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# Environmental impacts and benefits of organic Rankine cycle power generation technology and wood pellet fuel exemplified by electric arc furnace steel industry

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## HIGHLIGHTS

- Application of ORC and wood pellet fuel in an EAF was evaluated by real plant data.
- Environmental impacts and benefits were quantified using a cradle-to-gate approach.
- Benefit cost ratio of ORC and wood pellet were determined by cost benefit analysis.
- Environmental benefits from wood pellet fuel were higher than ORC power generation.
- ORC exhibited superior potentials on the capital and O&M costs to wood pellet fuel.

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## ABSTRACT

Iron- and steel-mill manufacturing are the material- and energy-intensive industries in the world, accounting for 22% of total industrial energy use in 2011; thereby leading to significant carbon dioxide ($CO_2$) emissions. In this study, the environmental impacts and benefits for the applications of organic Rankine cycle (ORC) power generation and wood pellet fuel in the electric arc furnace (EAF) steel industry were evaluated using a cradle-to-gate life-cycle approach. The business-as-usual scenario of the EAF manufacturing was first established, and then compared with the scenarios of ORC facility and wood pellet fuel. The system boundary of heavy fuel oil production includes resource extraction, refining and processing, and transportation. The inventory data used in life cycle assessment were gathered from the information of real plant operation. The results indicated that both the ORC facility and replacement of heavy fuel oil by wood pellet fuel can mitigate the environmental impacts on ecosystems, human health and resource depletion. The environmental benefits of integrating the ORC power generation in an EAF steelmaking plant were less than those of applying wood pellet fuel for reheating furnace. However, the benefit-cost ratio of ORC process was greater than that of wood pellet fuel because the capital, and operation and maintenance costs of ORC process were lower than that of wood pellet fuel process.


## 1. Introduction

Since the 18th century, $CO_2$ emissions have increased dramatically due to the increasing energy demands from the iron/steel-making and cement industries. Worldwide $CO_2$ emissions reached approximately 31.3 Gt in 2011 [1]. Mitigating $CO_2$ emission requires a portfolio of complementary technologies to (1) improve energy efficiency, (2) explore renewable energies, and (3) execute carbon capture, utilization and storage technologies [2–4]. Consequently, both "energy efficiency improvements" and "renewable energies" are the crucial components toward a more sustainable energy system, that may contribute to approximately 77% of global $CO_2$ emission reductions by 2050 [3,5].

It was noted that nearly half of the 123 Gt $CO_2$ emissions should be reduced between 2015 and 2050 via greenhouse gas (GHG) mitigation actions and industrial development around the world [6]. Iron- and steel-mill manufacturing are the second most energy-intensive industries in the world, which account for 22% of total industrial energy use in 2011 [5], leading to significant $CO_2$ emissions and waste generation [7,8]. Currently, world crude steel

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**Nomenclature**

*Environmental impacts*
ACP acidification (molc $H^+$ eq)
CCP climate change potential (kg $CO_2$ eq)
FEU freshwater eutrophication (kg P eq)
FET freshwater ecotoxicity (CTUe)
GWP global warming potential (kg $CO_2$ eq)
HTCN human toxicity, cancer effect and non-cancer effect (CTUh)
IRH ionizing radiation, human health (kBq U235 eq)
IRE ionizing radiation, ecosystems (CTUe)
LUS land use (kg C deficit)
MEU marine eutrophication (kg N eq)
MFRD mineral, fossil & renewable resource depletion (kg Sb eq)
ODP ozone depletion potential (kg CFC-11 eq)
PMF particulate matter formation (kg $PM_{2.5}$ eq)
POF photochemical ozone formation (kg NMVOC eq)
TEU terrestrial eutrophication (molc N eq)
WRD water resource depletion ($m^3$ water eq)

*Others*
BAU business as usual
BCA benefit cost analysis
EAF electric arc furnace
GHG greenhouse gas
ILCD international reference life cycle data network
LCA life cycle assessment
ORC organic Rankine cycle

production has reached 1621 Mt in 2015, and steel use by 2050 is projected to increase by 1.5 times of present level [9]. In the USA, approximately 37% and 63% of total steel production uses the integrated manufacturing process and electric arc furnace (EAF) process, respectively [10]. An EAF is a furnace that heats charged material up to 1800 °C by means of an electric arc. However, not only electricity but also coal, heavy fuel oil and natural gas are used as energy source in the EAF plant, such as in the reheating furnace.

Recently, various types of energy-efficient technologies (such as organic Rankine cycle [11,12] and combined heat and power [13]) and renewable energy (such as wood pellet [14,15]) have been attempted for industrial applications. However, several critical issues for these promising processes such as energy efficiency, net $CO_2$ emission reduction, indirect $CO_2$ emission avoidance, and cost-benefit analysis have not been comprehensively addressed yet. As a result, in this study, two selected emerging technologies, i.e., organic Rankine cycle (ORC) and wood pellet fuel, were evaluated via life cycle assessment (LCA) using existing process data from an EAF steelmaking plant.

The ORC power facility was selected because of its simplicity, reliability, low maintenance, and easy remote monitoring for heat recovery from the flue gas [16]. The system utilizes low- to medium-grade temperature thermal energy (i.e., 66–260 °C), and can be operated at low pressures (less than 1380 kPa or 200 psig) [16], making it favorable to extract waste heat in the flue gas for power generation [11,17,18]. It is expected to be a practically viable way to recover the exhaust flue heat in various industrial processes. In general, the parameters of net power output index and thermal efficiency are used to represent the economic and thermodynamic performances, respectively [19].

The wood pellet fuel has been considered as an environmentally friendly fuel because of its lower sulfur content and lower pollutant emission than heavy fuel oil during combustion. The advantages of using wood pellet fuel as an alternative heating source include (1) substantial increase in low heating value (LHV) compared with green chips, (2) reduction in transportation costs, (3) simplified transportation and handling, (4) reduction of biological activity and stable storing, and (5) homogenous manageable fuel for power plants. In addition, the bottom ashes generated from wood pellet combustion can be utilized as fertilizers because of the high contents of calcium, potassium, magnesium and phosphorus [20,21]. It has been demonstrated that the energy consumption for the life cycle of wood pellet was mainly on the manufacturing process (71%), followed by its transportation (23%) [22].

Extensive studies have been carried out in the literature to determine the technical performance of the aforementioned processes, i.e., biomass utilization [23,24] and ORC system [25–27]. However, few study on their environmental impacts and benefits was evaluated using the data from an industrial plant, and incorporated with cost benefit analysis. Therefore, the objectives of this study are to (1) evaluate the material and energy flows in a typical EAF steelmaking industry from a life cycle point of view; (2) quantify the environmental impacts of applying ORC power technology to recovery medium-grade exhaust heat; (3) determine the environmental impacts for the application of wood pellet energy in a reheating furnace; and (4) evaluate the environmental impacts and benefits of process modification using ORC and wood pellet energy.

## 2. Materials and methods

### 2.1. Life cycle assessment (LCA)

LCA is a scientific and technical tool providing a systematic approach to assessing the performance and its associated environmental impacts of a product or a service in the life cycle. In principles, LCA is utilized to quantify the environmental impacts of energy and resource consumption (e.g., GHG emissions and acidification) caused by the human development over their lifetimes from a cradle-to-grave approach. In this study, the environmental impacts of various scenarios in EAF steelmaking industry were quantified via LCA using Simapro 8.0.3, which employs an LCA method based on ISO 14040:2006 and ISO 14044:2006 International Standard [28,29]. The functional unit was defined as one ton of steel production in an EAF plant.

In this study, four scenarios in an EAF steelmaking industry were established. Scenario 1, i.e., business-as-usual (BAU) in an EAF plant (see details in Section 2.2), was designated as the base scenario throughout the LCA. Scenario 2 was designed to be the implementation of ORC facility for power generation (see details in Section 2.3), where the medium-grade exhaust heat in flue gas from a reheating furnace was recovered. Scenario 3 was referred to the implementation of wood pellet fuel in a reheating furnace (see details in Section 2.4). To evaluate the costs and benefits or process modification in an EAF plant, scenario 4 were also established by combining scenarios 2 and 3. For data inventory, the framework of electricity generation in Taiwan was obtained from the Ecoinvent 3.0 database in SimaPro (electricity, high voltage {TW}| production mix | Alloc Def, U) [30], and then updated to the 2014 air-pollutant emission factors [31], e.g., 0.521 kg $CO_2$-eq, 0.302 kg $SO_x$, 0.327 kg $NO_x$, and 0.027 kg $PM_{10}$ per kWh.