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Environmental impact of biomass based polygeneration – A case study through life cycle assessment

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HIGHLIGHTS

- LCA is modelled for a polygeneration fuelled by agricultural waste.
- Exergy based allocation approach is used for multi-utility generation system.
- Results are shown through both mid-point and end point indicators.
- Polygeneration with surplus rice straw is more beneficial than conventional plants.
- Environmental impacts depend on biomass distribution density and catalyst.

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ABSTRACT

Multi-generation or polygeneration is considered to be a potential sustainable energy solution. To assess environmental sustainability of multi-generation, life cycle assessment (LCA) is a useful tool. In this paper, environmental impact of polygeneration using an agro waste (rice straw) is assessed by LCA. Then it is compared with stand alone conventional plants with same utility outputs. Power, ethanol, heating and cooling are utility outputs of the polygeneration plant. System boundary for this polygeneration is defined for surplus biomass only. Exergy based allocation method is used for this analysis. Results of LCA are shown through both mid-point and end-point indicators. Results indicate that polygeneration with surplus rice straw is more environment-friendly than conventional stand-alone generation of same utilities.

1. Introduction

Fossil fuels are most widely used primary energy resources at present (IEA, 2014). Several environmental damages happen due to this use. It affects human health, degrade ecosystem and most significantly causes 'climate change' (IPCC, 2014). Alternative energy resources may play an important role in this context. In developing countries, plenty of agricultural residues are available. These residues are mostly unutilized or under-utilized though these can be used as energy resources (Bentsen et al., 2014). Use of these reduces greenhouse gas emission (Nguyen et al., 2010). Rice straw is abundantly available in south and south-east Asia. It is mostly burnt in the open air producing several pollutants. Otherwise, it is decomposed in the field and produces methane which is a potential greenhouse gas (Kadam et al., 2000). However, it may be a potential energy resource with suitable technologies. Decentralized use of it may cater to basic needs of rural people more economically (Chicco and Mancarella, 2009).

Polygeneration or multi-generation is the integration of multiple utility outputs in a single unit. Properly designed polygeneration with efficient system integration may be economically feasible, environmentally benign and socially acceptable through sustainable operation (Jana and De, 2015a). A conceptualized polygeneration combining power, ethanol, heat and chill was simulated using Aspen Plus® and a techno-economic analysis was done (Jana and De, 2015b). A case study of a polygeneration using locally available rice straw has been reported for an Indian district (Jana and De, 2015c). Monteleone et al. (2015) have identified straw as an energy resource for a long term sustainability, instead of its decomposition in the field. Cherubini and Strømman (2011) have reviewed the life cycle assessment (LCA) of bioenergy systems. Environmental aspects of rice straw based power generation in Malaysia were also assessed (Shafie et al., 2014). Jana and De

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Nomenclature

Abbreviations

CCGT	combined cycle gas turbine
FU	functional unit
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment

Symbols

DD	biomass distribution density (kg/km^2/y)
DT	distance travelled (km)
$\dot{Ex}$	exergy rate (MW)
$frac$	fraction
LT	plant life time (y)
$\dot{m}$	mass production rate (kg/s, t/y)
POH	plant operating hour (h/y)
$\dot{Q}$	heating/cooling (MW)
VC	vehicle capacity (t)
$\dot{W}$	power (MW)

Subscript

0	atmospheric condition
by	biomass per year
c	cooling
$chill$	chilling effect
eth	ethanol
evp	evaporator
h	heating
w	work

(2016) explored the net CO_2-negative polygeneration by using rice straw.

Life cycle analysis is important to assess the environmental sustainability of polygeneration (Wiloso et al., 2014). Polygeneration is system integration of multiple utilities and consists of several unit processes in different sub-modules. Environmental benefits of integration of these sub-modules may be estimated through LCA. LCA also identifies environmental benefit of 'straw to energy' instead of 'straw to soil' (Wiloso et al., 2016). It is also important to estimate additional environmental benefits due to integrated multi-utility generation over the generation of same utilities by conventional stand-alone plants, i.e., one for each utility in available standard conventional plants. Identification of critical environmental degradation and possible improvements of it should also be studied. In summary, to measure the environmental sustainability of polygeneration from agro-waste fuels, LCA is critical (Wiloso et al., 2016).

In this paper, results of LCA are reported for a polygeneration plant fuelled by surplus and 'otherwise unused' straw. By using exergy based allocation method, environmental impact of producing each utility is measured. This polygeneration is compared with stand-alone conventional plants delivering same utilities in the context of environmental impact. Results of sensitivity analysis are also discussed to identify the scope of possible improvement.

2. Materials and methods

Environmental impact of the polygeneration is estimated according to the framework of ISO 14040 (ISO, 2006). This framework consists of three inter-dependent steps i.e., goal and scope definition, inventory analysis and impact assessment. Interpretation of these three steps is included within the LCA framework. Results of Aspen Plus® simulation of the polygeneration are taken as input to the LCA (Jana and De, 2015c). Utility production rates for given inputs and integrated unit operations are obtained from that simulation.

2.1. Goal and scope definition

The goal of this LCA is to evaluate the environmental performance of the polygeneration fuelled by an agricultural waste i.e. rice straw. This study helps to estimate the life cycle emission, specifically greenhouse gas emission for this polygeneration. The sequestration of carbon into biomass during the growth phase represents a 'negative' GHG emission at this stage of the life cycle but this carbon subsequently returns to the environment in various ways depending on the subsequent use of it. This is mostly through combustion of the corresponding bio-fuel in gas turbines or combustion engines (Wiloso et al., 2016). However, sequestration of CO_2, i.e., 'negative emission' during the growth of paddy and 'positive' CO_2 emission during cultivation through the use of fertilizers, agriculture machineries etc. are benefits and burdens respectively of the crop (i.e., rice) cultivation process itself. Both are not considered in this LCA as only surplus (i.e., 'otherwise waste') straw is used for this study. Hence, the climate change potential of biogenic carbon is excluded from this study. Both mid-point (CML 2001) and end-point (Eco-indicator 99) indicators are used for environmental impact assessment (Hischier et al., 2010). Comparative environmental benefits of polygeneration both due to system integration instead of stand-alone generation of individual utilities in conventional ways and for utilizing agricultural waste as energy resource, are also discussed in this study. Impacts of these utility generations are estimated after allocation. Sensitivity analysis for different parameters to assess variations of impacts on the environment with variations of these parameters is also reported in this paper.

2.1.1. Functional unit

From this polygeneration, four utility outputs viz. power, cooling, heating and ethanol are obtained as outputs. All of these four utilities are some forms of energy services, though these energies are of different grades. The concept of 'exergy' of any available form and amount of energy as defined from the second law of thermodynamics is useful in this context. Exergy of any form of energy (or energy services) is the maximum theoretical useful work for a specified 'environment' (Dincer and Rosen, 2013). Hence, it is important to select a proper functional unit (FU) without biasing to any particular utility. One MJ of exergy output from any form of these four utilities is chosen as the functional unit (FU). Exergy of power, ethanol, cooling and heating are calculated by Eqs. (1)–(4) respectively (Dincer and Rosen, 2013)

$$\dot{Ex}_w = \dot{W} \tag{1}$$

$$\dot{Ex}_{eth} = \dot{m}_{eth} ex_{eth} \tag{2}$$

$$\dot{Ex}_c = \left| \left(1 - \frac{T_0}{T_{evp}}\right) \right| \dot{Q}_c \tag{3}$$