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Environmental consequence analysis for resource depletion

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ABSTRACT

Resource depletion is of concern to both present and future generations in terms of access to resources. It is a prominent impact category within life cycle assessment (LCA) and sustainability assessment. This paper examines existing resource depletion approaches and indicators in the context of natural gas depletion, and their limitations in modelling the wider environmental consequences of resource consumption. Some existing models assume substitution of scarce fossil fuels with an alternative fossil fuel or mix, but do not consider all of the subsequent change in impacts. An additional methodology is proposed to measure the impact changes when fossil fuel substitution occurs as a result of scarcity. The methodology will demonstrate the effect of resource scarcity for individual processes but also multiple processes which operate at different levels of resource consumption with varying degrees of impacts. The methodology is applied to a scarcity situation of natural gas in Australia, where black coal is substituted for gas. It is first applied to natural gas consumed for electricity generation only. In the second case, the methodology is applied to the substitution of natural gas for both electricity generation and hydrogen production. The varying impacts on emissions to air and water, together with solid waste generation and water depletion, as a result of the substitution are used to reflect the consequences of fossil fuel depletion. The indicators also provide information on the impacts of substitution in each product, thus enabling users to prioritise products based on the impacts produced during natural gas allocation.

Keywords: Resource depletion; LCA; Sustainability; Natural gas; Environmental impacts

1. Introduction

1.1. *Resource depletion*

Sustainable development (Brundtland, 1987) implies that meeting the needs of the present should not compromise the ability of future generations to meet their own needs. One important aspect of sustainable development is the conservation of natural resources for societal needs. This is particularly important in the case of fossil fuel resources, since once consumed, they cannot be re-used or recycled and therefore accelerated extraction will hasten their depletion, leading to scarcity. Consequences may include a decline in the accessibility, quality or purity of a resource, an escalation in selling price, and ultimately disruption to services and product manufacturing. Disruption to services or products affects all processes which rely on the resource in order to function and may lead to the need for the resource to be substituted with an alternative. Exploiting less accessible or lower quality reserves, or substituting the resource with an alternative resource, may cause a range of undesirable environmental, economic and social impacts.

Fossil fuels are examples of resources where scarcity occurs, as illustrated by the depletion of reserves in different

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Abbreviations: ACD, acidification; ADP, abiotic depletion potential; BlC, black coal; CCGT, combined cycle gas turbine; EFG, entrained flow gasification; GWP, global warming potential; NG, natural gas; P, product; PCST, pulverised coal steam turbine; Pr, annual production of a mineral or fossil fuel; PSF, photochemical smog formation; R, resource; RDI, Resource Depletion Index; Re, ultimate reserve of a mineral or fossil fuel; RWW, raw water withdrawal; SLD, solid waste; SMR, steam methane reforming; WTC, water consumption.

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parts of the world and speculation surrounding 'peak oil'. Natural gas is an example where scarcity has occurred recently in both the U.S. and Britain. The United States experienced a perceived natural gas shortage before shale gas development recently gained prominence (Hirsch et al., 2005). Britain experienced a sharp transition to gas under a natural gas conversion programme and was self-sufficient in natural gas for a significant period. Britain's proved reserves and production of natural gas however have been in decline since the year 2000 (BP, 2011) and Britain is currently a net importer of natural gas. These periods of peak production are symptomatic of predictions using the 'peak oil' theory, where oil, and by association gas, as a finite resource eventually reaches a peak in discovery and production, thus giving rise to discussions of far-reaching social, economic and political consequences (Owen et al., 2010; Campbell, 2012). Other than fossil fuels, other resources have been reported to exhibit a similar trend in peaking, for example 'Peak Water' by Gleick and Palaniappan (2010). Fossil fuels are to some extent substitutable with different fuel sources. For example, gasoline can be substituted with liquefied petroleum gas (LPG) or compressed natural gas (CNG), natural gas may be substituted with synthetic natural gas (from coal), and chemicals originating from either natural gas or crude oil can be reproduced from alternative hydrocarbons including other fossil fuels. However, each of these substitutions carries its own environmental burdens as well as economic and social costs.

In Australia, there would appear to be abundant reserves of natural gas that have led to a major expansion of the liquefied natural gas (LNG) industry driven mainly by export markets. At the same time, there is a strong dependence in Australia on natural gas for electricity generation, domestic and industrial fuel, and feedstock for chemicals manufacture. Much of this demand is linked to a growing demand for processing minerals (ABARE, 2011; Penney et al., 2012). Natural gas is a strategic fossil fuel as it is used as both a fuel to generate thermal and electrical energy and as a feedstock to manufacture chemicals. Its relative ease compared with liquid and solid fuels as a feedstock for manufacturing chemicals, and its flexibility to be converted into liquid fuels as alternatives to oil-derived products, make it a crucial fossil fuel. Therefore, its scarcity will have far-reaching consequences, and the analysis of these consequences is a key aim of this study.

1.2. *Resource depletion as a component of life cycle assessment*

Life cycle assessment (LCA) is a technique for assessing environmental impacts throughout a product's life cycle from raw material acquisition, through production sequencing, to product use and disposal. According to International Standard ISO 14040 (1997), LCA involves goal and scope definition, inventory analysis, impact assessment and interpretation of results. The life cycle inventory (LCI) accounts for raw material consumption and emissions in process and utility systems across the product life cycle. Raw materials consumption data is commonly used in formulating impact indicators for resource depletion.

Fig. 1 shows a typical life cycle impact assessment (LCIA) framework linking the life cycle inventory data (LCI) of a process to mid-point impact categories followed by end-point impact categories. For example, carbon dioxide and methane emissions identified in inventory data are classified and weighted under the mid-point impact category of 'Global Warming Potential' expressed in tonnes of carbon dioxide equivalent. The mid-point impact indicators can be then linked to end-point impact indicators such as rising sea levels and extreme hydrological cycles. Resources used in the life cycle can be characterised and expressed as resource depletion scores. The damage to resources is normally represented by either the depletion of the resource base or a cost to society.

The first CML Handbook on LCA by Heijungs et al. (1992) assessed the depletion of abiotic raw materials, which included energy carriers and minerals, by comparing the quantity used of each raw material in the LCI with the recoverable reserves of that raw material, whose reserves may become insufficient within 100 years. The effect score for the depletion of abiotic resources is calculated using Eq. (1).

$$\text{Abiotic depletion} = \sum_i \frac{\text{Material use}_i(\text{kg})}{\text{Reserves}_i(\text{kg})} \tag{1}$$

This approach was modified in the second edition of the CML Handbook on LCA by Guinée (2001a,b) where extraction rates Δx were used in conjunction with ultimate global reserves *Re*, and antimony was used as a reference. This basis was initially discussed in Guinée and Heijungs (1995), but was modified under the assumption that fossil fuels can be full substitutes both as energy carriers and as materials, therefore it was only necessary to give an overall abiotic depletion potential (*ADP*) for all fossil fuels, expressed in kg antimony eq./MJ fossil energy as shown in Eq. (2). The ultimate reserves of fossil fuels was based on total proven commercial reserves of coal, oil and natural gas from World Resources 1994–1995 (World Resources Institute, 1994). *ADP*s for individual fossil fuels can be derived by multiplying this overall fossil energy *ADP* with their respective heating value, with the final indicator expressed in kg antimony eq./kg of fossil fuel extracted.

$$ADP_{\text{fossil energy}} = \frac{\Delta x_{\text{fossil energy}}}{(Re_{\text{fossil energy}})^2} \times \frac{(Re_{\text{antimony}})^2}{\Delta x_{\text{antimony}}} \tag{2}$$

Another method of characterising resource depletion is through the Eco-indicator 99. The Eco-indicator method was developed by Goedkoop and Spriensma (2001) as a damage oriented approach for use in LCA to link midpoint impact categories into three major endpoint damage categories of damage to human health, to ecosystems, and to resources. The damage indicator adopted for resource depletion is based on the additional energy required to extract resources in the future arising from decreased concentrations of a mineral in an ore, or a decrease in fossil fuel available for extraction. The damage indicator is expressed as 'surplus energy' per kg of resource extracted, which is calculated by subtracting the current energy requirement for a fuel from the energy requirement for the replacement fuel or fuel mix. This concept was extended by Goedkoop et al. (2009) in the ReCiPe 2008 model, which links resource consumption of fossil fuels to the additional costs society has to pay in replacing conventional fossil resources with unconventional sources (e.g. tar sands, uranium, wind or solar). The marginal cost indicator uses the extraction cost of conventional oil as a reference against which other more expensive fossil fuel resources are compared. In order to consider how the costs change as resources are depleted, both the Eco-indicator 99 method and the ReCiPe 2008 model consider different perspectives based on Cultural

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