SUSTAINABILITY ASSESSMENT OF POWER GENERATION IN COMBINATION WITH LNG EVAPORATION: A COMPARISON OF LCA METHODS AND EXERGY ANALYSIS

L. Stougie [a] & H.J. van der Kooi [b]

[a] ***Faculty of Technology, Policy and Management***
Delft University of Technology
P.O. Box 5015, 2600 GA, Delft, Netherlands
Email: l.stougie@tudelft.nl

[b] ***Faculty of Civil Engineering and Geosciences***
Delft University of Technology
P.O. Box 5048, 2600 GA, Delft, Netherlands
Email: jvdkooi@casema.nl

Abstract

Several options exist for power generation, but it is difficult to determine which option is the most sustainable. When assessing the sustainability of an option or system, it is important to consider the environmental, economic and social aspects of sustainability and to take a life-cycle point of view. According to literature, a relationship exists between exergy and sustainability, but it is not common use to apply exergy analysis for improving sustainability. In this research, three options for power generation in combination with LNG evaporation are assessed, i.e. using the waste heat from a coal-fired power plant for LNG evaporation, integrating an oxy-fuel power plant with an air separation unit and an LNG terminal, and a separate power plant plus an LNG terminal combined with an Organic Rankine Cycle. The results of environmental LCA, environmental Life Cycle Costing, social LCA and the Cumulative Exergy Loss (CExL) method of the three options have been compared. The oxy-fuel option is preferred according to the results of the environmental, economic and exergetic assessment methods. The difference in the outcomes of the social assessment is too small to choose between the three options. From studying the three options in more detail, it became clear that the processes that contribute most to the overall score of a method are different. E.g., the natural gas production process is responsible for about 70 per cent of the LCA score, but causes only 2 to 3 per cent of the CExL.

Keywords: *Sustainability Assessment, Power generation, Life Cycle Assessment, Exergy Analysis*

1. Introduction

Electricity plays a major role in our society, but it is difficult to assess the sustainability of power generation from an environmental, economic as well as social point of view. When assessing the sustainability of power generation, it is important to take a life cycle point of view to avoid problem-shifting between different life cycle phases and/or sustainability aspects [1]. According to literature, e.g. [2], a relationship exists between sustainability and exergy losses, but exergy losses are not considered in regular life cycle assessment methods.

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The possibilities and consequences of involving exergy analysis in decisions regarding energy supply in the Netherlands are investigated by conducting a number of case studies. The case study that is presented here considers the following three technological options for power generation in combination with LNG evaporation: using the waste heat from a coal-fired power plant for LNG evaporation, integrating an oxy-fuel power plant with an air separation unit and an LNG terminal, and a separate power plant plus an LNG terminal combined with an Organic Rankine Cycle. The methods applied to assess the three options are environmental LCA, environmental Life Cycle Costing (LCC), social LCA and the Cumulative Exergy Loss (CExL) method [3].

2. Research Approach

The results of the environmental, economic, social and exergetic assessments are confronted with each other. From this, it can be concluded which option is preferred from an environmental point of view, which option is preferred from an economic point of view, etc. It can also be concluded what the consequences for the environmental, economic and social sustainability of the case study are if the option is chosen that is preferred from an exergetic point of view. Besides that, it is investigated whether the results of the methods differ along the supply chain by determining which processes contribute most to the overall score of a method. The following sections describe the assessment methods that have been applied.

2.1 Environmental Life Cycle Assessment

The Environmental Life Cycle Assessment has been carried out by determining the ReCiPe Endpoint indicators of the analysed options with the help of the SimaPro software tool version 7.3.2 [4] in combination with version 2.2 of the Ecoinvent database [5]. When calculating the Endpoint indicators the default normalisation/weighting set, i.e. ‘ReCiPe Endpoint (H) V1.04’ and ‘Europe ReCiPe H/A’ has been chosen.

2.2 Environmental Life Cycle Costing (LCC)

Environmental LCC is a method that takes into account the whole life cycle of a product, including the phases of use and disposal that are usually not considered in a traditional LCC. Despite the steady-state nature of LCA, it is not uncommon to calculate the Net Present Value (NPV) when performing environmental LCC (e.g. [6, 7]). However, the Present Worth Ratio (PWR) is applied in this research because it is important to consider the investment costs of the options as well when choosing between options. The PWR is defined as the Net Present Value of all revenues and costs during the lifetime of the installation divided by the Net Present Value of the investment costs of the installation.

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2.3 Social Life Cycle Assessment

A standard method of social life cycle assessment (S-LCA) is under development [8, 9]. This research makes use of the Inequality-adjusted Human Development Index (IHDI) [10] as it would be too time-consuming and costly to gather site-specific social data. The method to calculate the overall IHDI of a supply chain ([3, 11] starts with determining the number of man-hours of the different stages of the production chains (e.g. exploration, conversion, transport) and dividing these man-hours between the countries the employees originate from. This is followed by aggregating the number of man-hours per country over the whole production chain. Finally, the overall IHDI ($IHDI_{overall}$) can be calculated by summing the products of the percentage of man-hours per country ($perc.man.hrs_i$) and the IHDI of that country ($IHDI_i$) over all countries (Eq. 1):

$$IHDI_{overall} = \left(\sum_{i=1}^{i=n} \left(perc.man.hrs_i \cdot IHDI_i \right) \right) / 100 \tag{1}$$

2.4 Determination of the Cumulative Exergy Loss

The exergy analysis method that is used for the assessment of the sustainability of technological options is the Cumulative Exergy Loss (CExL) method [3]. The method takes into account the exergy losses caused by technological processes as well as the prevention of capturing new exergy from sunlight by the ecosystem. The CExL is the summation of the internal exergy loss caused by irreversibilities within the technological option including its supply chains, the exergy loss caused by abatement of emissions and the exergy loss related to the land occupied by the installations of the technological option including its supply chains. The CExL method can be regarded as a combination of, or extension to, the existing exergy analysis methods called Cumulative Exergy Consumption (CExC, [12]), Cumulative Exergy Consumption and Abatement (CExCA, [13]), Cumulative Exergy Extraction from the Natural Environment (CEENE, [14]), and Exergetic Life Cycle Assessment (ELCA, [15]).

3. Brief description of the case study options

This case study deals with different types of installations for power generation in combination with LNG evaporation. An amount of nitrogen is added to the evaporated LNG to obtain a gas mixture of about 95 vol.% methane and 5 vol.% nitrogen which complies with the H-gas that is used in the Netherlands.

3.1 Using the waste heat from a coal-fired power plant for LNG evaporation

In the Rotterdam port area of the Netherlands, a coal-fired power plant is under construction. The residual heat of this power plant will be used by an LNG import terminal. The power plant is an ultra-supercritical power plant with a capacity of 1070 MWe and an electrical efficiency of about 47 per cent [16]. The power plant uses ultra-supercritical

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steam of about 600 °C and 300 bars. In this case study option, called waste heat option, the carbon dioxide resulting from the combustion of coal is captured with monoethanolamine (MEA) absorption for reasons of comparability of the three compared options.

3.2 Integrating an oxy-fuel power plant with an air separation unit and an LNG terminal

The coal-fired oxy-fuel power plant is based upon the 30 MWe pilot plant in Schwarze Pumpe (Germany) [16]. The power plant has a capacity of 1000 MWe and an electrical efficiency of about 45 per cent. The integration between LNG evaporation, air separation and electricity production is described by [16, 17], but the compression of the captured carbon dioxide has not been taken into account in this research.

3.3 A separate power plant plus an LNG terminal combined with an Organic Rankine Cycle

This option makes use of the same ultra-supercritical power plant as the waste heat option, but instead of using the residual heat of the power plant for evaporating the LNG, the LNG cold is used for electricity production through an Organic Rankine Cycle (ORC), like described by [17, 18]. Seawater of 10 °C acts as the ‘high’ temperature heat source in the ORC. The selected working fluid of the ORC is ethane, as calculations with nitrogen, methane, ethylene and ethane as working fluids learnt that ethane is the most suitable.

4. Analysis

4.1 Functional unit and system boundaries

The functional unit is defined as the production of 27 PJ of electricity, 12 Mtons of H-gas and 15.3 Mtons of nitrogen per year. The reason for including nitrogen as one of the by-products is the comparability of the three options as the oxy-fuel option includes air separation and therefore produces a net amount of nitrogen. The 27 PJ of electricity is the net amount of electricity produced, i.e. the internal electricity consumption of processes like LNG compression and air separation has been accounted for.

The assessment includes the extraction, processing and transport of coal and (liquefied) natural gas. The amount of nitrogen produced in the oxy-fuel option is regarded as a valuable by-product. As the captured carbon dioxide from the power plant is not emitted to the environment, this flow is not regarded as an emission. The use of ethane as a working fluid in the ORC option, the use of seawater for heating and cooling purposes and all other auxiliary substances not mentioned in the following subsections have not been taken into account, because it is assumed that the effects thereof are negligible compared to the other effects.

4.2 Data

This case study is based upon a large number of data from various data sources, completed with additional calculations and educated guesses by the authors. The most important data are presented in the following subsections.

4.2.1 Environmental sustainability

The ultra-supercritical power plant, the oxy-fuel power plant including air separation unit, the ORC and the LNG terminal are modelled on the basis of the references mentioned in Sections 3.1 to 3.3. The Ecoinvent unit processes ‘Hard coal supply mix/NL’, ‘Natural gas, liquefied, at freight ship/DZ’ and ‘Nitrogen, via cryogenic air separation, production mix, at plant, gaseous EU-27 S’ have been used to model the coal, LNG and nitrogen supply chains. The installations of the power plant and LNG terminal are modelled by selecting the Ecoinvent unit processes ‘Hard coal power plant/RER/I U’ and ‘Liquid storage tank, chemicals, organics/CH/I U’, respectively. Table 1 gives an overview of the inputs and outputs of the three options used in SimaPro.

Table 1: *Overview of inputs and outputs of the three options per year.*

	[Mton/year]	Waste heat	Oxy-fuel	ORC
Inputs	Coal	2.9	2.6	2.7
	LNG	11	11	11
	Nitrogen	1.1	-	1.1
Products	Electricity [PJ/year]	27	27	27
	H-gas	12	12	12
By-products	Nitrogen (*)	(15.3)	15.3	(15.3)
	Captured CO_2	5.5	5.6	5.6
Flue gases	CO_2	1.0	0.30	0.91
	NO_x	1.4	0.0	1.3
	SO_x	11	0.0	10
	N_2	26	0.0	24
	O_2	2.5	0.72	2.3
	H_2O	1.4	0.98	1.3
Ashes		0.35	0.30	0.32

(*) When analysing the waste heat and ORC options, an additional production of 15.3 Mtons of nitrogen is taken into account for reasons of comparability of the three options.

4.2.2 Economic sustainability

The data needed for calculating the life cycle costs originate from [16, 20-23]. The costs of back-up installations to overcome an (unexpected) shut-down of a connected installation have not been taken into account.

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Table 2 presents an overview of the investment costs of the options and the capital and operational expenses. The capital and operational costs of the air separation unit have only been taken into account in the oxy-fuel option, because in the other two options it is assumed that the nitrogen needed for bringing the evaporated LNG to H-gas conditions is bought from another company. The price of nitrogen is estimated at 0.017 €/kg [24]. The costs of carbon dioxide capture with MEA absorption are assumed to be 5 €/ton CO_2 [16]. The price of LNG is calculated at 6.8 €/GJ, which is based on the 10.45 US$/MMBTU reported by [25], and the price of H-gas is estimated at 6.7 €/GJ [26]. According to these prices, which are of February 2013, it is not profitable to import LNG at that moment.

Table 2: *Overview of economic data of the three options.*

	Waste heat	Oxy-fuel	ORC
Investment costs [10^8 €]	26	23	25
Capital costs [10^7 €/year]	28	25	28
Operation and management costs [10^7 €/year]	10	9.1	10
Costs of fuels/feedstocks [10^8 €/year]	43	42	43
Sell of carbon credits [10^7 €/year]	11	11	11
Revenues of products [10^8 €/year]	44	47	44

4.2.3 Social sustainability

The man-hours per stage of the production chain (Table 3) were estimated on the basis of many references [27-38], completed with own estimates and calculations.

Table 3: *Overview of man-hours along the production chain.*

	Coal	LNG
Exploration/processing [man-hours/PJ coal or LNG]	$8*10^3$	$1*10^0$
Liquefaction [man-hours/PJ LNG]	-	$8*10^3$
Deep sea transport [man-hours/PJ coal or LNG]	$3*10^3$	$7*10^4$
LNG terminal [man-hours/year]	-	$6*10^4$
Power plant [man-hours/year]	$4*10^4$	-

The number of man-hours for operating the coal power plants was assumed to be equal for the three options. The man-hours needed for construction and decommissioning of the installations and equipment have not been considered because of lack of data. The transport of natural gas by pipeline to the liquefaction plant and the man-hours needed for loading/unloading of LNG and coal, and the storage of coal have been neglected. It was assumed that the people that are responsible for the extraction and processing of coal and the production of LNG originate from the country where these activities take place. The same holds for the operation of the power plants in the Netherlands. The man-hours

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needed for deep-sea transport (of coal, LNG) are divided over the countries the crew originates from.

4.2.4 Exergetic assessment

The CExL is the summation of the internal exergy loss, the exergy loss caused by emission abatement and the exergy loss caused by land use. The internal exergy loss of the options has been calculated from the cumulative exergy demand (CExD) reported by SimaPro minus the amounts of exergy of the products and emissions. The amount of exergy represented by the emissions is calculated from the amounts of emissions reported by SimaPro and the standard chemical exergy values of the emissions. The exergy loss caused by emission abatement is based on the values reported for CO_2 [39], sulphur dioxide, nitrogen oxides and phosphate [15]. The exergy loss caused by land use is calculated from the amounts of land use reported by SimaPro and a solar irradiation equal to 3.4 GJ exergy/m^2*year [14].

5. Results

5.1 Environmental sustainability

Table 4 presents the ReCiPe endpoint indicators of the three options. As becomes clear from this Table, the oxy-fuel option results in the best ReCiPe score of the three options, while the scores of the other two options are comparable. The ReCiPe damage category ‘Resources’ accounts for about 80 per cent of the ReCiPe score of the options.

Table 4: *ReCiPe scores of the three options per ReCiPe damage category.*

Damage category	Waste heat		Oxy-fuel		ORC	
	[GPt]	[%]	[GPt]	[%]	[GPt]	[%]
Human health	0.37	15	0.29	13	0.36	15
Ecosystems	0.21	9	0.17	8	0.21	9
Resources	1.88	76	1.82	80	1.87	76
Total	2.46	100	2.28	100	2.44	100

It has also been investigated which processes of the whole supply chain contribute most to the ReCiPe score of the three options. Table 9 of Section 5.5 presents the processes that are responsible for at least 80 per cent of the ReCiPe score of the oxy-fuel option. This Table clearly shows that the production of natural gas is the main contributor to the ReCiPe score, therefore the natural gas production process itself has been analysed as well. It appeared that the ReCiPe score of the three options analysed in this case study is mainly caused by the fact that natural gas is extracted from earth.

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5.2 Economic sustainability

The results of the economic assessment are presented in Table 5. As becomes clear from this Table, the Oxy-fuel option is the preferred option although none of the three options is profitable at the considered prices of energy carriers and carbon credits. The contributions of the investment costs and yearly costs and revenues to the PWR have been investigated, as depicted in Table 9 of Section 5.5. The purchase of LNG accounts for about 80 per cent of the PWR.

Table 5: *Life Cycle Costs of the three options.*

Life Cycle Costs	Waste heat	Oxy-fuel	ORC
PWR [-]	-1.5	-0.32	-1.4

5.3 Social sustainability

The difference in the Inequality-adjusted Human Development Index (IHDI) [10] between the three options appears to be negligible, see Table 6. This is understandable because the coal and LNG used in the three options originate from the same countries. The slight difference is caused by the difference in the amounts of coal used in the three options.

Table 6: *Results of the social LCA of the three options.*

	Waste heat	Oxy-fuel	ORC
$IHDI_{overall}$	0.605	0.606	0.606

It was investigated how the IHDI varies along the supply chain. The results thereof are presented in Table 9 (Section 5.5). The transport of coal has the lowest IHDI, closely followed by the transport of LNG.

5.4 Exergetic sustainability

Table 7 presents the results of the exergetic assessment. According to the results, the oxy-fuel option is preferred, followed by the ORC option, although the difference between the ORC and waste heat options is not very large.

Table 7: *Cumulative Exergy Loss of the three options.*

	Waste heat		Oxy-fuel		ORC	
	[PJ-eq.]	[%]	[PJ-eq.]	[%]	[PJ-eq.]	[%]
Internal exergy loss	203	80	166	79	194	80
Abatement exergy	47	18	42	20	46	19
Exergy loss land use	3.4	1	3.0	1	3.2	1
Cumulative Exergy Loss	253	100	210	100	244	100

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The influence of land use is almost negligible compared to the other exergy losses. In calculating the exergy loss causes by land use, it was assumed that only 0.75 per cent of the solar energy radiated on the land can be captured via photosynthesis [40]. When it is assumed that 10.8 per cent of the solar energy could be captured by means of photosynthesis, which is the theoretical maximum reported by [41], then the exergy loss caused by land use increases from about 3 to 46 PJ-eq., i.e. 16 to 17 per cent of the CExL.

SimaPro does not offer the possibility to calculate the contribution of the processes to the CExL. To be able to compare the ReCiPe and CExL scores along the supply chains in Section 5.5, it was decided to calculate the CExL of the processes with the highest contribution to the ReCiPe scores of the three options. According to Table 9 (Section 5.5), the use of natural gas for storage is the largest contribution to the CExL score of the oxy-fuel option.

5.5 Comparison of results

The results of the four assessment methods applied to the three options are summarized in Table 8. According to this Table, the oxy-fuel option is the preferred option of this case-study. The difference between the other two options is very small. Table 8 also presents an overview of the grading of the options. If two options have the same score, they are rated the same.

Table 8: *Overview of the assessment results and the grading of the options. The preferred option per assessment method is assigned the value '1', the second best '2' etc.*

	Waste heat		**Oxy-fuel**		**ORC**	
	absolute	**ranking**	**absolute**	**ranking**	**absolute**	**ranking**
ReCiPe [GPt]	2.46	2	2.28	1	2.44	2
PWR [-]	-1.5	2	-0.32	1	-1.4	2
IHDI [-]	0.605	1	0.606	1	0.606	1
CExL [PJ]	253	2	210	1	244	2

To be able to investigate the differences between the four methods in more detail, Table 9 presents the contributions of the processes to the total score of the oxy-fuel option. The process contributions of the other two options are comparable. According to this Table, the LNG supply chain contributes the most to the ReCiPe, PWR and CExL scores of the three options. The coal supply chain has the lowest IHDI of the options. When looking in more detail at the LNG supply chain, it appears that the natural gas production process accounts for two-third to three-quarters of the total ReCiPe score, while this process hardly contributes to the CExL score.

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Table 9: *Contributions of supply chains and processes to the total scores of the oxy-fuel option.*

		ReCiPe [%]	PWR [%]	IHDI [-]	CExL [%]
Coal supply chain	Hard coal mining	2.0		0.601	2.0
	Coal transport			0.554	
	Purchase of coal		3.3	-	
	Subtotal	*2.0*	*3.3*	-	*2.0*
LNG supply chain	Natural gas production	70		0.677	2.6
	Natural gas for storage	9.4			33
	LNG transport			0.573	
	Purchase of LNG		83		
	Subtotal	*80*	*83*	-	*36*
Power plant and LNG terminal	Power plant and LNG terminal	0.59		0.846	20
	Investment costs power plant		4.3		
	Investment costs LNG terminal		2.1		
	Capex		5.1		
	Opex		1.9		
	MEA costs		-		
	Subtotal	*0.59*	*13*	-	*20*
Total		83	100	0.606	58

6. Discussion and conclusions

According to the results of the environmental, economic and exergetic assessment methods, the same option is preferred and the difference between the other two options is too small to decide which option is second-best. Also the difference in the outcomes of the social assessment is too small to choose between the three options.

The methods differ in the process that contributes most to the total score of the method. The natural gas production process is responsible for about 70 per cent of the ReCiPe score but this process causes only 2 to 3 per cent of the CExL. The purchase of LNG is responsible for more than 80 per cent of the PWR and the coal transport has the lowest IHDI of the options. It can therefore be concluded that the methods differ a lot when looking into more detail at the options.

However, more research is needed with regard to the exergy loss caused by emission abatement and land use. Furthermore, the CExL could not yet be calculated of all processes that are part of the options, so it is unknown which process contributes the most to the CExL.

Another aspect to be mentioned is that the costs of back-up installations have not been taken into account. This is especially important in the case of the oxy-fuel option because of the continuous operation of the power plant and the discontinuity in the send-out of the LNG terminal. The LNG terminal is expected to send out natural gas about 60 per cent of the time, depending on the weather conditions. With regard to the interdependency

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between the installations, the ORC option is preferred because of the absence of interconnections.

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