Explore IJET International Journal of Engineering & Technology
CENTRE OF PROFESSIONAL RESEARCH PUBLICATIONS
ISSN 2049-3444
International Journal of Engineering and Technology Volume 5 No. 4,April, 2015

Techno-Economic Assessment of Large-Scale Aero-Derivative Industrial Gas Turbines Combined-Heat-And-Power

Barinyima Nkoi, Pericles Pilidis and Theoklis Nikolaidis
Department of Power and Propulsion, Energy and Power Division, School of Engineering, Cranfield University, Cranfield, Bedfordshire, MK43 0AL, United Kingdom

ABSTRACT

The aim of this paper is to assess and compare techno-economic viability of large-scale simple cycle (SC) and advanced cycles aero-derivative industrial gas turbines combined-heat-and-power (ADIGT-CHP) generation in the petrochemical industry in terms of net present value (NPV), internal rate of return (IRR), and simple-payback-period (SPBP). To achieve this, a techno-economic assessment method was applied using a case study of a large-scale Refinery CHP. Parameters of technical performance of the ADIGT-CHP such as fuel flow, power output, emissions, heat recovery, and steam flow, in conjunction with various cost elements were made inputs in an economic module utilising a 20 years life-cycle. Economic principles were applied to predict the NPV, IRR, and SPBP of the three ADIGT-CHP cycles over conventional case (Grid electricity plus on-site boiler). The advanced cycles considered are intercooled (IC) cycle and intercooled-recuperated (ICR) cycle. The result shows that all three ADIGT–CHP cycles exhibit positive NPV, good payback-period and internal-rate-of-return, which is an indication that all are viable, though the SC ADIGT–CHP was found to be more profitable than the others. The percentage savings in operational cost of SC, IC, and ICR cycle ADIGT–CHP over the conventional case were obtained as 21.1%, 20.5%, and 19.7% respectively. More so, SC ADIGT–CHP was found to exhibit higher CHP efficiency and steam flow than IC and ICR cycles. This sort of assessment would aid decision makers to make good choice of large-scale ADIGT-CHP cycle option in the petrochemical industry.

Keywords: *Aero-Derivative-Gas-Turbines, Combined-Heat-And-Power, Techno-Economic Assessment, Intercooled-Recuperated-Cycle, Net-Present-Value, Simple-Payback-Period*

NOMENCLATURE

Abbreviation	Description
ADIGT	Aero-derivative industrial gas turbines
CHP	Combined-heat-and-power
CO	Carbon mono-oxide
CO_2	Carbon(iv) oxide
Conv	Conventional case
DECC	Department of Energy and climate change
DLE	Dry Low Emission
DP	Design point
EI	Emission index
GT	Gas turbine
H_2O	Water vapour
HEPHAESTUS	Gas turbine engine emissions prediction code
HRSG	Heat recovery steam generator
ICR	Intercooled-recuperated
IC	Intercooled
IRR	Internal rate of return
ISA SLS	International standard atmosphere sea level static
LRCP	Large-scale Refinery and Chemical plant
N/A	Not available
NO_X	Oxides of Nitrogen
NPV	Net present value
OD	Off design point
O&M	Operation and maintenance
Ref	Reference
RoI	Return on investment
SC	Simple cycle (base engine)
SPBP	Simple-payback-period
TERA	Techno-economic and environmental risk analysis
TURBOMATCH	Gas turbine engine performance code

Symbol	Description	Unit
C_{Lr}	Equal annual loan repayment	£
C	Investment capital cost	£
C_{Bh}	Cost of boiler heat	£
C_e	Avoided cost of electricity by CHP	£
C_{emtx}	Emission tax	£
C_f	Cost of fuel for CHP	£
C_g	Investment grant	£
C_{Ge}	Cost of Grid electricity	£
C_h	Avoided cost of heat by CHP	£
$C_{o/m}$	Cost of operation and maintenance of plant minus fuel cost	£
d	Constant market discount rate	%
d_t	Variable market discount rate in time period t	%
F_0	Present worth of investment capital cost	£
F_t	Annual net cash flow for year t	£
f_t	Annual operation savings	£
FF	Fuel flow in combustor	kg/s
L	Loan	£
N	Life of CHP plant	years
R_e	Revenue from excess electricity sold from CHP	£
R_h	Revenue from excess heat sold from CHP	£
r	Interest rate on loan	%
r_T	Tax rate on income due to CHP	%
SV_N	Salvage value of the investment at the end of the economic life N	£
T_t	Taxable income in year t, due to CHP	£
→	Implies	
>	Greater than	
<	Less than	
=	Equal to	

1. INTRODUCTION

Techno-economic and environmental risk analysis (TERA) framework is a multi-disciplinary decision-making tool used in preliminary design analysis to assess the viability of power plants. This kind of assessment is herein extended to large-scale aero-derivative industrial gas turbines combined-heat-and-power (ADIGT-CHP) in the petrochemical industry, which are employed to generate both power and process steam from single fuel source. How would one make the choice of large-scale ADIGT-CHP cycle option in the petrochemical industry that would produce good return on investment (RoI), considering technical and economic benefits? This is a question that an asset manager or product developer would ask when faced with the challenge of making choice of large-scale ADIGT-CHP cycle option.

Explanation has been rendered of the emergence and application of TERA framework as having been conceived as a result of research work carried out in areas of multi-disciplinary optimization and management, and after-come on the environment, of both the design and operation, of power plants. The use of TERA was demonstrated in jet engine modeling and management to optimize the thrust, weight and geometry scaling [1]. Furthermore, a research was carried out on technical risk analysis of gas turbines to select gas turbine plant equipment for liquefaction of natural gas in which the risk assessment aspect of TERA was focused upon with respect to machine downtime identified as an empirical measure of technical risk [2].

The aim of this paper is to assess and compare techno-economic viability of large-scale simple (base engine), intercooled, and intercooled-recuperated cycles ADIGT-CHP in the petrochemical industry in terms of net present value (NPV), internal rate of return (IRR), and simple payback period (SPBP), over conventional case. The conventional case is made of grid electricity plus on-site boiler. This is done to provide a framework that would aid sound choice of large-scale ADIGT-CHP cycle option in the petrochemical industry that would produce good return on investment (RoI).

2. THEORY AND METHOD

2.1. Techno-economic and environmental risk analysis (TERA) modules

TERA is a modular framework that integrates the following modules: engine performance module, emission and environment module, economic and risk modules [1].

2.1.1. Engine performance module

Engine technical performance module involves the application of TURBOMATCH code in the preliminary design point (DP) and off-design (OD) performance analysis of the various aero-derivative gas turbine engine cycles. Also, it was implemented in the ADIGT-CHP DP and OD performance evaluation. The outputs of these technical performances are made inputs to the emissions, and economic modules. Detail description of TURBOMATCH code was presented by the authors in ref [3] as gas turbine engine performance prediction code developed at Cranfield University, UK and validated.

The cycle thermal efficiency, fuel flow, power, etc, of the engines, are essential performance parameters that are obtained as desired results of the simulation. Heat recovery steam generators (HRSG) of the ADIGT-CHP are also modelled in TURBOMATCH to determine steam flows.

2.1.2. Engine emissions module

This module calculates the total amount of emissions produced as products of combustion that occur in the engine over the range of design point and off-design performance. These combustion products include oxides of nitrogen (NO_x), carbon monoxide (CO), carbon (iv) oxide (CO_2), and water vapour (H_2O), which constitute bulk of pollutants to the environment.

A code called HEPHAESTUS – adapted for industrial gas turbines has been developed at Cranfield University, UK and validated to perform the engine emissions and environment module [4] [5]. The scheme simulates a single annular combustor, and introduces a technology factor so that it can calibrate the amounts of engine emissions to standards that apply to different technology combustors. Emission indices of the gaseous products at different power settings and ambient temperatures, and the total quantity of each emission per day are calculated.

Emission index of a gaseous product of combustion is defined as the ratio of the amount of product in grams to the amount of fuel consumed in kilograms. For instance, emission index of NO_x denoted by $EINO_x$ is given by Equation 2.1-1

$$EINO_X = \frac{\text{g of } NO_X}{\text{kg of fuel}} \qquad \text{Equation 2.1-1}$$

Similarly EICO, $EICO_2$, and EIH_2O are calculated. These quantities are computed and translated into annual total emissions based on the amount of fuel consumed [6].

2.1.3. Economic module

A method of this module was developed and applied in this work. This module takes inputs from the outputs of engine performance, and emissions modules, and applies economic principles with appropriate cost elements. Economic return drives investment in any new equipment, ADIGT-CHP not an exception. TERA tool is useful in predicting the future and reducing the risk of investing in new equipment. For a CHP generation scheme to be adjudged worthwhile it has to be profitable than the base load case assessment. The base load case is defined as the use of boiler to satisfy required steam demand of a site while the site power demand is met by purchasing grid electricity [7].

The Department of Energy and Climate Change (DECC), UK outlines some parameters used in the economic appraisal of CHP schemes as: simple payback period (SPBP), net present value (NPV), and internal rate of return (IRR) [8]. These capabilities are captured as contents of the economic method developed in this work. A discounting technique based on NPV method is presented to allow an initial assessment of the likelihood of various engine cycles being attractive in a specific situation of CHP application, over the conventional case**.**

2.1.3.1. Net present value

The difference between the present worth of all expenses and the present worth of all revenues during the life cycle of a CHP is termed net present value (NPV) [9]. It includes savings, and is the present worth of the total net cash flow of the CHP investment. It is calculated using Equation 2.1-2 or Equation 2.1-3

$$NPV = -F_0 + \sum_{t=0}^{N} \frac{F_t}{(1+d_t)^t} \qquad \text{Equation 2.1-2}$$

Or

$$NPV = -F_0 + \sum_{t=0}^{N} \frac{F_t}{(1+d)^t} \qquad \text{Equation 2.1-3}$$

Where

d_t = the market interest rate or market discount rate during the period t, and when it is considered constant $d_t = d$.

N = the period in time for which the CHP is assumed to operate (the life of the CHP plant). Time period in years is usually used, though day, month, six-month, could be used.

F_t = net cash flow in year t (revenue + savings – expenses). The term “net cash flow” here could be negative, which indicates loss in year t.

F_0 = the present worth of the investment (at time = 0), and it is negative. It is equal to the capital cost.

There are three possible solutions:

NPV > 0; → return on investment (RoI) > d; → economically viable investment, given condition (N, d)

NPV = 0; → return on investment (RoI) = d; → economically viable investment, given condition (N, d)

NPV < 0; → return on investment (RoI) < d; → investment is not economically viable under the given specification (N, d) [9].

2.1.3.2. Algorithm for computing the net present value of CHP

I. **Iinitial cash flow (F_0, t = 0):** This is given by Equation 2.1-4

$$\mathbf{F_0} = C_g + L + C$$

Where, C = investment cash at hand, C_g = investment grant, L = loan

F_0 may comprise of only C_g or L or C, and it is the capital cost of CHP installation.

II. **Net Cash Flow for N Years (F_t, t = 1 to N)**

Annual operation savings f_t: This is given by Equation 2.1-5

$$f_t = (C_e + R_e + C_h + R_h - C_{Ge} - C_{Bh} - C_{Lr} - C_f - C_{o/m} - C_{emtx}) \qquad \text{Equation 2.1-5}$$

Where, C_e = avoided cost of electricity = cost of electricity that would be purchased from the grid, if not cogenerated.
R_e = revenue from selling excess electricity, if any.
C_h = avoided cost of heat, i.e. cost of heat that, if not cogenerated, would be produced by boiler(s).
R_h = revenue from selling excess steam, if any.
C_{Ge} = cost of electricity purchased from the grid during outages of on-site generation.
C_{Lr} = Equal annual loan repayment
C_{Bh} = cost of heat produced by boiler(s) during outages of CHP.
C_f = cost of fuel for the cogeneration plant.
$C_{o/m}$ = operation and maintenance cost (except fuel) of the cogeneration plant.
C_{emtx} = emission tax = emission tariff x total gaseous emissions
Subscript t = the year (t = 1, 2,…, N) during which project lasted.

Assumptions:

The operation of the plant starts from the beginning of the first year, t = 1.

Construction period is assumed as year t = 0 which takes capital cost F_0

A life-cycle period of 20 years is chosen, (that is N = 20).

Annual net cash flow (F_t): This is given by Equation 2.1-6

$F_t = f_t — r_T\, T_t + SV_N$, for (t = 1, 2, ..., N) Equation 2.1-6

Where
F_t = net cash flow in year t,
f_t = operation saving in year t,
r_T = tax rate,
T_t = taxable income in year t, due to cogeneration,
SV_N = salvage value of the investment at the end of the economic life cycle, that is at the end of year N.

Assumptions:

Operation savings is main target for the CHP, thus T_t = 0

Assuming the scenario that savage value is used completely for disposal of plant as scrap.

III. NPV Calculation

Then applying Equation 2.1-3

$\mathrm{NPV} = -F_0 + \sum_{t=1}^{N} \frac{F_t}{(1+d)^t}$ where 0 ≤ NPV ≥ 0

Assumptions:

Total life-cycle of CHP plant (N) = 20 years
Discount rate (d) = constant = 10%
Electricity tariffs escalation rate = 5%
Heat tariffs escalation rate = 5%
Fuel price escalation rate = 5%
Operation & maintenance cost escalation rate = 3%
Emission tax escalation rate = 3%
Interest on loan = 5%
Loan repayment period = 10 years
Loan holiday = 2 years
Availability of on-site generation plant ~ 95%

The flow chart outlining the computation sequence of NPV is shown in

Where,
Capital investment cost of CHP = total installation cost of the CHP plant, and
Annual savings = (conventional base case annual total running cost) – (CHP case annual total running cost)
= (conventional base case annual total cost of energy, operation and maintenance) – (CHP case annual total cost of energy, operation and maintenance).

2.1.4. Internal rate of return

Internal rate of return is the discount rate that results in an NPV value of zero. This implies that IRR is the discount rate that makes the net present worth of future cash flows equal the CHP capital investment cost. An iterative method employing Equation 2.1-7 is used to determine IRR.

Internal rate of return, IRR = d, for NPV = 0 [9];

$\rightarrow 0 = -F_0 + \sum_{t=1}^{N} \frac{F_t}{(1+\mathrm{IRR})^t}$ Equation 2.1-7

2.1.5. Simple-payback- period

Simple-payback-period (SPBP) is the length of time usually in years taken to recover the initial investment capital of implementing the CHP scheme based on the annual savings realised. SPBP is computed using annual running cost of CHP operation [10]. Equation 2.1-8 is used to calculate SPBP.

$\mathrm{SPBP\ (in\ years)} = \frac{\text{Capital investment cost of CHP}}{\text{Annual savings from CHP over conventional case}}$ Equation 2.1-8

2.1.6. Loan repayment

Equal annual loan repayment was calculated using Equation 2.1-9 [11], given an interest rate of 5%, and loan duration of 10 years.

$\rightarrow C_{Lr} = (L * r)/[1-(1+r)^{-N}]$ Equation 2.1-9

Where r = interest rate. C_{Lr}, L, and N are as defined in section 2.1.3.2

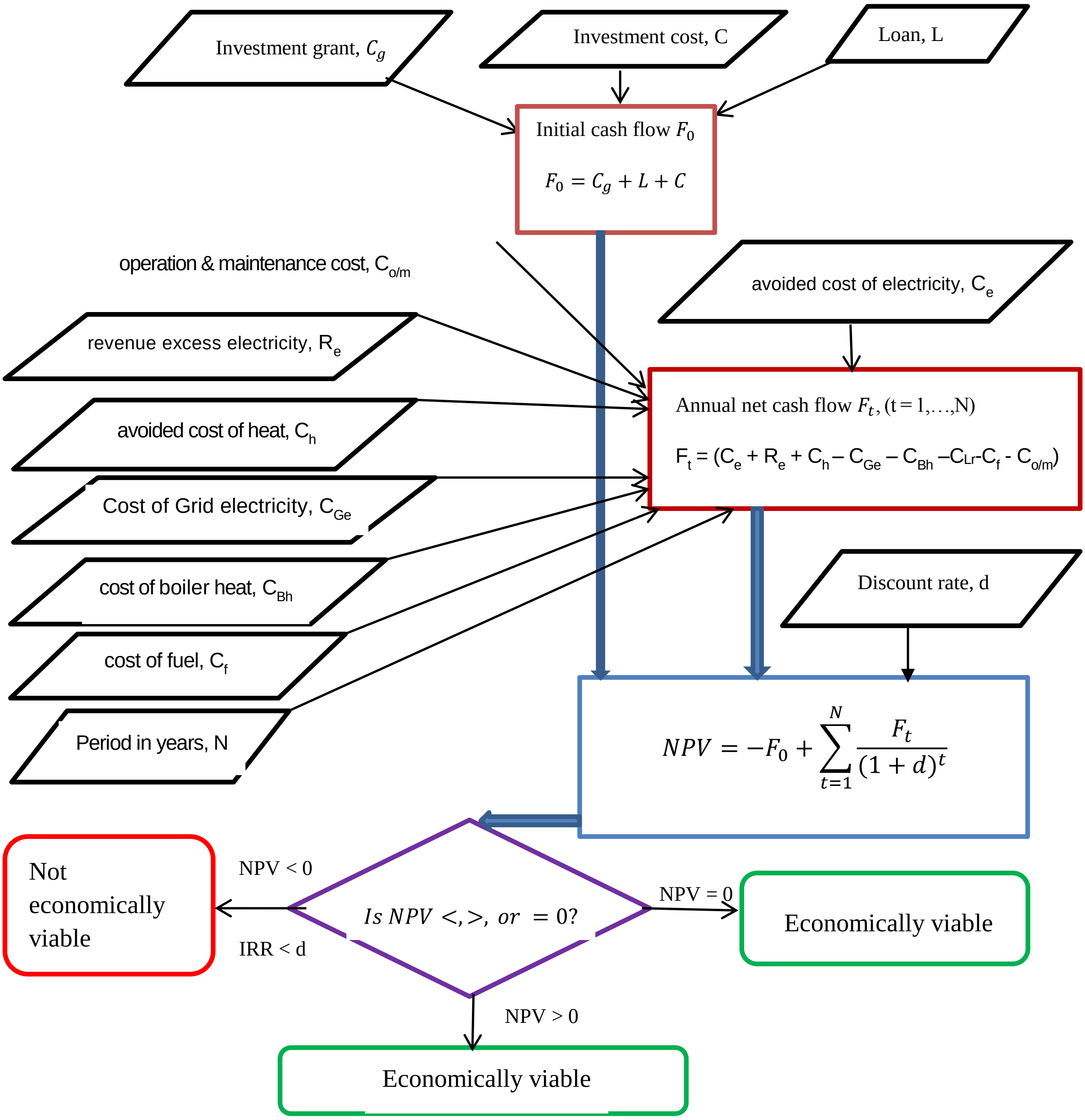

Figure 2.1-1 Flow chart for NPV computation

3. ANALYSIS AND RESULTS: CASE STUDY OF LARGE-SCALE REFINERY AND CHEMICAL PLANT (LRCP) CHP

3.1. Energy demand of LRCP

Table **3-1** below. It is worth noting that the process plant consumes energy at approximately constant rate, due to

The implementation of the ADIGT-CHP techno-economic analysis was done by examining typical case studies. With no particular interest one of such case studies is a Large-scale Refinery and Chemical plant CHP (LRCP-CHP) in the United Kingdom which has an installed capacity of 295MW and 2 x 250 tonnes/hour of steam [12]. This gives a total of 500tonnes/hour of steam = 47.61 x 500 = 23804.51kW$_{th}$ (because 1tonne/hour of steam = 47.61kW$_{th}$).

The annual electricity and steam demand of the LRCP were computed and are as shown in

routine plant operation. It was assumed that the power plant has an availability of about 95%.

Table 3-1 Energy demand of LRCP

Month	Hours of power plant operation	Power consumption demand from power plant (kWhe)	Excess power exported to grid (kWhe)	Grid electricity during plant outages (kWhe)	Steam consumption demand from CHP (kWh$_{th}$)	Excess steam exported (kWh$_{th}$)	Boiler steam during CHP outages (kWh$_{th}$)
Jan	693	204435000	45172477	14160000	16496525	15739666	1142616
Feb	692	204140000	45107293	1475000	16472721	15716954	119023
Mar	694	204730000	32958199	13865000	16520330	15647239	1118812
April	693	204435000	32910709	7670000	16496525	15624692	618917
May	694	204730000	21413197	13865000	16520330	15559431	1118812
June	694	204730000	21413197	7375000	16520330	15559431	595113
July	694	204730000	6151720	14160000	16520330	15420841	1142616
Aug	693	204435000	6142856	13570000	16496525	15398621	1095007
Sept	694	204730000	21413197	7375000	16520330	15559431	595113
Oct	695	205025000	33005689	13865000	16544134	15669785	1118812
Nov	693	204435000	32910709	7670000	16496525	15624692	618917
Dec	693	204435000	45172477	14160000	16496525	15739666	1142616
Total	8322	2454990000	343771719	129210000	198101132	187260449	10426375

3.2. Power plant performance

With the nominal capacity energy demand of the LRCP stated in section 3.1, 3 x 100MW ADIGTs and an additional 1 x 43.85MW ADIGT-CHP of same 50Hz frequency were considered to supply the demanded power and steam. This arrangement was made knowing that during hot days (in the summer) power generation on site may fall below demanded power. There may be surplus power and steam generated on site which are exported to the Grid. Conversely during plant outages electricity is imported from the Grid and steam produced in a stand-by boiler. The DP performance evaluation of the engine cycles using TURBOMATCH are shown in

Table **3-2** and Table 3-4, whereas validation of the engines performances are presented in Table 3-3 and Table 3-5.

Table 3-2 Summary of DP performance results of 100MW ADIGT engines simulation

Performance parameter	Value at DP of simulated three-spool large-scale aero-derivative engines		
	Simple cycle	Intercooled	ICR
Power turbine rating (kW)	100,000	100,000	100,000
Inlet mass flow (kg/s)	215.5	215.5	215.5
Exhaust mass flow (kg/s)	220.59	220.47	220.54
Fuel flow (kg/s)	5.09	4.97	5.04
Exhaust gas temperature (K)	783	692	690
Overall compression pressure ratio	42.15:1	42.15:1	42.15:1
Thermal efficiency	0.457	0.467	0.460

Table 3-3 Validating result of simulated 100MW ADIGT engine [13]

Performance parameter	Value at ISA SLS			
	Engine core inspired by LMS100	Simulated baseline engine (intercooled)	Variation	% variation
Power turbine rating	100,000kW	100,000kW	0.00	0.00
Inlet mass flow	N/A	215.5kg/s	-	-
Exhaust mass flow	220 kg/s	220.47kg/s	-0.47	-0.21
Fuel flow	N/A	4.97kg/s	-	-
Exhaust gas temperature	686K	692K	-6	-0.87
Overall pressure ratio	42.00:1	42.15:1	-0.15	-0.36
Thermal efficiency	0.440	0.467	-0.027	-6.9
TET	N/A	1730K	-	-

Table 3-4 Design point performance results for the 43.85MW ADIGT-CHP

Parameter	Values for the ADIGT-CHP		
	Simple (base engine) cycle	intercooled	ICR
Steam saturation temperature (K)	457	457	457
Pinch point	15	15	15
Approach point	8	8	8
Superheated steam temperature (K)	583	583	583
Steam mass flow (kg/s)	17.60	12.03	12.55
Economiser feed water temperature (K)	388	388	388
HRSG duty (kW)	45632.10	31199.70	32553.83
Power turbine rating (kW)	43,850	43,850	43,850
Inlet mass flow (kg/s)	125	125	125
GT Overall pressure ratio	29.04:1	29.04:1	29.04:1
Thermal efficiency	0.410	0.420	0.420
Gas turbine fuel flow (kg/s)	2.49	2.42	2.42
Gas turbine exhaust mass flow (kg/s)	127.49	127.42	127.42
Gas turbine exhaust temperature (K)	743	657	665
Gas temperature at evaporator exit (K)	709	634	641
Gas exit (stack) temperature (K)	437	448	447
Power : heat ratio	0.90	1.31	1.26
CHP efficiency	0.75	0.64	0.66

Table 3-5 Validating result of simulated 43.85MW ADIGT engine [14]

Performance parameter	Value at ISA SLS			
	Engine core inspired by LM6000	Simulated simple cycle baseline engine	Variation	% variation
Power turbine rating	43,850kW	43,850kW	0.0	0.0
Inlet mass flow	125kg/s	125kg/s	0.0	0.0
Fuel flow	N/A	2.49kg/s	-	-
Exhaust gas temperature	728K	743K	-15	-2.01
Overall pressure ratio	28.50:1	29.04:1	-0.54	-1.9
Thermal efficiency	0.420	0.410	0.010	2.4

TET	N/A	1550K	-	-

3.3. Engines emissions estimation

HEPHAESTUS code was employed to estimate engine emissions utilising dry low emission technology (DLE), and DP results are as presented in

Table **3-6** and Table 3-7.

Table 3-6 Design point emissions index for the 100MW engine cycles

Engine cycle	$EINO_X$ (g/kg fuel)	EICO (g/kg fuel)	$EICO_2$ (g/kg fuel)	EIH_2O (g/kg fuel)
SC (base engine)	1.97	0.96	51106.39	39755.64
IC	1.94	1.32	51034.23	39746.07
ICR	1.92	1.37	51027.20	39745.00

Table 3-7 Design point emissions index for the 43.85MW engine cycles

Engine cycle	$EINO_X$ (g/kg fuel)	EICO (g/kg fuel)	$EICO_2$ (g/kg fuel)	EIH_2O (g/kg fuel)
SC (base engine)	1.20	0.15	51169.05	39805.81
IC	1.17	0.22	51092.53	39796.50
ICR	1.11	0.21	51098.56	39796.90

The total annual emissions of the ADIGTs used in the economic analysis were computed based on the annual fuel consumptions.

3.4. Economic analysis of LRCP-CHP

3.4.1. LRCP Conventional case (grid electricity + on-site boiler)

Assumptions: the following were assumed in addition to those stated in section 2.1.3.2

I. The Refining and Chemical plant operate throughout the year implying 8760 hours of electricity purchase from grid and on-site steam generation in boiler.

II. Two industrial boilers of 23.804MW_{th} capacity each are installed on site of which one is kept on stand-by.

III. Year (0) is taken as initial installation and site construction period so that operation on site commences in year (1).

IV. Investment capital is made of Loan

$$\text{Boiler capital cost} = \text{number of boilers} \times \text{cost per } kW_{th} \times \text{Boiler capacity } (kW_{th})$$

$$= 2 \times 80\frac{£}{kW_{th}} \times 23.804kW_{th} = £3{,}808{,}722.00$$

$$\text{Boiler O\&M cost} = \text{annual steam consumption } (kWh_{th}) \times \text{O\&M cost per } kWh_{th}$$

$$= 208527507.6\ kWh_{th} \times 0.004\frac{£}{kWh_{th}} = £834{,}110.03$$

$$\text{Boiler fuel cost} = \text{annual steam consumption } (kWh_{th}) \times \text{fuel price per} kWh_{th}$$

$$= 208527507.6\ kWh_{th} \times 0.05\frac{£}{kWh_{th}} = £10{,}426{,}375.38$$

$$\text{Grid electricity cost} = \text{annual electricity consumption } (kWhe) \times \text{grid electricity tariff per } kWhe$$

$$= 2584200000\ kWhe \times 0.095\frac{£}{kWhe} = £245{,}499{,}000$$

$$\text{Boiler emission cost} = \text{annual heat consumption } (kWh_{th}) \times \text{emission tax per } kWh_{th}$$

$$= 208527507.6\ kWh_{th} \times 0.0015\frac{£}{kWh_{th}} = £312{,}791.26$$

$$\text{Year 1 annual operation cost} = £834{,}110.03 + £10{,}426{,}375.38 + £245{,}499{,}000 + £312{,}791.26 = £256{,}238{,}167.00$$

Present value of year 1 annual operation cost = £232,943,788.00, utilising the formula $\frac{F_t}{(1+d)^t}$

3.4.1.1. Conventional case life-cycle cash flow

Applying the escalation rates of prices (costs) to the life-cycle as spelled out in section 2.1.3.2, the life-cycle cash flow of the conventional case was computed and result is as shown in Table 3-9

Table 3-8 Conventional case economic analysis of LRCP (Grid electricity + Boiler)

			Electricity price £/kWh :		0.095	interest rate(%):	5
Boiler O & M cost £/kWh:		0.004	Grid electricity /annum kWh:		2584200000	Loan duration(yrs):	10
Boiler capital cost £/kW:		80	Hours of operation/annum:		8760	Loan (£)	260046888.24
Boiler capital cost £:		3808721.6	Boiler gas fuel price £/kWh:		0.05	Repayment Holiday	2 yrs
emissions tax £ /kWh :		0.0015	10% Discount rate (d) :		0.1		
End of year (t)	Boiler O & M cost, -$C_{o/m}$ (3% escalation rate) (£)	Grid electricity cost, -C_{Ge} (5% escalation rate) (£)	Boiler fuel cost, -C_h (5% escalation rate)(£)	Boiler emission cost -C_{bemtx} (3% escalation rate) (£)	Annual Loan repayment, C_{Lr} (£)	Annual cost (£)	Present value (10% discount rate) (£) $\frac{F_t}{(1+d)^t}$
1	834110.03	245499000.00	10426375.38	312791.26	0.00	256238166.64	232943787.86
2	859133.33	257773950.00	10947694.15	322175.00	0.00	269043819.15	222350263.76
3	884907.33	270662647.50	11495078.86	331840.25	33677261.73	316166828.34	237540817.68
4	911454.55	284195779.88	12069832.80	341795.46	33677261.73	330284669.86	225588873.62
5	938798.19	298405568.87	12673324.44	352049.32	33677261.73	345108204.36	214285042.85
6	966962.13	313325847.31	13306990.66	362610.80	33677261.73	360672710.51	203590342.36
7	995971.00	328992139.68	13972340.19	373489.12	33677261.73	377015230.73	193468426.35
8	1025850.13	345441746.66	14670957.20	384693.80	33677261.73	394174659.40	183885387.70
9	1056625.63	362713833.99	15404505.06	396234.61	33677261.73	412191835.40	174809575.71
10	1088324.40	380849525.69	16174730.32	408121.65	33677261.73	431109639.39	166211428.48
11	1120974.13	399892001.98	16983466.83	420365.30	33677261.73	450973095.84	158063318.92
12	1154603.36	419886602.08	17832640.17	432976.26	33677261.73	471829480.24	150339413.11
13	1189241.46	440880932.18	18724272.18	445965.55	0.00	460051169.91	133260436.78
14	1224918.70	462924978.79	19660485.79	459344.51	0.00	483044809.10	127200795.47
15	1261666.26	486071227.73	20643510.08	473124.85	0.00	507187862.66	121416741.86
16	1299516.25	510374789.12	21675685.59	487318.59	0.00	532537793.30	115895739.73
17	1338501.74	535893528.57	22759469.87	501938.15	0.00	559154936.59	110625823.29
18	1378656.79	562688205.00	23897443.36	516996.30	0.00	587102644.66	105595571.22
19	1420016.49	590822615.25	25092315.53	532506.18	0.00	616447436.96	100794081.87
20	1462616.99	620363746.01	26346931.30	548481.37	0.00	647259158.69	96210949.62
∑	**22412848.88**	**8117658666.31**	**344758049.77**	**8404818.33**	**336772617.33**	**8807594151.74**	**3274076818.23**

3.4.2. LRCP- CHP cases

The CHP economic analysis is implemented for both the simple and advanced cycle large-scale ADIGT-CHP, and results compared. The set of power plant is as described in section 1.1. The following assumption was made in conjunction to those stated in sections 2.1.3.2 and 3.4.1 (i), (iii), and (iv): One industrial boiler of 23.804MW_{th} capacity is installed on site to be kept on stand-by and brought on stream during CHP outages.

3.4.2.1. Simple cycle SC ADIGT-CHP case

Initial cash flow is the sum of installation costs of three 100MWe ADIGTs, one 43.85MWe ADIGT (with a set of HRSG), and one 23.805MW_{th} boiler.

$$\text{Initial cash flow } F_0 = (3 \times 100\text{MW GT} + 1 \times 43.85\text{MW GT}) \times \text{capital cost per kW} + \text{cost of 1 boiler}$$

$$\text{Initial cash flow} = (3 \times 100000\text{kW} + 1 \times 43850\text{kW}) \times \frac{850£}{\text{kW}} + 23805\text{kW} \times 80\ £/\text{kW}$$

$$\text{Initial cash flow } F_0 = £294{,}176{,}861.00$$

3.4.2.1.1. Year 1 annual net cash flow

$$\text{Annual Operation \& maintenance cost } C_{o/m} = \text{total annual energy generated (kWh)} \times \text{O\&M cost per kWh}$$

$$= (\text{annual electricity generated (kWhe)} + \text{annual steam generated (kWht)}) \times \text{O\&M cost per kWh}$$

$$= (2452900930.05 + 345860788.6 + 385361581.30 + 10426375.38)\text{kWh} \times 0.006£/\text{kWh} = £19146445.30$$

$$\text{Annual GT fuel cost } C_f = \text{total annual power generated (kWh)} \times \text{fuel price per kWh}$$

$$= (2452900930.05 + 345860788.6)\text{kWh} \times 0.05£/\text{kWh} = £139938085.93$$

Annual grid electricity cost during outages of CHP C_{Ge}

$$= \text{annual grid electricity consumption (kWhe)} \times \text{electricity tariff per kWhe}$$

$$= 129210000\text{kWhe} \times 0.095£/\text{kWhe} = £12{,}274{,}950$$

Annual boiler heat cost during outages of CHP C_{bh} = annual heat generated in boiler(kWht) × gas oil price per kWht

$$= 10426375.38\text{kWht} \times 0.05£/\text{kWht} = £521318.77$$

Annual emission tax C_{emtx} = (annual total emissions)(kg) × emission tax rate per kg

$$= (20873157972.16)\text{kg} \times 0.0025£/\text{kg} = £52182894.93$$

Annual saved electricity cost C_e = annual electricity consumption from CHP (kWhe) × electricity tariff per kWhe

$= 2454990000\ \text{kWhe} \times 0.095£/\text{kWhe} = £233224050$

Annual saved heat cost C_h = annual heat consumption from CHP(kWht) × gas oil price per kWht

$$= 198101132.2\ \text{kWht} \times 0.05£/\text{kWht} = £9905056.61$$

Annual revenue from excess electricity exported to grid R_e

$$= \text{annual electricity exported (kWhe)} \times \text{electricity tariff per kWhe}$$

$$= 343771718.65\ \text{kWhe} \times 0.05£/\text{kWhe} = £17188585.93$$

Annual revenue from excess steam exported R_h = annual steam exported (kWht) × gas oil price per kWht

$$= 187260449.08\ \text{kWht} \times \frac{0.025£}{\text{kWht}} = £4681511.23$$

Year 1 annual net cash flow $F_1 = C_e + C_h + R_e + R_h - C_{0/m} - C_f - C_{bh} - C_{Ge} - C_{emtx}$

$$= 233224050 + 9905056.61 + 17188585.93 + 4681511.23 - 19146445.30 - 139938085.93 - 12,274,950 - 521,318.77 - 52182894.93$$

$$= £40,935,509.00$$

$$\text{Present value of year 1 annual net cash flow} = \frac{F_1}{(1+d)^1}$$

$$\text{Present value of year 1 annual net cash flow} = \frac{40,935,509.00}{(1+0.1)^1}$$

$$\text{Present value of year 1 annual net cash flow} = £37,214,099.00$$

3.4.2.1.2. Simple cycle ADIGT-CHP case life-cycle cash flow

Applying the escalation rates of prices (costs) to the life-cycle as spelled out in section 2.1.3.2, the life-cycle cash flow of the simple cycle CHP case was computed and result is as shown in Table 3-9.

Table 3-9: Simple cycle (SC) ADIGT-CHP case economic analysis of LRCP

				Boiler O&M cost £/kWh :	0.004		
10% Discount rate (d) :	0.1	GT gas fuel price (£/kWh) :	0.05	Electricity tariff from grid £/kWh :	0.095	interest rate(%):	5
CHP capital cost £/kW:	850	GT fuel consumed/annum (kg) :	532066404.2	Electricity consumed/annum (kWh) :	2454990000	Loan duration(yrs):	10
CHP O & M cost £/kWh:	0.006	Hours of CHP outages/annum:	438	Grid electricity /annum (kWh) :	129210000	Loan (£):	294176860.80
Initial cash flow (F_0) £:	294176860.8	Hours of CHP operation/annum:	8322	Boiler gas fuel price £/kWh :	0.05	Repayment Holiday	2 yrs
		Excess electricity sold to Grid/annum(kWh):	343771719	Steam export price £/kWh :	0.025		
Emission tax £/kg :	0.0025	Boiler capital cost £/kW :	80	Electricity export tariff to grid £/kWh :	0.05		
		Total emission/annum kg:	20873157972				

End of year (t)	O & M cost, $-C_{o/m}$ (3% escalation rate) (£)	GT fuel cost, $-C_f$ (5% escalation rate) (£)	Grid electricity cost, $-C_{Ge}$ (5% escalation rate) during outages of CHP (£)	Boiler heat cost, $-C_{bh}$ (5% escalation rate) during outages of CHP (£)	Emission tax, $-C_{emtx}$ (3% escalation rate)(£)	Saved electricity cost, $+C_e$ (5% escalation rate) (£)	Saved heat cost, $+C_h$ (5% escalation rate) (£)	Revenue on excess electricity sold to Grid, $+R_e$ (5% escalation rate) (£)	Revenue on excess heat sold, $+R_h$ (5% escalation rate)(£)	Annual Loan repayment, C_{LR} (£)	F_t (annual net cash flow) (£)	Present value (10% discount rate) (£) $\frac{F_t}{(1+d)^t}$
1	19146445.30	139938085.93	12274950.00	521318.77	52182894.93	233224050.00	9905056.61	17188585.93	4681511.23	0.00	40935508.84	37214098.94
2	19720838.66	146934990.23	12888697.50	547384.71	53748381.78	244885252.50	10400309.44	18048015.23	4915586.79	0.00	44408871.08	36701546.35
3	20312463.82	154281739.74	13533132.38	574753.94	55360833.23	257129515.13	10920324.91	18950415.99	5161366.13	38097249.32	10001449.72	7514237.21
4	20921837.73	161995826.73	14209788.99	603491.64	57021658.23	269985990.88	11466341.16	19897936.79	5419434.43	38097249.32	13919850.62	9507445.27
5	21549492.87	170095618.06	14920278.44	633666.22	58732307.98	283485290.43	12039658.22	20892833.63	5690406.16	38097249.32	18079575.53	11225993.96
6	22195977.65	178600398.97	15666292.37	665349.53	60494277.21	297659554.95	12641641.13	21937475.31	5974926.46	38097249.32	22494052.79	12697306.38
7	22861856.98	187530418.92	16449606.98	698617.01	62309105.53	312542532.69	13273723.18	23034349.08	6273672.79	38097249.32	27177423.00	13946315.24
8	23547712.69	196906939.86	17272087.33	733547.86	64178378.70	328169659.33	13937409.34	24186066.53	6587356.43	38097249.32	32144575.86	14995681.87
9	24254144.07	206752286.85	18135691.70	770225.25	66103730.06	344578142.30	14634279.81	25395369.86	6916724.25	38097249.32	37411188.95	15865996.13
10	24981768.39	217089901.20	19042476.28	808736.52	68086841.96	361807049.41	15365993.80	26665138.35	7262560.46	38097249.32	42993768.35	16575958.87
11	25731221.45	227944396.26	19994600.10	849173.34	70129447.22	379897401.88	16134293.49	27998395.27	7625688.48	38097249.32	48909691.44	17142548.47
12	26503158.09	239341616.07	20994330.10	891632.01	72233330.64	398892271.97	16941008.17	29398315.03	8006972.91	38097249.32	55177251.85	17581172.88
13	27298252.83	251308696.87	22044046.61	936213.61	74400330.55	418836885.57	17788058.57	30868230.78	8407321.55	0.00	99912956.00	28941224.43
14	28117200.42	263874131.72	23146248.94	983024.29	76632340.47	439778729.85	18677461.50	32411642.32	8827687.63	0.00	106942575.47	28161322.54
15	28960716.43	277067838.30	24303561.39	1032175.50	78931310.68	461767666.34	19611334.58	34032224.44	9269072.01	0.00	114384695.06	27382786.57
16	29829537.92	290921230.22	25518739.46	1083784.28	81299250.01	484856049.66	20591901.31	35733835.66	9732525.61	0.00	122261770.36	26607723.42
17	30724424.06	305467291.73	26794676.43	1137973.49	83738227.51	509098852.14	21621496.37	37520527.44	10219151.89	0.00	130597434.63	25838006.21
18	31646156.78	320740656.32	28134410.25	1194872.17	86250374.33	534553794.75	22702571.19	39396553.81	10730109.49	0.00	139416559.40	25075293.67
19	32595541.49	336777689.13	29541130.76	1254615.78	88837885.56	561281484.49	23837699.75	41366381.51	11266614.96	0.00	148745317.99	24321048.09
20	33573407.73	353616573.59	31018187.30	1317346.57	91503022.13	589345558.71	25029584.74	43434700.58	11829945.71	0.00	158611252.43	23576552.01
∑	**514472155.38**	**4627186326.69**	**405882933.32**	**17237902.49**	**1402173928.70**	**7711775732.99**	**327520147.29**	**568356993.54**	**154798635.37**	**380972493.23**	**1414525769.38**	**420872258.52**
Annual running cost of CHP (£)				**=**	**202193597.77**							
Present value of annual running cost of CHP (£)				**=**	**183812361.61**				**NPV_{CHP} =**	**126695397.72**		
Saving in CHP running cost over conventional running cost (£)=					**49131426.24**				**IRR =**	**0.138**	**for NPV =**	**0.00**
Simple payback period SPBP				**=**	**6.0**	**Years**						

3.4.2.1.3. Simple payback period for SC ADIGT-CHP case

$$\text{Simple payback period } SPBP_{SC\_CHP} = \frac{\text{initial cash flow of SC ADIGTCHP case}}{\text{conventional case annual running cost} - \text{SC ADIGTCHP case annual running cost}}$$

$$\text{Simple payback period } SPBP_{SC\_CHP} = \frac{294,176,860.80}{232,943,787.86 - 183,812,361.61}$$

$$\text{Simple payback period } SPBP_{SC\_CHP} = 6.0 \text{ years}$$

3.4.2.1.4. Net present value for SC ADIGT-CHP case

Net present value NPV_{SC_CHP} = initial cash flow of SC ADIGTCHP − total life_cycle present value

Net present value $NPV_{SC\_CHP} = 420,872,258.52 - 294,176,860.80$

Net present value $NPV_{SC\_CHP} = £126,695,398.00$

3.4.2.1.5. Internal rate of return for SC ADIGT-CHP case

By method of iteration using Equation 2.1-7 the internal rate of return IRR for the SC ADIGT-CHP case is determined to be 13.8%

3.4.2.2. Intercooled cycle ADIGT-CHP case

Initial cash flow for IC cycle CHP in year (0), F_0:

Assuming 2.4% increment in GT capital cost due to intercooler, and applying the same method of section 3.4.2.1

Initial cash flow for IC cycle ADIGTCHP $F_0 = £301053860.80$

3.4.2.2.1. Year (1) annual net cash flow for IC cycle ADIGT-CHP

Using the same method of section 3.4.2.1.1

Annual Operation & maintenance cost $C_{\frac{o}{m}} = £19602003.27$

Annual GT fuel cost $C_f = £137250871.00$

Annual grid electricity cost during outages of CHP $C_{Ge} = £12274950$

Annual boiler heat cost during outages of CHP $C_{bh} = £521318.77$

Annual emission tax $C_{emtx} = £50286336.41$

Annual saved electricity cost $C_e = £233224050$

Annual saved heat cost $C_h = £9905056.61$

Annual revenue from excess electricity exported to grid $R_e = £14501371.00$

Annual revenue from excess steam exported $R_h = £1653950.71$

Year 1 annual net cash flow $F_1 = C_e + C_h + R_e + R_h - C_{0/m} - C_f - C_{bh} - C_{Ge} - C_{emtx}$

$= £39348949.00$

$$\text{Present value of year 1 annual net cash flow } = \frac{F_1}{(1+d)^1}$$

$$\text{Present value of year 1 annual net cash flow } = \frac{39348949.00}{(1+0.1)^1}$$

Present value of year 1 annual net cash flow $= £35771772.00$

3.4.2.2.2. Intercooled cycle IC ADIGT-CHP case life-cycle cash flow

Applying the escalation rates of prices (costs) to the life-cycle as spelled out in section 2.1.3.2, the life-cycle cash flow of the IC ADIGT-CHP case was computed and result is as shown in Table 3-10.

Table 3-10: Intercooled cycle (IC) ADIGT-CHP case economic analysis of LRCP

						Boiler O&M cost £/kWh :			0.004			
10%	Discount rate (d) :	0.1	GT gas fuel price (£/kWh):		0.05	Electricity tariff £/kWh :			0.095	interest rate(%):	5	
CHP capital cost £/kW :		870	GT fuel consumed/annum (kg):		519228887	Electricity consumed/annum (kWh) :			2454990000	Loan duration(yrs):	10	
CHP O & M cost £/kWh:		0.0065	Hours of CHP outages/annum:		438	Grid electricity /annum (kWh) :			129210000	Loan (£):	301053860.80	
Initial cash flow (F_0) £:		301053860.8	Hours of CHP operation/annum:		8322	Boiler gas oil price £/kWh :			0.05	Repayment Holiday	2 yrs	
		Excess electricity sold to Grid/annum(kWh):			290027420	Steam export price £/kWh :			0.025			
Emission tax £/kg :		0.0025	Boiler capital cost £/kW :		80	Electricity export tariff to grid £/kWh :			0.05			
			Total emission/annum kg:		20114534565							

End of year (t)	O & M cost, $-C_{o/m}$ (3% escalation rate) (£)	GT fuel cost, $-C_f$ (5% escalation rate) (£)	Grid electricity cost, $-C_{Ge}$ (5% escalation rate) during outages of CHP (£)	Boiler heat cost, $-C_h$ (5% escalation rate) during outages of CHP (£)	Emission tax, $-C_{emtx}$ (3% escalation rate)(£)	Saved electricity cost, $+C_e$ (5% escalation rate) (£)	Saved heat cost, $+C_h$ (5% escalation rate) (£)	Revenue on excess electricity sold to Grid, $+R_e$ (5% escalation rate) (£)	Revenue on excess heat sold, $+R_h$ (5% escalation rate)(£)	Annual Loan repayment, CLr (£)	F_t (annual net cash flow) (£)	Present value (10% discount rate) (£) $\frac{F_t}{(1+d)^t}$
1	19602003.27	137250871.00	12274950.00	521318.77	50286336.41	233224050.00	9905056.61	14501371.00	1653950.71	0.00	39348948.86	35771771.69
2	20190063.37	144113414.55	12888697.50	547384.71	51794926.51	244885252.50	10400309.44	15226439.55	1736648.24	0.00	42714163.10	35300961.24
3	20795765.27	151319085.27	13533132.38	574753.94	53348774.30	257129515.13	10920324.91	15987761.52	1823480.65	38987852.28	7301718.77	5485889.38
4	21419638.23	158885039.54	14209788.99	603491.64	54949237.53	269985990.88	11466341.16	16787149.60	1914654.69	38987852.28	11099088.11	7580826.52
5	22062227.38	166829291.52	14920278.44	633666.22	56597714.66	283485290.43	12039658.22	17626507.08	2010387.42	38987852.28	15130812.64	9395044.21
6	22724094.20	175170756.09	15666292.37	665349.53	58295646.10	297659554.95	12641641.13	18507832.44	2110906.79	38987852.28	19409944.73	10956407.78
7	23405817.03	183929293.90	16449606.98	698617.01	60044515.48	312542532.69	13273723.18	19433224.06	2216452.13	38987852.28	23950229.39	12290254.64
8	24107991.54	193125758.59	17272087.33	733547.86	61845850.94	328169659.33	13937409.34	20404885.26	2327274.74	38987852.28	28766140.12	13419616.67
9	24831231.28	202782046.52	18135691.70	770225.25	63701226.47	344578142.30	14634279.81	21425129.52	2443638.47	38987852.28	33872916.59	14365423.25
10	25576168.22	212921148.85	19042476.28	808736.52	65612263.27	361807049.41	15365993.80	22496386.00	2565820.40	38987852.28	39286604.19	15146686.61
11	26343453.27	223567206.29	19994600.10	849173.34	67580631.16	379897401.88	16134293.49	23621205.30	2694111.42	38987852.28	45024095.64	15780670.85
12	27133756.87	234745566.60	20994330.10	891632.01	69608050.10	398892271.97	16941008.17	24802265.56	2828816.99	38987852.28	51103174.73	16283046.35
13	27947769.57	246482844.93	22044046.61	936213.61	71696291.60	418836885.57	17788058.57	26042378.84	2970257.84	0.00	96530414.50	27961422.64
14	28786202.66	258806987.18	23146248.94	983024.29	73847180.35	439778729.85	18677461.50	27344497.78	3118770.73	0.00	103349816.45	27215236.80
15	29649788.74	271747336.54	24303561.39	1032175.50	76062595.76	461767666.34	19611334.58	28711722.67	3274709.27	0.00	110569974.93	26469572.90
16	30539282.40	285334703.37	25518739.46	1083784.28	78344473.63	484856049.66	20591901.31	30147308.81	3438444.73	0.00	118212721.37	25726532.39
17	31455460.87	299601438.53	26794676.43	1137973.49	80694807.84	509098852.14	21621496.37	31654674.25	3610366.97	0.00	126301032.56	24987985.97
18	32399124.70	314581510.46	28134410.25	1194872.17	83115652.08	534553794.75	22702571.19	33237407.96	3790885.32	0.00	134859089.56	24255592.66
19	33371098.44	330310585.98	29541130.76	1254615.78	85609121.64	561281484.49	23837699.75	34899278.36	3980429.58	0.00	143912339.58	23530817.50
20	34372231.39	346826115.28	31018187.30	1317346.57	88177395.29	589345558.71	25029584.74	36644242.28	4179451.06	0.00	153487560.96	22814947.92
∑	**526713168.71**	**4538331000.98**	**405882933.32**	**17237902.49**	**1351212691.11**	**7711775732.99**	**327520147.29**	**479501667.83**	**54689458.14**	**389878522.85**	**1344230786.79**	**394738707.97**
Annual running cost of CHP				=	203780157.75							
Present value of annual running cost of CHP (£)				=	185254688.86				NPV =	93684847.17		
Saving in CHP running cost over conventional running cost				=	47689098.99				IRR =	0.128	for NPV =	0.00
Simple payback period SPBP				=	6.3	Years						

3.4.2.2.3. Simple payback period for IC ADIGT-CHP case

$$\text{Simple payback period } SPBP_{IC\_CHP} = \frac{\text{initial cash flow of IC ADIGTCHP case}}{\text{conventional case annual running cost} - \text{IC ADIGTCHP case annual running cost}}$$

$$\text{Simple payback period } SPBP_{IC\_CHP} = \frac{301{,}053{,}860.80}{232{,}943{,}787.86 - 185{,}254{,}688.86}$$

$$\text{Simple payback period } SPBP_{IC\_CHP} = 6.3 \text{ years}$$

3.4.2.2.4. Net present value for IC CHP case

$$\text{Net present value } NPV_{IC\_CHP} = \text{initial cash flow of IC ADIGTCHP} - \text{total life\_cycle present value}$$

$$\text{Net present value } NPV_{IC\_CHP} = 394{,}738{,}707.97 - 301{,}053{,}860.80$$

$$\text{Net present value } NPV_{IC\_CHP} = £93{,}684{,}847.00$$

3.4.2.2.5. Internal rate of return for IC ADIGT-CHP case

By method of iteration using Equation 2.1-7 the internal rate of return IRR for the IC ADIGT-CHP case is determined to be 12.8%

3.4.2.3. Intercooled/recuperated cycle ICR ADIGT-CHP case

Following the method in section 3.4.2.1

Initial cash flow for ICR engine ADIGT-CHP in year (0), F_0:

Assuming 4.7% increment in GT capital cost due to intercooler and recuperator, and applying the same method of section 3.4.2.1

Initial cash flow for ICR engine ADIGTCHP $F_0 = £307{,}930{,}861.00$

3.4.2.3.1. Year (1) annual net cash flow for ICR cycle ADIGT-CHP

Applying the same method of section 3.4.2.1.1

Annual Operation & maintenance cost $C_{\frac{o}{m}} = £21194933.96$

Annual GT fuel cost $C_f = £137334334.34$

Annual grid electricity cost during outages of CHP $C_{Ge} = £12274950$

Annual boiler heat cost during outages of CHP $C_{bh} = £521318.77$

Annual emission tax $C_{emtx} = £50877386.93$

Annual saved electricity cost C_e = £233224050

Annual saved heat cost C_h = £9,905,056.61

Annual revenue from excess electricity exported to grid R_e = £14584834.34

Annual revenue from excess steam exported R_h = £1927549.04

Year 1 annual net cash flow $F_1 = C_e + C_h + R_e + R_h - C_{0/m} - C_f - C_{bh} - C_{Ge} - C_{emtx}$

= £37,438,566.00

$$\text{Present value of year 1 annual net cash flow } = \frac{F_1}{(1+d)^1}$$

$$\text{Present value of year 1 annual net cash flow } = \frac{37438566.00}{(1+0.1)^1}$$

Present value of year 1 annual net cash flow = £34,035,060.00

3.4.2.3.2. Intercooled/recuperated cycle ICR ADIGT-CHP case life-cycle cash flow

Applying the escalation rates of prices (costs) to the life-cycle as spelled out in section 2.1.3.2, the life-cycle cash flow of the ICR ADIGT-CHP case was computed and result is as shown in Table 3-11.

Table 3-11: Intercooled-recuperated cycle (ICR) ADIGT-CHP case economic analysis of LRCP

						Boiler O&M cost £/kWh :			0.004			
10% Discount rate (d) :		0.1	GT gas fuel price (£/kWh) :		0.05	Electricity tariff £/kWh :			0.095	interest rate(%):	5	
GT capital cost £/kW :		890	GT fuel consumed/annum (kg) :		525718049.8	Electricity consumed/annum (kWh) :			2454990000	Loan duration(yrs):	10	
O & M cost £/kWh:		0.007	Hours of CHP outages/annum:		438	Grid electricity /annum (kWh) :			129210000	Loan (£):	307930860.80	
Initial cash flow (F_0) £:		307930860.8	Hours of CHP operation/annum:		8322	Boiler gas oil price £/kWh :			0.05	Repayment Holiday	2 yrs	
		Excess electricity sold to Grid/annum(kWh):			291696687	Steam export price £/kWh :			0.025			
Emission tax £/kWh :		0.0025	Boiler capital cost £/kW :		80	Electricity export tariff to grid £/kWh :			0.05			
			Total emission/annum kg:		20350954771							
End of year (t)	O & M cost, -$C_{o/m}$ (3% escalation rate) (£)	GT fuel cost, -C_f (5% escalation rate) (£)	Grid electricity cost, -C_{Ge} (5% escalation rate) during outages of CHP (£)	Boiler heat cost, -C_h (5% escalation rate) during outages of CHP (£)	Emission tax, -C_{emtx} (3% escalation rate)(£)	Saved electricity cost , +C_e (5% escalation rate) (£)	Saved heat cost , +C_h (5% escalation rate) (£)	Revenue on excess electricity sold to Grid, +R_e (5% escalation rate) (£)	Revenue on excess heat sold, +R_h (5% escalation rate)(£)	Annual Loan repayment, CLr (£)	F_t (annual net cash flow) (£)	Present value (10% discount rate) (£) $\frac{F_t}{(1+d)^t}$
1	21194933.96	137334334.34	12274950.00	521318.77	50877386.93	233224050.00	9905056.61	14584834.34	1927549.04	0.00	37438565.99	34035059.99
2	21830781.98	144201051.06	12888697.50	547384.71	52403708.54	244885252.50	10400309.44	15314076.06	2023926.49	0.00	40751940.70	33679289.84
3	22485705.44	151411103.61	13533132.38	574753.94	53975819.79	257129515.13	10920324.91	16079779.86	2125122.81	39878455.25	4395772.30	3302608.79
4	23160276.61	158981658.79	14209788.99	603491.64	55595094.38	269985990.88	11466341.16	16883768.85	2231378.95	39878455.25	8138714.18	5558851.30
5	23855084.90	166930741.73	14920278.44	633666.22	57262947.22	283485290.43	12039658.22	17727957.30	2342947.90	39878455.25	12114680.08	7522263.18
6	24570737.45	175277278.82	15666292.37	665349.53	58980835.63	297659554.95	12641641.13	18614355.16	2460095.30	39878455.25	16336697.48	9221639.83
7	25307859.58	184041142.76	16449606.98	698617.01	60750260.70	312542532.69	13273723.18	19545072.92	2583100.06	39878455.25	20818486.58	10683175.40
8	26067095.36	193243199.90	17272087.33	733547.86	62572768.52	328169659.33	13937409.34	20522326.56	2712255.06	39878455.25	25574496.08	11930691.17
9	26849108.22	202905359.89	18135691.70	770225.25	64449951.58	344578142.30	14634279.81	21548442.89	2847867.82	39878455.25	30619940.92	12985844.02
10	27654581.47	213050627.88	19042476.28	808736.52	66383450.13	361807049.41	15365993.80	22625865.04	2990261.21	39878455.25	35970841.93	13868316.72
11	28484218.91	223703159.28	19994600.10	849173.34	68374953.63	379897401.88	16134293.49	23757158.29	3139774.27	39878455.25	41644067.42	14595991.58
12	29338745.48	234888317.24	20994330.10	891632.01	70426202.24	398892271.97	16941008.17	24945016.20	3296762.98	39878455.25	47657377.00	15185109.00
13	30218907.85	246632733.10	22044046.61	936213.61	72538988.31	418836885.57	17788058.57	26192267.01	3461601.13	0.00	93907922.82	27201780.21
14	31125475.08	258964369.76	23146248.94	983024.29	74715157.96	439778729.85	18677461.50	27501880.36	3634681.19	0.00	100658476.88	26506522.97
15	32059239.33	271912588.25	24303561.39	1032175.50	76956612.69	461767666.34	19611334.58	28876974.38	3816415.25	0.00	107808213.38	25808429.14
16	33021016.51	285508217.66	25518739.46	1083784.28	79265311.07	484856049.66	20591901.31	30320823.10	4007236.01	0.00	115378941.09	25109819.24
17	34011647.01	299783628.54	26794676.43	1137973.49	81643270.41	509098852.14	21621496.37	31836864.26	4207597.81	0.00	123393614.70	24412768.84
18	35031996.42	314772809.97	28134410.25	1194872.17	84092568.52	534553794.75	22702571.19	33428707.47	4417977.70	0.00	131876393.78	23719128.60
19	36082956.31	330511450.47	29541130.76	1254615.78	86615345.57	561281484.49	23837699.75	35100142.84	4638876.58	0.00	140852704.77	23030542.76
20	37165445.00	347037022.99	31018187.30	1317346.57	89213805.94	589345558.71	25029584.74	36855149.98	4870820.41	0.00	150349306.05	22348466.32
∑	**569515812.90**	**4541090796.04**	**405882933.32**	**17237902.49**	**1367094439.76**	**7711775732.99**	**327520147.29**	**482261462.88**	**63736247.95**	**398784552.47**	**1285687154.14**	**370706298.91**
Annual running cost of CHP =					**205690540.63**							
Present value of annual running cost of CHP (£) =					**186991400.57**				**NPV =**	**62775438.11**		
Saving in CHP running cost over conventional running cost =					**45952387.29**				**IRR =**	**0.119**	**for NPV =**	**0.00**
Simple payback period SPBP =					**6.7**	**Years**						

Simple payback period for ICR ADIGT-CHP case

$$\text{Simple payback period } SPBP_{ICR\_CHP} = \frac{\text{initial cash flow of ICR ADIGTCHP case}}{\text{conventional case running cost} - \text{ICR ADIGTCHP case running cost}}$$

$$\text{Simple payback period } SPBP_{ICR\_CHP} = \frac{307{,}930{,}860.80}{232{,}943{,}787.86 - 186991400.57}$$

Simple payback period $SPBP_{ICR\_CHP}$ = 6.7 years

3.4.2.3.3. Net present value for ICR ADIGT-CHP case

Net present value NPV_{ICR_CHP} = initial cash flow of ICR ADIGTCHP − total life_cycle present value

Net present value NPV_{ICR_CHP} = 370,706,298.91 − 307,930,860.80

Net present value NPV_{ICR_CHP} = £62,775,438.00

3.4.2.3.4. Internal rate of return for ICR ADIGT-CHP case

By method of iteration using Equation 2.1-7 the internal rate of return IRR for the ICR ADIGT-CHP case is determined to be 11.9%. Guides to unit prices and cost estimations of CHP and GT installations, electricity, gas fuel, operations and maintenance, and emissions tax, were obtained from refs [12] [15][16][17].

Figure 3-1, Figure 3-2, and Figure 3-3 show the comparison between the NPV, SPBP, and IRR of the simple, intercooled, and ICR cycle ADIGT-CHP for the LRCP. The percentage savings in operational cost of the three LRCP CHP scenarios over the conventional case is presented in Figure 3-4.

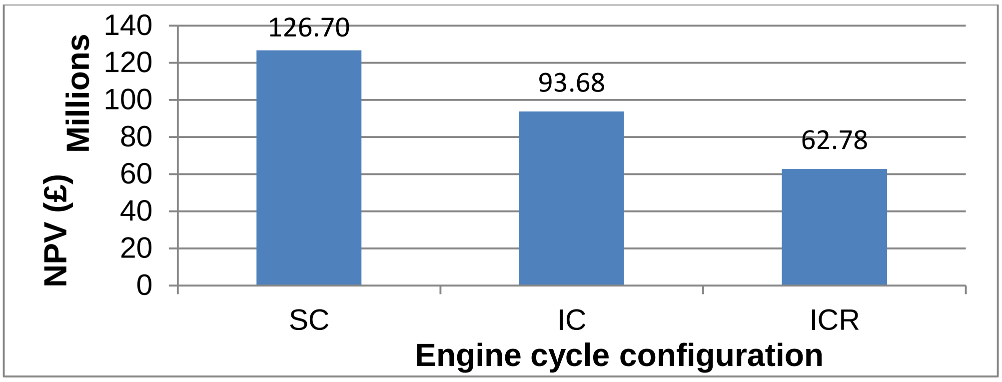

Figure 3-1 Net present value for LRCP CHP

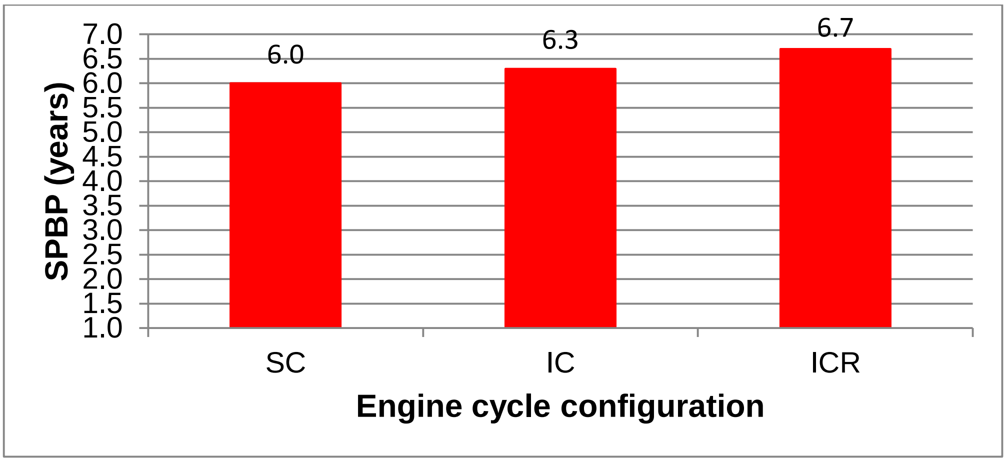

Figure 3-2 Simple payback period for LRCP CHP

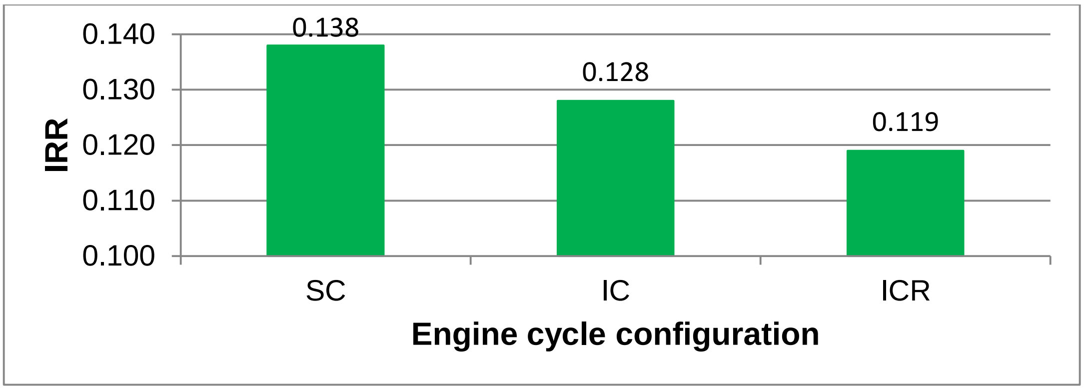

Figure 3-3 Internal rate of return for LRCP CHP

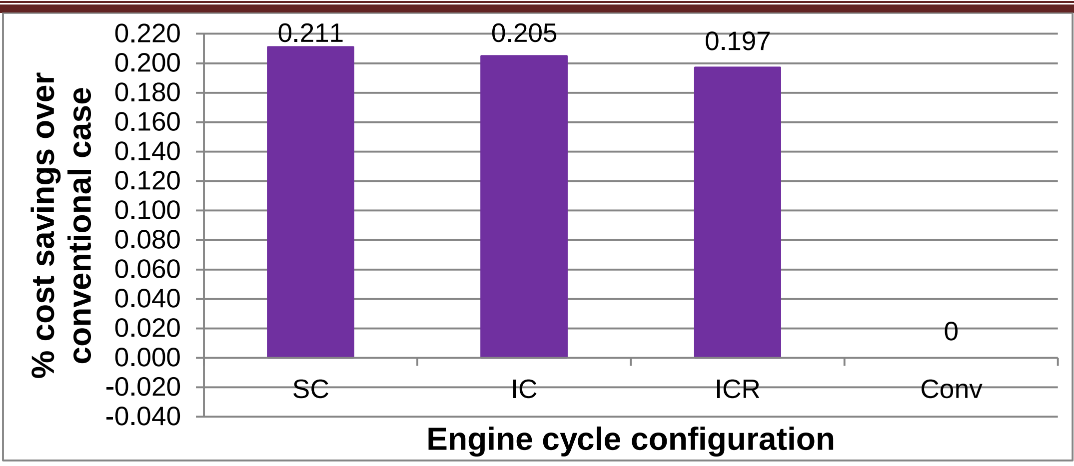

Figure 3-4 Percentage cost savings of LRCP CHP over conventional case

4. RESULTS DISCUSSION

The outcome of the techno-economic assessment by the method in the case study of the LRCP-CHP above indicates that all three cycle configurations, SC, IC, and ICR ADIGT-CHP register positive NPV and are profitable over and above the conventional case. However, the scenario of SC ADIGT-CHP recorded the highest profit in NPV, the shortest payback period, and the highest IRR, followed by the IC ADIGT-CHP. The bulk of annual net savings of the plant comes from sales of excess electricity and steam. These sales are observed to be huge in the case of SC ADIGT-CHP than in IC and ICR ADIGT-CHP. The much excess steam is as a result of high heat content of the exhaust gas of the SC aero-derivative engine compared to those of the IC and ICR cycles.

Similarly, the much excess electricity from the SC engine is as a result of SC cycle generating more power due to much lower ambient temperature (below international standard atmosphere sea level static ISA SLS) of the region (site) over a year period, where majority of annual seasons ambient temperature falls below ISA SLS. On the other hand, IC and ICR would generate more power in a region of ambient temperature higher than ISA SLS.

The avoided or saved electricity and steam cost, grid electricity, and boiler heat cost, are almost the same in all three scenarios due to the constant consumption rate of the process plant. Nevertheless, O & M cost, and capital/installation cost were highest in the case of ICR ADIGT-CHP, followed by the IC ADIGT-CHP, of course due to additional components and complexity (from intercooler, and recuperator). However, more fuel cost was incurred in the scenario of SC ADIGT-CHP than the advanced cycles, due to lesser GT thermal efficiency of the former. Besides, it is pertinent to note that of all the annual cost elements, GT fuel cost contributes the largest share in all three scenarios.

Furthermore, it is observed that IRR of the ADIGT-CHP cycle options increases as NPV increases, whereas SPBP decreases with increasing NPV, as shown in the combination of Figure 3-1, Figure 3-2, and Figure 3-3.

5. CONCLUSION

Assessment, prediction, and comparison have been done of the techno-economic viability of simple, intercooled, and intercooled-recuperated cycle large-scale aero-derivative industrial gas turbines CHP over the conventional case in the petrochemical industry, which is the aim of this paper. This was implemented by estimating NPV, IRR, and SPBP for all the ADIGT-CHP cycle options given inputs of technical performance parameters of the engines with various respective costs.

i. It was found that the percentage savings in operational cost of SC, IC, and ICR cycle large-scale ADIGT–CHP over and above the conventional case (grid electricity plus on-site boiler) are 21.1%, 20.5%, and 19.7% respectively.

ii. SC large-scale ADIGT-CHP exhibits better NPV, SPBP, and IRR than IC and ICR cycles over and above the conventional case. Nevertheless, all three cycle options are profitable than the conventional case.

iii. More-so, the results of SPBP, and IRR obtained compare favourably with trends available in the literature. For instance, a 66MW CHP plant in the UK was reported to register an IRR of 12% and SPBP of 4.8 years [18].

iv. Steam flow is more in SC large-scale ADIGT-CHP than in IC and ICR cycles.

v. SC large-scale ADIGT-CHP exhibits better CHP efficiency than IC and ICR cycles.

vi. It is noteworthy that this sort of assessment method would actually aid decision makers to make good choice of engine cycles pertaining to investment in large-scale aero-derivative industrial gas turbines CHP in the petrochemical industry.

Besides, future work is being contemplated by the authors for the risk and sensitivity analysis of NPV with respect to uncertainty in values of key inputs such as GT fuel price and grid electricity tariff.

Acknowledgments

The authors would like to thank Dr. Giuseppina Di Lorenzo of the Department of Power and Propulsion of Cranfield University, for her valuable contribution.

REFERENCES

[1] Ogaji S, Pilidis P, Hales R (2007). TERA: A Tool for Aero-Engine Modelling and Management. Second World Congress on Engineering Asset Management and the Fourth International Conference on Condition Monitoring, Harrogate, United Kingdom, June 11–14, 2007. Available from: http://dspace.lib.cranfield.ac.uk/handle/1826/3880. Date accessed: 10 April 2013

[2] Khan R.S.R, Lagana M.C, Ogaji S.O.T, Pilidis P, Bennett I. (2011). Risk analysis of gas turbines for natural gas liquefaction. J. Eng. Gas Turbines Power 2011; 133(7): 071704-1 – 8.

[3] Nkoi B, Pilidis P, Nikolaidis T. (2013). Performance assessment of simple and modified cycle turboshaft gas turbines. Journal of Propulsion and Power Research, Elsevier 2013; 2(2): 96 – 106. Available from: http://dx.doi.org/10.1016/j.jppr.2013.04.009. Date accessed: 12 July 2013

[4] Celis C. (2010). Evaluation and Optimisation of Environmentally Friendly Aircraft Propulsion Systems. [Dissertation]. School of Engineering, Cranfield University, UK. 2010; 31 – 98. Available from: http://dspace.lib.cranfield.ac.uk/handle/1826/4686. Date accessed: 15 May 2013.

[5] Kyprianidis K.(2008). Eva a Tool for Environmental Assessment of Novel Cycles. Proceedings of ASME Turbo Expo 2008: Power for Land, Sea and Air, Berlin, Germany. June 9 – 13, 2008; GT2008-50602: 547-556.

[6] Khan R, Barreiro J, Lagana M, Kyprianidis K, Ogaji S, Pilidis P, Bennett I. (2009). An Assessment of the Emissions and Global Warming Potential of Gas Turbines for LNG Applications. ASME Paper No. GT2009-59184: 2009; 123-132. Available from: http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleid=1647083 . Date accessed: 20 May 2013.

[7] Carbon Trust (2010). Introducing Combined Heat and Power. Available from: www.carbontrust.com/.../ctv044_**introducing_combined_heat_and_power**. Date accessed: 12 June 2013.

[8] DECC (2012). CHP Finance. Department of Energy and Climate Change. Available from: http://chp.decc.gov.uk/cms/chp-finance. Date assessed: 15 June, 2013.

[9] EDUCOGEN (2001). The European Educational Tool on Cogeneration. 2nd ed. 2001; p. 102 – 103.

[10] Milton M, Lucas B.H. (2010). Sustainable On-site CHP Systems: Design, Construction and Operations. McGraw-Hill Companies. p.141 – 142

[11] Gutierrez P.H, Dalsted N.L. Long-term Loan repayment methods, fact sheet No. 3.757. Farm and Ranch/Economics. Colorado State University Extension. Available from: www.ext.colostate.edu/pubs/farmmgt/03757.pdf . Date accessed: 06 March 2014.

[12] Greenpeace (2008). Securing Power, Potential for CCGT CHP Generation at Industrial Sites in the UK. A Report to Greenpeace. Poyry Energy (Oxford) Ltd. 3 June, 2008. Available from:

www.**greenpeace**.org.**uk**/files/pdfs/climate/**securingpower**0708.pdf. Date accessed: 19 May, 2013.

[13] GE Energy (2012). Gas Turbines: Aero-derivatives. Available from: http://www.ge_energy.com/products_and_services/products/gas_turbines_aeroderivative/index.jsp. Date accessed: 10 July 2012.

[14] Badeer G.H, Evendale O.H. (2000). GE Aero-derivative Gas Turbines: Design and Operating Features. GE Power Systems. GER-3695E. 2000; 10 – 11

[15] EPA-CPPD (2008). Technology Characterization: Gas Turbines. Environmental Protection Agency Climate Protection Partnership Division, Washington DC. December 2008. Available from: www.epa.gov/chp/documents/catalog_chptech_gas_turbines.pdf. Date accessed: 13 May, 2013.

[16] HM Revenue & Customs, DECC (2011). Carbon Price floor, Tax Information and Impact Note. 23 March 2011. Available from: https://www.gov.uk/government/organisations/hm-revenue-customs. Date accessed: 10 May, 2013.

[17] DECC (2013). Industrial Energy Prices Statistics. Available from: https://www.gov.uk/government/collections/industrial-energy-prices. Date accessed: 25 June, 2013.

[18] Merše S, Visočni B.P, Riddoch F, Craenen S, Gardiner P, Rotheray T, et al. (2011). Cogeneration Case Study Handbook. CODE project. Cogeneration Observatory and Dissemination Europe. Jozef Stefan Institute, Energy Efficiency Centre: Slovenia. 2011; 34 – 6.

