Land Use Policy 36 (2014) 478–484

Contents lists available at ScienceDirect

Land Use Policy

journal homepage: www.elsevier.com/locate/landusepol

Sustainable power plants: A support tool for the analysis of alternatives

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ARTICLE INFO

Article history:
Received 6 July 2013
Received in revised form
11 September 2013
Accepted 16 September 2013

Keywords:
Energy
Environmental Impact Assessment (EIA)
Environmental sustainability
Life Cycle Assessment (LCA)
Power plants
Renewable fuels

ABSTRACT

Shortage of fossil fuels and global oil crisis are leading many national energy authorities to switch from traditional fuels to other renewable ones. On the other hand, in several western countries – due to an increasing environmental awareness – public acceptance of traditional power plants (e.g., coal or fired oil) is steadily decreasing, mostly because of their significant environmental pressures. Decision makers' activities need to be supported by objective tools, which must be designed to be able to select the best alternative in order to achieve some prefixed goals. Therefore, in the present study, a tool is proposed to support decision makers: it is based on Life Cycle Assessment data from seven different power plants (coal, fired oil, fired gas, nuclear, wind, solar and hydroelectric), to understand what is taken into in terms of material fluxes, and how much it costs in a specific context. Consequently, an Analytic Hierarchy Process has been proposed to select which one might be the best alternative in function of the considered scale and ten environmental criteria. The proposed procedure aims to evaluate different power plants and identify the most environmentally sustainable one in function of plant construction and operation phases.

Introduction

The worldwide economic downturn has hit energy consumption, but an expected recovery in the next years could ignite again demand and boost prices, e.g. U.S. oil prices are forecast to rise to $110 in 2015 and $130 in 2030 (International Energy Outlook, 2011). Almost 75% of the rise in global energy demand through 2030 will occur in developing countries, particularly China, India, Russia and Brazil. Renewable energy, like wind and solar power, will be the fastest growing energy source, making up 11% of global supplies (International Energy Outlook, 2011).

Renewable energies provide 14% of the total world energy demand (UNDP, 2000). These include, among the others, hydropower, solar and wind. Renewable energies rely on fuels, which are clean and almost inexhaustible; e.g., hydropower nowadays contributes to 20% of global energy production (UNDP, 2000). In coastal areas, as well as in other windy regions, wind power can be a reliable energy source. Renewable energy production is forecast to notably increase in the next decades: the actual share of 15% is expected to rise up to roughly 50% in 2040 (Kralova and Sjöblom, 2010). Nowadays fossil fuel utilization is significantly growing due to life quality enhancement, industrialization of developing nations and global demographic increase. It has been acknowledged that this excessive fossil fuel consumption not only leads to an increase in the rate of diminishing their reserves, but it also has a significant adverse impact on the environment, resulting in increased health risks and threat of global climate change (Farhad et al., 2008). In western countries, environmental protection policies are gaining significant attention, and this trend might gradually spread all over the world, coupled with social development; the humankind is slowly moving toward seeking more sustainable production methods, waste minimization, reduced air pollution from vehicles, distributed energy generation, conservation of native forests, and reduction of greenhouse gas (GHG) emissions (Sims, 2003). Increasing consumption of fossil fuel to face current energy demands has generated a resurgence of interest in promoting renewable alternatives to meet the developing world's growing energy needs (Youm et al., 2000). Excessive use of fossil fuels has caused global warming by GHGs; it is clear that nations have to promote energy production from renewable and clean sources (Hall et al., 1991). To monitor emission of these greenhouse gases an agreement has been made with the overall pollution prevention targets, namely the objectives of the well-known Kyoto Protocol agreement (Wohlgemuth and Missfeldt, 2000).

Choosing which power plant should be built and where is up to national or local decision makers, but in order to select the best available solution in terms of the fuel to be employed, objective tools are needed (Pollard et al., 2004; Sorvari and Seppala, 2010). When decision makers try to select any alternative using a

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http://dx.doi.org/10.1016/j.landusepol.2013.09.008

particular set of criteria, they have to take into account conflicting issues that might undermine the quality of results. For example, two criteria that could be used in selecting a renewable energy alternative are reliability and implementation cost. These are two conflicting criteria, since an attempt to increase reliability possibly causes an increase in implementation cost. The selection among renewable/non-renewable energy alternatives is a multicriteria problem with many conflicting criteria. There is a need to evaluate alternatives by taking into account their advantages and disadvantages through selection criteria. Hence, this problem should be solved by a multicriteria method. In many current decision-making problems, the decision maker judgments are not objective, and it is relatively difficult for the panelist to provide precise numerical values for the criteria – or attributes. Therefore most of the evaluation parameters must be precisely given.

Technological advances in the field of renewable energy systems, requirement of climate mitigation and electricity system capacity deficits, as well as market restructuring and deregulation have led to an increasing interest in innovative energy technologies all around the world. When new technologies enter the market, however, their environmental superiority over competing options must be asserted based on a life cycle approach (Pehnt, 2006). Life Cycle Assessment (LCA) investigates environmental pressures of systems or products from cradle to grave throughout their full life cycle, from the exploration and supply of materials and fuels, to the production and operation of the investigated objects, to their disposal/recycling. Furthermore, LCA is an instrument to quantify these pressures due to the entire energy supply chain, e.g. to obtain the cumulative energy demand (CED) for production of a power plant, its life cycle carbon emissions, etc. Through LCA, the whole facility is split up into components and subcomponents and all energy and material flows through these are examined. With the increasing environmental operation standards of modern energy conversion systems, the upstream and downstream processes, e.g. fuel supply or power plant and infrastructure production, become increasingly relevant (Pehnt, 2006). In the prevailing LCA approach, future developments of the energy systems themselves and of the context in which the systems are going to be introduced are typically not considered, thus severely distorting the analysis of the environmental characteristics of future energy systems. Therefore, it is unclear which of the environmental pressures can be causally attributed to renewable energies, and which are 'imported' into the system due to the 'background system', as well as what may be the improvement potential of these technologies compared to that of competitors' technologies, e.g. due to process and system innovations or diffusion effects.

Nevertheless, the LCA can be applied to assess the environmental pressures due to electricity generation and allows producers to make better decisions for environmental protection (Góralczyk, 2003). In the past several studies (Kreith et al., 1990; Tahara et al., 1997) evaluated emissions due to energy plants introducing the LCA methodology.

The life cycle impact of typical renewable energy systems is important when comparing them to conventional fuel-based systems for rational choice of energy sources. In addition to the well-known differences between conventional and renewable energy systems in terms of their economic impact, a number of stark differences in all other impact areas strongly favor renewable energy solutions, the most significant being related to environmental protection (Sorensen, 1994).

However, once an LCA is assessed and eventually environmental pressures are defined, decision makers still need a useful tool to select among several options the most economically and environmentally sustainable. The Analytic Hierarchy Process (AHP) enables decision makers to structure a complex problem in the form of a simple hierarchy and to evaluate a large number of quantitative and qualitative factors in a systematic manner under multiple conflicting criteria (Huang et al., 2011). The AHP makes use of pair-by-pair comparisons, hierarchical structures, and ratio scaling to apply weights to attributes; this procedure is a subjective method for analyzing qualitative criteria to generate weighing of the operating units. Saaty (1987) has proposed the AHP as a decision-making method to solve unstructured problems since 1987. In the AHP, at each level in the hierarchy the decision maker is required to make pair-by-pair comparisons between decision alternatives and criteria using a scaling ratio for the weighting of attributes. AHP determines the relative ranks or priorities of the decision alternatives (Kablan, 2004). The AHP methodology is particularly convenient for comparing different investment alternatives and is a well-known tool for decision making in operational analysis. It has mostly been applied for decision making in operational and risk analysis for evaluation of project alternatives and to a lesser degree in evaluation of environmental consequences. The AHP technique has been applied in a wide variety of decision-making problems, including resource management and monitoring plans (e.g., Martin-Ortega and Berbel, 2010).

This paper investigates the environmental performance of energy plants powered by renewable and non-renewable sources, and develops an analytical tool to support decision makers through the selection process of a power plant, in order to reduce environmental pressures in a specific site.

Materials and methods

An accurate literature analysis has been developed to study a number of publications that performed LCAs for different energy plants (coal, fired oil, fired gas, nuclear, wind, solar and hydroelectric). Results from these LCAs have been taken as input data for the subsequent AHP process, namely the second step of the proposed tool, which aims to support decision makers in their effort to reduce environmental pressures related to power plants. LCA results have been reported in terms of employed resources, raw materials, CED, GWP100 (Global Warming Potential calculated over 100 years), produced waste and direct land use. Through an in-depth analysis of these and other indicators, it is possible to discuss whether a certain power plant may impact more than another one in terms of, e.g., waste production.

However, in land management it is likely to be required to choose between several alternatives for energy production, therefore the AHP is implemented in order to properly compare – and classify – all the considered power plants (Kaya and Kahraman, 2011) in terms of selected criteria, which have to be evaluated for each proposed power plant using quantitative indicators (LCA resulting data and plant parameters, e.g. plant size) as well as qualitative ones (e.g. panelists' opinions).

The implemented AHP methodology is primarily based on pair-by-pair comparisons instead of immediate assessment of scores and weights, and its general scheme is showed in Fig. 1, where hierarchically ordered steps are grouped in function of AHP levels. The final goal is obtained by two major elements, i.e. local and global scale scores; the first refers to pressures that arise locally, in the same context of the plant (such as traffic or noise), while the second represents effects that are typically regarded as global, e.g. climate change. At the criteria level, several environmental aspects are evaluated in terms of the specific site sensitivity to various environmental pressures.

Once characterization of each alternative (i.e. the power plants) has been fulfilled through LCA, the AHP requires to clearly define criteria and indicators which will be used to evaluate and sort all the proposed solutions. Following the proposed method, each alternative is evaluated in terms of pressures it generates at both local and global scale.