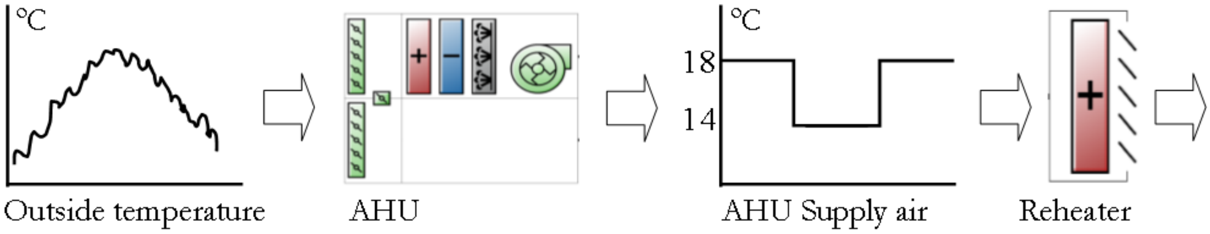


Figure 10 Schematic view of main HVAC installation

Although there is a net cooling requirement in the accommodation, the installation has an energy consumption for heating the outside air to the fixed temperatures of 14 °C and 18 °C. Also, the HVAC system in has an energy consumption for heating in the Gulf of Mexico because the cooled air of 14 °C needs to be reheated in order to maintain an interior average temperature of 20 °C.

The HVAC installation has a constant air flow to maintain 6 fresh-air-changes-per-hour. This causes a high energy consumption for the HVAC installation. Heat transfer by an airflow is given by the following equation (Engineering Toolbox, 2016):

$$Q = L \cdot c_p \cdot \rho \cdot \Delta T$$

Where

Q:	Heating or cooling effect of air-system in kW
L:	Air flow rate in m^3/s
c_p:	Specific heat of air (1.005 kJ/kg- °C)
ρ:	Density of air (1.2 kg/m^3)
ΔT:	Difference between supply air and room temperature

This shows that for the same cooling load, ΔT needs to be small if the air-flow-rate is high, i.e. a high amount of air needs to be conditioned to a temperature closer to the room temperature (20 °C).

Offshore accommodations require an air exchange rate of 6 fresh-air-changes-per-hour according the ILO Maritime Labour Convention, 2006 (American Bureau of Shipping, 2014). This is relative high compared to 0.5 – 3 for onshore buildings (Beekers & Steemers, 2000). Also in requirements for sea going vessels, one finds high air exchange rates up to 30 air-changes-per-hour for example for cargo holds of livestock carriers (Germanischer Lloyd, 2014). Simulations with the model show that if the number of air-changes-per-hour is reduced to 3, the energy consumption for the HVAC system is reduced by approximately 25%. This includes savings in fan power, and also in heating, cooling and humidification because less air needs to be conditioned. The airflow however is also used to condition the spaces. If the airflow is further reduced, the AHU is not able to maintain the temperature and humidity setpoints. The airflow is not able to exhaust the humidity and heat produced inside the accommodation.

4.2.1 Thermal bridges

Thermal bridges are local areas in the building's construction with a relative high heat transfer. These can occur due to materials with high heat conductivity or penetrations in the structure. For example, in offshore accommodations, thermal bridges appear at the area where the decks are welded to the accommodation's bulkheads. Thermal bridges are not simulated in this model in DesignBuilder. A finite element study by M. Otheguy showed that for a typical offshore accommodation structure the heat loss through the walls increases by approximately 17%. This assumes a temperature difference of 20 ºC between the inside and outside temperature. Figure 11 shows the finite element-calculated temperature profile in a 2D construction section of an offshore accommodation.

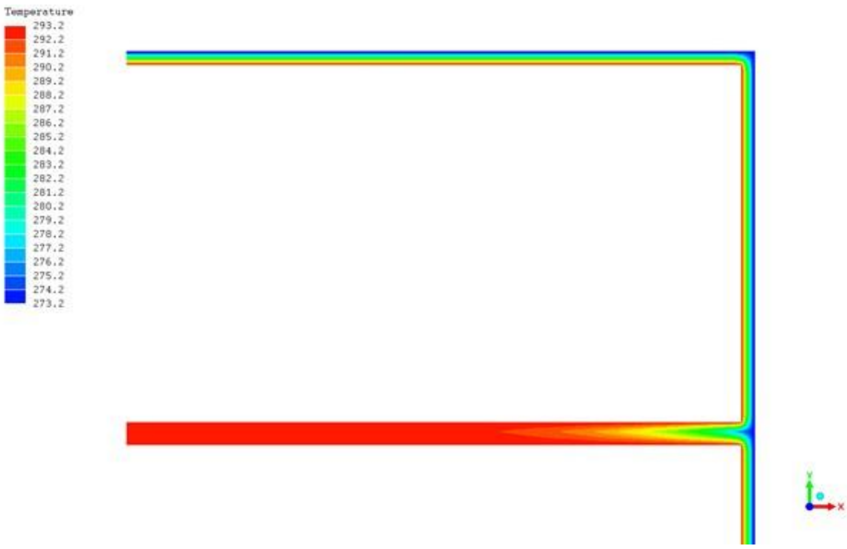


Figure 11 Model of thermal bridge in offshore accommodation (Otheguy, 2016)

Table 23 shows the heat losses in the accommodation in an extreme case, i.e. the coldest winter day in the North Sea. Due to the high air flow through the AHU, most of the heat loss occurs by exhausting warm air to the outside. Only a small part of the heat is lost through the walls. Hence, the cold bridge effect as estimated above would account for less than 1% of the HVAC energy use, meaning less than 0.5% of the total energy consumption. Because of this small value and in order to keep on the conservative side, heat bridges are not taken into account in further calculations in this research.

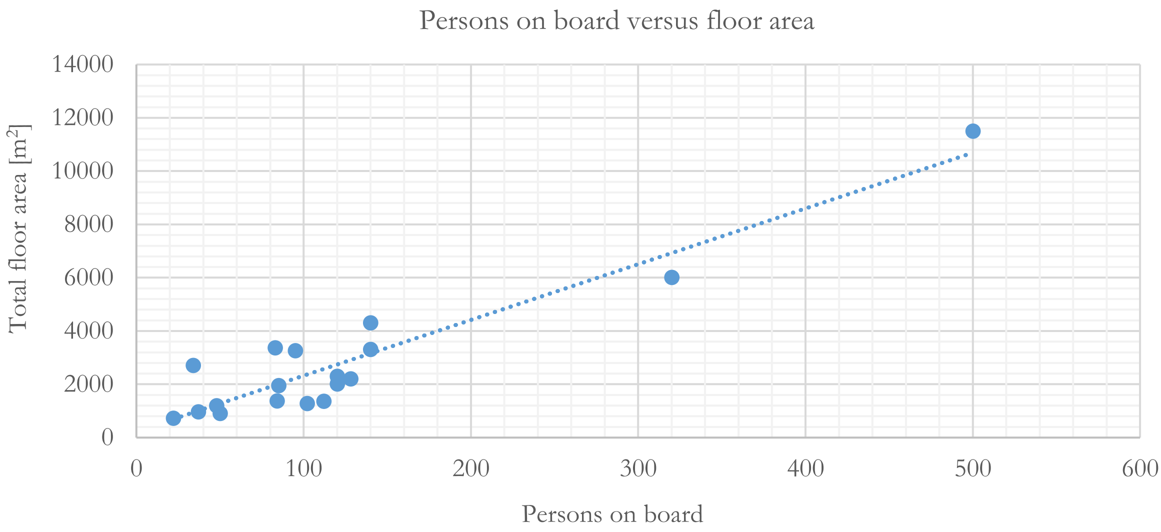
Windows	2%
Walls	5%
Ventilation	93%

Table 23 Heat loss on the coldest winter day in the North Sea

4.3 Change in capacity of the accommodation

The results presented are calculated for an accommodation unit with a capacity of 37 persons on board (POB). This section discusses the effects on the energy consumption if the capacity of the accommodation is increased for each of the consumer categories: HVAC, galley, laundry, lighting, domestic hot water and auxiliary.

The floor area of the accommodation is related to the number of persons on board. To get an estimate of the relation between the floor area and the number of POB, a regression analysis is done based on available data from 18 offshore accommodation units.



This graph shows the following relation between the floor area and the number of POB

$$A = 21 \cdot POB + 233$$

Where A: Total floor area of accommodation in m²
POB: Number of persons on board

4.3.1.1 Lighting

The energy consumption for lighting is linear dependent on the floor area of the accommodation. In the base case model, the lighting power density is set to 16 W/m². The usage factor for cabins is set to 0.07. The lighting in other zones is set on 24/7. The weighted average usage factor is 0.66, based on the usage factor and corresponding floor area. This results in the following relation:

$$W_{lighting} = 16 \cdot 0.66 \cdot (24 * 365)A = 16 \cdot 0.66 \cdot (21 \cdot POB + 233)$$

Where $W_{lighting}$: Energy consumption of lighting in Watt-hour per year
A: Total floor area of accommodation in m²
POB: Number of persons on board

4.3.1.2 Domestic Hot Water

The energy consumption for heating of water is linear dependent on the number of persons on board. The energy consumption for DHW per person is calculated by the amount of energy that is needed to heat water to the required temperature of 65 ºC based on the following assumptions:

- Consumption rate — 30989 L per person per year (for showering and washing hands)
- Temperature of water for shower and tabs — 40 ºC
- Inlet temperature — 10 ºC in North Sea and 15 ºC in Gulf of Mexico
- Outlet temperature — 65 ºC
- Specific heat of water — 4.18 kJ/ Kg K
- Density of water (at 35 ºC) — 994 kg/m^3
- Efficiency of boiler — 90%

Firstly, the mix ratio of hot (65 ºC) to cold water (10 ºC/15 ºC) is determined which results in a consumption temperature of 40 ºC. This determines the consumption rate of hot water. Then the specific heat and density of water is used to calculate the amount of energy that is needed to heat the water from the inlet to the outlet temperature. This is multiplied by the efficiency of the boiler to calculate the electric energy consumption of the boiler. Finally, this results in the following formula:

$$W_{DHW} = C_{HW} \cdot POB$$

Where
W_{DHW}: Energy consumption for DHW in kilowatt-hour per year
C_{HW}: Hot water consumption rate, 1202 kWh/person in North Sea and 1093 kWh/person/year in Gulf of Mexico
POB: Number of persons on board

4.3.1.3 Galley, Laundry and Auxiliary

The energy consumption for the galley, laundry and auxiliary (appliances and power sockets) depends on the number of POB. Data on these consumer categories of other platforms is not available. To get an estimate on the consumption rate, the energy consumption of the base case is divided by the number of POB in the base case accommodation (37). The consumption rates are shown in table 24 in MWh per person per year.

Consumer categories	Consumption rate [MWh/person/year]
Galley	4.3
Laundry	2.0
Auxiliary	2.2

Table 24 Consumption rates

4.3.1.4 HVAC

To gain insight in the relation between the consumption for HVAC and the floor area of the accommodation, a simplified version of the base case model is made in DesignBuilder. The simplified model has one air handling unit with a heating coil, cooling coil and a humidifier. Each deck has a reheater. The number of air changes is maintained at 6 air-changes-per-hour. The accommodation has the same length (20 m), width (16m) and deck height (2,9 m) as the base case model. The size of the accommodation is varied by changing the amount of decks. The occupancy, gains and schedules are set to an average based on the data of the base case model. The simplified model with the change in number of decks is shown in figure 12.

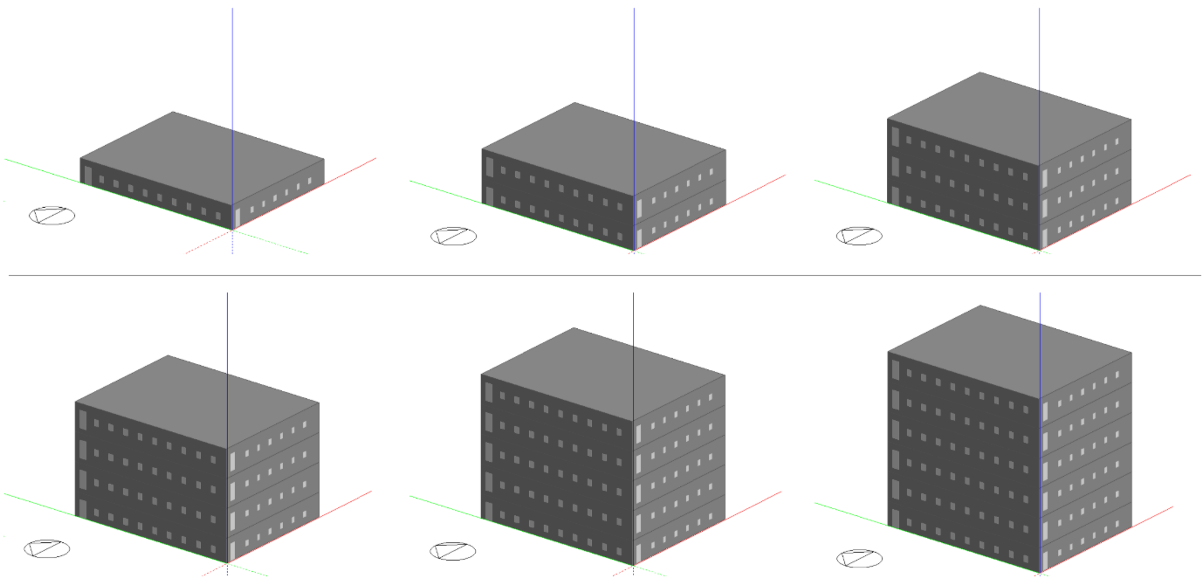
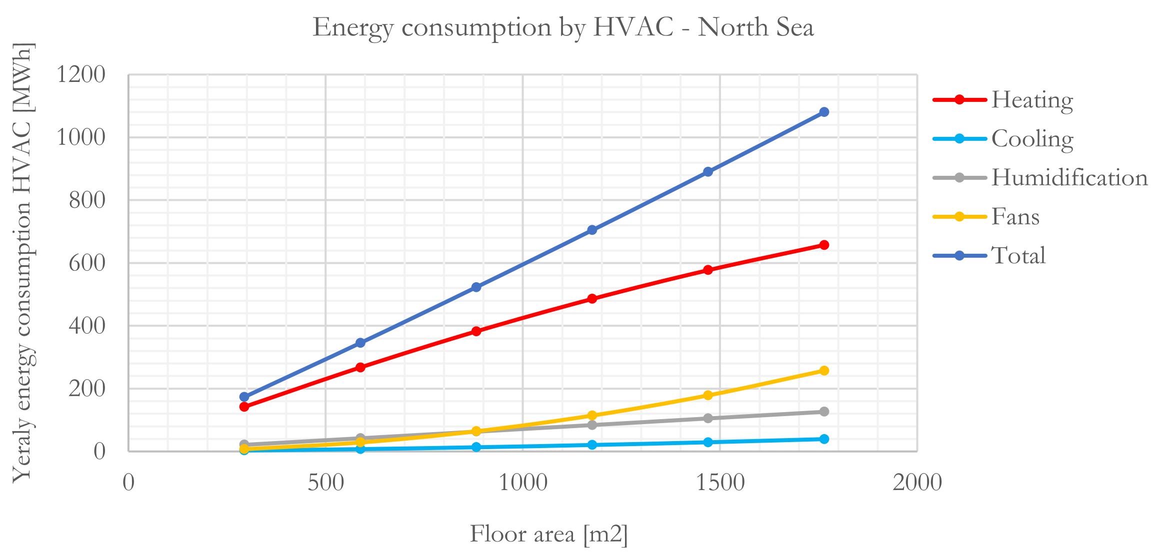
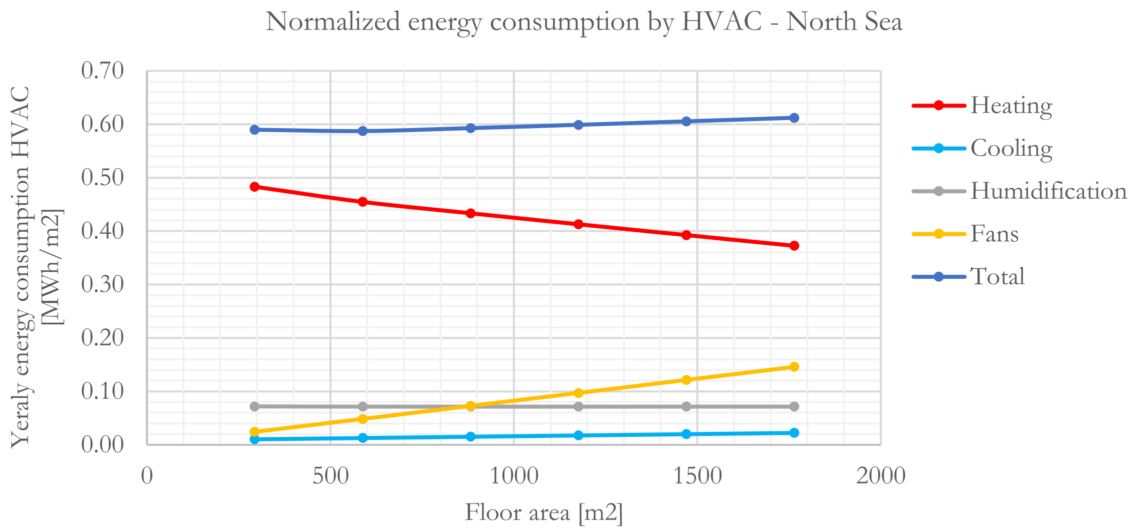


Figure 12 Simplified model with changing number of decks

The results of the variation in number of decks and the corresponding yearly energy consumption is shown in the graphs below. It shows the absolute consumption and the normalized values with respect to the floor area.





The model shows a linear increase in the consumption for cooling and humidification. The energy consumption of the fans shows an exponential increase.

The fan power in DesignBuilder is calculated with the following formula:

$$P_{fan} = \frac{Q \cdot \Delta P}{e_{tot}}$$

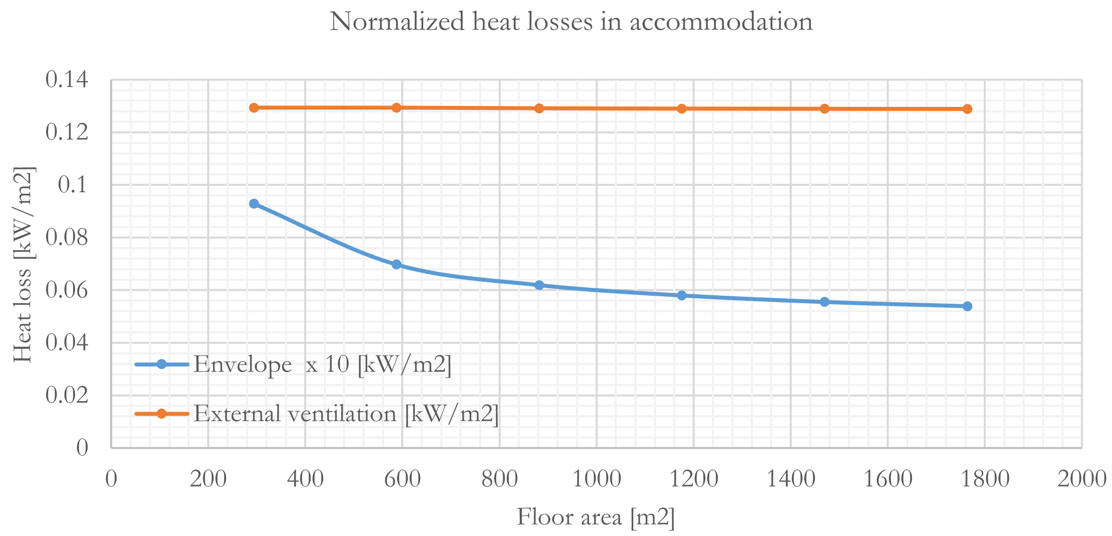
Where:

Where:	P_{fan}	fan power in W
	Q	volumetric flow rate in m^3 per second
	ΔP	fan pressure rise in Pa
	e_{tot}	total efficiency of fan

If the size of the accommodation is increased, the air flow is increased linear to maintain the number of air-changes-per-hour. The pressure drop in the ducting system is also increased linear to reflect the increase of ducting. This combined results in an exponential increase in fan power.

In this case study, fan motors are placed in the air stream. Therefore, part of the waste heat of the motor is added to the airflow. An increase in fan power therefore decreases the heating load and increases the cooling load.

The graph showing the normalised energy consumption by HVAC in the North Sea shows a small increase in the heating consumption for 1 deck. Part of the heat is lost via the accommodation's envelope and part is lost via ventilation. When the number of decks and thus the floor area, is decreased, the relative heat loss via the envelope is increased. This is shown in the graph 'Normalized heat losses in accommodation'. There is relatively more envelope per square meter floor area. The heat loss via external ventilation is dependent on the volume, which is increased linear with each deck.



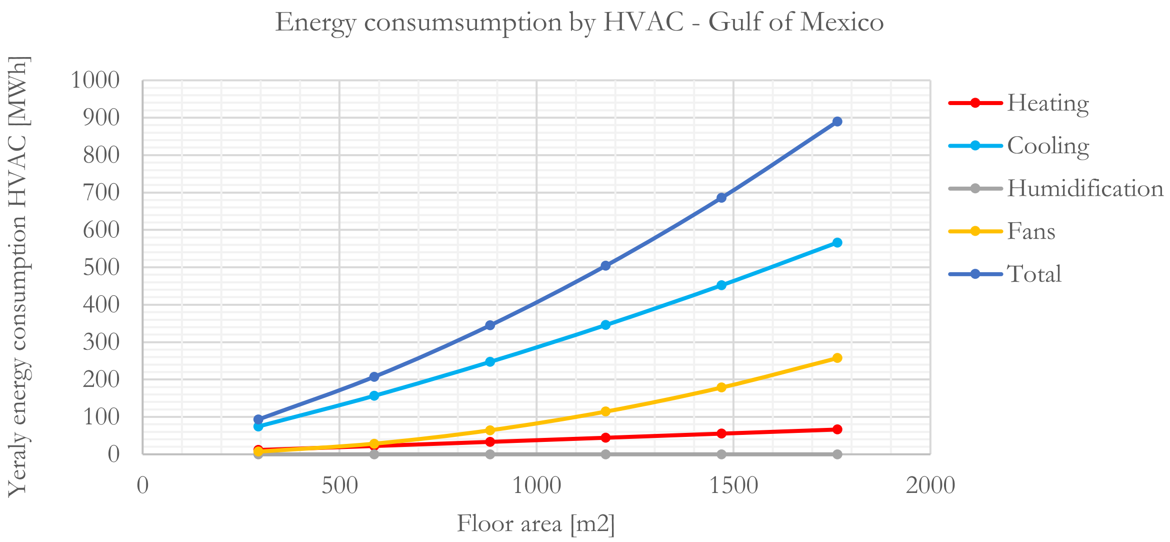
The curve of the HVAC consumption in the North Sea related to the floor area can be approached with the following polynomial:

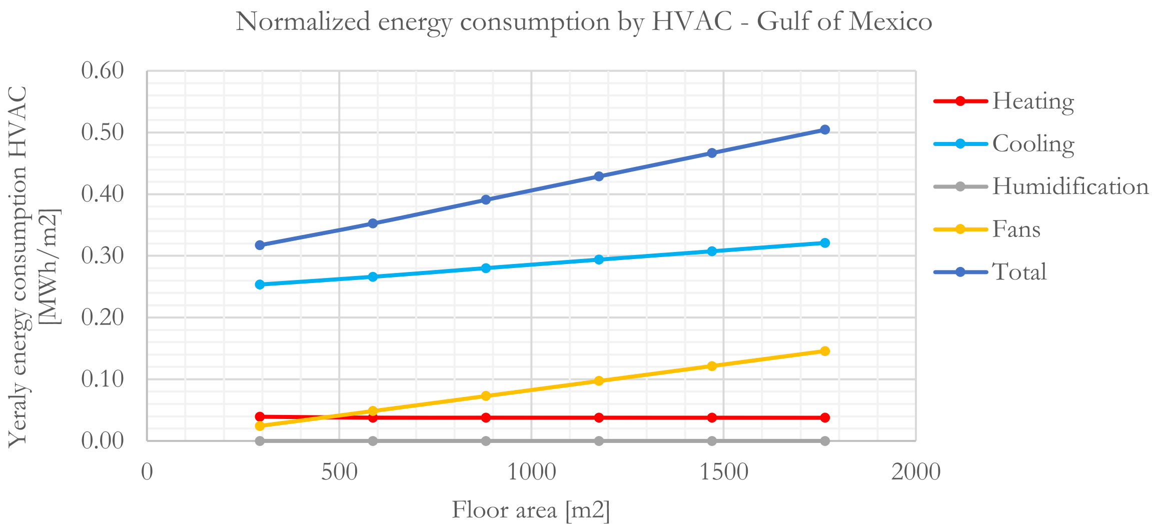
$$W_{HVAC,\ North\ Sea} = 3 \cdot 10^{-5} \cdot A^2 + 0.57 \cdot A + 4.84$$

Where W_{HVAC}: Energy consumption for HVAC in megawatt-hour per year

A: Total floor area of accommodation in m²

The same calculations are done for the Gulf of Mexico.





The curve of the HVAC consumption in the Gulf of Mexico related to the floor area can be approached with the following polynomial:

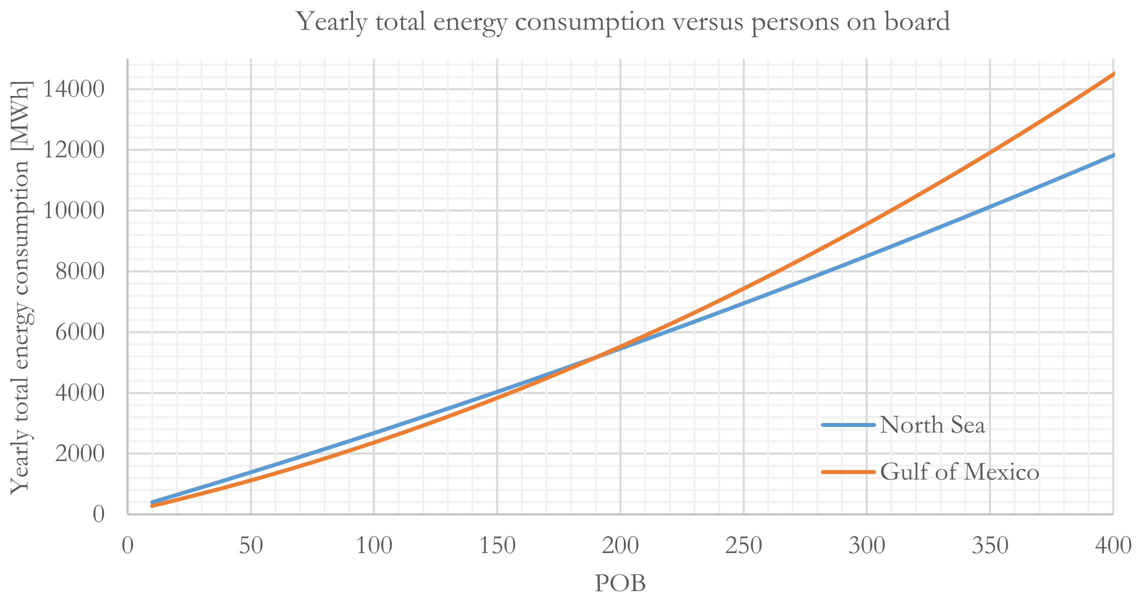
$$W_{HVAC,\ Gulf\ of\ Mexico} = 1 \cdot 10^{-4} \cdot A^2 + 0.28 \cdot A + 0.82$$

Where W_{HVAC}: Energy consumption for HVAC in megawatt-hour per year

A: Total floor area of accommodation in m²

4.3.1.5 Total

The yearly total energy consumption related to the number of persons on board in both the North Sea and Gulf of Mexico is shown in the graph 'Yearly total energy consumption versus persons on board'. It is constructed by summing the energy consumer categories as described above



These curves can be approached with the following polynomials:

$$W_{Total,\ North\ Sea} = 0.013 \cdot POB^2 + 23.84 \cdot POB + 160.83$$

$$W_{Total,\ Gulf\ of\ Mexico} = 0.044 \cdot POB^2 + 18.32 \cdot POB + 93.04$$

Where W_{Total}: Yearly total energy consumption in megawatt-hour per year

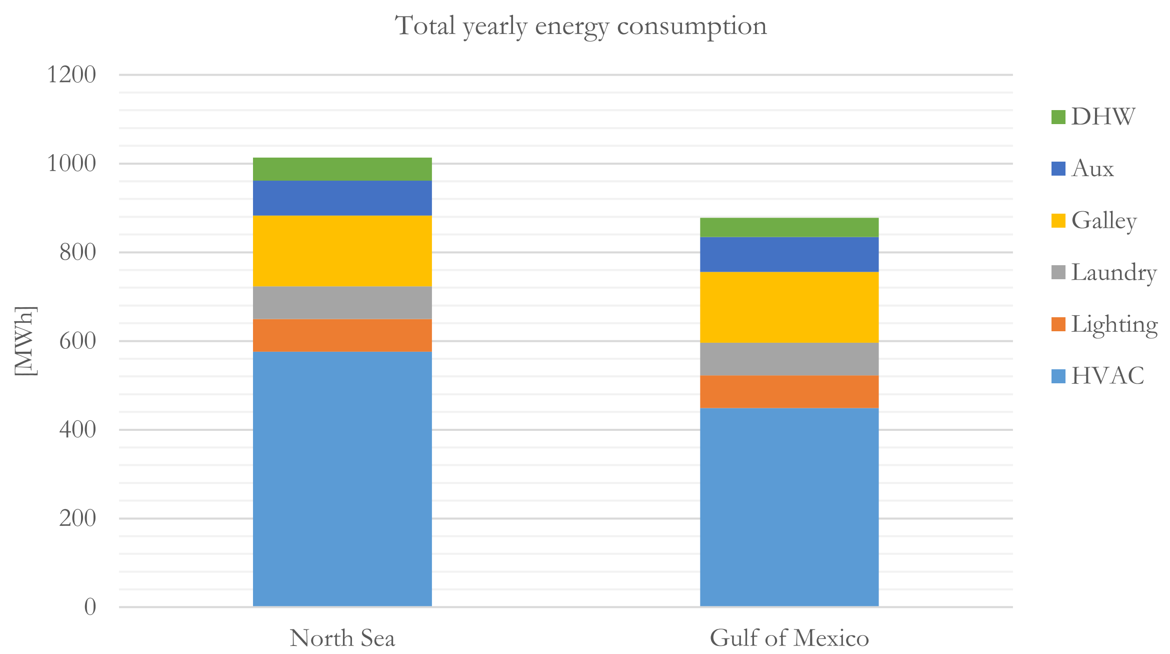
POB: number of persons on board

The graph shows that the energy consumption in the Gulf of Mexico exceeds the energy consumption in the North Sea at 190 POB. The model has a higher cooling load in the Gulf of Mexico. The increased cooling load caused by the fan motor, as described above, is therefore more relevant in the Gulf of Mexico.

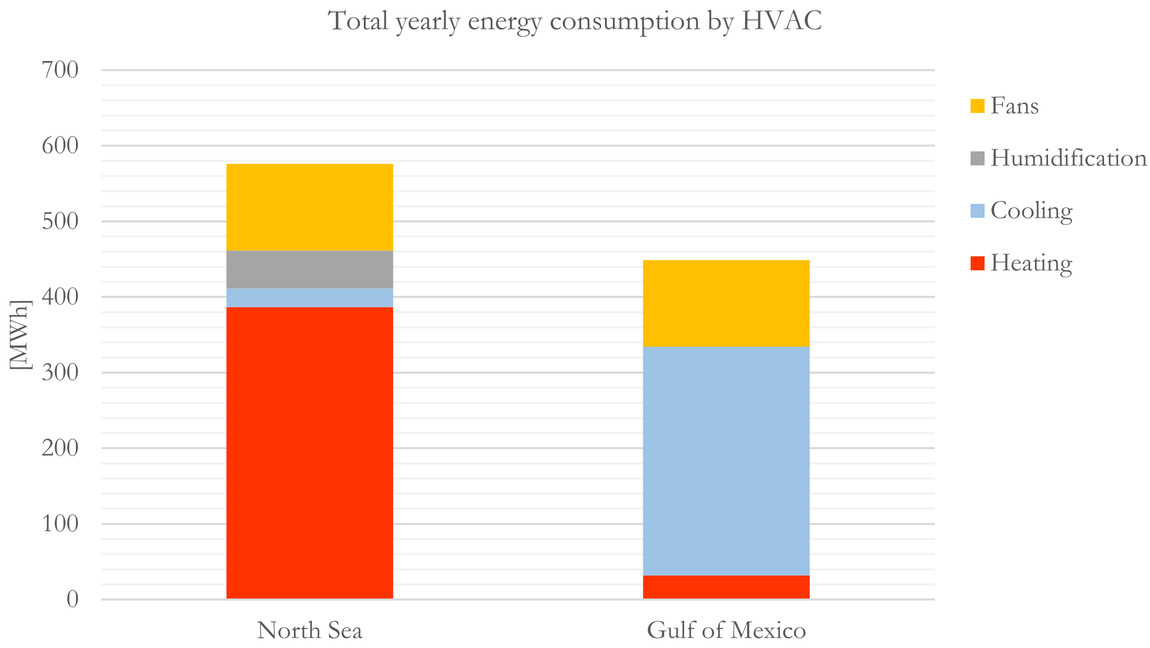
According to the simplified model, the base case model would have a yearly total energy consumption of 1061 MWh in the North Sea and 831 MWh in the Gulf of Mexico.

4.4 Conclusion

The base case model has an energy consumption of 1031 MWh in cold environments and 877 MWh in hot environments. The distribution of the yearly energy consumption is shown in the diagram below.



About 50% of the energy consumption is attributable to the HVAC system. The HVAC system takes care of heating, cooling, ventilation and humidification of the accommodation. The yearly energy consumption for the HVAC system is shown in the diagram below:



The consumption rates are high compared to onshore buildings. This is mainly caused by a high rate of air-changes-per-hour. If the number of air-changes-per-hour could be reduced with 50%, the consumption for HVAC can be reduced with 25%. Most of the heat gain in the accommodation is caused by lighting and equipment.

The amount of energy consumed per POB increases non-linear due to the non-linear behaviour of the fan power. Analysis of the consumer categories show the following relations between the number of persons on board and the yearly total energy consumption:

$$W_{Total,\ North\,Sea} = 0.013 \cdot POB^2 + 23.84 \cdot POB + 160.83$$

$$W_{Total,\ Gulf\,of\,Mexico} = 0.044 \cdot POB^2 + 18.32 \cdot POB + 93.04$$

Where W_{Total}: Yearly total energy consumption in megawatt-hour per year

POB: number of persons on board

The size and distribution of the energy consumption is used to assess different energy saving strategies described in section 5. The results for the base case model is used as a bench mark to determine the savings in operational expenditures described in chapter 6.

5 Energy saving strategies

Figure 13 shows the energy flows in and out of the accommodation. This indicates the options where to apply strategies to reduce CO_2 emissions and cost. This can be done on the input side, by generating energy without using fossil fuels, or on the output side by reducing the energy demand and losses. A third option is to recover energy that otherwise would have been lost. In this chapter a wide scope of energy saving strategies that is applicable to buildings and accommodations is discussed. With this information, a selection of strategies is made which are further assessed. As mentioned before, only off-the-shelf strategies are considered in this research. Therefore, only existing products for which a supplier can be found are shown in this chapter. Also, the external energy supply to the accommodation is out of the scope of this research. Energy saving strategies considering the building's envelope are studied in a parallel research by Lars Hammer at Keppel Verolme BV.

The first section describes a water sourced heat pump and natural heating and ventilation. The second section describes LED lighting and demand controlled ventilation. The third section describes an enthalpy wheel, a drain water heat recovery system and a bio-gas digester. Finally, a selection is made out of these strategies that is further examined and used for the design.

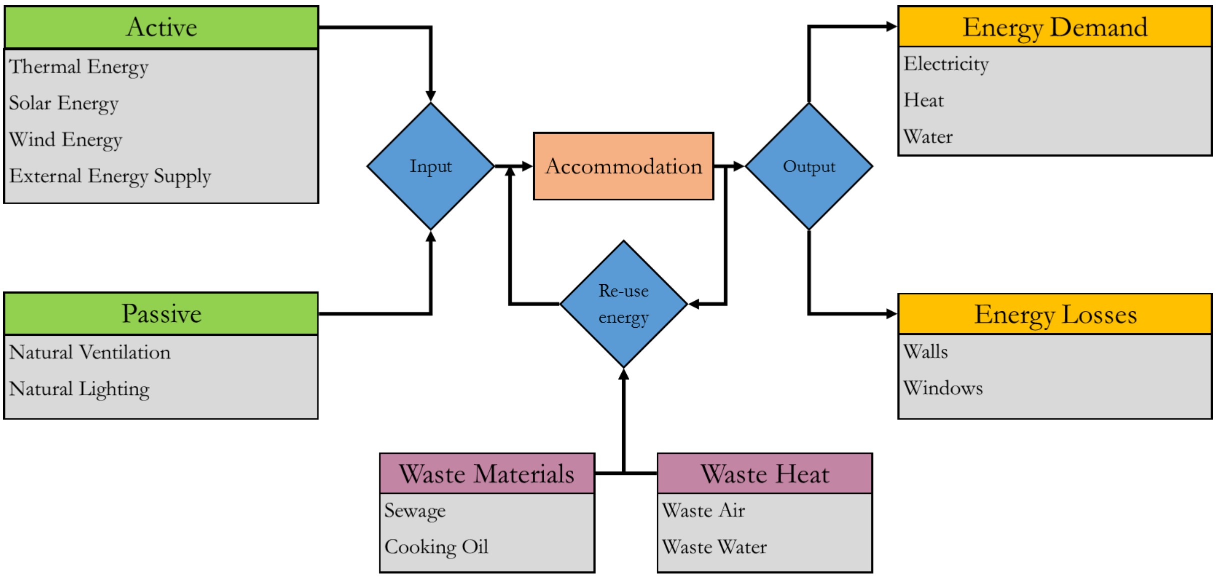


Figure 13 Energy flows in accommodation

5.1 Energy input

As mentioned in the introduction, CO_2 emissions can be reduced in two ways: generating energy without using fossil fuels or reducing the amount of energy consumed. This part elaborates on ways to obtain energy from sustainable sources.

5.1.1 Water Sourced Heat Pump (WSHP)

Heat pumps extract heat from a heat source and transfer it to a heat sink. This principle is also used in, for example, refrigerators. In an offshore accommodation, the WSHP could be used to decrease the energy needed for domestic hot water or the HVAC unit.

The heat is transferred via a refrigerant liquid. The heat source is used to evaporated the liquid into gas (1). This gas is then compressed by a compressor (2) leading to an increase of temperature. This hot gas is then liquefied in the condenser by transferring the heat to the heat sink (3). Finally the pressure is decreased by the expansion valve (4). This process is displayed in figure 14.

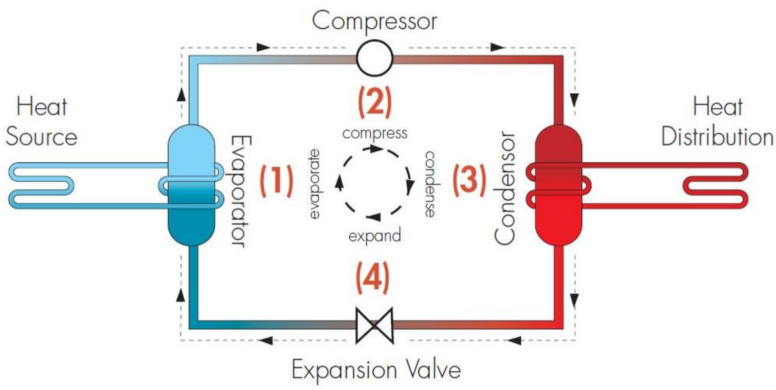


Figure 14 Heat pump cycle, Reprinted from Vent-Axia, n.d. Retreived April 3rd, 2016, from vent-axia.com/heatpump/how. Copyright 2016 by Vent-Axia Group Limited

Mechanical energy is needed for the compressor. The efficiency of a heat pump is rated with the coefficient of performance (COP). A feasible COP for heat pumps is 3. This means that for each 1 kW of electrical energy used to operate the compressor, 3 kW of heat is generated. The 2 kW of free heat is extracted from the heat source. Next to water, the heat source can be air or the ground.

There are two types of WSHP's: open and closed loop. In case of an open loop, source water flows directly along the heat exchangers. In a closed loop system, an anti-freeze water mixture flows through a pipe system which is placed in the water. (Barker Brown, 2012)

This technology is used onshore to realize heating for buildings or whole city areas. An example is the Alaska SeaLife center. Energy is extracted from seawater with a temperature betwee 3^{0}C and 13 ^{0}C and transferred to heat the building with a temperature of 55 ^{0}C (EETG: Seawater Heat Pump Demonstration Project, 2016). An example of a WSHP on a larger scale is Värtan Ropsten. This heat pump provides heating for an entire district. It has a capacity of 180 MW and produces 2600 GWh of heat per year. (Friotherm, 2016)

The main advantages and disadvantages are shown in table 25 for a WSHP's in general and for closed and open loops specific.

Advantages	Disadvantages
General	
+ High efficiency	- Efficiency depends on seawater temperature
+ Reversible process	- Complex system of pumps and compressors
+ Able to extract heat from low temperature water	
Open Loop	
+ No losses in pipe system	- Salt corrosion by using seawater
	- Filters and corrosion resistant pumps and valves needed
Closed Loop	
+ No corrosion inside system	- Losses in pipe system
	- Pipe system underwater

Table 25 Advantages and disadvantages of a WSHP

5.1.2 Natural lighting

During day time, energy can be saved by making efficient use of natural light. This is done by an increased window-to-wall ratio and applying skylights in combination with shading and a lighting control system. The advantages and disadvantages of natural lighting are shown in table 26.

Advantages	Disadvantages
+ Saving in energy cost for artificial lighting	- Possible glare
+ Improved well-being of occupants (Edwards & Torcellini, 2002)	- Less privacy (Brown, 2006)
	- Effects depend on the orientation of the accommodation
	- Variance in intensity of daylight

Table 26 The advantages and disadvantages of natural lighting

Natural lighting also affects the energy balance of the building. An increased window-to-wall ratio could lead to increased heat gains by solar penetration. On the other hand, windows generally have a lower insulation value than the wall itself which leads to increased losses through the building's envelope. Whether these phenomena are beneficial depends on whether the building is in heating or cooling mode. As a rule of thumb, the window-to-wall ratio should be between 25% and 50% to balance between profits from saving on artificial lighting and prevent overheating by solar penetration. (Beekers & Steemers, 2000).

These issues can be controlled by applying shading which has three purposes:

- Reduce solar heat gain to the room
- Prevent sunlight from falling onto occupants
- To reduce glare

However, it should be kept in mind that shading might also reduce the illuminance levels of natural lighting. Natural lighting should also be combined with a lighting control system to dim the artificial lighting system when natural lighting is available. Because the lighting level in lumen does not add up linearly, artificial lighting will not be contributing to over-illumination, hence there will not be an incentive for occupants to switch off the lighting manually. Therefore, the lighting system has to be controlled automatically.

The floor area to which daylighting is available depends on the fraction of glazing, the glazing type and the depth of the building's plan. For typical ceiling heights, daylighting is available up to 6 m inside the building. This range can be extended with skylights. (Beekers & Steemers, 2000)

5.1.3 Natural ventilation

In natural ventilation there are two working principles: wind driven and buoyancy driven (also referred to as stack ventilation). Air is flowing due to a pressure difference between two areas. With wind driven natural ventilation, the pressure difference is caused by velocity differences due to the wind. With buoyance driving ventilation, the pressure difference is caused by a temperature difference, for example caused by sunlight. Most of the time both principles are combined. A diagram of both principles is shown in figure 15.

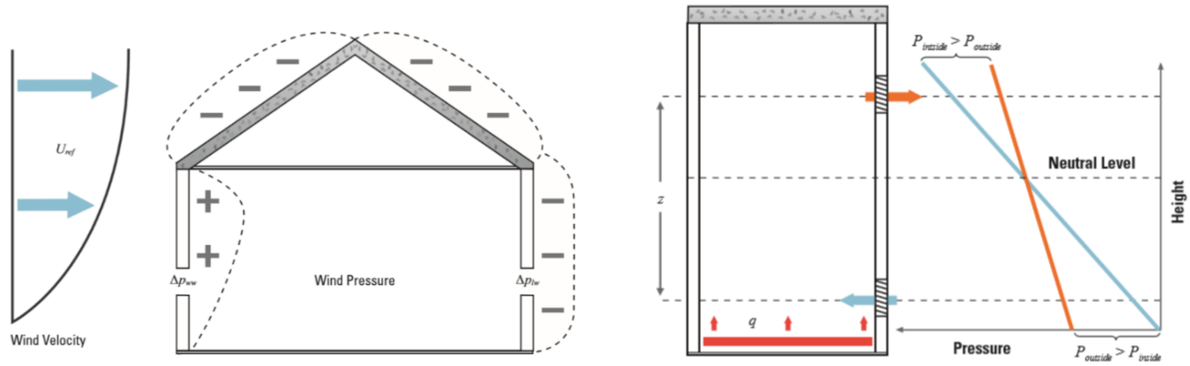


Figure 15 Wind driven ventilation (left) and buoyancy driven ventilation (right) Reprinted from Engineering Guide Natural Ventilation (page 7,13), by Price. Copyright 2011 by the Price Industies Limited.

Wind driven ventilation can be divided in cross flow ventilation (openings on both side of the building) or single sided ventilation (opening on one side of the building). The one sided flow can be enhanced by using wind catchers which can for example be placed on top of the accommodation as shown in figure 16.

Figure 16 Windcatcher, Reprinted from Rooftop Natural Ventilation in ArchiExpo. Retrieved June 12, 2016, from archiexpo.com/prod/monodraught-limited/product-62747-382333.html. Copyright 2016 by Virtual Group

Solar chimneys can be used to increase buoyancy driven ventilation. The heat of the sun is used to warm the air and increase the temperature difference. This principle is used for both heating and cooling. The two principles are shown in figure 17.

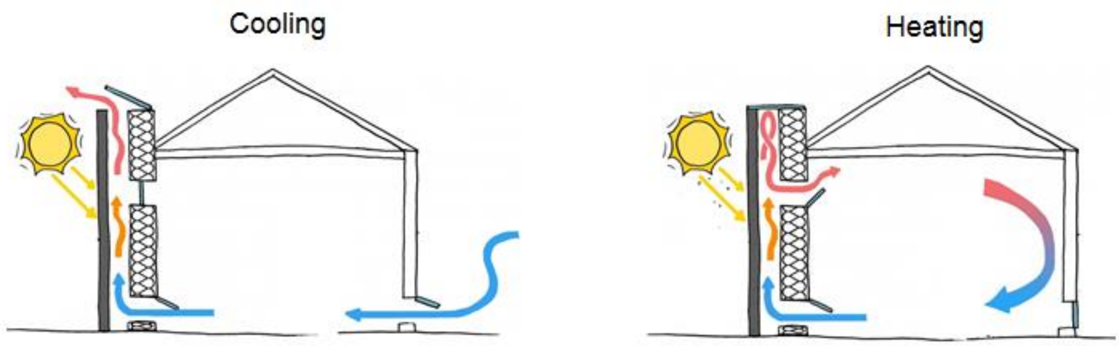


Figure 17 Solar chimney for heating and cooling. Adapted from Stack Ventilation and Bernoulli's Principle in Autodesk Education Community. Retrieved June 11, 2016, from sustainabilityworkshop.autodesk.com/buildings/stack-ventilation-and-bernoullis-principle. Copyright 2011-2015 by Autodesk, Inc.

Natural ventilation is used to reduce the ventilation and cooling load. Mechanical ventilation can be partly or completely replaced by natural ventilation. It has already been applied to onshore buildings. Bakers and Steemers (2000) assessed that natural ventilated office buildings can consume less than half of the total energy compared to mechanical ventilated buildings. An overview of the advantages and disadvantages of natural ventilation is shown in table 27.

Advantages	Disadvantages
General	
+ Reduction of energy consumption by mechanical ventilation and/or cooling	- High impact on façade and building design, decreased feasibility for retrofit
+ Passive system, low maintenance	- Depends on the volatility of the weather, difficult to control
	- Depends on building orientation
	- Direct input of outside air, caution with pollutants required dependent on platform's activity
	- Possible increased draft inside accommodation, leads to cooling of occupants, max 1,5 m/s is practical (Beekers & Steemers, 2000))
Wind driven	
+ Higher volumes of airflow compared to buoyance driven natural ventilation	- Knowledge of wind profile at location is required
Buoyancy driven	
+ Not dependent on wind	- Depends on inside and outside temperature differences
	- Location and size of air inlets and outlets is crucial (Price, 2011)

Table 27 Advantages and disadvantages of natural ventilation

The amount of fresh air, expressed in air-changes-per-hour, is an important factor when considering natural ventilation. Computational fluid dynamics might be essential to incorporate natural ventilation into the accommodation design. Another issues which should be taken care of is fire safety. Air flow paths and circulation areas might conflict with compartments for fire safety.

5.2 Energy output

The second way to save on the cost of energy is to reduce the amount of energy consumed. This section elaborates on strategies on the output side.

5.2.1 Lighting

Savings in lighting can be achieved by installing energy efficient lighting. The standard used to be incandescent lighting. However nowadays most lighting in housing and buildings have been replaced by fluorescent lighting. One step further in energy efficiency and lifespan is the LED. A comparison is shown in table 28.

	Incandescent	Fluorescent	LED
Watts used (at equal lumen)	60W	14W	10W
Average lifespan	1,200 hours	8,000 hours	25,000 hours
Approximate cost per lightsource[1] (2015)	€ 0.90	€ 1.80	€ 7.10

Table 28 Comparison of different lighting types (Johnson, 2015)
[1] With incandescent lighting these are bulbs, with fluorescent these are mostly tubes and with LED lighting these are a bundle of LED's.

The comparison shows that fluorescent lights consume about 75% and LED lights about 85% less energy compared to incandescent lighting. Also, fluorescent lights last about 6 times and LED lights about 20 times longer than incandescent lights. This saves in the cost of replacing the light bulbs. These benefits come at extra investment cost of twice as much for fluorescent lights and 8 times more for LED lights. However, the efficacy (output of lumens per watt consumed) of LED's is increasing while prices continue to drop according the US Energy Information Administration. In 2020 the price of LED lighting is expected to level the price of fluorescent lighting (Comstock & Jarzomski, 2014). The forecast is shown in figure 18.

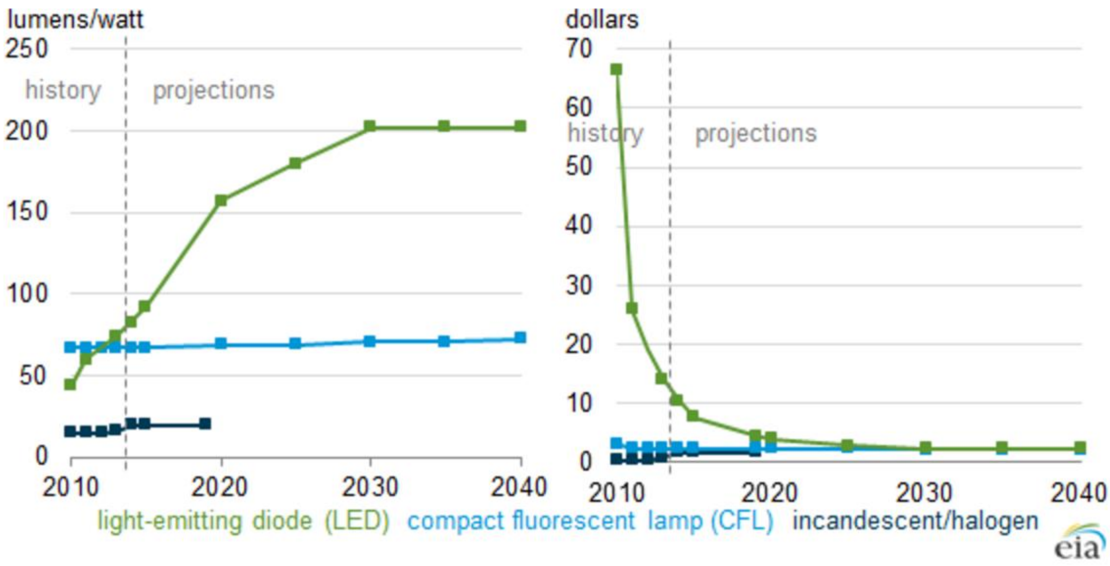


Figure 18 Average efficacy and cost of LED. Reprinted from Today in Energy in US Energy Information Administration. Retrieved July 12, 2016, from eia.gov/todayinenergy/detail.cfm?id=15471. Copyright US Department of Energy (n.d.).

A disadvantages of fluorescent lights is that they need some time to reach full brightness. Also, they contain a small amount of mercury which can be harmful to health and environment if not processed properly.

Lighting also affects the heat balance of the accommodation. Lighting causes heat gain which is dissipated into the conditioned space dependent on the type of luminaire and in what way it is mounted to the ceiling. Fluorescent and LED lights dissipate less heat then incandescent lights, which reduces the heat gain by lighting. This can either decrease the cooling load in hot environments or increase the heating load in cold conditions. (Chantrasrisalai & Fisher, 2007)

Besides saving on lighting by reducing the energy consumption of the lighting, one could also save energy by dimming or switching off the lighting. In some spaces the lighting could be switched off when the space is unoccupied. This is not always done manually by the occupants, therefore it might be profitable to install occupancy sensors. Dimming might be profitable if, during daytime, the artificial lighting can be partly or completely replaced by natural lighting.

5.2.2 Demand controlled ventilation

Depending on the HVAC system, there are some options to save energy in its consumption. One of these options is demand controlled ventilation (DCV). Most air handling units (AHU) have a fixed temperature setpoint and a constant air volume. The output of the AHU depends on the required heating or cooling load and occupancy in the conditioned spaces. Reheaters are used to maintain the temperature setpoints in the spaces and adjust to personal preferences. This can lead to over-ventilation.

With DCV, the temperature setpoint and air volume setpoint of the AHU is determined by the actual demand of the controlled spaces. Therefore, sensors have to be installed to provide feedback to the AHU. The energy consumption of the heaters or coolers can be decreased by installing temperature sensors. The fan power can be decreased by installing occupancy or CO_2 sensors to determine the required ventilation. This way the AHU may run at part load if, for example, only half of the cabins is occupied. If the amount of fresh air can be reduced because fewer people are present in a space, energy is not only saved in fan power, but also in heating or cooling of outside air. This concept has already been applied to cruise vessels where the environmental settings of cabins are set to low-energy settings when passengers are away. According the Texas University, Center for Electromechanics, savings up to 25% of the HVAC operating costs are possible. (Texas University Center for Electromechanics, 2016)

5.3 Energy recovery

Next to generating energy in a sustainable way, one could also recover energy that otherwise would have been exhausted. This section elaborates on two energy recovery strategies: one to recover energy from the exhaust airflow and one to recover heat from drain water.

5.3.1 Enthalpy wheel

An enthalpy wheel is a way to recover energy by recovering the heat from the exhaust airflow. Next to the heat, also the humidity can be exchanged between the incoming and outgoing airflow. Therefore, the wheel is called a enthalpy wheel. It is a rotating wheel consisting of a matrix structured heat absorbing material. The exhaust air is heating the wheel, which in its turn heats the incoming air. The same principle works for cooling. The wheel is covered with a desiccant (humidity absorbing) material. This absorbs the humidity of the outgoing airflow. This evaporates when the wheel enters the incoming airflow. Figure 19 shows an enthalpy wheel.

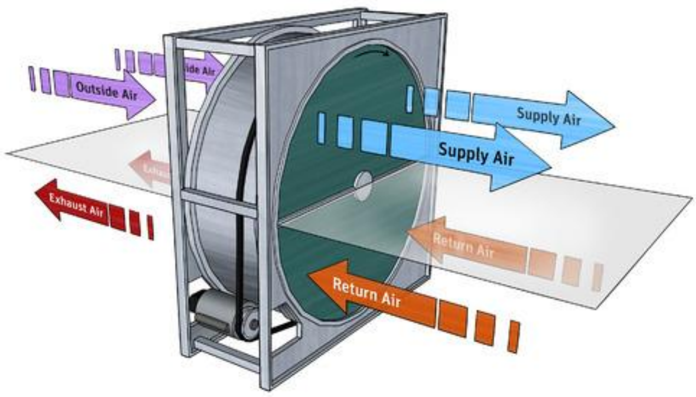


Figure 19 Enthalpy wheel. Reprinted from Recovery enthalpy in Indiamart. Retrieved January 21, 2016, from indiamart.com/proddetail/recovery-enthalpy-4912508448.html. Copyright 1996-2016 by IndiaMART InterMESH Ltd.

An enthalpy wheel has proved itself to be a profitable concept. By recovering heat and humidity, the heating cooling and humidifying load of the AHU is decreased. It is already applied in HVAC systems of onshore buildings and ship accommodations.

The advantages and disadvantages of a enthalpy wheel are shown in table 29.

Advantages	Disadvantages
+ Works reversible (heating vs. cooling and humidifying vs. dehumidifying)	- Increased fan power due to pressure drop
+ Effectiveness of 55% to 85%	- Air streams are not completely separated, so they should be clean, or filtration might be required
+ Compact system	- Air streams should be adjacent
+ Low investment costs	- Wheel requires maintenance and cleaning

Table 29 Advantages and disadvantages of an enthalpy wheel (Enthalpy Wheels, 2016)

5.3.2 Drain water heat recovery

A drain water heat recovery system (DWHR) is used to recover heat from hot water flows. The hot drain water is conducted through a pipe system that is adjacent to the incoming flow. Heat is then transferred in order to decrease the heating load of the boiler. In principle there are three types of heat exchangers: counter, cross and parallel flow. Since the temperature difference in the counter flow is greater it needs a smaller heat exchanger surface area. Crossflow heat exchanger is mostly used to exchange heat between gasses and liquids. A diagram of a counterflow heat exchanger is shown in figure 20.

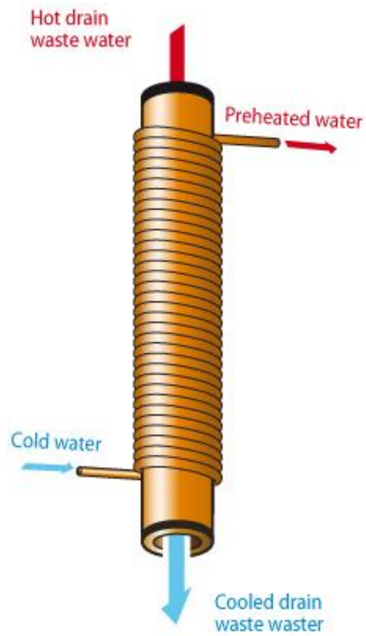


Figure 20 Counterflow heat. Reprinted from Heat Recovery in Setanta Energy & Water. Retrieved January 8, 2016, from setnrgh2o.com/Heat%20Recovery-Residential.html.

The DHWR system can be used for recovering heat from shower water, cooling water, water from laundry, etc. It has already been applied in housing, commercial and industrial buildings.

The efficiency of the system depends on the volume of the flow, the temperature difference between incoming and outgoing flow, and the duration and timing of the flows. Installing the system in a new construction raises some benefits compared to refurbishments (Cautley, 2013):

- Hot and cold drain water flows can be separated
- Installation costs are reduced
- Optimisation of the piping system

The advantages and disadvantages of a DHWR system are shown in table 30.

Advantages	Disadvantages
+ Up to 50% recovery of energy (Heat Recovery, 2016)	- Incoming and outgoing flow should be adjacent
+ Simple system, no moving parts	- No energy storage (simultaneous hot water use and drain is required)
+ Low investment cost	- Hot and cold drain water should be separated for optimal efficiency (for example shower and toilet water)

Table 30 Advantages and disadvantages of a DWHR system

5.3.3 Bio-gas digester

An accommodation produces not only exhaust air and water, but also organic waste such as human feces or food waste from the galley. This waste can be digested to produce bio-gas, a mixture of methane (CH_{14}) and carbon dioxide (CO_2). The waste has to be collected in an air-tight container. Anaerobic bacteria will then digest the waste and produce the desired gas. Three factors are important for an efficient gas production process:

- A constant temperature between 35 ^{0}C and 38 ^{0}C
- An air-tight tank so no oxygen is present
- A gentle mixing action so bacteria get in good contact with the waste (Rutan, 2004)

The gas produced is clean and burns clean. It can be used for heating, hot water production or cooking. (Bio-Gas Production & Use, 2016). According to P.A. Cook (2010), the usable energy that one human produces is 1102.2 kJ per day. For an accommodation of 37 POB, this would be 4.14 MWh per year. This is calculated for optimal carbon over nitrogen (C/N) ratios in the mixture. However, the C/N ratio of human feces is between 6 and 10. This ratio can be increased by adding sawdust (C/N ratio of 200 to 500) to the reactor or by removing urine, which has a high nitrogen content, from the feces. (Cook, 2010) The advantages and disadvantages of a bio-digester are shown in table 31.

Advantages	Disadvantages
+ Sustainable production of gas to save on heating, hot water production or cooking	- Induced safety risk due to gas tank
	- Heating of tank and adding of high C/N ratio component is needed for high efficiency
	- Extensive change of systems to work on gas, normally accommodations are all-electric

Table 31 Advantages and disadvantages of bio-gas digester

5.4 Design matrix

In this section, all the strategies are ranked based on the advantages and disadvantages discussed in this chapter and the results of the simulations with the base case model. The following strategies are considered:

- Water sourced heat pump
- Natural lighting
- Natural ventilation
- LED lighting and occupancy sensors
- Demand Controlled Ventilation (DCV)
- Enthalpy wheel
- Drain Water Heat Recovery (DWHR)
- Bio-gas digester

The resulting most promising strategies are modelled and compared with the base case model in the next chapter.

The assessment is done by creating a design matrix. The strategies are rated based on relevant design criteria. This is done in consultation with Keppel Verolme BV and within the scope of the research. Other parties might set different priorities and rate from another perspective. These criteria are given a weight, on a scale of 1 to 5, to represent the importance of the criteria. This is explained below. The criteria that are used to rank the strategies are shown in table 32.

Design criteria	Weight
Potential savings	5
Maturity of technology	4
Maintenance cost	3
Reliability	3
Applicability retrofit	2
Applicability newbuild	1

Table 32 Design criteria and corresponding weight

The main goal for offshore operators is saving in operational expenditures which can be done by saving in energy consumption. The potential savings are therefore given the highest rate. The maturity of the technology reflects into what extend the technology is developed. This lowers the investment costs and also increases the reliability. Therefore, 'maturity of technology' is given the second highest priority. As mentioned in the introduction, operators want their equipment to be working at all time because downtime is very costly. This is reflected by the reliability of the technology. The maintenance cost are subtracted from the saving in energy cost. Maintenance and reliability are given a weight of 3. The applicability to newbuild and retrofit reflects the ease of designing and installing the strategies. This determines the CAPEX, which have to be overcome by the savings in OPEX. It also incorporates the extent to which strategies are generally applicable to different accommodation designs versus a design which is very specific for one accommodation. The CAPEX are a one-time cost and therefore are given a low weight because once they are paid back, they are irrelevant. The main activity of Keppel Verolme BV is maintenance and retrofit. Therefore the applicability to retrofit is given a higher weight than the applicability to newbuild.

Each strategy is rated on the criteria on a qualitative scale: --, -, 0 , +, ++. The total score is then calculated as a weighted average of the scores on the individual criteria. This is done by converting the scores in % and on the +/- scale to a scale of 1 to 5. This is then divided by the total possible score (the total of the weights times 5). The calculation is defined in the following formula:

$$S_{tot} = \frac{\sum_{c=1}^{6} W_c \cdot S_c}{\sum_{c=1}^{6} W_c \cdot 5} \times 100$$

Where S_{tot} Total score of a strategy in percentages

$W_c \in \{1,\ldots,10\}$ Weight of a criterion 'c'

$S_c \in \{1,\ldots,5\}$ Score on criterion 'c'

The potential savings are based on the average percentage of total energy consumption in the North Sea and Gulf of Mexico. This is multiplied by the estimated savings which are possible with the strategy. An example is given below for demand controlled ventilation, with which you can save 25 % on the consumption for heating and cooling (average 39%).

$$Potential\ savings\ on\ total = saving\ on\ part\ \times \%\ of\ total$$

$$Potential\ savings\ on\ total = 25\% \times 39\% = 9.8\%$$

The resulting design matrix is shown in table 33.

	Weight	Enthalpy wheel	DCV	Heat pump	LED	DWHR	Nat. Vent.	Nat. Lighting	Bio-gas digester
Part of total consumption		*42%*	*39%*	*39%*	*7%*	*5%*	*53%*	*7%*	*5%*
Potential Savings per part		*22%*	*25%*	***70%***	*45%*	*35%*	*50%*	*22%*	*9%*
Potential Savings of total	5	9.1%	9.8%	27.3%	3.2%	1.8%	26.5%	1.6%	0.4%
Maturity of technology	4	++	+	0	++	++	-	+	-
Maintenance costs	3	+	+	0	+	++	++	+	0
Reliability	3	++	+	0	++	++	-	+	0
Applicability retrofit	2	--	0	--	+	--	--	--	-
Applicability newbuild	1	++	+	0	++	+	-	-	0
Total score		**69%**	**65%**	**67%**	**70%**	**64%**	**64%**	**50%**	**37%**

Table 33 Design matrix to assess energy saving strategies

The section below describes the considerations for the scores for each strategy. These are based on the information on the strategies given in the previous sections.

The enthalpy wheel saves on heating, cooling and humidification which together account for 42% of the total energy consumption. As stated before, literature shows that 60% of the energy can be recovered. The enthalpy wheel recovers energy of air that is not exhausted (60%) and not recirculated (60%). This results in total potential savings of 22%. Enthalpy wheels might need some cleaning but other than that require little maintenance. They can be easily incorporated in the AHU when being installed on new accommodations. However, it is not feasible to add an enthalpy wheel to an existing platform. A new AHU needs to be installed, for which there might be no space available. It is not a complex system and contains not many parts. It is therefore considered to be reliable. Also it has already been applied in onshore buildings as well as marine accommodations.

DCV saves on heating and cooling which accounts for 39% of the total energy consumption. Research shows that 25% savings are possible with DCV (Texas University Center for Electromechanics, 2016). The system requires no extra maintenance. The system needs some wiring which is easily installed in a newbuild accommodation. When retrofitting, wall and ceiling panels need to be opened, which makes it less easy to install. DCV has no moving parts and is therefore considered reliable, however it is dependent on the software. The technique is offered by suppliers and has been applied already on cruise vessels.

A heat pump can be used for heating and cooling which accounts for 39% of the total energy consumption. A supplier of Keppel Verolme BV reported that a heat pump saves 70% of the heating and cooling required for the case study. The heat pump itself does not need much maintenance. However, the piping system which is placed in the seawater might get eroded. The design of the HVAC system has to be adapted to the heat pump. This decreases the ease of applying the system, mainly with retrofitting. The efficiency of the heat pump depends on the temperature of the seawater. Also the system has not yet been applied in marine accommodations.

LED saves on lighting which is 7% of the total energy consumption. LED lighting consumes 50% less energy than fluorescent lighting. LED's have a longer lifespan than incandescent and fluorescent lighting. This reduces the maintenance costs compared to other lighting types. When installing LED armatures, there are no increased installation cost compared to other types of lighting. When retrofitting, the light fixtures need to be replaced. LED's have a long lifespan and are well developed and therefor score good on reliability and maturity.

A DWHR system recovers energy of the 5% used for heating water. Suppliers claim heat recovery efficiencies starting from 37.5%. To stay on the save side, a recovery of 35% is used. The DWHR pipe is a passive system and does not require any maintenance. It is not feasible to apply the system for retrofitting. The installation cost would be high because wall panels need to be removed and adjustments have to be made in confined spaces. The system has no moving parts or software and is therefore reliable. It has been developed and used in housing and industrial applications.

With natural ventilation, one is able to save on fan power, this accounts for 12% of the total energy consumption. It is a passive system and needs no extra maintenance. It might save on maintenance because the fans are less used. For a good design, computational fluid dynamics simulations are essential. It also has a great impact on the design and is therefore not suitable for retrofit. The effectiveness of natural ventilation depends on location and orientation of the accommodation, a parameter which is unknown in most offshore platforms. Therefore, the system is very unpredictable and thus unreliable. Natural ventilation has not been applied yet to marine accommodations.

Natural lighting saves on the energy consumption for lighting which is 7% of the total energy consumption. It is estimated that natural lighting is available one third of the day in two third of the accommodation's spaces. Natural lighting means an increased number of windows which require cleaning, other than that is requires no extra maintenance. If one wants to make efficient use of natural lighting, the design of the accommodation has to be adjusted extensively. It is therefore considered to be not easily applicable. Natural lighting is a passive system and is therefore reliable. However, the efficiency depends on weather conditions. Knowledge on natural lighting is available from onshore building technology.

Bio-gas digesters produce gas which can be used as a heat source for DHW. The previous section showed that a digester might produce 4 MWh per year for an accommodation of 37 POB. This would be 9% of the energy consumption for DHW. A substance with a high C/N ratio, like sawdust, would need to be added to increase the efficiency. Therefore, the digester is considered to score medium on maintenance cost. Offshore accommodations have electric systems. Extra systems need to be installed to use the gas, this makes is less applicable. Bio-gas digesters have not been found in many onshore commercial applications and it is therefore considered not to be a mature technology.

5.5 Other energy saving strategies

This section assessed the most promising strategies within the scope of the research. There are some more energy saving strategies that are known in building technology that might lead to additional savings. When trying to reduce the energy consumption as much as possible, these strategies might also be considered:

- Insulation. A very common way to save energy in building technology is increasing the insulation. The application of extra insulation in offshore accommodation was studied in a research by Lars Hammer. It showed that 7% savings on the total energy consumption were obtained by increasing the R-value with 7 m2-K/W (Hammer, 2016). (These results are based on the same case study as assessed in this research.
- Window shading. This could be done by overhang and sideways, blinds or solar films. However, research showed that this does not have a significant effect on the heating and cooling load of offshore accommodations due to a low window-to-wall ratio of 4% (Hammer, 2016).
- Radiant heating and cooling. If radiant heating and cooling is applied, the fresh-air supply and humidification can be separated from heating and cooling. This way the ventilation can be more accurate adjusted to the actual need in the conditioned spaces. (Cubick, 2016)
- Energy efficient appliances. The laundry and galley equipment are big energy consumers in the accommodation. Mainly in older accommodations, savings might be obtained by replacing old equipment with new, more efficient, equipment. Because these savings can be analysed per device individually, it was not considered in this research.
- High efficient chillers, heater and fans. This research only looked at adding or replacing complete systems. However, some extra savings might be possible by replacing components, like heaters, chillers and fans, by more energy efficient components. As for energy efficient appliances, here also goes that this is mainly profitable for retrofitting older accommodations with outdated equipment.
- Maintenance. Some equipment might operate at lower efficiency caused by overdue maintenance. Updating the maintenance is a low-cost measurement which can result in energy savings.
- Instruction on personnel. An important factor in the consumption of energy are humans. Examples of ways personnel can contribute to savings in energy consumption are: switching of lighting and turning down heating/cooling when leaving the cabin, reducing shower time, switching of equipment when not in use and wearing warmer clothes instead of increasing heating.

5.6 Conclusion

This chapter elaborated on the following energy saving strategies applicable to offshore accommodations: Water sourced heat pumps, natural lighting, natural ventilation, LED lighting, demand controlled ventilation, an enthalpy wheel, drain water heat recovery and a bio-gas digester. These strategies were rated on the design criteria and weights as listed in table 34.

Design criteria	Weight
Potential savings	5
Maturity of technology	4
Maintenance cost	3
Reliability	3
Applicability retrofit	2
Applicability newbuild	1

Table 34 Design criteria and corresponding weights

Based on the advantages and disadvantages discussed in this chapter and the results of the simulations with the base case model, the strategies were ranked. This resulted in the scores as shown in table 35.

Strategy	Score [% of maximum score]
LED	70%
Enthalpy wheel	69%
Heat pump	67%
DCV	65%
DWHR	64%
Nat. Vent.	64%
Nat. Lighting	50%
Bio-gas digester	37%

Table 35 Results of design matrix

LED lighting, the enthalpy wheel, a water sourced heat pump, demand controlled ventilation and drain water heat recovery is further examined in the next chapter. They are assessed with DesignBuilder and hand-calculations to determine the yearly savings in kWh. Also, the CAPEX and savings on OPEX are determined with the cost of energy and quotations by suppliers of Keppel Verolme BV.

6 Assessment of energy saving strategies

In this chapter, the most promising energy saving strategies are further examined. In the first section, the cost of energy on board is determined. This is used to convert saved kilowatt-hours in saved cost. After that, it shows for each strategy the actual savings in energy consumption on a yearly basis. These is determined by comparing the results with the base case energy consumption. This is done for both hot and cold environments. After that, a financial assessment is made with the cost of energy, internal information and quotations obtained by Keppel Verolme BV. This resulted in CAPEX and savings in OPEX for the selected strategies to determine the payback time. All calculations are done for two cases: newbuild and retrofit.

6.1 Cost breakdown of energy on board

An important parameter in calculating the payback time of energy saving strategies is the cost of energy expressed in euro per kilowatt-hour. This is the factor between energy savings and reduced costs. In onshore buildings one can take the cost of electricity from the grid. For windfarm transformer substations one could use the income from energy sale to the grid (Otheguy, 2014). However, most offshore platforms are not connected to the grid and therefore have their own energy supply. In most cases electric energy is supplied by diesel generator sets (gensets). These run on marine diesel oil which is purchased on a nearby coastal supply location and shipped to the platform in a supply vessel.

Energy savings lead to continuous savings in, for example, fuel consumption. However energy savings can also lead to cost savings on a discrete scale. If four gensets are installed and a reduction in the total required peak power of 25% is achieved, one whole genset would not be needed anymore. Other savings percentages in between may mean that smaller gensets could suffice, which are cheaper to purchase and with cheaper maintenance. This is limited by the discrete nature of genset available sizes. The same applies to fuel shipments. If one is able to reduce the fuel consumption by 50%, half of the shipments suffice to supply the platform with fuel. The actual savings in supply vessel cost will depend on what the supply shipments consist of (often combining fuel, food, drinking water, technical supplies, etc.).

The actual cost of energy then depends on multiple factors:

- the power generating configuration
- the systems efficiency, depending on the design load and the actual load
- the fuel price
- the mode and cost of fuel transport to the platform

For this case study, the electric power is generated by diesel generators sets. A representative genset for drilling jack-up vessels has a rated electric power of 1800 kW (according Keppel Verolme BV). To gain insight in the total cost of energy, the cost is divided into four parts: fuel, lubrication oil, transport and purchase and maintenance cost. All parts are expressed in euro per kilowatt-hour to be able to sum them in the end.

6.1.1 Fuel costs

The fuel costs are determined by the bunker price. This depends on the location and varies over time. To exclude the dependency on the location, a bunker index for marine diesel oil (MDO) is used which represents an average of all the prices in all ports published on the website of Bunker Index. (BunkerIndex, 2016) For the calculations below, the average bunker index over the period June 2015 to June 2016 is used. This was € 412 per metric ton (MT).

The price from $\frac{€}{MT}$ is converted to $\frac{€}{kWh}$ with the specific fuel oil consumption (SFOC) of the genset. Based on communication with the supplier, a typical 1800 kW genset has a SFOC of 186 $\frac{g}{kWh}$. This results in a fuel cost of 0.08$\frac{€}{kWh}$.

6.1.2 Lubrication oil costs

Besides fuel oil, diesel engines also consume lubrication oil. According Dr. Ing. Y. Wild, the specific lubrication oil consumption of a four stroke medium speed engine is roughly 1 $\frac{g}{kWh}$ (Wild, 2005). Yves reports lubrication oil prices ranging from 630 to 1340 $\frac{€}{MT}$. With a price of 1340 $\frac{€}{MT}$, the cost for lubrication oil is 0.0013 $\frac{€}{kWh}$. Therefore, the cost for lubrication oil is considered insignificant for the total cost of energy.

6.1.3 Transport costs

The transport costs depend on a wide range of variables, such as the day rate for a supply vessel, distance to port, frequency of supplies, etc. To get an estimate of the costs, the following assumptions are made:

▪ Day rate of supply vessel (including fuel for own use)	€ 35,000 per day
▪ Time needed for bunkering (either at port or at platform)	4 hours
▪ Number of shipments per year	12
▪ Distance to port	300 km
▪ Cruising speed of vessel	11 knots
▪ Percentage of transport cost to fuel	15%
▪ Total energy consumption (average NS and GOM)	900 MWh

These assumptions are based on communication between Keppel Verolme BV and clients.

The distance to port is divided by the speed of the supply vessel to calculate the sailing time. The time needed for bunkering is added. The total is multiplied by two to calculate the total time that a supply vessel is needed. This is multiplied by the day rate and the number of shipments per year to determine the yearly cost of transport. The percentage of cost to fuel is used to allocate a share of the total yearly cost of transport to the transport of fuel. Finally, the cost is divided by the total energy consumption to calculate the cost per kWh. The resulting cost of transport of fuel is 0.11 $\frac{€}{kWh}$.

6.1.4 Purchase and maintenance costs

The price of a representative 1800 kW genset is €590,000, as quoted by selected suppliers for Keppel Verolme BV as per 2016. According to the supplier, the lifetime is considered to be 20 years, which results in €29,500 per year.

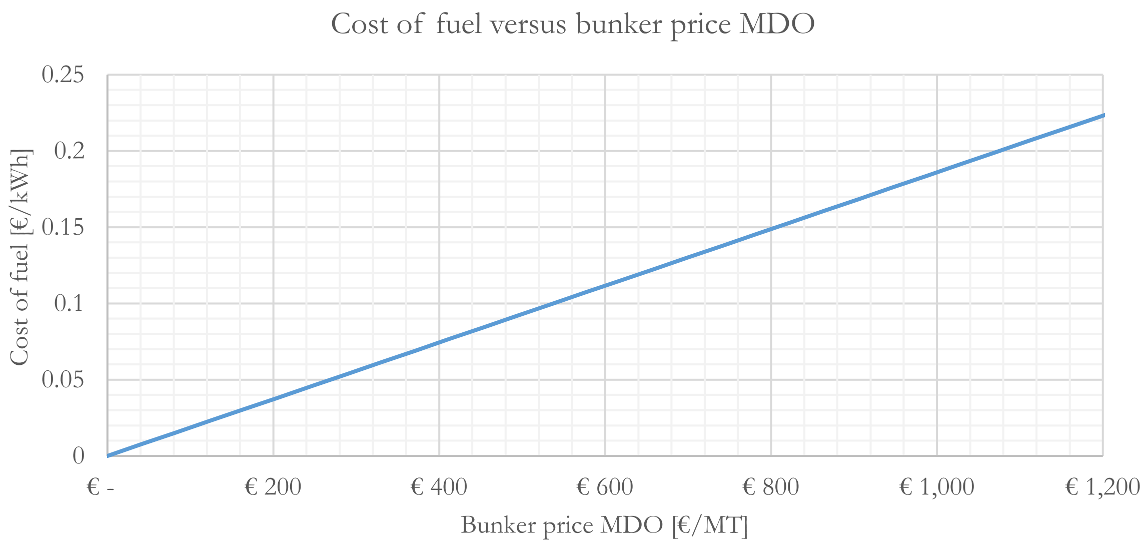
The average maintenance cost per year depend on the number of running hours. To have an estimation on the maintenance cost, the engine is assumed to run half of the time (4800 hours per year). According to suppliers, the average maintenance cost are €65,000 per year under this condition. When the genset is running 4800 hours on 1710 kW, the resulting capital costs are $0.012 \frac{€}{kWh}$.

6.1.5 Sensitivity study

As mentioned above, the cost of fuel depends on many uncertain variables. It is therefore useful to perform a sensitivity study. The section below shows the cost of energy for variations in the bunker cost, specific fuel oil consumption, lifetime of the genset and transport cost.

6.1.5.1 Bunker cost

The bunker price used in section 6.1.1 gives an useful indication of the contribution of fuel cost in the cost of energy on board, given the current volatility in fuel prices. However, they correspond to a relatively short period of time and a relatively low MDO price compared with the records of up to 20 years ago. If the chosen data period would have been the last 20 years, the fuel price would have been 23% higher. For a period of the last 12 years, it goes up to +65%, while the last 5 years give +87%. In 2012, fuel prices have been up to 2.6 times more expensive than the average used in section 6.1.1. (U.S. Energy Information Administration, 2016) This is calculated based on Ultra-Low-Sulfur No. 2 Diesel Fuel in Los Angeles, US, assuming MDO prices following same correlation along time. The graph below shows the cost of fuel for a varying bunker price of MDO.



6.1.5.2 Specific Fuel Oil Consumption

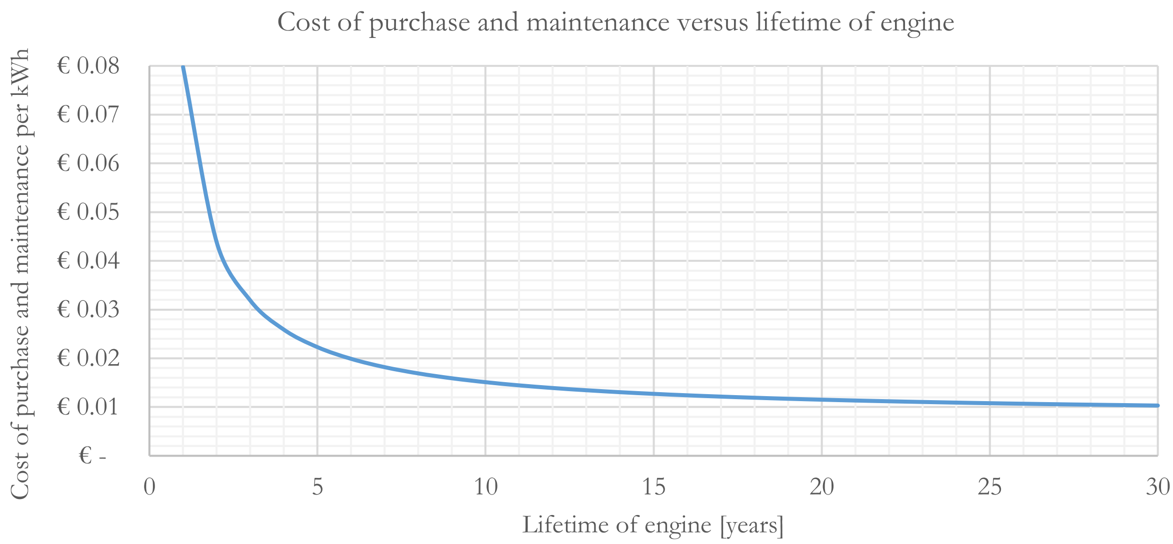
The SFOC of the genset mentioned above is a rated SFOC at ISO conditions. When a diesel engine is running at part load, the specific fuel oil consumption increases. Table 36 shows the SFOC in % of the rated SFOC and as function of the load in % of the maximum continuous rating (MCR) (Klein Woud & Stapersma, 2002). It also shows the corresponding SFOC for the selected genset and the resulting cost of fuel, whilst maintaining a constant bunker price of €415 per MT.

% of MCR	% of SFOC	SFOC [g/kWh]	Cost of Fuel [€/kWh]
100%	100%	186	€ 0.080
75%	102%	189	€ 0.081
50%	105%	196	€ 0.084
25%	115%	215	€ 0.092

Table 36 Sensitivity study for SFOC

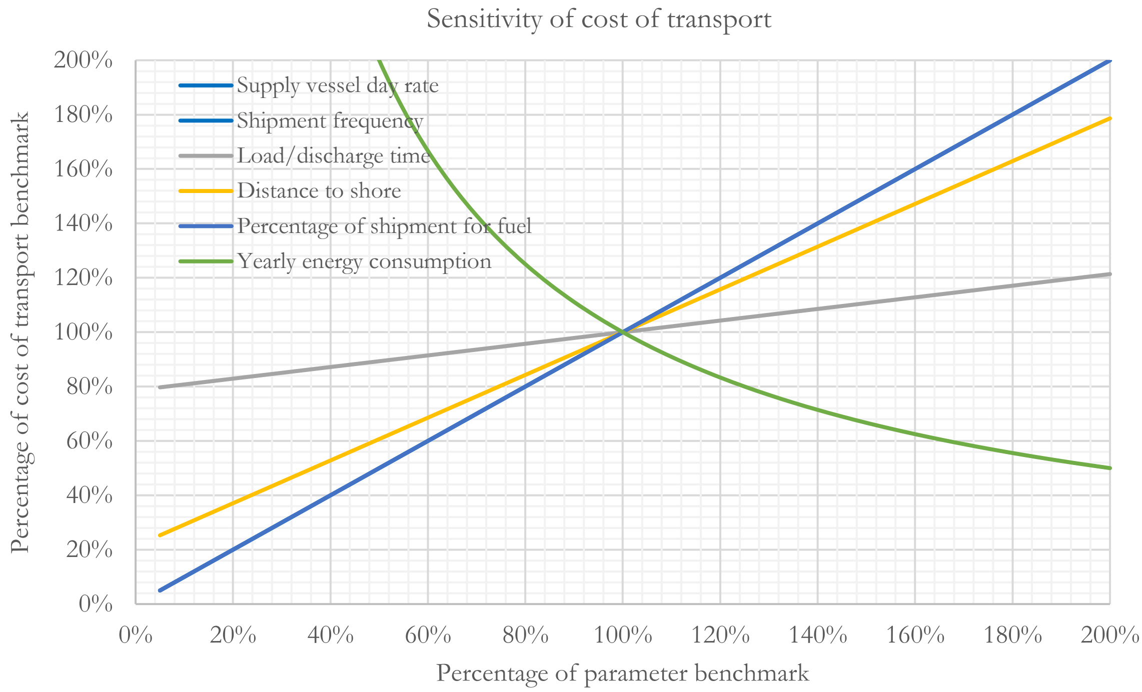
6.1.5.3 Lifetime of engine

The cost of the genset per kWh consists of the purchase cost and the maintenance cost. The maintenance cost are considered to be constant per year. The purchase costs depend on the lifetime of the engine, i.e. over how many years the purchase cost can be written-off. The graph below shows the purchase and maintenance cost per kWh for variations in the lifetime of the genset. The graph is approaching a horizontal asymptote at € 0.008. This is the cost of maintenance per kWh per year.



6.1.5.4 Transport cost

The biggest contributor to the cost of energy is the cost of transport. The cost of transport depends on the parameters which are listed below. The graph shows the increase in cost of transport if one of the parameters is increased, keeping the other parameters constant. The values listed in section 6.1.3 are taken as the benchmark values.



The graph shows a linear relation for all parameters except for the yearly energy consumption of the accommodation. The slope of the line is an indicator for the sensitivity of the parameter. The duration the supply vessel needs to be rented depends on the distance to the shore and the load/discharge time. Therefore, the cost of transport is less sensitive to the parameters individually. The total transportation cost are divided by the total energy consumption of the accommodation to get the cost per kWh. Therefore, the yearly energy consumption has an inverse relation to the cost of transport.

6.1.6 Conclusion

Table 37 shows the total cost of energy.

Cost factor	Cost per kWh
Fuel	€ 0.08
Transport	€ 0.11
Purchase and Maintenance	€ 0.01
Total cost of energy	**€ 0.20**

Table 37 Cost of energy for base case model

With €0.20 per kWh, the cost of the energy based on the base case model are:

- North Sea € 5476 per person per year
- Gulf of Mexico € 4741 per person per year

6.2 Enthalpy wheel

This section elaborates on the assessment of the enthalpy wheel. It describes the way it is modelled and shows the results. Finally, it shows the payback time and gives a conclusion.

6.2.1 Model

An enthalpy wheel is able to recover sensible heat, a change in temperature, and latent heat, a change in humidity. The recovering efficiencies of an enthalpy wheel depend on the temperature and humidity differences between the incoming and outgoing airflow. These efficiencies are based on data obtained from suppliers. The efficiencies are based on the average temperature and humidity difference for the North Sea and the Gulf of Mexico over a year. The input for DesignBuilder is shown in the table 38. An enthalpy wheel is applied to the main air handling unit (AHU1). A yearly simulation is run to determine the annual savings in kWh. In the case study, the HVAC system for the galley and stores does not return the air to the AHU for recirculation. The exhaust unit of the galley is connected to the canopies. In order to install an enthalpy wheel, extra ducting would be required to have the outgoing airflow adjacent to the incoming airflow. It is therefore decided not to consider an enthalpy wheel for AHU2 and AHU3. In the galley also extra complications might occur because the air in the galley is contaminated with fat and grease from cooking.

	North Sea	Gulf of Mexico
Sensible heat efficiency	58.6%	58.7%
Latent heat efficiency	58.2%	55.9%

Table 38 Efficiency of enthalpy wheel as input in DesignBuilder

DesignBuilder does not automatically increase the fan pressure rise. However the enthalpy wheel causes a pressure drop of 113 Pa according to the supplier. The original pressure rise of the fan in AHU 1 is 1200 Pa. This input is manually set to 1313 Pa. This also has an effect on the heating and cooling because the fan motor loses heat to the airstream.

The enthalpy wheel is installed after the recirculation. If an enthalpy wheel is installed, further savings can be obtained by switching off recirculation. The number of fresh-air-changes-per-hour is kept at 6. However, because there is no recirculation, the airflow now contains 100% fresh air. Therefore, the airflow can be reduced, leading to savings in fan power.

DesignBuilder uses the following formula to calculate the fan power:

$$P_{fan} = \frac{Q \cdot \Delta P}{e_{tot}}$$

Where:

P_{fan} fan power in W

Q volumetric flow rate in m^3 per second

ΔP fan pressure rise in Pa

e_{tot} total efficiency of fan

According the Darcy-Weisbach equation, the head loss in a pipe is proportional to the square of the flow velocity (Wikipedia, 2016):

$$\Delta P = f_D \cdot \frac{\rho}{2} \cdot \frac{L}{D} \cdot V^2$$

Where:	ΔP	pressure rise in Pa
	f_d	the Darcy friction factor
	ρ	the air density in kg per m^3
	L	length of pipe in m
	D	hydraulic diameter of pipe in m
	V	flow velocity

This means that the reduce in fan power is proportional to the third power of the reduction in volumetric flow rate. This is also seen in the fan infinity laws (Engineering Toolbox, 2016):

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2}$$

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3$$

Where	P	power in W
	Q	volumetric flow rate in m^3 per second
	N	shaft rotational speed (RPM)

DesignBuilder does not automatically reduce the pressure when the airflow is reduced. This is done manually. When the airflow is reduced to 60%, the pressure is reduced to 36%.

This is a simplified approach. The efficiency of the fan depends on the airflow and the pressure rise. Also the density of air depends on the temperature. The Darcy friction factor depends on the characteristics of the pipe systems (or ducts in this cases), the density of the air and the velocity of the air.

The enthalpy wheel uses an electromotor to rotate the wheel. The enthalpy wheel in this model has a motor of 180 W. Over a year this consumes an extra 1,6 MWh per year. This is added to the power consumption for fans.

6.2.2 Energy savings

The results of the simulations are shown in table 39.

	North Sea			Gulf of Mexico		
	Base case	Incl. wheel	Savings	Base case	Incl. wheel	Savings
Heating	387	296	23.4%	32	32	0.0%
Cooling	24	26	-6.0%	302	282	6.9%
Fans	114	121	-5.6%	114	121	-5.6%
Humidity	50	26	49.4%	0	0	0.0%
Total HVAC	576	469	18.6%	449	435	3.2%
Total	**1013**	**906**	**10.6%**	**877**	**863**	**1.6%**

Table 39 Yearly energy savings in MWh and savings in percentage of base case energy consumption

The results show that the savings on heating in the North Sea are about a third of the efficiency of the enthalpy wheel. Since some spaces have exhaust fans, only 60% of the air is returned to the AHU. 40% of that air is recirculated. The enthalpy wheel then recovers 60% of heat in the 60% air that is exhausted. This results in about 20% savings in energy consumption by the HVAC installation.

The savings in the North Sea are six times higher than in the Gulf of Mexico. This has two reasons. Firstly, the average outside temperature in the North Sea is 6.8 ºC versus 24.1 ºC in the Gulf of Mexico. This means that the temperature difference between incoming and outgoing air (20 ºC) is bigger in the North Sea. Secondly, the absolute humidity in the North Sea is lower than in the Gulf of Mexico. This means that more humidification is required in the North Sea to get the air to the required humidity level. This means that recovering the latent heat is also more effective. Table 39 shows an increase in the energy consumption for cooling in the North Sea. The return air has a temperature of 20 ºC. If the outside air has a temperature between 14 ºC and 20 ºC and it needs to be cooled to the setpoint of 14 ºC, the heat exchange between the outgoing and incoming airflow increases the cooling load.

Table 4 shows the results when recirculation is switched off. This leads to a reduction in the consumption for fan power. Two other effects occur when switching off recirculation. These are caused by the AHU supply air temperature setpoints of 14 ºC in summer and 18 ºC in winter. Firstly, the air which was recirculated is about 20 ºC which preheats the incoming airflow. When the outside air is already higher than the temperature setpoints, the recirculation causes an increase in the cooling load. Secondly, the air which is supplied to the zones is generally cooler than required and needs to be reheated with the local reheaters. When the airflow is reduced by switching off recirculation, less 'overcooled' air is supplied to the zone, so less energy is consumed by the reheaters. Switching off recirculation therefore also saves on the energy consumption for heating and cooling, besides a reduced fan power.

	North Sea			Gulf of Mexico		
	Base case	Incl. wheel, excl. recirculation	Savings	Base case	Incl. wheel, excl. recirculation	Savings
Heating	387	305	21.2%	32	7	78.0%
Cooling	24	14	42.1%	302	240	20.5%
Fans	114	76	33.3%	114	76	33.3%
Humidity	50	43	14.6%	0	0	0.0%
Total HVAC	576	438	23.9%	449	324	27.8%
Total	**1013**	**876**	**13.6%**	**877**	**753**	**14.2%**

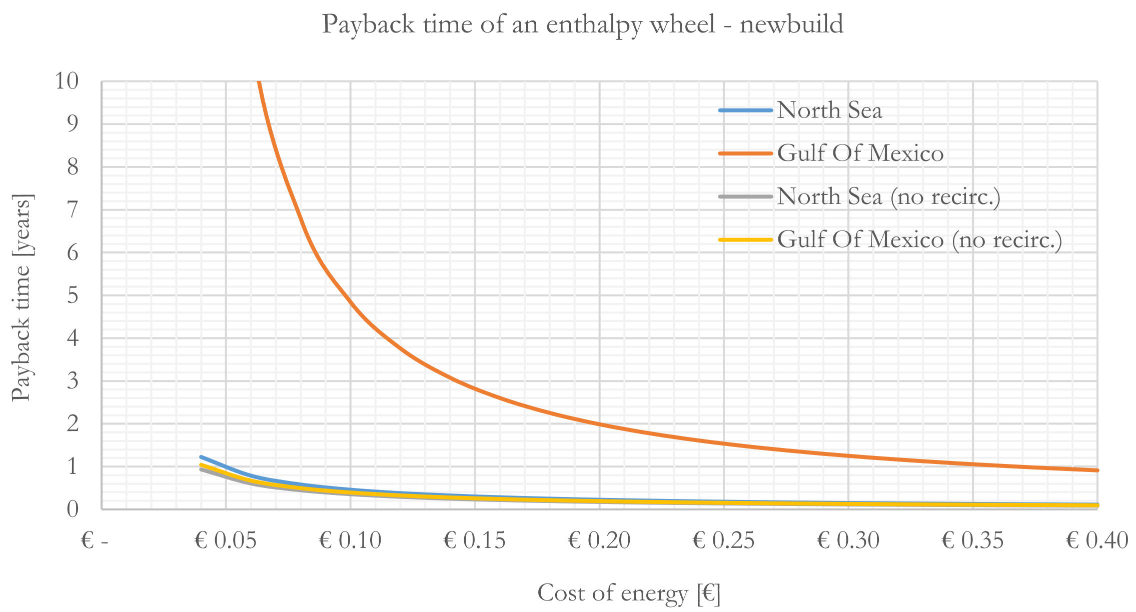
Table 40 Yearly energy savings in MWh with an enthalpy wheel and without recirculation

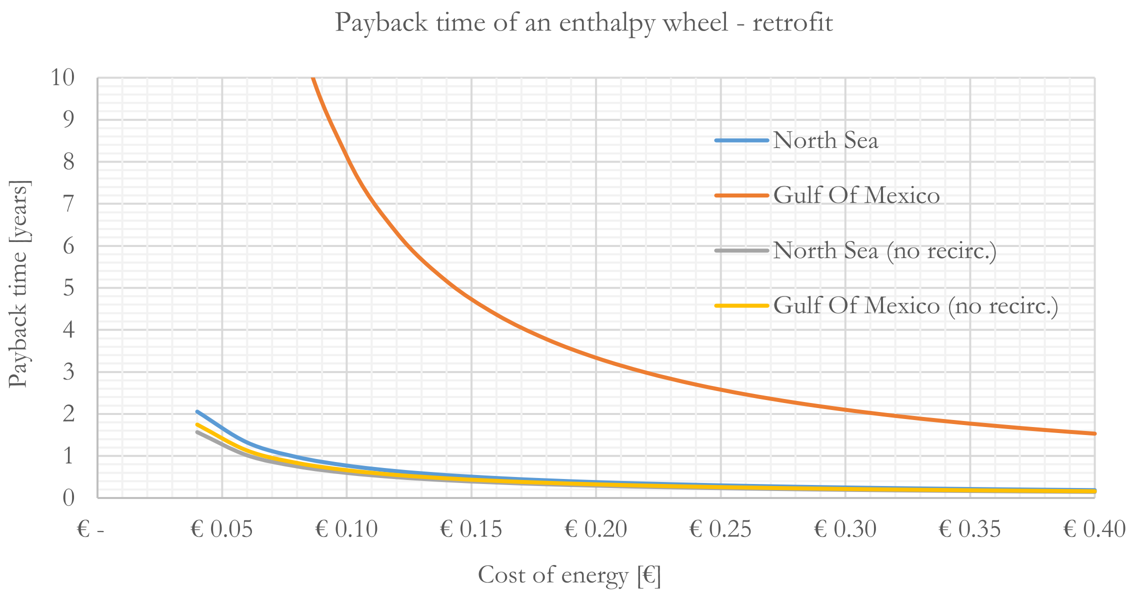
6.2.3 Financial analysis

The savings in OPEX are determined by the savings in energy consumption minus the increased cost of maintenance. The savings are obtained by multiplying the saved MWh's by the cost of energy. The increased maintenance for the enthalpy wheel is assumed to be 9% per year of the purchase price, according the supplier.

The CAPEX are the sum of the purchase price and the cost of installation. For newbuild, it is assumed that the extra cost of an AHU incorporating an enthalpy wheel is that of the wheel itself, hence no extra installation cost. The enthalpy wheel will be part of the AHU which is often supplied by a subcontractor. The purchase price is as quoted by suppliers of Keppel Verolme BV as per 2016. In the case of retrofitting, installing an enthalpy wheel introduces some challenges. Firstly, the enthalpy wheel has to be integrated in the AHU. AHU's are modular units fit to the components inside. If an enthalpy wheel needs to be added, a new AHU has to be designed to fit the enthalpy wheel. Secondly, there might not be enough space to fit a bigger AHU in the accommodation. For these calculations it is assumed that the enthalpy wheel can be added to the AHU within 64 man-hours and without adjusting the AHU or AHU space.

The payback time of an enthalpy wheel for varying cost of energy are shown in the graphs below for both with and without recirculation. The payback time is calculated by dividing the CAPEX by the savings in OPEX.





6.2.4 Conclusion

The results presented show that an enthalpy wheel is working most efficiently in cold environments. This is because the temperature difference between the outside and inside air is bigger. Also, it benefits from the difference in humidity levels inside and outside.

If an enthalpy wheel is installed, it becomes beneficial to switch off recirculation. This reduces the airflow and therefore saves fan power and energy consumption for the reheaters. Because the energy consumption for heating in a hot environment is mostly due to the reheating of overcooled air, switching off recirculation is most beneficial in hot environments.

Installing an enthalpy wheel has a low impact on the design and low CAPEX in case of a newbuild. Retrofitting, however, might become very costly since the AHU might need to be replaced and there might not be space available for a bigger AHU. Table 41 and 42 show the percentage of savings and payback times for a cost of energy of €0.20 per kWh.

	Savings of total [%]	Payback time [years]
North Sea, newbuild	10.6%	0.2
Gulf of Mexico, newbuild	1.6%	2.0
North Sea, retrofit	10.6%	0.4
Gulf of Mexico, retrofit	1.6%	3.3

Table 41 Savings and payback time of enthalpy wheel

	Savings of total [%]	Payback time [years]
North Sea, newbuild	13.6%	0.2
Gulf of Mexico, newbuild	14.2%	0.2
North Sea, retrofit	13.6%	0.3
Gulf of Mexico, retrofit	14.5%	0.3

Table 42 Savings and payback time of enthalpy wheel and no recirculation

6.3 LED lighting and occupancy sensors

This section elaborates on the assessment of LED lighting and occupancy sensors. It describes the way it is modelled and shows the results in energy savings. Finally, it shows the payback time and gives a conclusion.

6.3.1 Model

The lighting is modelled in DesignBuilder with a normalised power density of 15.95 W/m^2. This is reduced with 54% to model the replacement of fluorescent lighting by LED lighting. This is according technical specifications from the supplier. The selected LED lighting has the same light output in lumens as the original fluorescent lighting.

The occupancy sensors are modelled by setting the schedules for lighting according to the occupancy schedules for the corresponding zones. This is done for all zones except the circulation areas.

6.3.2 Energy savings

The yearly consumption in MWh and savings are shown in table 43 and 44 for the North Sea and the Gulf of Mexico.

	North Sea			
	Base case	LED & Occ. Sens.	Savings [%]	Savings [MWh]
Heating	*387*	*409*	*-5.8%*	*-22*
Cooling	*24*	*24*	*0.1%*	*0*
Humidification	*50*	*47*	*7.2%*	*4*
Fans	*114*	*114*	*0%*	*0*
Total HVAC	*576*	*595*	*-3.2%*	*-19*
Lighting	74	24	68.0%	50
Total	**1013**	**982**	**3.1%**	**31**

Table 43 Energy saving by LED lighting and occupancy sensors in North Sea

	Gulf of Mexico			
	Base case	LED & Occ. Sens.	Savings [%]	Savings [MWh]
Heating	*32*	*45*	*-39.6%*	*-13*
Cooling	*302*	*300*	*0.7%*	*2*
Humidification	*0*	*0*	*0%*	*0*
Fans	*114*	*114*	*0%*	*0*
Total HVAC	*449*	*459*	*-2.4%*	*-11*
Lighting	74	24	68.0%	50
Total	**877**	**838**	**4.5%**	**39**

Table 44 Energy savings by LED lighting and occupancy sensors in Gulf of Mexico

Tables 43 and 44 show 68% savings on lighting. 54% is due to the switch from fluorescent lighting to LED. The remaining 14% is due to switching of the lighting when the rooms are unoccupied.

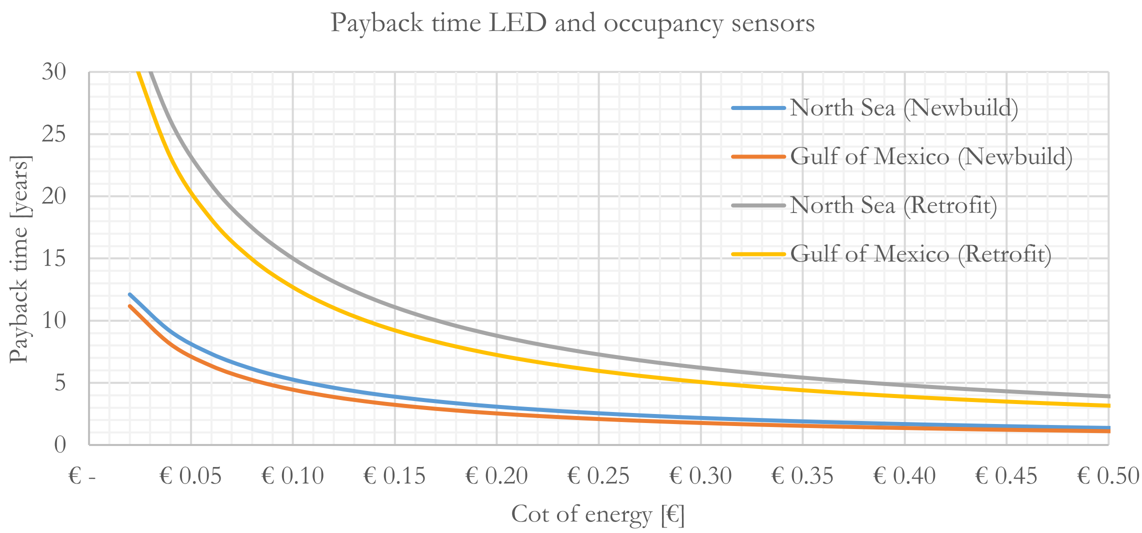
Light which is emitted is eventually absorbed in the accommodation as heat. Since less energy is used by LED lighting, less heat is added to the accommodation. This leads to increased energy consumption during heating and decreased energy consumption during cooling. Since the accommodation is mainly heating in the North Sea and cooling in the Gulf of Mexico, the savings in the North Sea are less due to increased heating loads.

6.3.3 Financial analysis

The payback time and cost of savings are calculated for both newbuild and retrofit. The purchase cost of LED lights are about 1.5 times as much as fluorescent lighting according quotations for Keppel Verolme BV per 2016. Newbuild designs with LED lighting have no extra installation cost compared to fluorescent lighting.

The maintenance cost for lighting depends on the lifespan of the lights. Fluorescent lights have a lifespan of 12,000 hours, LED's have a lifespan of 50,000 hours according the technical specifications of the supplier. This means that fluorescent lights have to be replaced every 1.7 years and LED's every 5.7 years (assuming 8760 burning hours per year). The extra cost for LED's are less than the factor 4.2 increased lifespan and therefore LED's save in maintenance cost compared to fluorescent lighting. Replacing lightbulbs can be done by crew on board. It is assumed that the man-hour cost of crew on board is 50% lower than yard crew.

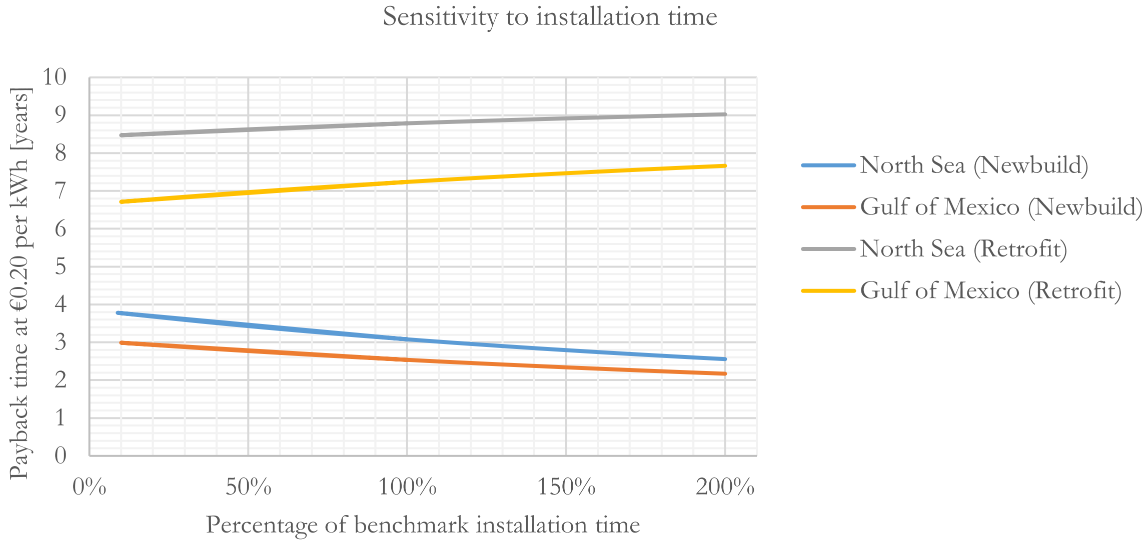
The CAPEX for retrofit are higher since the existing lighting fixtures have to be replaced by LED lighting fixtures which induces man-hour cost. The graph below shows the payback time for newbuild and retrofit.



The payback time depends on the installation and replacement cost per item. The following installation times were used for the calculation of the payback time

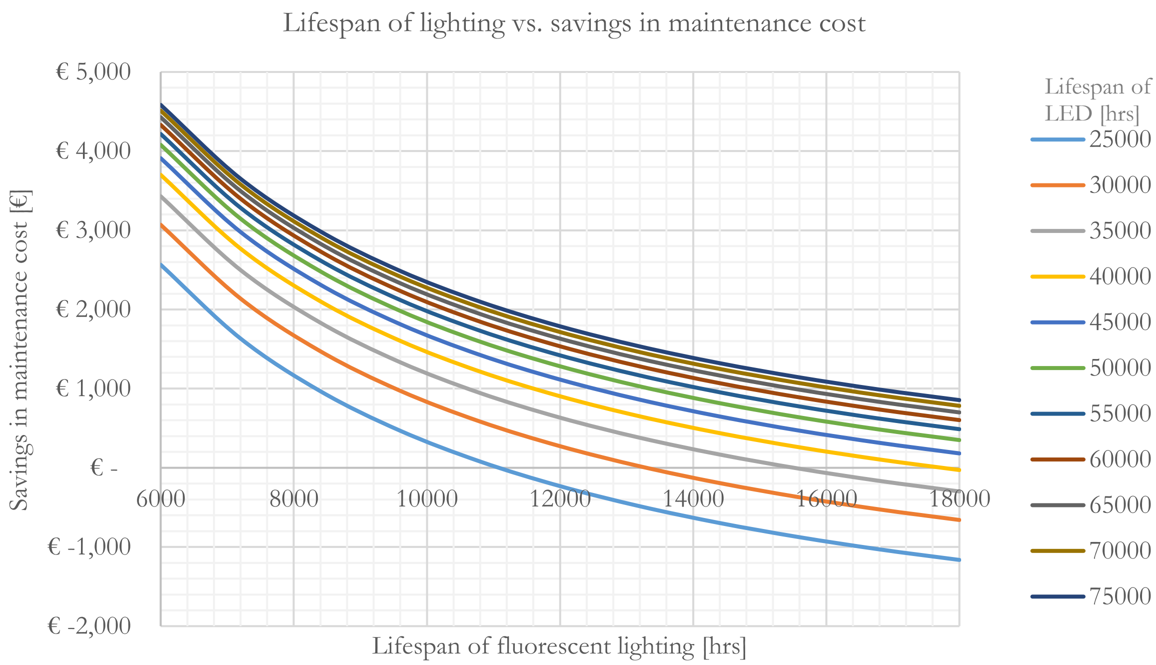
- Installation ceiling light 1.5 hrs
- Replacement bulb ceiling light 0.5 hrs
- Installation desk/berth light 0.5 hrs
- Replacement bulb desk/berth light 0.25 hrs

The graph below shows the effect of variations in these times. For example, 150% of benchmark time means that all installation times are multiplied with a factor 1.5. The payback time is calculated for a cost of energy of €0.20 per kWh.



Firstly, an increase in the replacement time has a positive effect on the savings in maintenance cost. The higher the cost for replacing the lamps, the bigger the difference in cost for maintenance between fluorescent lighting and LED lighting, since LED's have a longer lifespan and need to be replaced less often. Secondly, an increase in installation time has a negative effect on the CAPEX for retrofitting. The relevance of the cost savings due to savings in kWh's becomes less, so the curves for the North Sea and Gulf of Mexico are approaching each other.

The savings in maintenance cost mentioned earlier depend on the lifespan of the lighting. The graph below shows the savings in maintenance cost for varying lifespans. Negative savings imply that the longer lifespan of LED's does not outweigh the increased costs of LED's.



6.3.4 Conclusion

Installing LED's saves about 50% in the energy consumption for lighting. For this case study, about 15% extra savings can be obtained by installing occupancy sensors in public spaces, excluding the circulation areas. Changing the lighting from fluorescent to LED also has an effect on the cooling and heating load since the heat gain by lighting is decreased.

The CAPEX are lower for newbuild than retrofit. In case of retrofit, all original fixtures have to be replaced. The CAPEX of LED lighting are relatively high compared to other energy savings strategies because it concerns many items (260 for this case study).

An increase in the installation time per light has a positive effect on the savings in maintenance compared to fluorescent lighting and a negative effect on the CAPEX for newbuild.

Table 45 shows the percentage of savings and payback times for a cost of energy of €0.20 per kWh.

	Savings of total [%]	Payback time [years]
North Sea, newbuild	3.1%	3.1
Gulf of Mexico, newbuild	4.5%	2.5
North Sea, retrofit	3.1%	8.8
Gulf of Mexico, retrofit	4.5%	7.2

Table 45 Savings and payback time of LED lighting and occupancy sensors

6.4 Drain water heat recovery

This section elaborates on the assessment of a drain water heat recovery system. It describes the way it is modelled and shows the results. Finally, it shows the payback time and gives a conclusion.

6.4.1 Model

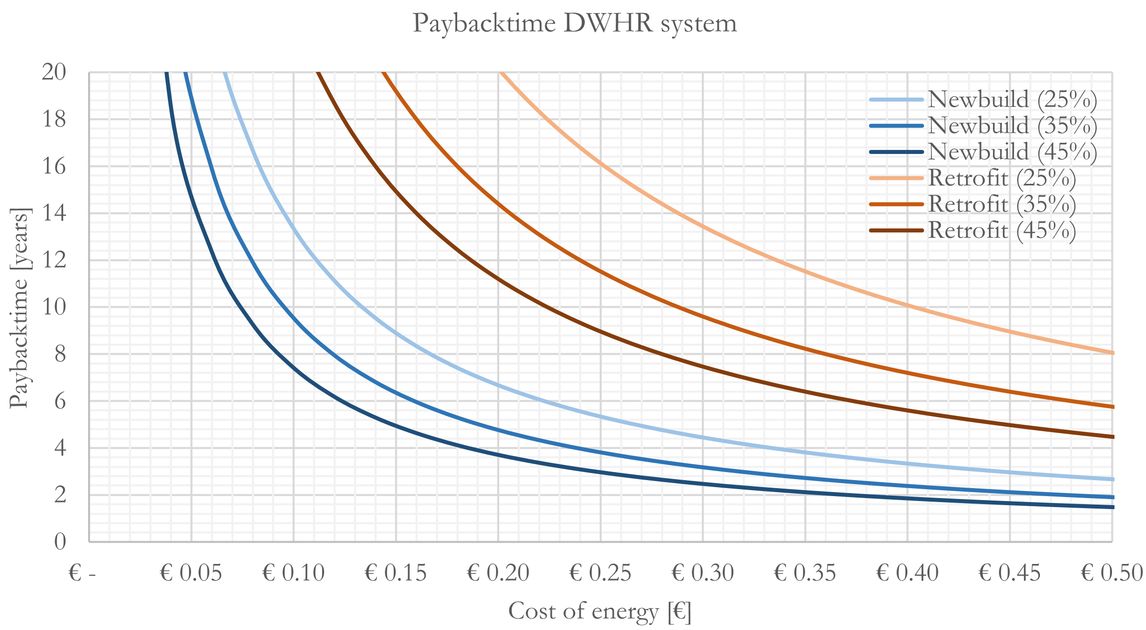
The savings in hot water consumption have no effect on the rest of the accommodation. The savings are calculated by hand calculations. Firstly, it is determined how much heat is left in the hot drain water. Therefore, the following variables are used:

- Temperature of drain water: 37 ºC (Eco Home Tips, 2016)
- Specific enthalpy of water at 37 ºC 155 kJ/kg

The hot water consumption rate per year is calculated by DesignBuilder based on input described in section 3.3.3. The amount of heat in the drain water is calculated with the specific heat of water at 37 ºC. According to the supplier, the DHWR system recovers about 37.5% to 45% of the heat. To stay in the save side, an efficiency of 35% is used. This results in an energy recovery of 16,423 kWh per year. Taking into account an efficiency of the boiler of 90%, this leads to an energy saving of 18,248 kWh.

6.4.2 Financial analysis

The purchase price of a DWHR pipe is as stated by the supplier as per 2016. The DWHR systems have no increased maintenance cost. There are no moving parts and it has a life time up to 30 years according the supplier. The installation time is considered to be 1 extra man-hour per item for newbuild compared to the base case situation. The installation cost for retrofitting would be very high because wall panels need to be removed and extensive adjustments have to be made in confined spaces. The installation time is estimated to be 20 hours per item. The payback time for a DWHR system is shown in the graph below for heat recovery efficiencies of 25%, 35%, and 45%.



6.4.3 Conclusion

A drain water heat recovery system is a simple and reliable system. For the case study is saves about 18 MWh per year. In newbuild designs, the system can be incorporated in the design. However, for retrofit, the installation becomes costly because wall panels need to be removed and extensive adjustments have to be made in confined spaces. This makes the system not feasible for retrofit.

Table 46 shows the percentage of savings and payback times for a cost of energy of €0.20 per kWh.

	Savings of total [%]	Payback time [years]
North Sea, newbuild	1.8%	4.8
Gulf of Mexico, newbuild	2.1%	4.8
North Sea, retrofit	1.8%	14.4
Gulf of Mexico, retrofit	2.1%	14.4

Table 46 Savings and payback time of DWHR system

6.5 Demand controlled ventilation

This section elaborates on the assessment of a drain water heat recovery system. It describes the way it is modelled and shows the results. Finally, it shows the payback time and gives a conclusion.

6.5.1 Model

In the base case model, the temperature setpoints of the air handling units is set to fixed temperatures, 14ºC for summer months and 18 ºC for winter months. This is not always the actual required supply temperature. The heat gains in the accommodation are not constant over time and therefore the heating and cooling load is also not constant over time. The reheaters are used in this case to adjust the zone temperature to the required temperature. This might cause the AHU to cool down outside air to 14 ºC in order for the reheater to heat again to higher temperatures. This is called overcooling.

Overcooling can be prevented by setting the temperature of the AHU to an actual required temperature. This is modelled in DesignBuilder by changing the temperature setpoint managers to 'Multi-zone heating average' and 'Multi-zone cooling average'. This way DesignBuilder calculates the temperature setpoint based on the averaged need of all the zones served by the AHU. The airflow rates are kept constant to maintain 6 air-changes-per-hour.

6.5.2 Energy Savings

The yearly savings in MWh are shown in table 47 and 48 for the North Sea and the Gulf of Mexico.

	North Sea			
	Base case	DCV	Savings %	Savings MWh
Heating	387	269	30.5%	118
Cooling	24	6	73.8%	18
Humidification	50	125	-147.9%	-75
Fans	114	114	0%	0
Total HVAC	576	515	10.6%	61
Total	**1013**	**952**	**6.0%**	**61**

Table 47 Savings in MWh by DCV in North Sea

	Gulf of Mexico			
	Base case	DCV	Savings %	Savings MWh
Heating	32	0	100%	32
Cooling	302	118	61.1%	185
Humidification	0	0	0%	0
Fans	114	114	0%	0
Total HVAC	449	323	48.3%	217
Total	**877**	**661**	**24.6%**	**217**

Table 48 Energy savings by DCV in MWh in Gulf of Mexico

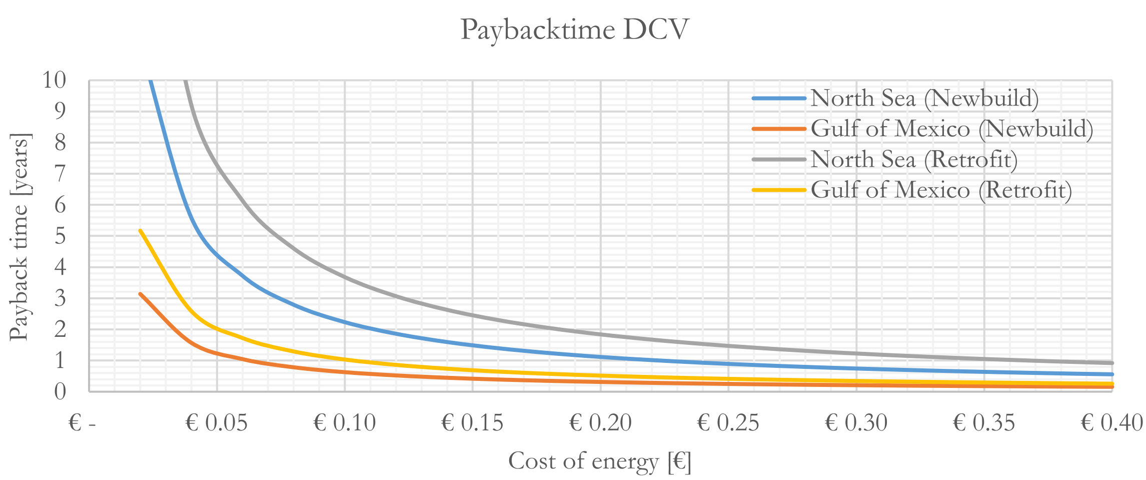
The AHU is mainly cooling in the Gulf of Mexico, the biggest savings by preventing overcooling can thus be obtained in hot environments. Also, in the North Sea some energy saving is lost by increased humidification needs. The AHU has a setpoint manager which dictates the relative humidity of the supply air. In the base case model the supply air temperature is 14 °C in the summer and 18 °C in the winter. The minimum relative humidity ratio is set to 30%, this is an absolute humidity ratio of 0.0036 kg/m^3 at 14 °C . With DCV, the supply air temperature is closer to the inside temperature setpoint of 20 °C. The absolute humidity ratio at 20 °C is 0.0052 kg/m^3, which is higher than 0.0036 kg/m^3, hence the extra humidification needs. The air in Gulf of Mexico already contains sufficient humidity.

For these calculations it is assumed that all overcooling can be discarded. However, in reality, overcooling might be used for dehumidification. The temperature is then lowered to the dew point and moisture in the air will condensate.

If 6 air-changes-per-hour is not a fixed requirement, extra savings might be possible. If ventilation is switched on only when one or more people are present in the room, the weighted average occupancy factor is 0.56. This assumes the ventilation to be on 24 hours per day in the circulation areas, stores and HVAC room. This means that on average the airflow can be reduced with 44% for AHU 1 (main) and AHU 2 (galley).

6.5.3 Financial Analysis

DCV requires temperature sensors to feedback temperatures in the zone to the AHU. A network system is installed to communicate between the sensors and the AHU. The installation of these sensors is assumed to take 0.5 man-hours in newbuild and 3 man-hours in retrofit. The system requires no extra maintenance. This results in payback times as shown in the graph below.



6.5.4 Conclusion

Demand controlled ventilation prevents overcooling. DCV is most beneficial in warm environments because there the AHU is mainly cooling. The CAPEX are relatively low compared to the other energy saving strategies, resulting in low payback times. Extra savings could be obtained if the airflow is also adjusted to the occupancy, i.e. lowering the amount of air-changes-per-hour when spaces are unoccupied. The yearly savings in MWh and payback times are shown in table 49.

	Savings of total [%]	Payback time [years]
North Sea, newbuild	6.0%	1.1
Gulf of Mexico, newbuild	24.6%	0.3
North Sea, retrofit	6.0%	1.8
Gulf of Mexico, retrofit	24.6%	0.5

Table 49 Savings and payback time of DCV system

6.6 Water sourced heat pump

This section elaborates on the assessment of a water sourced heat pump. It describes the way it is modelled and shows the results. Finally, it shows the payback time and gives a conclusion.

6.6.1 Model

DesignBuilder does not offer a module to model a water sourced heat pump. Therefore, calculations are made based on information from suppliers by Keppel Verolme BV as per 2016. Two heat pumps are required to fulfil the heating and cooling load in AHU 1 and the hot water boiler. Each heat pump has a power range from 14 to 54 kW, depending on the compressor speed. The output of the heat pumps depends on the weather conditions. Therefore, a 60 kW electric heating boosting system is installed to ensure that the system can respond rapidly to quick weather changes. The information from the suppliers showed that, for this case study, 99.97% of the energy consumption is supplied by the heat pumps and 0.03% by the electric heating system.

The heat pumps use seawater as the source of heat. The supplier reported the savings in percentages for different seawater temperatures. Linear interpolation is used to determine the savings for given seawater temperatures in the North Sea. The monthly energy consumption for heating and cooling by AHU 1 and the hot water boiler are used to determine the savings. The results are shown in table 50.

Month	Seawater temperature [°C]	Savings [%]	Energy consumption Heating and cooling AHU 1 and boiler [MWh]	Savings [MWh]
January	6.1	75%	29	22
February	4.9	74%	26	19
March	4.2	74%	23	17
April	5.2	74%	20	15
May	8.5	76%	16	12
June	12.5	78%	8	6
July	15.3	79%	11	9
August	16.5	80%	11	9
September	15.9	79%	9	7
October	14.5	79%	12	10
November	10.5	77%	21	17
December	8.5	76%	28	21
Total			**214**	**163**

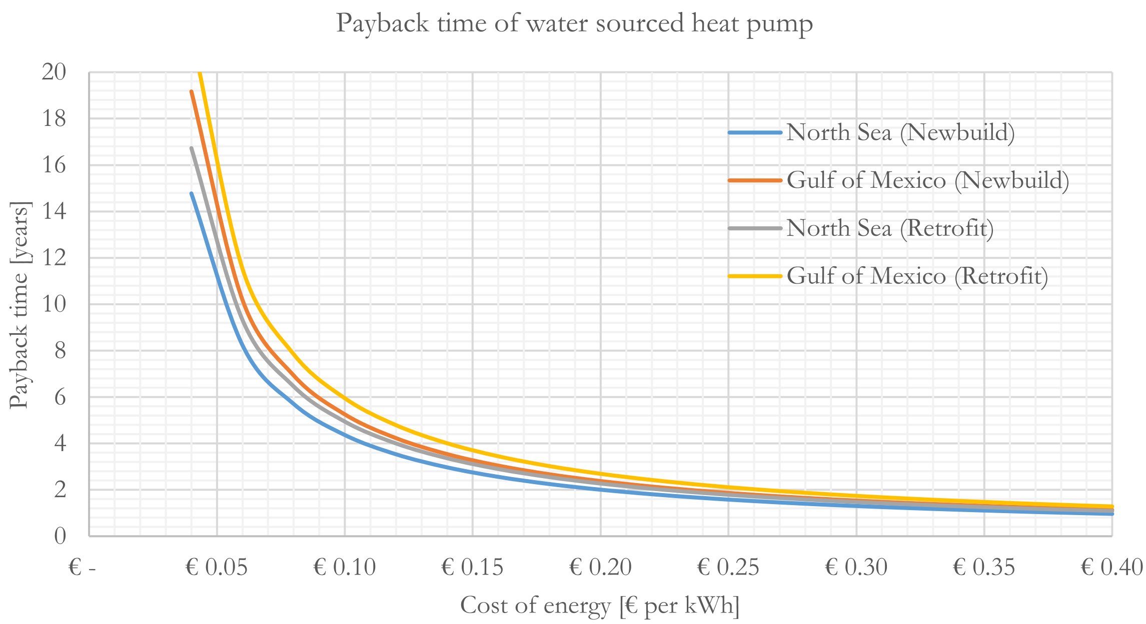
Table 50 Seawater temperatures and savings by heat pump in the North Sea

Percentages of savings for the Gulf of Mexico are not on hand. To stay on the save side, an average saving of 70% is used for the calculations. The total energy consumption for heating and cooling by AHU 1 and the hot water boiler in the Gulf of Mexico are 199 MWh. This leads to a yearly saving of 139 MWh.

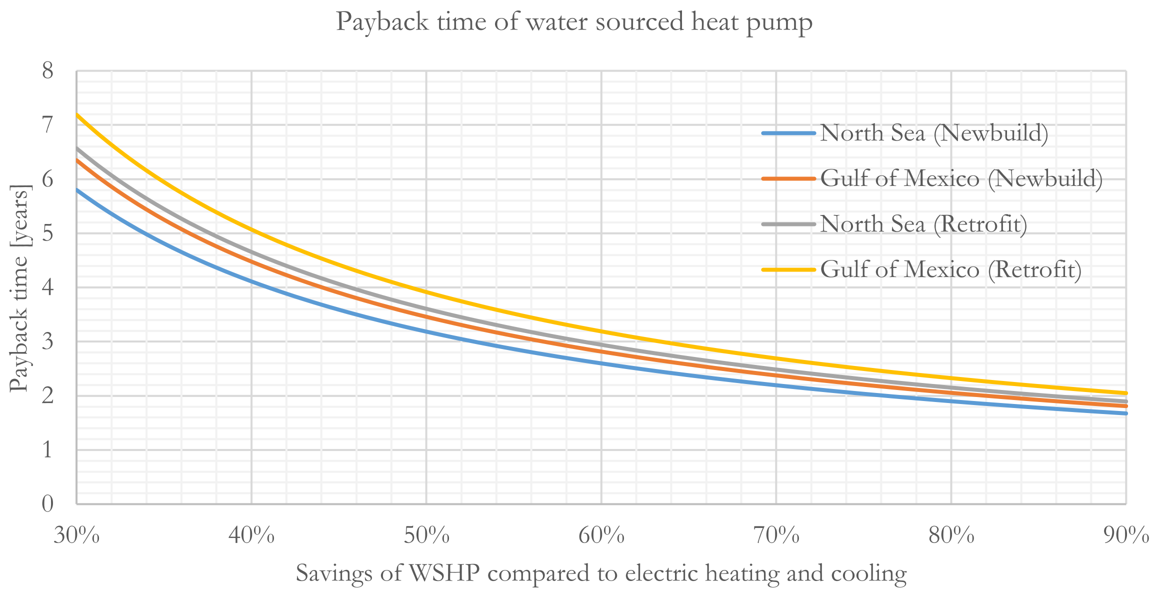
6.6.2 Financial analysis

The purchase price is as quoted by the supplier to Keppel Verolme BV as per 2016. The maintenance cost are quoted to be about 4% of the purchase price. The installation time required is estimated to be 160 man-hours for retrofit. The installation cost are relatively low compared to the purchase price. A sensitivity study shows that a double installation time would lead to a 12% increase in the payback time. Installing a heat pump in a newbuild is assumed to have no significant extra installation cost.

The graph below shows the payback time for a water sourced heat pump in the North Sea and in the Gulf of Mexico.



The graph shows a payback time of about 2 years in the North Sea and about 2.5 years in the Gulf of Mexico based on €0.20 per kWh. As stated before, the efficiency of the heat pump depends on the seawater temperature. These temperatures vary over time and location. The graph below shows the payback time for varying efficiencies with a constant cost of energy of €0.20 per kWh. A fixed average efficiency is used over the year.



6.6.3 Conclusion

A water sourced heat pump has a relatively high purchase price compared to the other strategies. The payback time, however, remains low due to high energy savings. This is due to a high coefficient of performance of heat pumps, as described in section 5.1.1. The results show a payback time of 2 years in the North Sea and 2.5 years in the Gulf of Mexico based on €0.20 per kWh. Changes in installation cost or savings of the heat pump do not show significant effects on the payback time.

6.7 All strategies combined

The enthalpy wheel, demand controlled ventilation and LED lighting all have an effect on the energy consumption for HVAC. All strategies are combined in the base case model in DesignBuilder to get insight in the combined effects. In section 6.7.2, a water sourced heat pump is added. The results of the simulations are shown in table 51 and 52 for the North Sea and the Gulf of Mexico.

	Base case North Sea	Combined strategies	Savings [%]	Savings [MWh]
Heating	387	337	13%	50
Cooling	24	3	86%	21
Humidification	50	74	-46%	-23
Fans	114	76	33%	38
Total HVAC	576	490	15%	86
Lighting	74	24	67%	49
Laundry	74	74	0%	0
Galley	159	159	0%	0
Aux	79	79	0%	0
DHW	52	34	34%	18
Total	**1013**	**860**	**15%**	**153**

Table 51 Yearly energy saving by combining the strategies in North Sea

	Base case Gulf of Mexico	Combined strategies	Savings [%]	Savings [MWh]
Heating	32	4	89%	28
Cooling	302	198	35%	105
Humidification	0	0	0%	0
Fans	114	76	33%	38
Total HVAC	449	278	38%	171
Lighting	74	24	67%	49
Laundry	74	74	0%	0
Galley	159	159	0%	0
Aux	79	79	0%	0
DHW	43	25	41%	18
Total	**877**	**639**	**27%**	**238**

Table 52 Yearly energy saving by combining the strategies in Gulf of Mexico

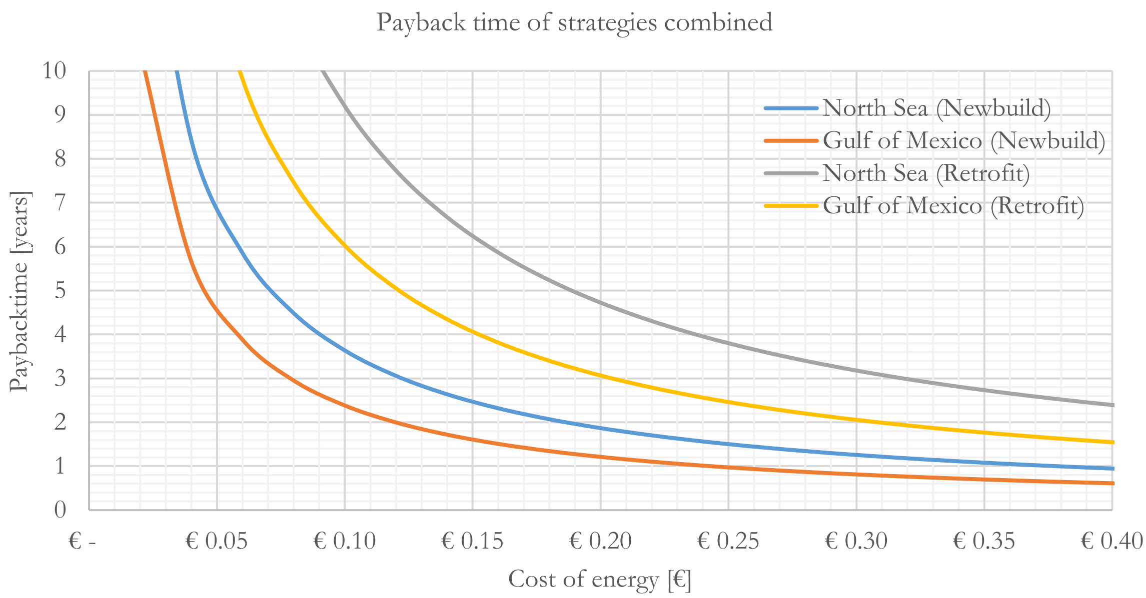
If all savings in MWh by the individual models would be summed, this would lead to 247 MWh in the North Sea and 398 MWh in the Gulf of Mexico. Compared to 153 MWh and 238 MWh shown in tables 51 and 52, both results show only 60% of the savings if the strategies are combined. Two reasons for this can be found.

As seen in the section on demand controlled ventilation, there is an increase in the humidification load in the North Sea. This is caused by a higher output temperature of the AHU and thus a higher absolute humidity level if the relative humidity level is maintained. If LED lighting is used, the heat gain in the accommodation is decreased. This has to be compensated with a higher temperature output of the AHU, leading to a higher humidification load if LED lighting and DCV are combined.

In the Gulf of Mexico, increased savings can be reached by switching of recirculation. This decreases the airflow. Because the output air of the AHU is overcooled, a decreased airflow leads to savings in the energy consumption of the reheaters. However, if DCV is applied, energy already is saved on the reheaters since the temperature of the output air is close to the setpoint temperature of the spaces.

6.7.1 Financial analysis

The payback time of the combined strategies is calculated by adding all CAPEX and OPEX other than the savings in energy. The savings in energy are added based on 153 MWh in the North Sea and 238 MWh in the Gulf of Mexico, as shown in the results above. The resulting payback time is shown in the graph below.



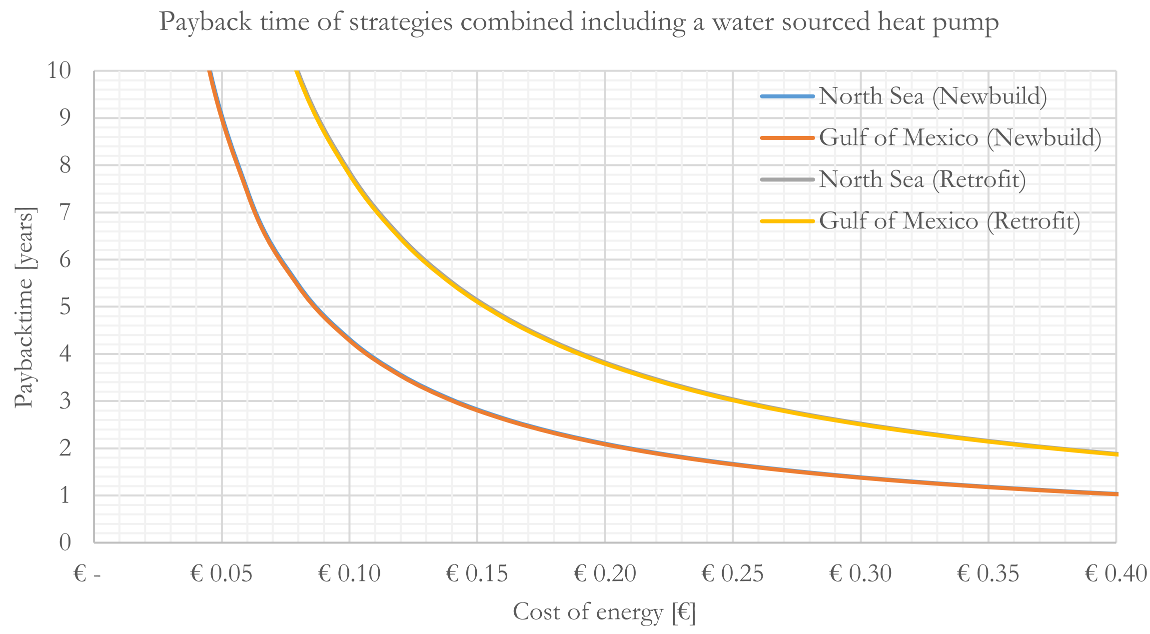
For a cost of energy of €0.20 per kWh, the strategies combined show savings and payback times as shown in table 53.

	Savings of total [%]	Payback time [years]
North Sea, newbuild	15%	1.9
Gulf of Mexico, newbuild	27%	1.2
North Sea, retrofit	15%	4.7
Gulf of Mexico, retrofit	27%	3.1

Table 53 Savings and payback time of strategies combined

6.7.2 Including a water sourced heat pump

This sections shows the results for the combined strategies in case a water sourced heat pump is included. The calculations are done in the same way as it is done for the calculations for installing a heat pump individually. This leads to additional saving of 139 MWh in the North Sea and 56 MWh in the Gulf of Mexico when a heat pump is added to the model with combined strategies applied. This leads to the following payback times as shown in the graph below. The curves for the North Sea and the Gulf of Mexico are coincidentally almost identical.



For a cost of energy of €0.20 per kWh, the strategies combined including a heat pump show savings and payback times as shown in table 54.

	Savings of total [%]	Payback time [years]
North Sea, newbuild	28%	2.1
Gulf of Mexico, newbuild	34%	2.1
North Sea, retrofit	28%	3.8
Gulf of Mexico, retrofit	34%	3.8

Table 54 savings and payback times for combined strategies including a heat pump

Installing a water sourced heat pump increases the savings in both the North Sea and Gulf of Mexico. The HVAC energy consumption in the Gulf of Mexico for the combined strategies is lower than in the North Sea. The absolute savings by installing a WSHP are therefore smaller in the Gulf of Mexico. The CAPEX are the same. This leads to a decreased payback time in the North Sea and an increased payback time in the Gulf of Mexico.

The payback times versus the cost of energy follow a hyperbolic curve. This is caused by the varying cost of energy in the denominator. The payback time is calculated by dividing the CAPEX by the savings in OPEX. The saving in OPEX is a product of the cost of energy and the energy savings. This means that the effect of increasing the cost of energy is decreasing for higher cost of energy.

Compared to the newbuild price of a typical offshore accommodation unit based on existing platforms built at Keppel Verolme BV, the total extra CAPEX for all strategies combined correspond to +4% for newbuild and +7% for retrofit. This represents the extra upfront cost of implementing these strategies.

7 Conclusion

A combined package of energy saving strategies leads to 29% savings in cold environments (the Norwegian North Sea) and 34% in hot environments (Gulf of Mexico). This package contains an enthalpy wheel, LED lighting and occupancy sensors, a drain water heat recovery system, demand controlled ventilation and a water sourced heat pump. This leads to the payback times based on a cost of €0.20 per kWh as shown in table 55.

	Payback time [years]
North Sea, newbuild	2.1
Gulf of Mexico, newbuild	2.1
North Sea, retrofit	3.8
Gulf of Mexico, retrofit	3.8

Table 55 Payback times combined energy saving strategies

Compared to the newbuild price of a typical offshore accommodation unit based on existing platforms built at Keppel Verolme BV, the total extra CAPEX for all strategies combined correspond to +4% for newbuild and +7% for retrofit. This represents the extra upfront cost of implementing these strategies.

7.1 Yearly energy consumption and distribution

A base case model is made using DesignBuilder. The model has a capacity of 37 persons on board and a total floor area of 960 m^2. The model showed a yearly energy consumption of 1013 MWh in the North Sea and 877 MWh in the Gulf of Mexico. The difference is caused by the heating, ventilation and air-conditioning (HVAC) system. The outside conditions in the Gulf of Mexico are closer to the inside temperature and humidity setpoint. This causes lower heating/cooling and humidification loads compared to the North Sea. Table 56 shows the consumer categories with their corresponding percentage of the total energy consumption:

	North Sea	Gulf of Mexico
Heating	38%	4%
Cooling	2%	34%
Humidification	5%	0%
Fans	11%	13%
Total HVAC	57%	51%
Lighting	7%	8%
Laundry	7%	8%
Galley	16%	18%
Aux	8%	9%
DHW	5%	5%

Table 56 Distribution of energy consumption

The high energy consumption of the HVAC installation is caused by a high fixed airflow rate and fixed temperature setpoints of the AHU. Offshore accommodations require 6 fresh-air-changes per hour which is relatively high compared to onshore buildings. If the number of fresh-air-changes is reduced by 50%, the consumption of the HVAC system is reduced by 25%.

Mainly in a warm environment energy is wasted by overcooling. The temperature setpoint of the air handling unit is set to 14 ⁰C in summer. Reheaters then have to reheat the overcooled air.

The relation between the number of persons on board and the total yearly energy consumption can be approached with the following formula:

$$W_{Total,\ North\,Sea} = 0.013 \cdot POB^2 + 23.84 \cdot POB + 160.83$$

$$W_{Total,\ Gulf\,of\,Mexico} = 0.044 \cdot POB^2 + 18.32 \cdot POB + 93.04$$

Where W_{Total}: Yearly total energy consumption in megawatt-hour per year

POB: number of persons on board

7.2 Energy saving strategies

This research assessed eight energy saving strategies applicable to offshore accommodations: water sourced heat pump, natural lighting, natural ventilation, LED lighting and occupancy sensors, demand controlled ventilation, enthalpy wheel, drain water heat recovery system and a bio-gas digester. These strategies are ranked based on relevant criteria in designing a package of energy saving strategies which can be offered to offshore operators. The results of the ranking are shown in table 57.

	Weight	Enthalpy wheel	DCV	Heat pump	LED	DWHR	Nat. Vent.	Nat. Lighting	Bio-gas digester
Part of total consumption		*42%*	*39%*	*39%*	*7%*	*5%*	*53%*	*7%*	*5%*
Potential Savings per part		*22%*	*25%*	***70%***	*45%*	*35%*	*50%*	*22%*	*9%*
Potential Savings of total	5	9.1%	9.8%	27.3%	3.2%	1.8%	26.5%	1.6%	0.4%
Maturity of technology	4	++	+	0	++	++	-	+	-
Maintenance costs	3	+	+	0	+	++	++	+	0
Reliability	3	++	+	0	++	++	-	+	0
Applicability retrofit	2	--	0	--	+	--	--	--	-
Applicability newbuild	1	++	+	0	++	+	-	-	0
Total score		**69%**	**65%**	**67%**	**70%**	**64%**	**64%**	**50%**	**37%**

Table 57 Design matrix energy saving strategies

This matrix shows that LED lighting, an enthalpy wheel, a heat pump, demand controlled ventilation and a drain water heat recovery system are the five most promising and available strategies.

7.3 Savings and payback times

LED lighting, an enthalpy wheel, demand controlled ventilation, a drain water heat recovery system and a water sourced heat pump are applied to the base case model.

The cost savings by the strategies are determined by the cost of energy on board. The cost of energy is calculated to be €0.20 per kWh. This comprises of €0.08 for fuel, €0.11 for transportation of the fuel and €0.01 for purchase and maintenance of the generator sets. The payback times below are calculated for a cost of energy of €0.20 per kWh

An enthalpy wheel is most profitable in cold environments. If an enthalpy wheel is installed, it becomes profitable to switch of recirculation. This leads to savings in fan power. It also saves in reheating overcooled air mainly in warm environments. The investment cost for installing an enthalpy wheel in a newbuild accommodation are low. However, installing an enthalpy wheel in an existing platform might not be feasible because the air handling unit must be replaced and there might be no space available. About 14% savings on the total energy consumption can be reached if an enthalpy wheel is installed and the recirculation is switched off. This results is a payback time of about 6 months for newbuild.

LED lighting saves about 50% of the energy consumption for lighting compared to fluorescent lighting. An extra 15% savings can be obtained with occupancy sensors. Reducing the power density of lighting also reduces the heat gain by lighting and therefore increases the HVAC consumption with about 3%. No extra installation cost are involved if LED lighting is installed in a newbuild. In case of retrofitting, all lighting fixtures need to be replaced, this increases the investment cost due the large number of lights (260 for the case study). LED lighting and occupancy sensors save about 4% on the total energy consumption. This results in a payback time of about 3 years for newbuild and 8 years for retrofit.

A drain water heat recovery system is a low maintenance and reliable system. A drain water heat recovery system saves about 35% of the energy consumption for domestic hot water. This saves 2% of the total energy consumption. The system is not feasible for retrofitting. The installation cost will be high because wall panels need to be removed and extensive adjustments have to be made in confined spaces. The system has a payback time of about 5 years for newbuild and 15 years for retrofit.

Demand controlled ventilation prevents overcooling. It is therefore most profitable in hot environments. The system has relatively low investment costs. Extra savings can be obtained if the airflow is also reduced based on the occupancy of the spaces. The system saves about 5% of the total energy consumption in cold environments and 25% in hot environments. This results in payback times of 1.5 years in the North Sea and 0.5 years in the Gulf of Mexico.

A water sourced heat pump has relatively high CAPEX. The payback time, however, is low due to high savings. The results show a payback time of 2 years in the North Sea and 2.5 years in the Gulf of Mexico. Changes in installation cost or savings of the heat pump do not show significant effects on the payback time.

The strategies combined lead to 29% savings in cold environments and 34% in hot environments. This leads to payback times of 2 years for newbuild and 4 years for retrofit.

8 Recommendations

The results showed that strategies concerning the accommodation's heating, ventilation and air-conditioning system are the most promising. It is therefore recommended to install an enthalpy wheel and demand controlled ventilation. LED lighting and drain water heat recovery systems are only recommended for newbuild accommodations. It is recommended to install a heat pump. It results in high savings and can be used for both heating and cooling as well as heating of water.

This research calculated savings only based on savings in energy consumption. For further research it is recommended to assess additional savings. Decreased loads on the HVAC system might reduce maintenance cost. When considering newbuild, a smaller HVAC system might be sufficient. This would lead to lower CAPEX. The same applies to the generator sets.

The high number of air-changes-per-hour causes a high energy consumption by the HVAC system. This is required by classification societies. It is recommended to further research the origin of this requirement and investigate whether this can be altered. If this requirement is dropped, demand controlled ventilation systems can also adjust the airflow according the occupancy of the spaces.

This research focussed on the accommodation unit from the plug. However, the accommodation unit is placed on a platform. Waste heat from processes on board the platform could be a useful sources of energy. One could think of waste heat from generator sets, transformers and compressors.

To further save on energy cost and reduce CO_2 emissions, it is recommended to investigate the feasibility of generating energy from sustainable sources. Options might be solar, wind or wave energy. Research by Lars Hammer studied the feasibility of applying solar panels onto the façade of the base case model. It showed an energy generation of 72 MWh in the North Sea and 118 MWh in the Gulf of Mexico. This is based on a 100% coverage of the façade and roof (excluding doors and windows). Both the research by Hammer (2016) and Otheguy (2014) show payback times of about 10 years.

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Appendices

Appendix I: Working schedules

	Working 1(15):	Working 2(15):	Facility 1 (3)	Facility 2 (3)
00:00:00	sleep	eat	sleep	work
01:00:00	sleep	work	sleep	work
02:00:00	sleep	work	sleep	eat
03:00:00	sleep	work	change	change
04:00:00	sleep	work	eat	rest
05:00:00	sleep	change	work	rest
06:00:00	eat	eat	work	rest
07:00:00	change	rest	work	sleep
08:00:00	work	rest	eat	sleep
09:00:00	work	rest	laundry	sleep
10:00:00	work	sleep	work	sleep
11:00:00	work	sleep	work	sleep
12:00:00	eat	sleep	work	sleep
13:00:00	work	sleep	work	sleep
14:00:00	work	sleep	eat	sleep
15:00:00	work	sleep	change	change
16:00:00	work	sleep	rest	eat
17:00:00	change	sleep	rest	work
18:00:00	eat	eat	rest	work
19:00:00	rest	change	sleep	work
20:00:00	rest	work	sleep	eat
21:00:00	rest	work	sleep	laundry
22:00:00	sleep	work	sleep	work
23:00:00	sleep	work	sleep	work

Nomenclature

List of abbreviations

AHU	Air Handling Unit
CAPEX	Capital Expenditures
COP	Coefficient Of Performance
C/N Ratio	Carbon to Nitrogen ratio
DCV	Demand Controlled Ventilation
DHW	Domestic Hot Water
DWHR	Drain Water Heat Recovery
Genset	Generator set
GOM	Gulf Of Mexico
HVAC	Heating, Ventilation and Air-Conditioning
MCR	Maximum Continuous Rating
MDO	Marine Diesel Oil
NPV	Net Present Value
NS	North Sea
OPEX	Operational Expenditures
POB	Persons On Board
SD	Standard Deviation
SFOC	Specific Fuel Oil Consumption
WSHP	Water Sourced Heat Pump

List of Symbols

A	total floor area of accommodation	m^2
AH	absolute humidity	kg/m^3
D	hydraulic diameter of pipe	m
ΔP	pressure rise	Pa
e_{tot}	total efficiency of fan	%
f_d	the Darcy friction factor	-
L	length of pipe	m
N	shaft rotational speed	RPM
p_{atm}	atmospheric pressure	hPa
P	power	W
P_{fan}	fan power	W
Q	volumetric flow rate	m^3/s
RH	relative humidity	%
R_v	specific gas constant for water vapour	461.5 J/mol K
ρ_{air}	the air density	kg/m^3
S_c	score on criterion 'c'	-
S_{tot}	total score of a strategy	%
T	temperature	^0C
V	flow velocity	m/s
W_c	weight given to criterion 'c'	-