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Greenhouse gas emissions from renewable energy sources: A review of lifecycle considerations

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ABSTRACT

Electricity and heat generation are key contributors to global emissions of greenhouse gases (GHG). In this paper, specific attention is paid to renewable energy technologies (RETs) for electricity and heat generation and reviews current understanding and estimates of life cycle GHG emissions from a range of renewable electricity and heat generation technologies. Comprehensive literature reviews for each RET were carried out. The 79 studies reviewed involved the life cycle assessment (LCA) of renewable electricity and heat generation based on onshore and offshore winds, hydropower, marine technologies (wave power and tidal energy), geothermal, photovoltaic (PV), solar thermal, biomass, waste, and heat pumps. The study demonstrates the variability of existing LCA studies (results) in tracking GHG emissions for electricity and heat generation from RETs. This review has shown that the lowest GHG emissions were associated with offshore wind technologies (mean life cycle GHG emissions could be 5.3–13 g CO_2 eq/kWh). Results compared with GHG estimates by fossil fuel heat and electricity indicated that life cycle GHG emissions are comparatively higher in conventional sources as compared to renewable sources with the exception of nuclear-based power electricity generation. In this present study, considering renewable energy sources, waste treatment and dedicated biomass technologies (DBTs) were found to potentially have high GHG emissions based on the feedstock, selected boundary and the inputs required for their production. The study identifies additional impacts associated with renewable electricity and heat technologies, points out the effectiveness of life cycle analysis (LCA) as a tool for assessing environmental impacts of renewable energy sources and concludes with opportunities for improvement in the future.

Contents

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1. Introduction

Renewable energy sources are considered to be those that are primary, clean, low risk, and inexhaustible [1,2]. Renewable energy sources include biomass, hydropower, (shallow and deep) geothermal (i.e., indirect solar energy), solar, wind and marine energies. Nuclear energy is not normally considered to be a renewable energy source as it does not replenish within the lifetime of a person [3]. At the turn of the century, renewable energy sources supplied ~14% of the total world energy demand [4]; by 2010, this had risen to almost 17% with an estimated 50% of energy demand by 2040 [5].

Sustainable development requires methods and tools to measure and compare the environmental impacts of human activities for various products [6]. In order to understand where net savings in GHG emissions can be made, and the magnitude of the opportunities, renewable energy systems can be analysed and compared with the energy systems they would replace [7]. The life cycle analysis/assessment (LCA) method has been widely used to study the environmental burdens of energy produced from various renewable and non-renewable sources [8]. Depending on the scope of the LCA study, life stages of energy production systems may include all or part of (i) fuel production (i.e., to also account for the non-consumable portion of the produced fuel) and transportation to the plant, (ii) facility construction, (iii) facility operation and maintenance, and (iv) dismantling [9]. For example; Hondo [10] developed the life cycle greenhouse gas emissions of nine power generating systems including coal-fired, oil-fired, liquefied natural gas (LNG)-fired, LNG-combined cycle (LNG-CC), nuclear, hydropower, geothermal, wind power and solar photovoltaic (PV). The life stages included (i) plant construction and equipment production, (ii) fuel acquisition, processing, and transportation (in the case of fossil fuels and nuclear), geothermal wells drilling (for both exploration and production wells of the geothermal option), (iii) facility operation, and (iv) storage, disposal, or decommissioning (nuclear) of waste. All the GHG emissions attributed to renewable sources were due to indirect emissions, while for fossil fuel sources, direct CO_2 emissions accounted for the majority of GHG.

This paper reviews current understanding and estimates of life cycle GHG emissions from a range of renewable electricity and heat technologies identified from the Scottish Government's 2020 route map [11] for renewable energy, and discuss potential impacts associated with these emissions. The purpose of this review is therefore two-fold to identify the environmental benefits and impacts associated with renewable electricity and heat technologies; and secondly to assess how life cycle approaches can aid in technology evaluation and selection.

2. Methodology

2.1. Search strategy and study evaluation

This was a purposive review of peer-reviewed literature related to the use of LCA to estimate GHG emissions from renewable energy production technologies. In a few cases, the review was supplemented with literature from web-accessible documents and other grey literature. A computerised search of the following international databases was carried out: BIDS (Joint Information Systems Committee, University of Bath, Bath, UK, www.bids.ac.uk) and ISI Web of Knowledge (Mimas, University of Manchester, UK, wok.mimas.ac.uk). A systematic, staged search strategy was employed using the following search terms: 'biomass' OR 'bioenergy' OR 'energy from waste' OR 'fuel cells' OR 'hydropower' OR 'offshore wind' OR 'onshore wind' OR 'marine' OR 'tidal' OR 'photovoltaic/PV' OR 'geothermal' OR 'solar thermal' OR 'heat pumps' OR 'anaerobic digestion/AD' OR 'biogas' OR 'combined heat and power/CHP' AND 'life cycle analysis/LCA' OR 'greenhouse gas/GHG' OR 'nitrous oxide/N_2O' OR 'methane/CH_4' OR 'carbon dioxide/CO_2'.

2.2. LCA case studies included

In this review almost 9000 references were found. The search was further refined to 197 papers that explicitly estimated the life cycle GHG emissions from the specific renewable energy technologies. Only papers written in English were fully included. Original full texts were obtained for all studies. Upon examination of the full texts, only 102 provided any form of quantitative estimation of lifecycle GHG emissions. Therefore, wider, more descriptive studies and accounts were also included while the following types of studies were excluded (except where a method was used that showed principles relevant to the context of this review): (i) studies that did not provide a whole life cycle (i.e., cradle to grave) estimate of GHG emissions. (ii) Where relevant, studies that did not take land use and management into account as part of the life cycle (a significant contributor to total GHG emissions which is often overlooked). The 85 studies that remained after this filtering process formed the primary basis of this review, although other papers within the database were used as background material. Table 1 provides an overview of the studies reviewed.

2.3. Greenhouse gas emissions

Although there are other environmental emissions (e.g., NO_x and SO_2), this review focuses on emissions of greenhouse gases (GHG), such as CO_2 and CH_4 from renewable energy sources