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Highlights

Ocean Engineering ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Investigation of offshore thermal power plant with carbon capture as an alternative to carbon dioxide transport

Q1 Björn Windén [a], Mingsheng Chen [b], Naoya Okamoto [c], Do Kyun Kim [d,e], Elizabeth McCaig [f], Ajit Shenoi [a], Philip Wilson [a]

[a] *Fluid Structure Interactions, University of Southampton, Southampton, United Kingdom*
[b] *The Centre for Offshore Research and Engineering, National University of Singapore, Singapore*
[c] *Japan Marine United Corporation, Technical Research Center, Tsu, Japan*
[d] *The Lloyd's Register Foundation Research Centre of Excellence, Pusan National University, Busan, South Korea*
[e] *Graduate School of Engineering Mastership, Pohang University of Science and Technology, Pohang, South Korea*
[f] *Lloyd's Register, London Design Support Office, London, United Kingdom*

- Concepts for the offshore thermal power plant with CCS (OTPPC) are introduced.
- General design selection process is established.
- Cost analysis with case study also performed.

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Investigation of offshore thermal power plant with carbon capture as an alternative to carbon dioxide transport

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[a] Fluid Structure Interactions, University of Southampton, Southampton, United Kingdom
[b] The Centre for Offshore Research and Engineering, National University of Singapore, Singapore
[c] Japan Marine United Corporation, Technical Research Center, Tsu, Japan
[d] The Lloyd's Register Foundation Research Centre of Excellence, Pusan National University, Busan, South Korea
[e] Graduate School of Engineering Mastership, Pohang University of Science and Technology, Pohang, South Korea
[f] Lloyd's Register, London Design Support Office, London, United Kingdom

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ABSTRACT

Carbon Capture and Storage (CCS) technology is considered as one option to reduce CO_2 emissions in order to mitigate climate change. The conventional CCS technology has its own complications including high costs and risks for storing CO_2. This paper introduces the concept of Offshore Thermal Power Plant with CCS (OTPPC), which eliminates the needs for transporting CO_2 and therefore reduces the complications of the whole system. A general design selection process for the OTPPC is established. A case study is carried out to demonstrate the application of OTPPC and the cost-effectiveness of this concept is evaluated by calculating the Levelised Cost Of Energy (LCOE) for both the OTPPC and conventional CCS technology for an onshore power plant with assumption that CCS is necessary.

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1. Introduction

Carbon Capture and Storage (CCS) is considered as one option in the portfolio for mitigating climate change that is mainly caused by the large anthropogenic emissions of CO_2 from burning fossil fuels (IPCC, 2005, 2007a, 2007b, 2007c, 2007d). According to the International Energy Agency (IEA), fossil fueled power generation accounts for 41% of the total emissions of CO_2 (IEA, 2011). Therefore, many researches focus on the capture of CO_2 emitted from power generation and the subsequent transport and storage of CO_2.

However, the conventional CCS technology has its own complications, such as high energy penalty, high costs, technology immaturity, the complexity of transporting CO_2 and uncertainties in the long-term storage of CO_2 (IPPC, 2005). Although transportation of CO_2 does not contribute to the largest part of the total costs, it increases the complexity of the whole system and therefore increases risks for leakage. In addition, the current CCS technologies mainly focus on the pursuit of CO_2 storage in onshore geological formations, which may lead to the concerns from the public towards the safety of storing CO_2 underground. However, the concept of Offshore Thermal Power Plant with CCS (OTPPC) may eliminate the above problems, which moves the power plant offshore to facilitate storing CO_2 into offshore geological formations.

The concept of offshore thermal power plant is not really new in the literature. Many companies have shown interest in developing this concept in order to reduce the need for lengthy permitting applications that are needed for conventional land based power plants (Waller Marine, 2011). In addition, the Gas to Wire (GTW) concept provides an attractive solution for marginal gas fields and stranded gas. Instead of transporting the natural gas from marginal gas fields to an onshore terminal, it generates electricity offshore and then transmits the electricity via subsea power cables to onshore electricity grids, which generates a higher thermal efficiency compared with the conventional approaches (HITACHI, 2011). The concept of combining an offshore power plant with CCS has been addressed previously when considering power generation for offshore installations since the 1990s (Bjerve and Bolland 1994). A more recent concept is by Hetland et al. (2008). The SEVAN GTW concept, developed by SEVAN MARINE and Siemens is a cylindrical platform equipped with a combined cycle power plants with four blocks, each consisting of two gas turbines and one steam turbine. These are connected to an amine based carbon capture system (Hetland et al., 2009). However, the cost benefits of this concept have not

* Corresponding author. Tel.: +82 51 510 2750; fax: +82 51 512 8836.
E-mail addresses: dk_kim@pusan.ac.kr, dokyun@postech.ac.kr (D.K. Kim).

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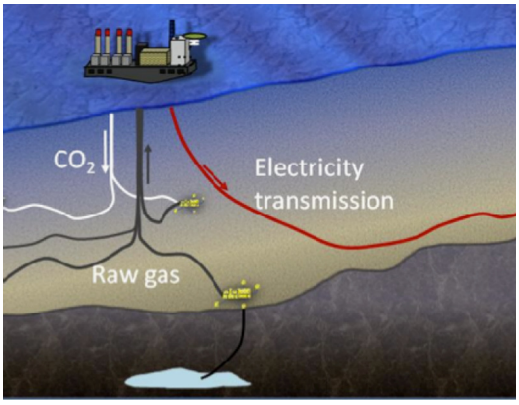

Fig. 1. Schematic of offshore thermal power plant with inclusion of CCS.

been investigated before. This raises the question whether OTPPC is cheaper than the conventional CCS technology for power plants.

Hence, the main purpose of this paper is to illustrate the concept of offshore thermal power plant with CCS, establish the corresponding design selection process and evaluate this concept in terms of availability for application and cost-effectiveness.

The concept of an OTPPC involves integrating power generation equipment, gas processing equipment, carbon capture systems and electricity transmission modules onto one offshore platform (Windén et al., 2011). As with the GTW concept, OTPPC can be applied in marginal gas fields where the high costs of production and transportation of gas make such developments non-viable. Compared to onshore power plants, offshore power plants have the advantages of shorter construction periods (Waller Marine, 2011) and ease of mobility. In addition, the cost of natural gas may be significantly reduced since natural gas can be directly supplied from the existing offshore gas fields as shown in Fig. 1.

Different from conventional CCS technology for power plants, this concept eliminates the need for long distance transportation of CO_2 via pipelines or ships by directly capturing CO_2 from fuel gases and injecting it into offshore geological formations. The generated electricity can either be transmitted to onshore electricity grids via subsea power cables or be used to support other offshore operations (Hetland et al., 2009).

This section has introduced the concept and features of an OTPPC, the design process of which is discussed in Section 2. A case study, discussing the cost-effectiveness of an OTPPC is given in Section 3. Finally, concluding remarks are given in Section 4.

2. Design selection process

Like the other offshore platforms, the OTPPC has to be capable of operating and surviving in the offshore location for a long period. Therefore, it is important to evaluate the environmental load effects based upon a given site in the design stage. Design codes and regulations that are applicable for offshore platforms may also be adapted to guide the design of the OTPPC. However, the OTPPC has its own complications and limitations. By integrating different systems onto one platform, the complexity of the overall system increases. In addition, the capacity of the power plant is limited by the deck area and storage capacity of the supporting platform. Before implementing this concept, a variety of factors that govern the design of the OTPPC need to be evaluated.

The engineering design process is an iterative decision making process where a system is devised to meet the required needs. It involves several stages including concept design, a feasibility study, preliminary design, detailed design and production design (Ertas and Jones 1996). The purpose of this section is to describe the process by which the concept design and the associated feasibility study of the OTPPC can be carried out. In general terms, it must be decided what type of vessel should be used, if a single or multiple vessels are to be used and what equipment goes on board (Hill et al., 2002).

The more specific design selection process and the associated feedback loops may differ depending on the motivation for implementing an OTPPC. Three motivations can be distinguished: power output, exploitation and CO_2 storage. Fig. 2 shows the design selection process for the motivation to produce electricity. The power output determines the configuration of the OTPPC that then decide where the location is so that the gas supply can be matched to the power output requirement (Hill et al., 2002). Based on the chosen location and the capacity of the OTPPC, the CO_2 storage option can then be determined. The electricity transmission system is designed based on a combination of power output and offshore distances.

The second motivation is to explore marginal gas fields or stranded gas. Here the gas field location is fixed, which determines the capacity of gas fields and offshore distances. The configuration of the OTPPC, electricity transmission system and CO_2 storage option can be adjusted accordingly as shown in Fig. 3.

The third motivation is to pursue the storage of CO_2 into offshore geological formations. This then fixes the location and an appropriate power output is chosen based on the gas supply as illustrated in Fig. 4. This can also depend on how much CO_2 can be stored in the storage site since if CO_2 sequestration is the primary motivation then it follows that the maximum amount of CO_2 needs

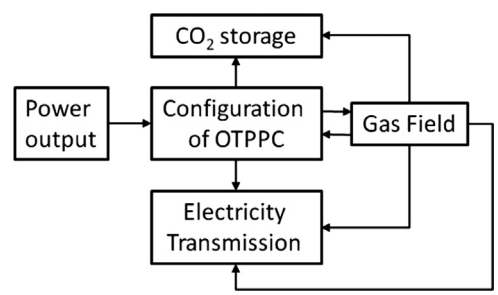

Fig. 2. Design selection process for producing electricity.

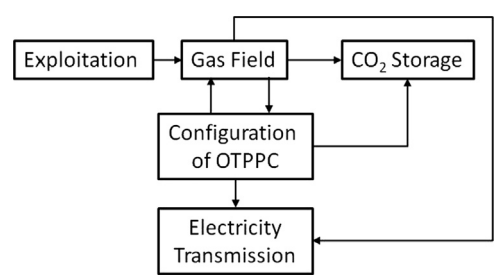

Fig. 3. Design selection process for exploiting gas fields.

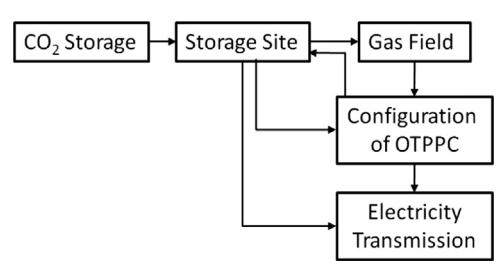

Fig. 4. Design selection process for storing CO_2.

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to be extracted from the fuel gas, which means that the capacity of the carbon capture system becomes a main driver.

By following the design selection process, a variety of design considerations need to be investigated. The location of the offshore thermal power plant is the most important factor since it determines a number of design considerations such as gas field characteristics, existing infrastructure, CO_2 storage capacity, government and marine environment. It is assumed in this section that there will be some storage opportunities close to the extraction site. If this is not true, further considerations include where to place the facility between the chosen extraction site and the chosen storage site. This will depend on the systems involved and the price of extracting gas from a remote plant versus injecting CO_2 to a remote plant. In addition, the characteristics of the offshore thermal power plant needs to be considered, such as the types of floating platform and prime mover, gas processing plant and subsea power cables. Besides, a carbon capture and storage technique needs to be chosen appropriately based on the characteristics of offshore thermal power plant. Furthermore, risks related to an OTPPC have to be assessed and identified. These include environmental, physical and economic risks that will cause harm to life, property and profit.

3. Application of the OTPPC

This section introduces the application of an OTPPC in terms of complexity and cost-effectiveness. A case study was performed in this section by following the design selection process as shown in the previous section. The costs for both the OTPPC and the conventional onshore power plant were calculated and compared under the assumption that CCS is necessary and offshore geological storage of CO_2 is pursued for both offshore and onshore power plants.

3.1. Specifications of the OTPPC in the case study

Australia was chosen as the country to implement this concept due to its large offshore gas resources, suitability for storing CO_2 into offshore geological formations and carbon tax. All of these factors are mentioned by IPPC (2005) as contributors to the likelihood of successful and economically viable implementation of CCS. The presence of carbon tax in particular has been said to play an important part in the implementation of CCS and the absence or removal of the same may lead to CCS projects not being economically viable (Vass 2013). The Australian offshore gas fields are mostly located off the west coast in the Carnarvon, Browse and Bonaparte basins (AER, 2010). The suitability of the Australian offshore sedimentary basins for geological storage of CO_2 has been extensively mapped by the Geodisc project (Bradshaw et al., 2002). As can be seen in Fig. 5, the gas fields are quite close to the perspective storage sites, which is suitable to implement an OTPPC.

The Torosa gas field in Browse basin is chosen as the final location due to its suitability. It is 50% owned and fully operated by Woodside that currently has plans to develop the field together with the Brecknock and Calliance fields in the Browse LNG project. The location is 285 km from Augustus Island that is also the length of the subsea power cables required. In case a landing at Augustus Island is not applicable, an alternative landing at James Price Point is also investigated which is 405 km from the location of the OTPPC. Both alternatives will be considered in the cost analysis. The details of the chosen location are demonstrated in Fig. 6.

The FPSO type of floating platform was chosen as the supporting platform for the OTPPC due to its large storage capacity, large deck area and workability in deep water depth. The main dimensions of the FPSO were chosen as 150 m in length, 32 m in width

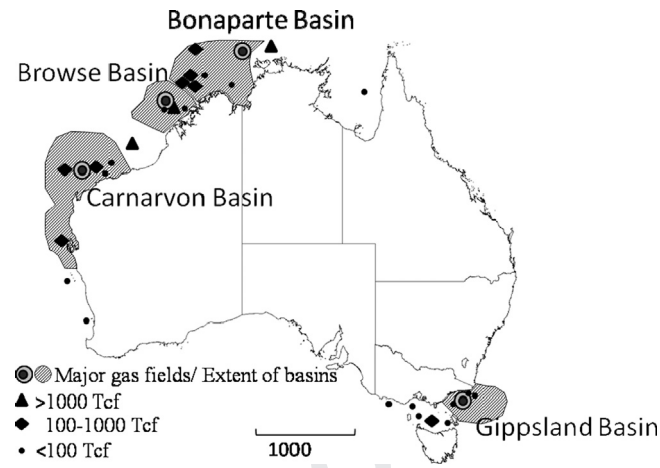

Fig. 5. Location of major offshore gas fields and prospective offshore storage sites in Australia.

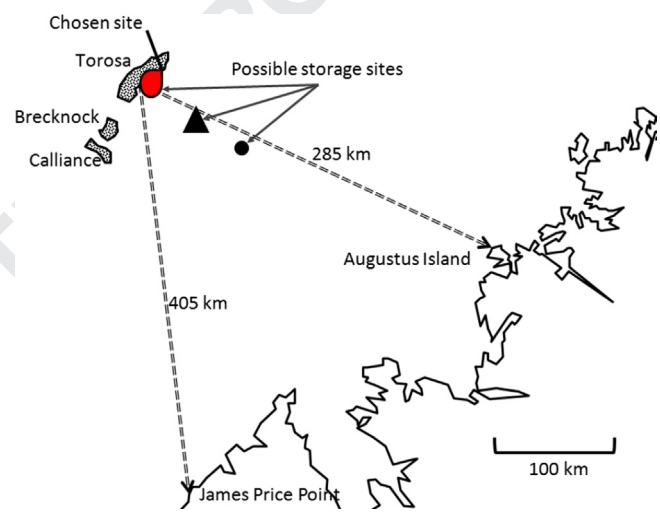

Fig. 6. Details of the chosen location.

and 25 m in depth, in order to provide enough deck area to support power generation equipment, gas processing equipment, and carbon capture system and electricity transmission modules. The designed OTPPC adopts Combined Cycle Gas Turbines (CCGT) as the prime mover and a post-combustion carbon capture system.

The main equipment of the OTPPC are based on the SEVAN GTW concept (Hetland et al., 2009). The design has four power-generation blocks with each block consisting of two Siemens SGT-800 gas turbines, two heat recovery steam generators (HRSG) and one Siemens SST-700 steam turbine as shown in Fig. 7.

Table 1 shows the main equipment and corresponding volumes and energy penalties. In this table, smaller equipment such as piping and smaller processing equipment have been left out. It is assumed that this can be fitted around the larger equipment as to not occupy a significantly larger space by utilizing dead space. Furthermore, the systems needed and the volume for these would be specific to every implementation of this concept and will not be addressed here. The impact of neglecting these in the volume estimate will depend on the specific scenario and again, the final design of the full system will be a tradeoff between size, efficiency and capacity.

Volumes for the turbines are estimated from drawings of Siemens turbines. The volume of the HRSGs is hard to estimate since it will depend on the way they can be installed in connection with the gas turbines inside the hull. An estimate is given based on drawings by Hetland et al. (2008) which have been used as they

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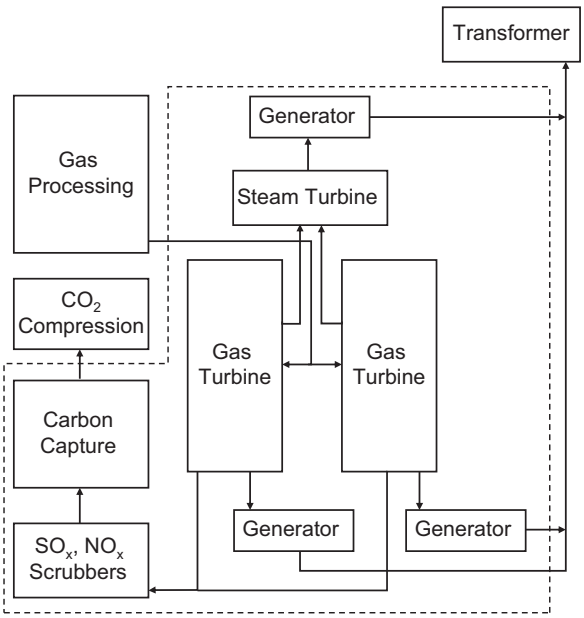

Fig. 7. Arrangement of one power generation block.

Table 1
Main equipment and corresponding volume and energy penalty.

Equipment	Approx. volume	Energy penalty
8 Gas turbines (Siemens)	16,000 m^3	2.4%
4 Steam turbines	4000 m^3	
8 Heat recovery steam generators	8000 m^3	
Gas processing	15,000 m^3	3.25%
Carbon capture and compression	10,000 m^3	10%
Electricity transmission	26,000 m^3	5%
Total	79,000 m^3	20.7%
Total capacity		540 MW
Net capacity		430 MW

refer to an offshore power generation concept. It should be noted that this is a low estimate since drawings by Siemens (2010) show HRSGs in onshore plants at more than twice the size of the gas turbine itself. One reason for this may be that there is less incentive for onshore plants to minimize the space taken up by the HRSGs whereas this is critical for offshore systems. It is likely that the actual design of the HRSGs will be a tradeoff between size and efficiency depending on what is vital for the system to work. Volumes for the CCS systems are given by figures and drawings by Hetland et al. (2009) and volumes for electricity transmission and gas processing are estimated from drawings of similar capacity plants.

Each gas turbine is capable of generating 47 MW with an efficiency of 37.5% (Siemens, 2009) and when combined with a steam turbine, each block will generate 135 MW with an efficiency of 54.4%. The combined generated power of the four power generation blocks is 540 MW.

Based on a Capacity Factor of 0.5, the required fuel consumption is approximately 425 million m^3 of natural gas per year, which is around 52,083 m^3/h based on 340 operational days per year. The energy penalty associated with the turbines includes the auxiliary systems as well as the power required to scrub the nitrous oxides and sulfur dioxides, which is assumed to be 2.4%. The power for the gas processing is supplied by the main gas turbines. Based on the assumption that 0.28 kWh are need to produce 1 m^3 of gas (CEPA, 2009) and the heat rate is 6,445 Btu/kWh, an energy penalty of 3.25% is needed to maintain a gas flow rate to satisfy the required fuel consumption. The CO_2 from power generation is captured by using an aqueous solution of mono ethanol amine (30% MEA) with a capture rate of 90% (Hetland et al., 2009). Four absorber units are used to capture the CO_2 and one common desorber unit is used to separate the captured CO_2 from solvent. There are varying figures for the energy penalty of a carbon capture unit. According to IPCC (2005), the increase in fuel consumption is between 11% and 22% whereas according to ACIL Tasman (2008) the increase in the percentage of power used by the auxiliary systems is between 2.4% and 4.5%. For the purpose of this case study, an energy penalty of 10% is assumed for the carbon capture system. The generated power is transmitted to shore via High Voltage Direct Current (HVDC) cables. In order to convert the voltage from AC to DC, a rectifier is used in combination with a transformer. The energy penalty of the integrated transformer module is assumed to be 5%. In total, the energy penalty of all the equipment is 20.7% as shown in Table 1, which results in a net power output of 430 MW. The general layout of the OTPPC, based on the volume estimates in Table 1, is shown in Fig. 8.

3.2. Methodology for cost analysis

3.2.1. Levelized cost of energy (LCOE)

The purpose of the cost analysis is to evaluate the cost-effectiveness of the OTPPC by comparing the energy costs of the OTPPC and conventional CCS technology for the onshore power plant. One way in which the energy costs can be calculated is the Levelised Cost of Energy (LCOE). This is the price at which electricity must be generated from a specific source to break even.

$$LCOE = \frac{total\ life\ time\ expenses}{total\ expected\ output} \tag{1}$$

The total lifetime expenses include the capital costs, fuel costs and the annual fixed and variable operating and maintenance costs. The total expected output is based on the power output combined with the capacity factor. A discount factor is applied to give the annual costs that are then summed over the lifetime of the plant. The discount factor can be based on just interest rates or can include measures of risk and tax as well.

$$LCOE = \frac{\sum_{t=1}^{n}(I_t + M_t + /(1+r)^t)}{\sum_{t=1}^{n}(E_t/(1+r)^t)} \tag{2}$$

where:

LCOE = Average lifetime levelised electricity generation cost
I_t = Investment expenditures in the year t
M_t = Operations and maintenance expenditures in the year t
F_t = Fuel expenditures in the year t
E_t = Electricity generation in the year t
r = Discount rate
n = Life of the system

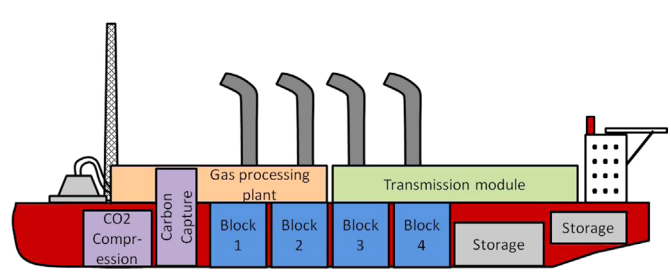

Fig. 8. General layout of the designed OTPPC.

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3.2.2. Transport costs of GTW concept versus conventional approaches

The OTPPC involves transmitting electricity by HVDC cables whereas conventional CCS technology for the onshore power plant involves transporting natural gas and CO_2. To get an idea of the range of applicability of GTW for a gas fired plant with CCS, a cost analysis for transportation costs for both the OTPPC and the onshore power plant was carried out. The costs of transmitting electricity from an OTPPC to shore via HVDC cables were compared to that of transporting natural gas from an offshore field to an onshore power plant and returning the generated CO_2 to the offshore location for storage.

Several assumptions were made before carrying out the analysis. The emissions from a typical gas fired power plant were assumed as 356 g CO_2/kWh (UK SDC, 2006). The distance for transporting natural gas is assumed to be the same as that for transporting CO_2 and the onshore power plant is assumed to be located close to the coast since offshore geological storage of CO_2 is pursued here. In addition, a 570 MW Siemens SCC5-8000H CCGT power plant (Siemens, 2011) was used as a reference fuel consumption of 5700 Btu/kWh. Based on the above assumptions, the total required transportation capacities for both CO_2 and natural gas could be found. Furthermore, the cost of transporting one Btu of natural gas by offshore pipelines and LNG tankers has been stated by Cornot-Gandolphe et al. (2003) and the cost of transporting one ton of CO_2 was given by IPCC (2005). Combining these two sources gives an estimate of the yearly transportation costs per MW for an onshore power plant depending on the distance to the gas field.

An example of costs for subsea HVDC cables was given by Thomas (2009). Windén et al. (2011) investigated the costs of the HVDC cables based on the existing long-range HVDC cables. The costs of HVDC cables were estimated in the range of 2000–4000 USD/MWkm (Windén et al., 2011), initially an average value of 3000 USD/MWkm was chosen. The results are shown for a 500 MW power plant in Fig. 9 for 25 years of operation. The maintenance costs were omitted here. It can be seen that GTW concept is more attractive when the distance is below 1300 km. The total cost benefit of GTW concept compared to conventional transportation methods (least costly option) is shown in Fig. 10. Here, several values are given for the operational lifespan. Since cables will have a very high initial material cost but rather low operational costs, the benefit of GTW increases with the lifespan of the plant. It must be noted that the results for distances less than 100 km should not be seen as reliable since the estimates are mostly based on longer distances. Since the costs of HVDC cables were estimated in a small range, Fig. 10 is recreated for 4000 and 2000 USD/MWkm as shown in Figs. 11 and 12 respectively. In Figs. 10–12, a positive cost reduction indicates a benefit of GTW over conventional techniques and a negative reduction means that GTW is more expensive.

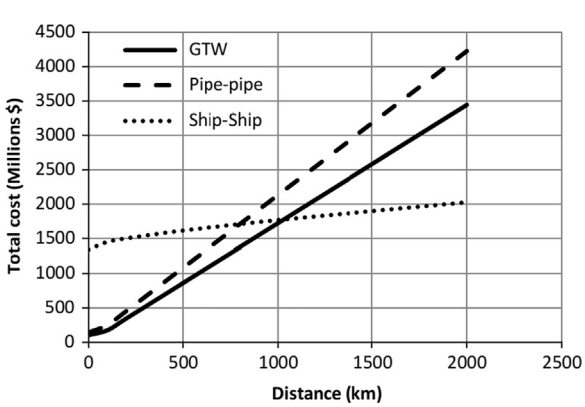

Fig. 9. Comparison of total transportation cost.

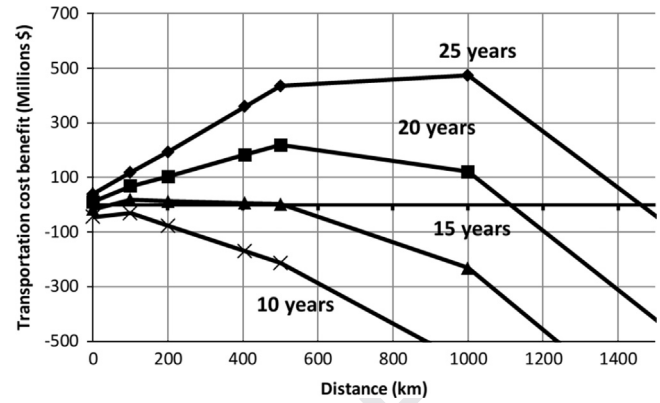

Fig. 10. Cost reduction of GTW compared to conventional transportation at the average estimation of cable cost.

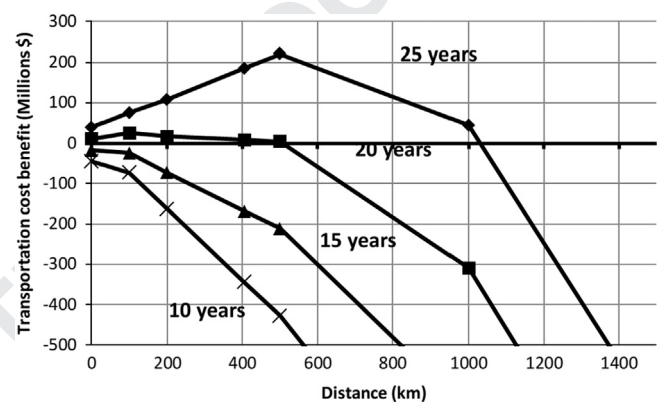

Fig. 11. Cost reduction of GTW compared to conventional transportation at high estimation of cable cost.

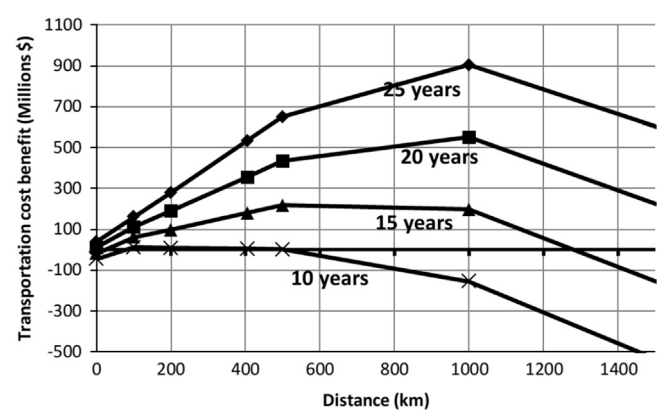

Fig. 12. Cost reduction of GTW compared to conventional transportation at low estimation of cable cost.

3.3. Cost analysis

In the cost analysis, four scenarios were considered as shown in Table 2. The lifetime for both the OTPPC and the onshore power plant was assumed to be 25 years. The costs can be generally divided into two parts: capital costs which is the initial investment and annual costs including operating and maintenance costs, fuel costs and transportation costs. Finally, the LCOE for both the OTPPC and conventional CCS technology for the onshore power plant was calculated. Many figures were given in Australian dollars

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Table 2
Scenarios used in the cost analysis.

No.	Distance (km)	Costs of HVDC cables (USD/MWkm)
One	285	2000 (Low)
Two	285	4000 (High)
Three	405	2000 (Low)
Four	405	4000 (High)

Table 3
Exchange rates used in the cost analysis.

AU$	USD	SGD
1	1.042	1.256

Q2 (AU$) as well as Singapore dollars (SGD). These were converted to US dollars (USD.) The exchange rates used in the cost analysis are shown in Table 3.

3.3.1. Capital cost

Capital investment for a new power station includes a variety of costs such as Engineering, Procurement and Construction (EPC), planning and approval, and professional services, etc. The estimated capital costs of the onshore power plant were based on the report commissioned by the Energy Market Authority of Singapore (PA, 2010). According to PA (2010), the cost of building a 400 MW Combined Cycle Gas Turbine (CCGT) plant is 589 Million USD, which is 1,472.57 USD/kW. Costs for buildings and structures were deducted from the EPC for the OTPPC since these are instead included as hull construction costs. For more details on the breakdown of different parts of the EPC and what parts are included offshore and onshore, see (Windén et al. 2011). The costs for power generation equipment can also be applied for the OTPPC. The onshore power plant has a cost for land and site that do not apply to the OTPPC. In addition, costs for hull construction, risers, moorings, towing and gas processing plant are only applied to the OTPPC. In order to estimate these costs, the report detailing the concept design of a FLNG vessel was used as the reference (Sheffield, 2005). Since the vessel is 300 m in length, 60 m in breadth and 30 m in depth, whereas the dimensions of the designed OTPPC in this case study are 150 m by 32 m by 25 m, it is necessary to scale down the numbers. To do this, an estimate of the proportion of the costs that are material and outfitting is required. This was obtained by making the assumption that the labor costs associated with the build were 63.75% (based on a 85% labor cost for the first vessel, reducing by 25% by the 10th vessel) and that the material and outfitting costs were approximately 50% of the non-labor costs (Cooper et al., 2007). The scaling factor was calculated based on the ratio of the surface areas of the vessel hull envelopes. This factor was calculated to be 0.325 and the corresponding reduction hull cost was 25 million US dollars as shown below in Table 4.

Table 4 also shows a reduction in the cost for gas reception/cleaning cost. This was calculated using a factor of 0.27 that was determined by dividing the production capacity of the FLNG vessel by the fuel requirements of the power plant. Whilst the relationship between gas processing plant size and capacity is almost certainly not linear, this was felt to be an adequate assumption for this case study. Moreover, the estimated costs for the hull are likely to be higher than necessary as they are based on LNG requirements. Table 5 shows the total capital costs in US dollars for both the onshore power plant and the OTPPC. The capital costs of the OTPPC are quite higher than that of the onshore power plant.

Table 4
Additional capital costs for the OTPPC.

Type of cost	FLNG (USD)	Power plant (USD)
Hull and accommodation	200,000,000	175,000,000
Mooring	50,000,000	50,000,000
Risers	45,000,000	45,000,000
Towing	40,000,000	40,000,000
Gas reception/cleaning	80,000,000	21,270,000

Table 5
Capital costs of generating power.

CAPEX	Onshore (USD)	OTPPC (USD)
EPC	479,194,960	41,908,198
Connection to grid	26,122,940	26,122,940
Through-life costs	15,869,660	15,869,660
Land & site costs	11,368,220	0
Owner's costs	56,236,740	56,236,740
Hull construction	0	175,629,100
Risers	0	45,160,280
Mooring	0	50,182,720
Towing	0	40,148,260
Gas processing	0	21,350,580
Total	588,792,520	849,771,840
Average (USD/kw)	1471.98	2124.44

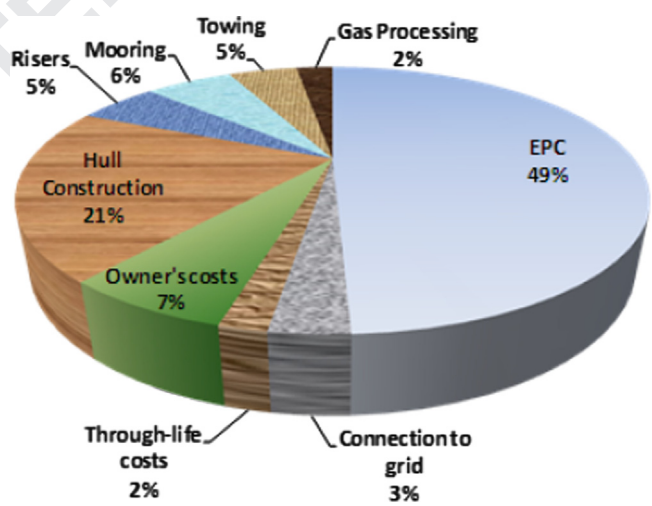

Fig. 13. Distribution of capital costs for the OTPPC.

Figs. 13 and 14 illustrate the distribution of capital costs for the OTPPC and the onshore power plant, respectively. It can be seen that EPC costs are the largest part capital costs for both an OTPPC and an onshore power plant.

3.3.2. Annual costs

The annual costs include annual operating costs, fuel costs, transportation costs and costs for carbon capture and storage

3.3.2.1. Annual operating costs. The annual operating costs (not including fuel) consist of two parts: fixed and variable. The fixed costs include manning, fixed operations and maintenance, and other miscellaneous costs. The fixed annual operating costs were determined from the Energy Market Authority of Singapore (PA, 2010) and are summarized in Table 6. The manning costs will depend on the specific design but workers operating the power plant will be paid considerably more than their onshore equivalents. In Table 6, the manning cost for the power plant is

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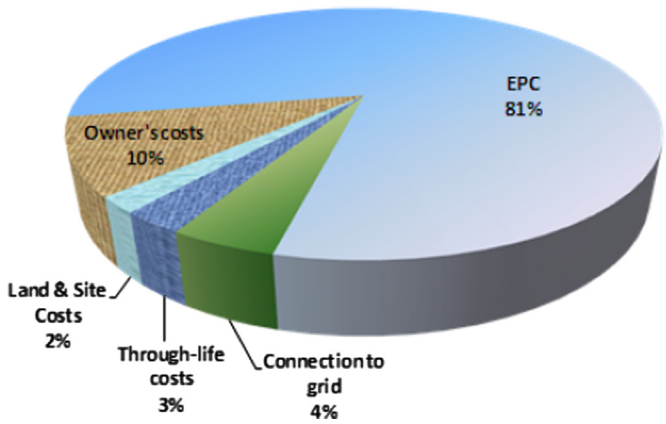

Fig. 14. Distribution of capital costs for onshore power plant.

Table 6
Fixed operating costs of power generation.

Fixed OPEX	Onshore (USD)	OTPPC (USD)
Manning power plant	1,740,140	1,740,140
Manning floater	0	3,313,560
Fixed O&M	7,189,800	25,153,880
Miscellaneous	4,334,720	3,271,880
Total	13,264,660	33,489,880
Average USD/kW	33.18	83.72
% CAPEX	2.34	4.10

set to the same amount offshore and onshore however, this is counteracted with a large buffer in the manning costs for operating the floater itself. This is done since the sharing of tasks between power plant and floater operations is not known.

The annual fixed operating and maintenance for the onshore power plant is 3% of the capital cost of the plant (PA, 2010). However, it is not the case for the offshore power facility. The cost of maintenance will be more expensive offshore. In addition, the costs of corrosion need to be considered as the cost of corrosion for offshore structures is typically higher than that of their onshore equivalents (Ruschau and Al-Anezi, 2000). Since it is difficult to obtain the fixed operating and maintenance costs for the OTPPC, data from the offshore wind industry were used here. Typically, the cost of generating the electricity onshore is 0.49 pence per kWh (PB Power, 2004). This increases to 1.7 pence per kWh offshore that is an increase of 347%. Based on this, the fixed O&M was multiplied by 3.5 as shown in Table 6.

The variable annual costs include the variable O&M, consumables, town water and other fees. The OTPPC would not need to budget for buying town water but would instead have to budget for desalinating fresh water. The cost of consumables is therefore set to the same as the onshore plant. This is likely to be a low but reasonable estimate of the costs of consumables. Other considerations with regards to consumables is that food and other supplies need to be transported by ship to the platform. The variable O&M depends on a number of factors, including the way in which wear and tear builds up between scheduled maintenance and whether the power plant is operating on a base load basis. An allowance is also included for major maintenance of the gas turbines. This is because, rather than being periodic, this maintenance is based on hours of use and the number of starts-ups. As Table 7 shows, the only difference between the onshore and offshore facilities is the cost of the consumables. This is due to the town water cost being excluded for the OTPPC.

Table 7
Variable operating costs.

Variable OPEX	Onshore (USD)	OTPPC (USD)
Gas turbine	118,37,120	11,837,120
Steam turbine	635,620	635,620
Consumables	1,781,820	1,271,240
Fees	1,417,120	1,417,120
Total	15,671,680	15,671,680
Average USD/kW	29.03	29.03

Table 8
Annual cost of gas supplied to turbines.

Cost of gas	Onshore (USD)	Offshore (USD)
Feed gas	99,302,600	0
Raw gas	0	11 462 000
Total	99,302,600	11,462,000
Average USD/kW	183.9	21.2

3.3.2.2. Fuel costs. The fuel costs are based on a combination of the raw gas price, the cost of extracting the gas, processing the gas and then transporting it to the power plant. In this case the raw gas price is assumed to cover the investment in the field (drilling, surveys, etc.) (Sheffield, 2005).

As the capital costs of the gas processing plant were already included in the total capital costs of the OTPPC, the only fuel cost that was applied was the cost of the raw gas (The maintenance costs are also included in the power plant costs). Using the same factor of 0.27 that was calculated to estimate the cost of the gas processing plant, the annual raw gas cost used for the FLNG concept was scaled down.

The cost of the feed gas for the onshore power plant was obtained from a report that included various gas costs in Australia (ACIL Tasman, 2009), which is 4.75 USD/GJ. One of the main objectives of this paper is to show if reducing the transportation costs using GTW can reduce the overall costs of generating electricity. To do this in a more direct way, the transportation costs must be separated from the onshore feed gas costs. This is done by reducing the fuel costs for the onshore plant by 20% to account for transportation as stated by ACIL Tasman (2009). The validity of this assumption can be discussed since it deviates from known values and estimated values were used instead. However, removing the transportation costs from the fuel costs for the onshore power plant does make the comparison and evaluation of the benefits of each concept more straightforward. A range of gas costs were provided by ACIL Tasman (2009), the average value was selected. The costs of both the raw gas and the feed gas (corrected for transportation costs) are shown below in Table 8.

3.3.2.3. Transportation costs. The transportation cost associated with supply of fuel was assumed to be zero in the case of the offshore facility. For the onshore power plant the cost of transporting the gas was calculated using the methodology in Section 3.2 using the prescribed power and heat rate and assuming a life cycle of 25 years. The results are shown below for both the 285 km option and the 405 km option in Table 9. For the costs of HVDC cables, both a lower and an upper figure are given for each option that is estimated from the lower and upper estimates of the cable costs given in Section 3.2.2. Table 9 also shows the cost of transporting the CO_2 from the onshore power plant to the offshore storage site via pipelines. It can be seen that transmitting electricity is cheaper than transporting gas and CO_2

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Table 9
Cost of transporting electricity, gas and CO_2.

Unit: USD/yr	285 km	405 km
HVDC (High)	19,610,440	27,873,500
HVDC (Low)	9,805,220	13,931,540
Gas transport	19,016,500	29,165,580
CO_2 transport	12,493,580	14,921,440

Table 10
Q3 Cost of carbon capture & storage and carbon taxing.

	Carbon capture	CO_2 storage	Carbon tax
CO_2 emitted Mt/year pre CCS	0.99	0.99	0.99
CO_2 emitted Mt/year post CCS	0.11	0.11	0.11
Cost USD/ton CO_2	46.9	5.0	24.0
Total cost (USD)	44,331,890	4,925,765	2,625,840

by pipeline in all scenarios. The figures for the transportation costs of CO_2 were based on the IPCC report on CCS, which uses a benchmark figure of 6 $MtCO_2$ per year for the cost estimates (IPCC, 2005).

3.3.2.4. Costs of carbon capture and storage. Since the cost of transporting CO_2 from the onshore power plant to the offshore storage sites is already included, the costs of CCS only include the costs for carbon capture and storage and not transport. In order to investigate the cost-effectiveness of the OTPPC as an alternative to CO_2 transport, the same costs for carbon capture and storage were assumed for both the OTPPC and the onshore power plant. In reality, the costs will differ between offshore and onshore operations. The difference in costs between the two concepts will vary however, depending on which systems are used and whether they are available offshore and onshore (e.g. water, transport solutions for chemicals used in the capture process and waste disposal.) This will depend on the specific scenario and, for example, may well be easier to achieve offshore with a single supply ship which would need to serve the plant in any case than with several different transport contractors at a remote location onshore.

According to the IPCC, the range of costs for carbon capture is between 15 and 75 USD per ton of CO_2 captured (IPCC, 2005). The range for CO_2 storage is between 0.6 and 8.3 USD per ton of CO_2 stored. Values of 45 USD per ton of CO_2 and 4.6 USD per ton of CO_2 were used as these are the average values. Although there is an exchange rate of 0.96 USD to the Australian dollar, these values were not altered. Furthermore, since only 90% of the CO_2 emissions were captured, a carbon tax was calculated for the remaining 10% of the CO_2 emissions, which is 24 USD per ton of CO_2 as mandated by the Australian government. Table 10 summarizes the costs for carbon capture & storage and carbon tax. The amount of CO_2 emitted is based on an emission rate of 0.19 $kgCO_2$/MWh with a capture rate of 90%. This gives total emissions as 0.11 $MtCO_2$/year after CCS has been applied which is the value used to calculate the total carbon tax per year in Table 10.

Finally, the comparisons of annual costs between the OTPPC and the onshore power plant for 285 km and 405 km are shown in Figs. 15 and 16, respectively. It can be seen that the annual costs of the OTPPC for both four scenarios are less than the onshore power plant. In addition, only the transportation costs vary between the four scenarios and the concept of an OTPPC can save more money for longer distance for annual costs. It must be noted that this conclusion is sensitive to the fact that the fuel costs are taken to be so much higher in the onshore case. This is due to the assumption

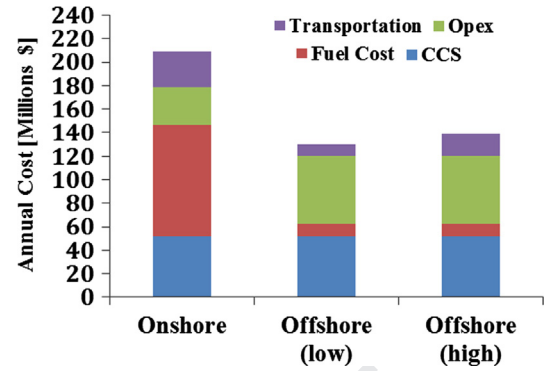

Fig. 15. Comparison of annual costs for 285 km.

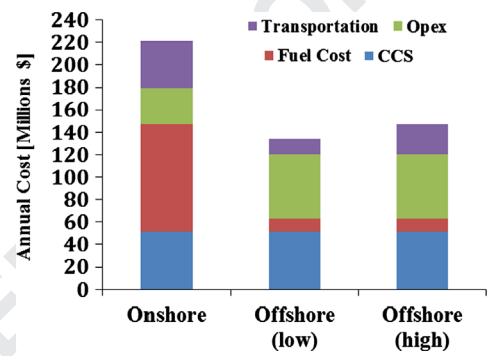

Fig. 16. Comparison of annual costs for 405 km.

made earlier that the feed gas costs for the onshore plant are based on the commercial price of gas in Australia and that the deduction of 20% from this is an accurate way of representing transportation. However, it must be remembered that the feed gas costs for the onshore plant will include the cost of the processing plant for the gas (which is included in the CAPEX for the OTPPC) and third party profit margins for the company supplying the gas. Furthermore, for the onshore costs in Figs. 15 and 16 to break even with the high estimate offshore costs, the price of gas would have to be reduced by 60% from the values assumed here. This is deemed as sufficient evidence that there will be a reduction in costs regardless of the assumption made for gas prices.

3.3.3. LCOE for onshore power and the OTPPC

Before the LCOE can be calculated, the discount rate needs to be chosen. ACIL Tasman provided information on a discount rate that could be applied to obtain the net present value of the cash flow (NPV), which is the Weighted Average Cost of Capital (WACC) that allows for the inclusion of factors such as tax and risk (ACIL Tasman 2008). By using Eq. (2), the LCOE of both the OTPPC and the onshore power plant can be calculated for the all four scenarios as given in Table 2.

It can be seen in Fig. 17 that the LCOE of the OTPPC is lower than that of the onshore power plant for all scenarios. The OTPPC can save 10 USD/MWh for scenario one, 7 USD/MWh for scenario two, 13 USD/MWh for scenario three and 8 USD/MWh for scenarios four. This implies that the OTPPC can generate more economical benefits for longer offshore distance since it can save more money by transmitting electricity via HVDC cables, instead of transporting natural gas and CO_2 by pipelines or ships.

However, according to the IPCC, at around 1000 km ships become more economical than pipelines for transporting CO_2 and the curve representing the cost of ships levels off with increasing distance. This suggests that at distances greater than

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1000 km, transporting CO_2 by ship will be more economical. This can be seen in Fig. 9 where the point at which ships become cheaper than cables is at a distance of around 1300 km. This is likely to be further exasperated since the cost of transporting gas by ship versus the cost of a gas pipeline follows the same trend.

3.3.4. Sensitivity analysis

Since the OTPPC is a concept that has not yet been implemented, many of the calculations leading to these costs estimates have been based on assumptions, some cruder than others. In order to assess the effect of changing some of these assumptions on the LCOE, a sensitivity analysis was carried out using the 285 Low Offshore scenarios as a basis where each of the key factors was adjusted one at a time whilst keeping the other factors constant. Each factor was adjusted by −20%, −10%, 0%, 10% and 20%. The results are plotted in Fig. 18 where, with the exception of "Power Generated" and "Capital Costs", all of the factors resulted in a change in LCOE between plus five and minus five USD. This is less than the difference in cost between the LCOE for the onshore power station and the OTPPC which suggests that the majority of the costs could increase by 20% and the OTPPC would still be the more cost-effective solution. Furthermore, a 20% increase in the cost of the transmission of the electricity resulted in an increase of just 0.77 USD suggesting that this is not a critical component of the overall cost of the system.

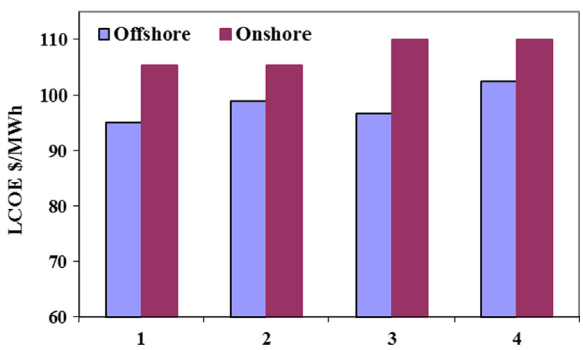

Fig. 17. Comparison of LCOE between the OTPPC and onshore power plant.

However, varying only one factor at a time does not take into account the interaction between the different factors as this method does not allow for the simultaneous variation of input variables. For example, increasing the "Power Generated" will also increase the "Capital Costs". Whilst it is difficult to quantify how much of an increase this will be as the link between power generated and capital costs is almost certainly not linear, the effect of increasing both of these by the same percentage can be seen in Fig. 19. Previously, it was seen that increasing the amount of power being generated by 20% produced a significant decrease in the LCOE of 11.5 USD. When this increase was combined with an increase in the capital expenditure of 20%, this decrease was reduced to 5.5 USD. The effect of increasing the operating costs should also be considered in conjunction with increasing the capital costs and amount of power being generated however this is beyond the scope of the sensitivity analysis as it requires more computing power than was available at the time of writing. It should be recognized that if the amount of power being generated was increased for the onshore power station, again the capital costs would also increase and this should not have a significant effect on the difference in LCOE between the onshore power concept and the OTPPC.

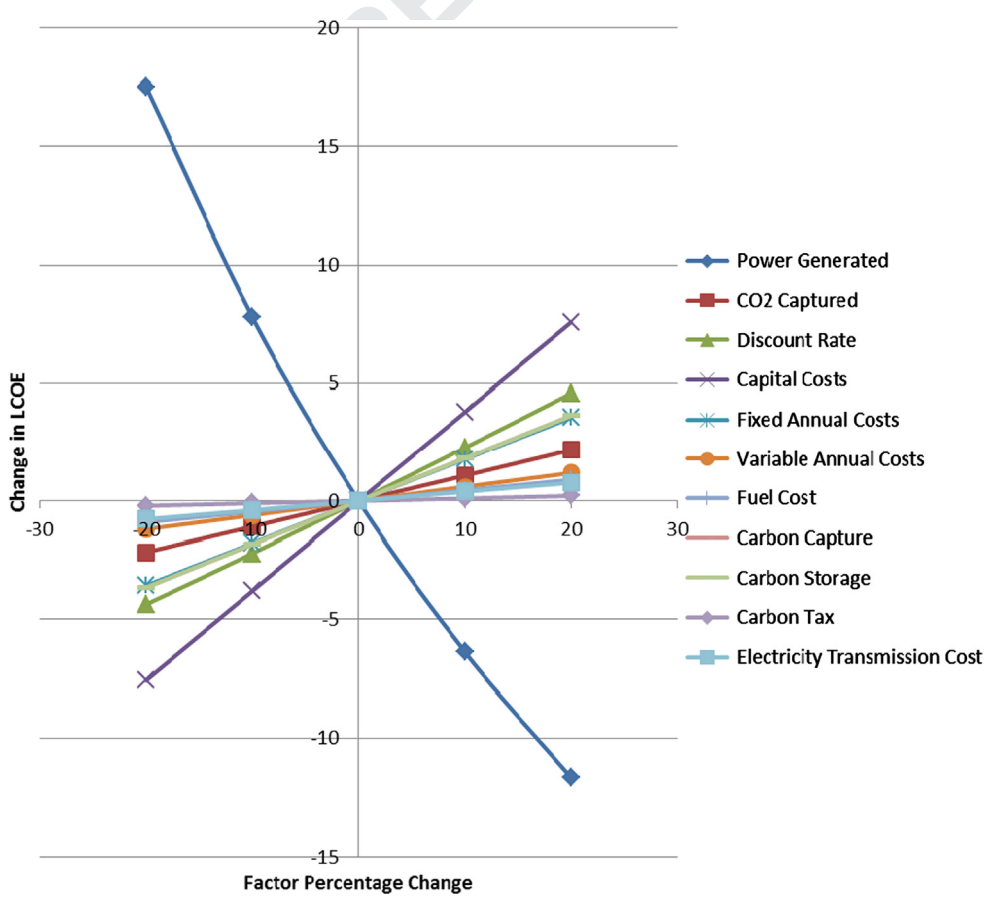

Fig. 18. Changes in LCOE resulting from percentage changes in factors.

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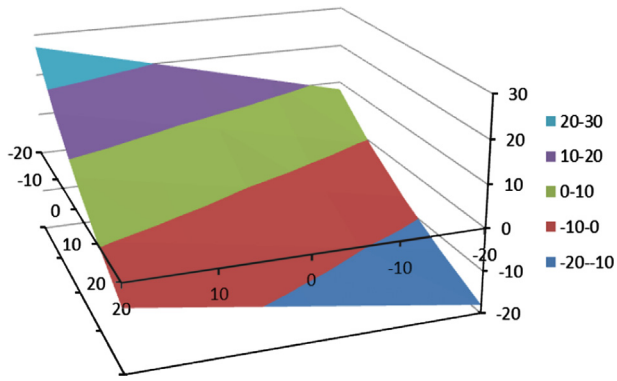

Fig. 19. Effect on LCOE of varying Power Generated and Capital Costs.

Table 11
Effect of increasing capital costs on LCOE.

Scenario	LCOE USD			
	Onshore	0%	10%	20%
285 low	105	95	99	103
285 high	105	99	103	107
405 low	110	97	101	104
405 high	110	102	106	110

Therefore, the key factor is the capital costs and the effect on LCOE of increasing the capital costs was investigated for all four offshore scenarios. As Table 11 shows, for all four scenarios the capital costs can be increased by 10% for the OTPPC and the LCOE for each scenario will be less than the LCOE for the onshore scenarios.

However, when a 20% increase is applied scenarios two and four are no longer cost-effective as these are the two scenarios where the high cost of electricity transmission was applied. It should, however, be noted that the estimate for the capital costs was quite conservative as they were assumed to be 87% higher than for the onshore concept.

4. Concluding remarks

This paper mainly introduced the concept of offshore thermal power plant with CCS (OTPPC) and established the general design selection process and design considerations. A case study based in Western Australia was carried out by following the design selection process in order to demonstrate the application of the OTPPC. In the case study, some aspects of the design had to be based on assumed values of cost and size since no data was available. In such cases, buffers have been added so the final values are reliable as rough estimates of what a real implementation would include. Nevertheless, the results are sensitive to what gas price can be achieved by the OTPPC compared to an onshore facility buying gas from the grid. It is also sensitive to Capital expenses associated with the construction of the hull and the installation of onboard systems. Furthermore, the case study does not consider some factors such as what happens if the gas field and storage sites are far apart, changes in local taxation situation and global fuel/material costs etc. Nevertheless, the case study shows encouraging results for the applicability of the concept.

In addition, further considerations which have not been mentioned or discussed but may have a large impact on the profitability of the concept are mentioned here. If the designed offshore thermal power plant is nearby other existing FPSOs, gas processing plants may not be integrated onto the platform since the processed gas can be supplied by an adjacent FPSO, which reduces the overall initial construction costs and complexity of the whole system. The OTPPC may also be used as an offshore terminal to provide energy for injecting CO_2 that is captured from other sources. This service could be profitable and thereby reduce the net annual costs.

The concept of an OTPPC is found to be more cost-effective than conventional onshore power plants based on the calculated LCOE from the cost analysis. The cost analysis did not consider storage of CO_2 with Enhanced Oil/Gas Recovery, which may generate extra economical benefits.

In summary, it is recommended that more research is carried out to bring this concept into reality.

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