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Environmental performance assessment of utility boiler energy conversion systems

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ABSTRACT

A significant amount of global electric power generation is produced from the combustion of fossil fuels. Steam boilers are one of the most important components for steam and electricity production. The objective of this paper is to establish a theoretical framework for the sustainability analysis of a utility boiler. These analyses can be used by decision-makers to diagnose and optimize the sustainability of a utility boiler. Seven utility boiler systems are analyzed using energy and embodied solar energy (emergy) principles in order to evaluate their environmental efficiencies. They include a subcritical coal fired boiler, a supercritical coal fired boiler, an oil fired boiler, a natural gas fired boiler, a concentrating solar power boiler utilizing a tower configuration, a biomass boiler, and a refuse derived fuel boiler. Their relative environmental impacts were compared. The results show that the natural gas boiler has significantly lower CO_2 emission than an equivalent coal or oil fired boiler. The refuse derived fuel boiler has about the same CO_2 emissions as the natural gas boiler. The emergy sustainability index of a utility boiler system is determined as the measure of its sustainability from an environmental perspective. Our analyses results indicate that the natural gas boiler has a relatively high emergy sustainability index compared to other fossil fuel boilers. Converting existing coal boilers to natural gas boilers is a feasible option to achieve better sustainability. The results also show that the biomass boiler has the best emergy sustainability index and it will remain a means to utilize the renewable energy within the Rankine steam cycle. Before solar boiler technology can be widely used in the United States' utility power industry, its capital cost and the O&M cost should be reduced. Using the results of this research, decision-makers can make better-informed, environmentally-efficient selections of future utility scale boilers.

1. Introduction

Significant amounts of global electric power generation are derived from fossil fuel fired boilers. A steam generating unit or simply a boiler is a major component of a thermal power plant and thus has attracted a tremendous research interest particularly due to the worldwide concern about greenhouse gas emission and the sustainability in electricity production [1]. Conventional fossil fuel fired utility boilers has been widely used in past decades. Renewable energy based utility boilers have also seen increased implementation over the past several years. The unique design challenges of SRSG are discussed [2]. Predicted unit performance and process descriptions are presented, as well as the engineering design achievements and first of kind concepts. Combustion issues encountered with biomass co-firing on a 500 MW down fired utility boiler are described [3]. The biomass particle size and physical properties are studied and the flame stability and slagging are reviewed. The results indicate that the air flow around the injectors plays an important role in the boiler operation. Conventional exergy analysis and advanced exergy analysis are performed on a biomass boiler [4]. The sources of inefficiency and irreversibility are recognized. The results show that the maximum exergy destruction occurs in furnace. The fuel-saving strategies are also discussed. A new mechanism has been proposed to integrate solar–coal hybridization system effectively [5]. This mechanism is validated by simulation results of a mid and low temperature solar-hybridization system. A numerical study of a 13 MW_{th} waste wood-fired boiler is presented [6]. To better address the effects of the elevated CO_2 and H_2O concentrations on radiative heat transfer in the boiler, a refined weighted-sum-of-grey-gases-model is used in the study.

To evaluate system sustainability performance an emergy method was developed [7]. The emergy method, which is considered to be "energy memory", was defined as the available energy previously used directly or indirectly to make a product. Emergy

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Nomenclature

F	feedback from society (seJ/unit)
m	mass (kg)
N	nonrenewable input (seJ/unit)
P	pressure (bar)
Q	heat (J)
R	renewable input (seJ/unit)
T	temperature (K)
U	total solar emergy (seJ)
Y	yield ($R + N + F$) (seJ/unit)

Abbreviations

AH	air heater
bar	bar, absolute
CDN	condenser
ELR	environmental load ratio
ESI	emergy sustainability index
EYR	emergy yield ratio
EIA	energy information administration
EF	efficiency
EC	economizer
EA	excess air
EPA	environmental protection agency
FEGT	furnace exit gas temperature
FG	flue gas
GN	generator
GNP	gross national product
HTR	heater
HP	high pressure
IP	intermediate pressure
LP	low pressure
MCR	maximum continuous rating
O&M	operations & maintenance
QrO	total heat output
RH	reheater
RDF	refuse derived fuel
SRSG	solar receiver steam generator
SH	superheater
Tr	transformity (defined in Section 2.3)
WW	waterwall

theory expresses all the different process inputs and outputs, such as energy, fuel, labor, money, and natural resources, in terms of solar energy equivalents. In order to do so, different system inputs will go through a conversion process to emergy units using transformity. The transformity is defined as the solar emergy required to provide a unit of a product or service. The emergy method has been used to evaluate sustainability performance in different application categories. These categories include the energy industry, building service engineering, and information and services.

The use of biomass as a fuel in a district heating system is studied [8]. The environmental impacts of building service engineering using the emergy method is evaluated [9], finding that the method used to generate electric power in an energy source plays an important role in determining the overall environmental performance. An analysis where Malaysia's transportation sector would replace fossil fuels with palm oil based fuel is presented [10]. The results show a low ESI for palm oil based fuel. However, it is an option if shortages of conventional fuels precipitate a future energy crisis. Their conclusion is based on the fact that only 8% of the available agricultural area would be sufficient to all fuel requirements for the transportation sector. Six different electricity generation systems are evaluated based on their thermodynamic and environmental efficiency [11]. The paper concluded that systems using renewable energy are more sustainable than fossil fuel based systems. To account for the costs and benefits of waste management, some changes are proposed for the traditional emergy indices [12]. The new indices were applied to a polyethylene production process. The results show that they provide a conceptually sound basis to evaluate the impacts of waste management investment and emissions. Life cycle assessment and emergy assessment of a 20 MW dry steam geothermal power plant are performed [13]. The results indicate that the generation of 1 kW h of electricity releases 248 g of CO_2, which is much less than that produced by fossil powered electricity. They also presented the environmental impacts associated with the direct utilization of a geothermal fluid. The low heat-to-electricity conversion efficiency further elevates the environmental impact compared to other renewable sources. A Mixed-Integer Non-linear Programming (MINLP) model is developed to help the decision-maker select the most sustainable design [14]. The emergy sustainability index was used in the model as the single objective. The model considered multiple feedstocks, multiple transportation models and multiple regions for building biodiesel plants and distribution centers. A demonstration case shows the proposed model is able to help the decision-makers find the most sustainable design.

Other researchers have also conducted emergy analysis on various thermal systems. Environmental performance evaluation of retrofitting coal fired power plants to co-firing with biomass is performed [15]. Carbon footprint and emergy approach are used in the paper. The results indicate that the addition of 20% biomass to the combustion mixture will reduce the CO_2 by 11–25% and total emergy flow by 8–15%. Emergy method is used to evaluate a combined heat and power cogeneration processes [16], finding that the biomass-based cogeneration is 3.3 times more emergy-efficient than coal-based production. The results also indicate that the sustainability index for biomass is 15 times higher than coal. Environmental sustainability of a combined heat and power plant is evaluated [17], indicating that the reservoir is suitable for a long-term exploitation of the designed system. The result also shows that the system based on a hybrid geothermal–solar solution is an environmentally sound application.

Due to the complexity of the sustainability development and the availability of fuel, much more efforts are needed to study and ensure utility boiler's sustainability. Based on the efforts in the literatures, this paper presents a theoretical framework for the environmental evaluation of a utility boiler. These analyses can be used for decision-makers to diagnose and optimize the sustainability of a utility boiler. The novelty is twofold. The first is the environmental evaluation and embodied solar energy method, which has not been used for boiler analysis in the literatures. The second is the comprehensiveness of the studied utility boilers, which cover most of the boiler systems with the Rankine cycle.

2. Methods

2.1. Energy analysis

The conventional energy analysis will not be discussed in this paper. The boiler fuel efficiency can be calculated using the equation from ASME PTC 4 as follows: [18]