Environmental, economic and exergetic sustainability assessment of power generation from fossil and renewable energy sources

Stougie, Lydia; Giustozzi, Natalìa; van der Kooi, Hedzer; Stoppato, Anna

DOI
10.1002/er.4037

Publication date
2018

Document Version
Final published version

Published in
International Journal of Energy Research

Received: 21 September 2017 | Revised: 24 January 2018 | Accepted: 31 January 2018
DOI: 10.1002/er.4037

SPECIAL ISSUE PAPER

WILEY INTERNATIONAL JOURNAL OF ENERGY RESEARCH

Environmental, economic and exergetic sustainability assessment of power generation from fossil and renewable energy sources

Lydia Stougie[1] | Natalìa Giustozzi[2] | Hedzer van der Kooi[3] | Anna Stoppato[2]

[1] Department of Engineering Systems and Services, Faculty of Technology, Policy and Management, Delft University of Technology, P.O. Box 5015, 2600GA Delft, Netherlands

[2] Department of Industrial Engineering, University of Padova, via Venezia 1, 35131 Padova, Italy

[3] Department of Geoscience and Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, P.O. Box 5048, 2600GA Delft, Netherlands

Correspondence
Lydia Stougie, Delft University of Technology, Faculty of Technology, Policy and Management, Department of Engineering Systems and Services, P.O. Box 5015, 2600GA Delft, Netherlands.
Email: l.stougie@tudelft.nl

Summary

Energy conversion systems have assumed a crucial role in current society. The threat of climate change, fossil fuel depletion and the growing world energy demand ask for a more sustainable way of electricity production, eg, by using renewable energy sources, by improving the conversion efficiency and/or by controlling power plant emissions. Despite the relationship between exergy and sustainability stated in literature, exergy losses are usually not considered when comparing systems and energy sources for power generation. The exergetic sustainability assessment method named Total Cumulative Exergy Loss (TCExL) has been used to assess several systems for electricity production, ie, a coal-fired power plant, a coal-fired power plant including carbon capture and storage, a biomass-fired power plant, an offshore wind farm and a photovoltaic park. The results of the TCExL method have been compared with an environmental sustainability indicator, ie, the overall ReCiPe endpoint indicator and the economic indicator named Present Worth Ratio. The offshore wind farm is the best system from the exergetic and environmental point of view. The photovoltaic park is the system with the second-best scores. However, from the economic viewpoint including subsidy by the Dutch government, the photovoltaic park performs better than the wind farm system and the system that performs best is the biomass-fired power plant. Without subsidy, only the coal-fired power plant without carbon capture and storage is profitable. The exergetic sustainability scores of the coal-fired and biomass-fired power plants are similar, but from the environmental sustainability viewpoint, the biomass-fired power plant performs better than both coal-fired power plants. As the results of environmental and economic sustainability assessments strongly depend on models, weighting factors, subsidy, market prices, etc, while the results of the exergetic sustainability assessment do not, it is recommended that the exergetic sustainability be taken into account when assessing the sustainability of power generation and other technological systems.

KEYWORDS

exergy, fossil energy, power generation, renewable energy, sustainability

1 | INTRODUCTION

Electricity has become crucial in modern society. However, the impact on the environment of its production is considered as one of the main causes of global warming. Not only the threat of climate change but also the exhaustion of fossil energy sources stimulate the transition from a power generation system based on coal, oil and gas to one where renewable energy sources like biomass, sunlight, and wind are strongly exploited. Usually, the assessment and comparison of power generation systems is done by applying environmental and economic sustainability assessment methods. Environmental sustainability assessment methods have the disadvantage that they use models and weighting factors for the quantification of environmental impact. Economic methods do not include all indirect costs and their results strongly depend on market developments causing the outcomes of an economic assessment to change over time. The quality of energy, ie, exergy, is usually not considered when assessing and comparing power generation systems, although every process and activity requires exergy and is accompanied with the loss of exergy. This loss of exergy is irreversible. Capturing exergy from solar and/or tidal energy is the only way to replenish the amount of exergy on earth. According to literature, eg, Dincer and Rosen,[1] exergy and sustainability are related. They illustrate qualitatively that the environmental impact of a process decreases and its sustainability increases when the exergy efficiency of the process is increased. Hammond[2] states that energy and exergy analyses are appropriate measures of sustainability in and beyond the energy sector even if their results have to be applied with some care. Al-Zareer et al[3] use exergy analysis to evaluate the sustainability of an integrated system for compressed hydrogen and electricity production based on a Generation IV nuclear reactor, while Ozlu and Dincer[4] perform an energetic and exergetic analysis and an environmental impact assessment to study and optimise a multigeneration energy system where solar energy is used to produce electricity for a building by means of a Kalina cycle. The Total Cumulative Exergy Loss (TCExL) method has been developed as a means that enables taking into account as many aspects of sustainability as possible in an objective way.[5] All exergy losses caused by a technological system during its life cycle are considered. In this paper, the TCExL method, a regular environmental sustainability assessment method that calculates ReCiPe endpoint indicators, and a method for the assessment of the economic sustainability that calculates the Present Worth Ratio (PWR) of the systems are used to assess the following five systems for power generation: a coal-fired power plant, a coal-fired power plant including carbon capture and storage (CCS), a biomass-fired power plant, an offshore wind farm and a photovoltaic park. This study differs from other studies in the sense that not only the environmental and economic sustainability of the five power generation systems is assessed but also their exergetic sustainability. The results of the assessments are compared and discussed. This paper is an improved version of the paper presented by Stougie et al,[6] which has also been extended with the results of the economic sustainability assessment.

2 | SUSTAINABILITY ASSESSMENT

The assessment of the environmental, economic and exergetic sustainability of the power generation systems is carried out from a life cycle perspective as it is important to include the supply chains of the systems as well as the life cycle stages of the systems. These life cycle stages comprise not only the construction of the systems and their operation but also their decommissioning. The life cycle viewpoint implies that technological systems such as the wind farm and the photovoltaic park consume nonrenewable resources and cause emissions such as carbon dioxide from fossil origin as well. The functional unit used in the sustainability assessments is set at 1 PJ of power generation. The three sustainability assessment methods are described in more details in sections 2.1 to 2.3.

2.1 | Environmental sustainability

The environmental sustainability of the power generation systems is determined by modelling the systems with the help of the life cycle assessment software tool named SimaPro,[7] ie, version 8.1.1.6, which includes ecoinvent database version 2.2.[8] SimaPro provides several methods for the calculation of environmental indicators.

The ReCiPe 2008 method[9] was selected for this research as it has been developed by life cycle assessment experts and because it enables the calculation of one overall environmental sustainability indicator per system. The ReCiPe method is a life cycle impact assessment method that comprises harmonised category indicators at the midpoint and the endpoint level. The original midpoint and endpoint approaches that the ReCiPe method builds on are the CML midpoint approach[10] and the Eco-indicator 99 endpoint approach,[11] respectively.[9] The overall ReCiPe endpoint indicator is based on three ReCiPe endpoint indicators, which separately indicate damage to human health, ecosystem diversity and resource availability. The damage to human health is measured in disability-adjusted loss of life years. The damage to ecosystem diversity considers the loss of species during a year. The damage to resource availability measures the increased costs of mineral and fossil resources and is calculated from the marginal cost increase, the annual consumption of resources and the net present value (NPV) of money.[9] In accordance with the default normalisation and weighting set, ie, "ReCiPe Endpoint (H) V1.12/Europe ReCiPe H/A," the three endpoint indicators account for 40%, 40% and 20% of the overall ReCiPe endpoint indicator, respectively, as there was no reason to deviate from the default normalisation and weighting set. A lower ReCiPe score of a system indicates a higher environmental sustainability of this system.

2.2 | Economic sustainability

Two indicators of the economic sustainability of the systems have been calculated, ie, the NPV as well as the PWR.[12] The PWR is defined as the NPV of the revenues and costs during the lifetime of the system over the NPV of the investment costs (I) of the system (Equation 1).

$$\mathrm{PWR} = \mathrm{NPV}/\sum_{t=0}^{t=i}\frac{I_t}{(1+r)^t} \tag{1}$$

An advantage of the PWR over the NPV is that the PWR considers the investment costs of the systems as well.[12] If the PWR of a system is a positive number, it is profitable to invest in the system. The higher the PWR, the more likely the investment is. The PWR differs from the (conventional) benefit cost ratio, which needs to be larger than 1 for an investment to be profitable.[13,14] The costs related to decommissioning of the power generation systems themselves are not taken into account as it is assumed that these costs are low compared with the investment costs. In accordance with the discount rate used for private effects in social cost-benefit analyses in the Netherlands, this discount rate (r) has been specified at 8 per cent.[15]

If the capacity of the main installation, ie, the power generating system itself, is larger than 1 PJ per year, the investment costs are assumed to be proportional to the original investment costs. If the main installation produces less than 1 PJ of electricity per year, the well-known six-tenths rule is applied to calculate the investment costs. It is assumed that the time needed for building the coal-fired and biomass-fired power plants equals five years and that it takes three years to construct the wind farm and photovoltaic park. The investment costs are assumed to be spread equally over the construction period. The lifetime of the systems after construction is assumed to be 20 years with the exception of the photovoltaic park, which is assumed to have a lifetime of 30 years. Unless stated otherwise in section 3, the yearly operation and maintenance costs (OpEx) are assumed to be 4% of the investment costs. Finally, it is assumed that the price of electricity equals 60 €/MWh.[16]

2.3 | Exergetic sustainability

In 2012, the TCExL method was introduced as a result of research into sustainability and exergy aimed at finding or developing a method that considers as many aspects of sustainability as possible in an objective way.[5] The method can be regarded as a combination and/or extension of the Cumulative Exergy Consumption and Abatement (CExCA) method,[17] the Cumulative Exergy Extraction from the Natural Environment (CEENE) method,[18] and the Exergetic Life Cycle Assessment (ELCA) method.[19] Aspects of sustainability that are only indirectly considered in the TCExL method are the depletion and scarcity of resources. These aspects are taken into account via the exergy loss caused by the extraction of these resources, which is assumed to increase as a resource becomes scarcer. Alternatively, the assessed technological system could include technological installations for the transformation of the outputs to the required inputs, ie, closing the material cycles.

The economic and social aspects of sustainability have not been incorporated in the TCExL method as adding factors or equations to do so would result in a less objective method and because the economic and social aspects are already related to exergy loss via the inputs and outputs of technological systems.

The TCExL method takes into account all exergy losses caused by a technological system by considering the following three components: internal exergy loss caused by the technological system itself, the exergy loss resulting from abatement of emissions to an acceptable level and the exergy loss related to the use of land (Equation 2). The latter is important as the ecosystem is prevented from capturing new exergy from sunlight by land occupation.[20] The higher the TCExL indicator, the lower the exergetic sustainability of a technological system is.

$$\mathrm{TCExL} = Ex_{\mathrm{loss,internal}} + Ex_{\mathrm{loss,abatement}} + Ex_{\mathrm{loss,land\ use}} \tag{2}$$

The internal exergy loss of a technological system is calculated with the help of the Cumulative Exergy Demand (CExD)[21] of the system as reported by the

SimaPro software, which represents the exergy input. Subtracting the amount of exergy represented by the product or products and the emissions and waste flows from the CExD results in the internal exergy loss (Equation 3). The amount of exergy represented by the outputs is calculated from the amounts of emissions and waste flows reported by SimaPro and the standard exergy values of these components.[22] The calculation of the amount of exergy represented by emissions is limited to the emissions that amount to 99% by mass of all emissions as it is undoable to calculate the exergy values of the nearly 900 pollutants reported by SimaPro.

$$Ex_{\text{loss,internal}} = \text{CExD} - Ex_{\text{product(s)}} - Ex_{\text{emissions\,\&\,}\textit{waste flows}} \tag{3}$$

The exergy loss related to the abatement of emissions to an acceptable level is calculated from the amounts of carbon dioxide of fossil origin, nitrogen oxides, sulfur dioxide and phosphate emitted by the system as reported by SimaPro and the abatement exergy loss values of these emissions (Equation 4). The abatement exergy loss of the four emissions equals 5.86,[23,24] 16, 57 and 18 MJ/kg,[19] respectively. The reason for limiting the calculation of the abatement exergy loss to these emissions is that exergetic data about the abatement of other emissions have not yet been found in the literature.

$$Ex_{\text{loss,abatement}} = \sum \left(\text{emission}_i \cdot ex_{\text{loss,abatement},i}\right) \tag{4}$$

The exergy loss related to land use is calculated from the amounts and types of land occupation by the technological system as reported by SimaPro and a worldwide average exergy loss of 215 GJ per hectare per year (Equation 5). This worldwide average exergy loss originates from the net primary production reported by Haberl et al,[25] ie, the net amount of biomass produced when land is not occupied, and an average biomass exergy conversion factor of 42.9 MJ exergy per kg of carbon.[26] The land use types that refer to biomass are not taken into account when calculating the exergy loss related to land use to prevent double counting. Land use types that refer to marine ecosystems are neither taken into account because of the very small amount of solar energy that is captured by these ecosystems.[18]

$$Ex_{\text{loss,land use}} = \text{land use} \cdot 215\ \text{GJ}/(\text{ha}\cdot\text{year}) \tag{5}$$

3 | POWER GENERATION SYSTEMS

The following sections briefly describe the power generation systems that have been assessed.

3.1 | Coal-fired power plant

The MPP3 power plant, a new ultrasupercritical power plant in the Rotterdam port area of the Netherlands,[27] forms the basis of the coal-fired power plant of this research. By using ultrasupercritical steam of about 600°C and 300 bar, the power plant obtains an electrical efficiency of about 46%.[28] Its gross capacity amounts to about 1100 MWe. Table 1 presents an overview of the inputs and outputs of the MPP3.

The investment costs of the power plant amount to €1.7 billion,[29] which becomes €59 million when allocated to the production of 1 PJ of electricity. The coal price is assumed to equal €2.15 per GJ.[30]

3.2 | Coal-fired power plant with CCS

The coal-fired power plant with CCS is modelled on the MPP3 power plant as well, but in this case, about 23 vol% of its flue gases is led through a CCS unit in which monoethanolamine is used to capture about 90% of the carbon dioxide. The CCS unit and its effects on the electrical efficiency of the power plant are modelled on the Rotterdam capture and storage demonstration (ROAD) project.[31] In line with the ROAD project, the captured carbon dioxide is transported to a nearly empty gas field in the North Sea. The conditions during transport are about 128 bar and 65°C. The carbon dioxide capture results in a 57 MWe decrease in power generation capacity because of its electricity and steam consumption.[32] Table 2 presents the inputs and outputs of this variant of the MPP3 power plant.

For the construction of a CCS unit of a 400 MWe power plant, 5560 ton of carbon steel and 1470 ton of stainless steel are needed.[33] As the CCS unit of the ROAD project has the size of a CCS unit meant for a 250 MWe power plant, it was assumed that 3475 ton of low-alloyed

TABLE 1 Inputs and outputs of the MPP3 related to the production of 1 PJ of electricity

Name	Unit	Amount
Coal	kton	92
CO_2	Mton	0.21
NO_x	ton	53
SO_2	ton	32
PM10	ton	3.3
HCl	ton	0.63
HF	ton	0.36
Waste heat (flue gases)	TJ	83
Waste heat (water)	PJ	1.2

TABLE 2 Inputs and outputs of the MPP3 including carbon capture and storage related to the production of 1 PJ of electricity

Name	Unit	Amount
Coal	kton	98
CO_2	Mton	0.19
NO_x	ton	56
SO_2	ton	34
PM10	ton	3.5
HCl	ton	0.66
HF	ton	0.38
Waste heat (flue gases)	TJ	63
Waste heat (water)	PJ	1.3

(carbon) steel and 919 ton of chromium (stainless) steel are needed, ie, 250/400 times the amount needed for a 400 MWe CCS unit. The influence of this assumption on the results has been investigated by carrying out environmental and exergetic sustainability assessments of the power plant with a 400 MWe CCS unit as well. The transport of the materials needed for constructing the CCS unit was modelled analogous to the transport of the other materials needed for constructing the power plant described in the ecoinvent database. The construction of the 5 km onshore and 20 km offshore pipelines was modelled on the ecoinvent processes "pipeline, natural gas, long distance, high capacity" onshore and offshore pipelines,[34] which have been modified in accordance with the information about the pipelines to be used in the ROAD project.[35] The construction of the platform needed for the injection of the carbon dioxide is not included in the assessment as the ROAD project describes the use of an existing platform.

The investment costs of the CCS unit equal about €450 million.[29] The total investment costs related to 1 PJ of electricity generation amount to €79 million. The OpEx of the 1 PJ power system have been calculated at €2.8 million per year, which is based on the investment costs of the power plant itself and the reported additional OpEx of the CCS unit. The credits that can be obtained by selling the rights not needed for carbon dioxide emission, which is in line with the European Union carbon dioxide emission trading system, were set at €20 per ton. This is a reasonable price although the current price is much lower because of an abundance of emission rights.

3.3 | Biomass-fired power plant

The biomass-fired power plant is based on unit 8 of the Amercentrale power plant located in Geertruidenberg, Netherlands,[36] which normally co-fires coal and about 30 mass% biomass. It has a capacity of 645 MWe and 250 MWth. The transformation of this unit into a 100% biomass-fired power plant results in a power plant with an electrical efficiency of 39%, which produces 17 PJ of electricity and 8 PJ of heat per year.[37] The biomass, ie, wood pellets, is assumed to originate from Georgia (USA).[5] The model of this modified power plant is an improved version of the model developed by Giustozzi.[38] Table 3 shows the inputs and outputs.

The investment costs of unit 8 of the Amercentrale power plant, its conversion to a 100% biomass-fired power plant plus the wood pellet plant are estimated at €977 million and equal €77 million when related to 1 PJ of electricity production. A subsidy by the Dutch government of €35.3 million per year, related to 1 PJ of electricity, is taken into account during the first 15 years of operation. The OpEx of the combined system have been calculated at €2.4 million per year for a 1 PJ power system. The price of wood pellets is assumed to be €120 per ton.[38]

3.4 | Offshore wind farm

The offshore wind farm is a model of the planned offshore wind farms named Borssele I and II, located near Borssele, Netherlands, which will be taken into operation in 2019.[39] The effective areas of the sites equal 49 and 63 km^2, respectively. Giustozzi[38] developed the model of the offshore wind farm that is used for the sustainability assessment of this system. According to this model, each site comprises 95 offshore wind turbines of the Siemens SWT-4.0-130 type[40] with a capacity of 4 MW each, which are the same wind turbines as applied in the Gemini offshore wind farm in the Netherlands.

The investment costs amount to €2 billion, ie, €162 million per PJ, and a subsidy of €0.086 per kWh by the

TABLE 3 Inputs and outputs of the biomass-fired power plant related to the production of 1 PJ of electricity

Name	Unit	Amount
Wood pellets	million m^3	0.23
CO_2 (biogenic)	Mton	0.22
CO (biogenic)	kton	1.2
NO_x	kton	0.47
PM10	ton	35
Total organic carbon[a]	ton	12
Waste heat (flue gases)	PJ	0.65
Waste heat (water)	PJ	0.22
Slags and ashes	kton	1.5

[a]Organic components in the flue gas measured as carbon.

Dutch government during the first 15 years is considered.[38]

3.5 | Photovoltaic park

The photovoltaic park is modelled on the largest solar park in the Netherlands, ie, the Sunport Delfzijl, which was taken into operation on 19 January 2017.[41] The capacity of this solar park equals about 30 MW and it consists of about 123 000 modules of the CS69-265P type with a capacity of 265 Wp.[42] The model of the photovoltaic park by Giustozzi[38] including a few adaptations made on the basis of new information about the solar park was used for the sustainability assessments.

The investment costs for this photovoltaic park amount to €30 million. As described in section 2.2, this leads to €124 million per PJ of electricity generation. Furthermore, a subsidy by the Dutch government of €0.084 per kWh during the first 15 years is considered.[38]

4 | RESULTS AND DISCUSSION

The results of the environmental sustainability assessment are presented in Tables 4 and 5. Table 4 presents the results including infrastructure processes and Table 5 presents the results without infrastructure processes. It is learnt from a comparison of Tables 4 and 5 that the environmental sustainability of the offshore wind farm and the photovoltaic park is mainly caused by infrastructure processes, which is understandable because of the nature of the energy sources they use during operation, ie, wind and solar energy, respectively. The environmental impact of using coal and biomass as an energy source is much higher and results in a small difference between the results of the environmental sustainability assessment with and without infrastructure processes. As reported in Tables 4 and 5, the environmental sustainability scores of the MPP3 systems with and without CCS are comparable to each other and are worse than the environmental sustainability score of the three systems that generate power from renewable energy sources. Both tables present the results of the MPP3 with a 250 MWe CCS unit. It was calculated that the environmental performance of the MPP3 with a 400 MWe CCS unit would be only negligibly worse. Similar results were calculated for a plant fed by natural gas with and without CCS.[43] The biomass-fired power plant outperforms the coal-fired systems, but the ReCiPe scores of the offshore wind farm and photovoltaic park are considerably lower than the scores of the coal-fired and biomass-fired power plants. The system that is preferred from the environmental sustainability point of view is the wind farm system.

The inputs and outputs of the MPP3 system with a CCS unit that treats the total amount of flue gases instead of only 23 vol% have been estimated from the data about the coal-fired power plant with CCS. It was assumed that the amount of carbon dioxide captured, the decrease in net electricity consumption and the amount of materials needed for constructing the CCS unit are all linear. The amount of extra electricity needed to compress the captured carbon dioxide to a pressure of 175 bar instead of

TABLE 4 Results of the environmental sustainability assessment of the systems including infrastructure

Damage Category (MPt)[a]	MPP3	MPP3 with CCS	Biomass	Wind	Solar
Human health	8.6	8.0	2.7	0.19	0.74
Ecosystems	4.5	4.0	7.9	0.070	0.75
Resources	6.2	6.6	1.5	0.25	0.61
ReCiPe total	19	19	12	0.51	2.1

Abbreviation: CCS, carbon capture and storage.

[a]The damage category results have already been weighted on the basis of the selected ReCiPe average weighting set.

TABLE 5 Results of the environmental sustainability assessment of the systems excluding infrastructure

Damage Category (MPt)[a]	MPP3	MPP3 with CCS	Biomass	Wind	Solar
Human health	8.4	7.7	2.5	0.0019	0.20
Ecosystems	4.3	3.8	7.7	0.0010	0.51
Resources	6.1	6.4	1.2	0.0029	0.15
ReCiPe total	19	18	11	0.0058	0.86

Abbreviation: CCS, carbon capture and storage.

[a]The damage category results have already been weighted on the basis of the selected ReCiPe average weighting set.

128 bar has been considered as well, as the pipelines have the capacity to transport 5 Mton of carbon dioxide per year at 175 bar.[35] The resulting environmental sustainability score equals 14 MPt for the system including infrastructure processes. The performance of this total CCS system is better than that of the coal-fired power plants of Tables 4 and 5 but worse than the biomass-fired system.

Table 6 shows the results of the economic sustainability assessment of the power generation systems. Of the systems that make use of renewable energy sources, the results with and without taking into account subsidy are presented. The MPP3 without CCS is not subsidised and the amount of subsidy to be received by the MPP3 with CCS system is unclear and therefore not included in Table 6. As reported in Table 6, the systems that use renewable energy sources are not profitable without subsidy. The profitability of the MPP3 with CCS system depends on subsidy and the credits obtained from selling carbon dioxide emission rights, ie, the rights obtained from the government that are not needed because of applying CCS are sold. Assuming that the construction of the CCS unit is fully subsidised, the PWR would equal 0.34, which is about the same as the PWR of the MPP3 without CCS, but at the moment, the carbon dioxide credits are (much) lower than the €20 per ton used in this calculation. According to the results, the biomass system is preferred from an economic sustainability point of view, followed by the photovoltaic park and offshore wind farm systems. However, the costs of especially the latter two systems are declining rapidly, which makes it difficult to draw firm conclusions about which system is the most profitable.

The results of the exergetic sustainability assessment of the five systems are summarised in Tables 7 and 8, including and excluding infrastructure processes, respectively. The CExD of the MPP3 with CCS system is higher than the CExD of the MPP3 system, which can be explained by the larger fuel consumption. As the carbon dioxide emission of the system with CCS is lower, the abatement exergy loss is lower as well. Overall, this results in almost the same exergetic sustainability scores of both power plants. Thus, the exergetic sustainability of the systems is hardly influenced by the construction of the CCS unit. The exergetic sustainability of the MPP3 with a 400 MWe instead of a

TABLE 6 Results of the economic sustainability assessment of the systems including infrastructure

(M€)	MPP3[a]	MPP3 with CCS[b]	Biomass	Wind	Solar
Including subsidy					
NPV			156	110	170
PWR			2.2	0.73	1.5
Excluding subsidy					
NPV	16	−2.5	−103	−65	−0.69
PWR	0.32	−0.038	−1.5	−0.43	−0.0060

Abbreviations: CCS, carbon capture and storage; NPV, net present value; PWR, Present Worth Ratio.

[a]The MPP3 system is not subsidised.

[b]The possible amount of subsidy received by the MPP3 with CCS system is unknown.

TABLE 7 Results of the exergetic sustainability assessment of the systems including infrastructure

(PJ)	MPP3	MPP3 with CCS	Biomass	Wind	Solar
CExD	2.7	2.9	4.0	1.1	1.4
Exergy of product	1.0	1.0	1.0	1.0	1.0
Exergy of emissions	0.38	0.38	0.52	0.018	0.086
Internal exergy loss[a]	1.3	1.5	2.4	0.13	0.29
Abatement exergy loss	1.4	1.2	0.27	0.020	0.077
Exergy loss land use	0.035	0.037	0.072	7.5e-4	0.20
TCExL[b]	2.7	2.8	2.8	0.15	0.57

Abbreviations: CCS, carbon capture and storage; CExD, Cumulative Exergy Demand; TCExL, Total Cumulative Exergy Loss.

[a]The internal exergy loss is calculated as the exergy input minus the exergy output in the form of products and emissions/waste flows.

[b]The TCExL is the summation of the internal exergy loss, the abatement exergy loss and the exergy loss related to land use.

TABLE 8 Results of the exergetic sustainability assessment of the systems excluding infrastructure

(PJ)	MPP3	MPP3 with CCS	Biomass	Wind	Solar
CExD	2.6	2.8	3.9	1.1	1.1
Exergy of product	1.0	1.0	1.0	1.0	1.0
Exergy of emissions	0.36	0.35	0.50	1.9e − 4	0.035
Internal exergy loss[a]	1.3	1.4	2.4	0.076	0.037
Abatement exergy loss	1.4	1.2	0.24	3.5e − 4	0.022
Exergy loss land use	0.029	0.031	0.059	2.3e − 7	0.20
TCExL[b]	2.7	2.7	2.7	0.076	0.26

Abbreviations: CCS, carbon capture and storage; CExD, Cumulative Exergy Demand; TCExL, Total Cumulative Exergy Loss.

[a]The internal exergy loss is calculated as the exergy input minus the exergy output in the form of products and emissions/waste flows.

[b]The TCExL is the summation of the internal exergy loss, the abatement exergy loss and the exergy loss related to land use.

250 MWe CCS unit would only be negligibly higher when considering the systems including infrastructure. As expected, the results of the systems without infrastructure processes are not influenced at all by the amount of materials used for constructing the CCS unit.

The higher CExD of the biomass-fired power plant compared with the CExD of the coal-fired power plants also results in a higher internal exergy loss caused by the biomass-fired power plant. This can be explained by the lower electrical efficiency of the biomass-fired power plant, ie, about 39% versus about 46% electrical efficiency of the coal-fired power plant without CCS. The abatement exergy loss of the biomass system is considerably lower than that of the two MPP3 systems, which is understandable as its carbon dioxide emission of fossil origin amounts to less than 20% of the emission caused by the MPP3 systems and also because the abatement exergy loss is mainly caused by the abatement of carbon dioxide emissions from fossil origin (and to a smaller extent by the abatement of the other emissions included in the calculation of the abatement exergy, ie, nitrogen oxides, sulfur dioxide and phosphate). The abatement exergy loss caused by the wind farm and the photovoltaic park is small, but not zero as these systems cause emissions during their life cycle that need to be abated, such as carbon dioxide from fossil origin.

Tables 7 and 8 show as well that the TCExL scores of the coal-fired and biomass-fired systems are higher than those of the offshore wind farm and photovoltaic park systems. From the exergetic sustainability point of view, the offshore wind farm is preferred, but its TCExL score is only a little lower than that of the photovoltaic park. The same order of preference of the systems is obtained regardless of whether the systems are assessed with or without infrastructure processes.

The relative contribution of the three elements of the TCExL to its overall value can be considerably different, as shown in Table 9, and is strongly related to the intrinsic characteristics of each system. Nevertheless, it should be kept in mind that the abatement exergy loss is calculated with the limitation that only carbon dioxide from fossil fuels, nitrogen oxides, sulfur dioxide and phosphate are considered, as information about the contribution of other pollutants has not yet been discovered in literature. However, this simplification does not have a great impact on the results, because carbon dioxide, nitrogen oxides and sulfur dioxide are by far the largest emissions.

The exergetic sustainability of a coal-fired power plant in which the total amount of flue gases is treated in a CCS unit has been calculated on the basis of the aforementioned estimate of the inputs and outputs of this power plant. This MPP3 with total CCS has a TCExL score of 2.6 PJ, which is a little lower than the scores of the MPP3 with and without CCS mentioned before. It seems that a maximum exists because the TCExL score of the MPP3 with CCS is slightly higher (not visible in Table 8)

TABLE 9 Relative contribution of the components to the TCExL score of the systems including infrastructure

(%)	MPP3	MPP3 with CCS	Biomass	Wind	Solar
Internal exergy loss	48	54	88	86	51
Abatement exergy loss	51	45	10	14	13
Exergy loss land use	1	1	3	1	36
Total	100	100	100	100	100

Abbreviations: CCS, carbon capture and storage; TCExL, Total Cumulative Exergy Loss.

than the TCExL score of the MPP3. However, the difference between the TCExL scores of the MPP3 with and without CCS is small and these calculations are based on many assumptions.

The abatement exergy value of carbon dioxide has been checked by comparing the results of the exergetic sustainability assessment of the MPP3 systems without, with partial and total CCS. Hereto, the increase of internal exergy loss per amount of carbon dioxide captured has been calculated. This resulted in 6.24 and 4.99 MJ internal exergy loss per kilogram of captured carbon dioxide for the MPP3 with partial CCS and MPP3 with total CCS, respectively, which is of the same order of magnitude as the 5.86 MJ/kg originating from literature that is used in this research.

Summarising, the results of the environmental and exergetic sustainability assessment are more or less comparable as the offshore wind farm is the preferred system and the photovoltaic park is second best. The difference among the ReCiPe scores of the systems is larger than the difference between the TCExL scores of the power generation systems. The environmental sustainability assessment indicates that the biomass-fired power plant performs better than the coal-fired power plants with and without CCS, but the difference among the TCExL scores of the coal-fired and biomass-fired power plants is too small to decide which system performs better. The results of the economic sustainability assessment are largely influenced by whether these systems receive subsidy or not. Without subsidy, the MPP3 without CCS is the only profitable system. Of the three systems that make use of renewable energy sources, the biomass power plant appears to be the preferred system when taking into account subsidy, but it would be the least-preferred system of all five systems when subsidy is not considered.

5 | CONCLUSIONS AND RECOMMENDATIONS

The offshore wind farm system has the best environmental and exergetic sustainability scores of the five systems that have been assessed. The second-best system is the photovoltaic park. This applies to the results including infrastructure processes as well as the results excluding infrastructure processes. The environmental sustainability of the biomass-fired system lies in between the performance of the offshore wind farm and photovoltaic park at the one hand and the coal-fired power plants at the other hand. The exergetic sustainability of the biomass-fired power plant is comparable to the coal-fired power plants.

The three systems that make use of renewable energy sources, ie, the biomass power plant, the offshore wind farm and the photovoltaic park, are not profitable without subsidy. The same holds for the coal power plant with CCS assuming that the carbon dioxide credits equal €20 per ton. When the subsidy by the Dutch government is taken into account, the biomass power plant is the system with the highest economic sustainability score and the photovoltaic park performs second best, followed by the offshore wind farm system as the third system. The coal power plant without CCS does not need subsidy to be profitable. The profitability of the coal power plant with CCS not only depends on subsidy but also on the credits obtained from selling carbon dioxide emission rights. Assuming that the construction of the CCS unit is fully subsidised, the PWR of the MPP3 with CCS would equal 0.34.

The results of the environmental, economic and exergetic sustainability assessment are not unanimous about the preference of the biomass-fired system compared with the coal-fired systems.

From an environmental and exergetic sustainability point of view, the difference between the results of the coal-fired power plants with and without CCS is very small. The environmental sustainability score of a total CCS system would be in between the scores of the coal-fired and biomass-fired power plants. The resulting exergetic sustainability score of this total CCS system would be about the same as the score of the other coal-fired power plants. It is concluded that more research into the advantages and disadvantages of CCS is needed. As exergy is required for all processes and activities to occur and the exergetic sustainability assessment is based on thermodynamic laws while the environmental sustainability uses models and weighting factors and the economic sustainability is influenced by market prices, subsidy, etc, it is advisable that attention be paid to the exergetic sustainability of systems for power generation. Preferably by calculating the TCExL score as it considers the total loss of exergy caused by a technological system during its life cycle.

ORCID

Lydia Stougie http://orcid.org/0000-0002-0351-1995
Anna Stoppato http://orcid.org/0000-0001-6986-872X

REFERENCES

1. Dincer I, Rosen MA. *Exergy: Energy, Environment and Sustainable Development*. Amsterdam: Elsevier Ltd.; 2013.
2. Hammond GP. Engineering sustainability: thermodynamics, energy systems and the environment. *Int J Energy Res.* 2004;28(7):613-639.
3. Al-Zareer M, Dincer I, Rosen MA. Assessment and analysis of hydrogen and electricity production from a Generation IV lead-

cooled nuclear reactor integrated with a copper-chlorine thermochemical cycle. *Int J Energy Res.* 2018;42(1):91-103.

4. Ozlu S, Dincer I. Analysis and evaluation of a new solar energy-based multigeneration system. *Int J Energy Res.* 2016;40(10):1339-1354.
5. Stougie, L. Exergy and sustainability—Insights into the value of exergy analysis in sustainability assessment of technological systems [PhD thesis]. Delft, Netherlands: Delft University of Technology; 2014.
6. Stougie L, Giustozzi N, Van der Kooi H, Stoppato A. Sustainability assessment of power generation from fossil and renewable energy sources by applying the Total Cumulative Exergy Loss method. In: Nizetic S, Solic P, Milanovic Z, eds. *Proceedings of the 9th International Exergy, Energy and Environment Symposium (IEEES-9)*, 14–17 May 2017. Split: Croatia; 2017:853-859.
7. PRé Consultants, Amersfoort, Netherlands. SimaPro LCA software, https://www.pre-sustainability.com/simapro.
8. Ecoinvent Centre (Swiss Centre for Life-Cycle Inventories) St-Gallen, Switzerland. Ecoinvent database, http://www.ecoinvent.org.
9. Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J, Van Zelm R. *ReCiPe 2008, A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level, Report I: Characterisation*. The Hague, Netherlands: Ministry of Housing, Spatial Planning and Environment; 2009.
10. Guinée JB, Gorrée M, Heijungs R, et al. Handbook on life cycle assessment. Operational guide to the ISO standards. *I: LCA in perspective IIa: Guide IIb: Operational annex III: Scientific background* Dordrecht, Netherlands: Kluwer Academic Publishers; 2002.
11. Goedkoop M, Spriensma R. *The Eco-indicator 99. A damage oriented method for life cycle impact assessment. Methodology report and annex*. Pré Consultants: Amersfoort, Netherlands; 1999.
12. Adekunle SE. Applying integrated project-management methodology to hydrocarbon-portfolio analysis and optimization. *JPT*. 2007;59(02):44-49.
13. Remer DS, Nieto AP. A compendium and comparison of 25 project evaluation techniques. Part 2: ratio, payback, and accounting methods. *Int J Prod Econ*. 1995;42(2):101-129.
14. Biezma MV, San Cristobal JR. Investment criteria for the selection of cogeneration plants—a state of the art review. *Appl Therm Eng*. 2006;26(5):583-588.
15. Warringa G, Blom M, Bles M. MKBA Windenergie Flevoland, [Cost Benefit Analysis Wind Energy Flevoland, in Dutch], CE Delft, Report No. 12.7590.21; 2012.
16. Zicht op Energie, Actuele elektriciteitsprijzen in 2012 voor kalenderjaren 2013–2017, [Current electricity prices in 2012 for the years 2013–2017, in Dutch]. http://www.zichtopenergie.nl/index.php?option=com_content&view=article&id=15&page=prijsontwikkeling&Itemid=40. Accessed August 23, 2017.
17. Dewulf J, Van Langenhove H, Dirckx J. Exergy analysis in the assessment of the sustainability of waste gas treatment systems. *Sci Total Env*. 2001;273(1–3):41-52.
18. Dewulf J, Bösch M, De Meester B, et al. Cumulative Exergy Extraction from the Natural Environment (CEENE): a comprehensive life cycle impact assessment method for resource accounting. *Environ Sci Technol*. 2007;41(24):8477-8483.
19. Cornelissen RL. Thermodynamics and sustainable development; the use of exergy analysis and the reduction of irreversibility [PhD thesis]. Enschede, Netherlands: Twente University; 1997.
20. Stougie L, Van der Kooi HJ. Possibilities and consequences of the Total Cumulative Exergy Loss method in improving the sustainability of power generation. *Energy Convers Manage*. 2016;107(1):60-66.
21. Bösch ME, Hellweg S, Huijbregts MAJ, Frischknecht R. Applying Cumulative Exergy Demand (CExD) indicators to the ecoinvent database. *Int J LCA*. 2007;12(3):181-190.
22. Szargut J. *Appendix 1.* Standard chemical exergy, *Egzergia. Poradnik obliczania I stosowania*. Gliwice: Widawnictwo Politechniki Shlaskej; 2007.
23. Dewulf J, Van Langenhove H, Mulder J, Van den Berg MMD, Van der Kooi HJ, De Swaan Arons J. Illustrations towards quantifying the sustainability of technology. *Green Chem*. 2000;2(3):108-114.
24. Van der Vorst G, Dewulf J, Van Langenhove H. Developing sustainable technology: metrics from thermodynamics. In: Bakshi BR, Gutowski T, Sekulic D, eds. *Thermodynamics and the Destruction of Resources*. Cambridge: Cambridge University Press; 2011:249-264.
25. Haberl H, Erb KH, Krausmann F, et al. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *Proc Natl Acad Sci*. 2007;104(31):12942-12947.
26. Alvarenga RA, Dewulf J, Van Langenhove H, Huijbregts MA. Exergy-based accounting for land as a natural resource in life cycle assessment. *Int Journal LCA*. 2013;18(5):939-947.
27. Uniper, MPP3 [in Dutch], http://www.energyhubwest.nl/energy-hub-west#!/mpp3-centrale. Accessed January 31, 2017.
28. Kema, *Milieu-effectrapport 1100 MWe kolengestookte centrale Maasvlakte* [Environmental effect report 1100 MWe coal-fired power plant Maasvlakte, in Dutch], E.ON Benelux N.V., report No. 50662145-Consulting 06–1037, http://api.commissiemer.nl/docs/mer/p17/p1745/1745-041mer_001.pdf; 2006.
29. Rooijers F, Croezen H, Blommerde J. *CO_2-reductie bij een moderne kolencentrale* [CO_2 decrease at a modern coal power plant, in Dutch], CE Delft, Report No. 16.3J22.89; 2016.
30. CBS, Statistics Netherlands. *Ketelkolen; invoerprijs uit niet EU-landen, 09 februari 2017* [Steam coal; import price from non-EU countries, 09 February 2017, in Dutch]. http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=37215&D1=0–2&D2=(l-11)-l&VW=T. Accessed February 9, 2017.
31. Royal Haskoning, *Milieueffectrapportage CCS Maasvlakte (ROAD-project), Samenvattend hoofdrapport MER ROAD* [Environmental impact report CCS Maasvlakte (ROAD project), Main report, in Dutch], Report No. 9V7319.20/R0010_rev9/903423/ILAN/Rott. http://www.rvo.nl/sites/default/files/sn_bijlagen/bep/70-Opslagprojecten/ROAD-project/Fase1/2_MER/MER-samenvatting-en-hoofdrapport-1-353748.pdf; 2011.

32. Royal Haskoning, *Milieueffectrapportage CCS Maasvlakte (ROAD project), Deelrapport Afvang*, [Environmental impact report CCS Maasvlakte (ROAD project), Capture report, in Dutch] Report No. 9V7319.20. http://www.rvo.nl/sites/default/files/sn_bijlagen/bep/70-Opslagprojecten/ROAD-project/Fase1/2_MER/MER-deelrapport-afvang-incl-bijlagen-1-353749.pdf; 2011.
33. Kleijn R, Van der Voet E, Kramer GJ, Van Oers L, Van der Giesen C. Metal requirements of low-carbon power generation. *Energy*. 2011;36(9):5640-5648.
34. Faist Emmenegger M, Heck T, Jungbluth N, Tuchschmid M. Erdgas. In: Dones R et al., eds. *Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. Final report ecoinvent No. 6-V*. Dübendorf, Switzerland: Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories; 2007.
35. Royal Haskoning, *Milieueffectrapportage CCS Maasvlakte (ROAD project), Deelrapport Transport*, [Environmental impact report CCS Maasvlakte (ROAD project), Transport report, in Dutch] Report No. 9V7319.20. Available at: http://www.rvo.nl/sites/default/files/sn_bijlagen/bep/70-Opslagprojecten/ROAD-project/Fase1/2_MER/MER-deelrappport-transport-incl-bijlagen-1-353745.pdf; 2011.
36. RWE, Amercentrale [in Dutch], http://www.rwe.com/web/cms/nl/1771654/rwe-generation-se/brandstoffen/overzicht-locaties/nederland/amercentrale/. Accessed January 31, 2017.
37. Warringa GEA, Vergeer R, Croezen HJ, Rooijers FJ, De Bruijn SM. Alternatieven voor biomassameestook in kolencentrales. Onderzoek naar de subsidiekosten en overige effecten van alternatieve maatregelen voor het Energieakkoord [Alternatives for biomass co-firing in coal power plants, in Dutch], CE Delft, Report No. 16.7I44.10; 2016.
38. Giustozzi N. Exergy analysis and sustainability assessment of renewable energy systems by means of the Total Cumulative Exergy Loss method [master's thesis]. http://tesi.cab.unipd.it/53434/. Padova, Italy: University of Padova; 2016.
39. NEA (Netherlands Enterprise Agency), Borssele wind farm zone—wind farm sites I and II, project and site description, version 2. https://www.rvo.nl/sites/default/files/2015/09/33953992.pdf; 2015.
40. Siemens, Wind turbine SWT-4.0-130. Technical specifications. https://www.siemens.com/content/dam/internet/siemens-com/global/market-specific-solutions/wind/data_sheets/data-sheet-wind-turbine-swt-4.0-130.pdf; 2016.
41. Groningen Seaports, Grootste zonnepark van Nederland officieel in gebruik! [Largest solar park of the Netherlands officially in operation!, in Dutch]. https://www.groningen-seaports.com/nieuws/grootste-zonnepark-van-nederland-officieel-in-gebruik/. Accessed January 24, 2017.
42. Canadian Solar Inc., PV module product datasheet V5.531_EN. http://www.canadiansolar.com/fileadmin/user_upload/downloads/datasheets/v5.531/canadian_solar-datasheet-CS6P-P-v5.531en.pdf; 2017.
43. Hammond GP, Ondo Awke SS. Thermodynamic and related analysis of natural gas combined cycle power plants with and without carbon sequestration. *Int J Energy Res.* 2007;31(12):1180-1201.

How to cite this article: Stougie L, Giustozzi N, van der Kooi H, Stoppato A. Environmental, economic and exergetic sustainability assessment of power generation from fossil and renewable energy sources. *Int J Energy Res*. 2018;42:2916–2926. https://doi.org/10.1002/er.4037