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Implications of energy policy on a product system's dynamic life-cycle environmental impact: Survey and model

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ABSTRACT

Successfully developing and manufacturing industrial products requires considering the economic- and environmental-factors that span multiple spatial- and temporal-scales. Here, we propose an integrated approach combining an energy-economic model with a life-cycle assessment to analyze the impacts of energy policies on the dynamic changes in the various environmental impacts of a product system. We employ the Market Allocation (MARKAL) framework to foresee the changes in several economic- and technological-parameters over specific periods for different energy policies. Furthermore, we create a dynamic life-cycle inventory database to assess the changes in the future life-cycle environmental impact of a current product/process system. Our proposed method may guide industry to proactively prepare for the possible effects of different energy policies on their current product/process system's environmental profile so that they can make strategic decisions on modifications to, and investments in their production processes thereby to enhance their environmental- and economic-performance while meeting the various emission-abatement targets.

Contents

1. Introduction

Integrating environmental aspects into corporate social responsibility (CSR) and management strategy has become a fundamental factor driving producers towards choosing technologies with low environmental impact while maintaining their products economic feasibility [1]. New energy standards, such as ISO 50001, require industries to commit to efficient usage of energy in their production process and supply-chain management while meeting their goal of abating emissions [2]. In addition to these voluntary actions, different energy policies, such as carbon taxes and cap-and-trade, directly and indirectly affect the supply and demand of energy commodities. While there are many different tools for modeling

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energy economy, most methods for assessing technology and analyzing policy tend to focus on the macroeconomic-scale levels. However, for making strategic management decisions, manufacturers need methods and tools to assess the effects of energy- and environmental-policies at the value-chain level. Industries are interested in addressing two questions: How will the environmental- and the economic-performances of current product/process systems be changed with potential future energy policies? Which part of the process should be enhanced to meet, at the minimum cost, the required emission-reduction target of the energy policies?

Although some energy economic models, such as the Market Allocation (MARKAL) offer information about anthropogenic emissions generated by the economic activities, they often lack sufficient detail to allocate the information to each part of a product's life cycle. Life cycle analysis (LCA) can provide information about a product's environmental features of most interest based on the past/current life cycle inventory database. However, general LCA is a static accounting model, rather than an optimization model. It usually does not support either the systematic evaluations of the impacts of substituting technologies on a medium- or a long-term basis, or the cost effectiveness and market competition of alternative choices. Therefore, it is difficult to model the prospective change in environmental impacts of a product/process system caused by the changes in various potential federal/state-level energy policies and environmental regulations. In this paper, we integrate the strengths of both approaches to create a dynamic lifecycle inventory database that is applicable for analyzing the changes in the future lifecycle environmental impact of a current product/process system under a set of alternate energy/environmental policies. In Section 2, we review existing energy economic models, various life-cycle analyses, and previous studies on combined models. In Section 3, we explain our proposed methodology using the case study of the Photovoltaic dynamic LCA. Section 4 illustrates the results of the proposed methodology that will afford guidance for industrial designers in foreseeing the impact of certain macro-economic energy policies and environmental regulations on their decision-making during the process of developing the product.

2. Literature reviews

2.1. Energy-economy modeling tools

Extensive research on modeling the relationship between the economy and environment has focused specifically on the relationship between the economy and the energy system. Energy-economy models can be categorized into *top-down* and *bottom-up* models [3]. The former evaluate the system from aggregate economic variables, and concentrate on the economic description of interactions and relations between aggregate economic systems. Therefore, they cannot detail the behavior of the energy system. These top-down approaches can be classified further into input–output models, econometric models, partial equilibrium- and computable general-equilibrium (CGE) ones [4–6]. Bottom-up models utilize detailed information about different technologies, and relate energy consumption or supply to technical performance. The limitation of this approach is that it usually neglects feedback effects from the economy. The bottom-up approaches are classified into dynamic optimizations and dynamic simulation-models [7–12]. They utilize dynamic linear- and nonlinear-optimization for energy supply and demand systems. To overcome the weakness of both the bottom-up model and the top-down model, a *hybrid model* also was formulated by combining the two approaches, such as MARKAL-MACRO [13].

Among the many choices of energy-planning models, we selected Market Allocation (MARKAL) for assessing our proposed methodology. It is a technology- rich energy systems analysis approach to evaluate the long-term impacts of environmental- and policy-decisions on the cost-effective deployment of advanced technologies and resources. It identifies the optimal developmental pathway for an energy system over time under given technology characteristics and boundary conditions. More than 100 institutions in 70 countries around the world have used it to analyze a wide array of issues, such as environmental policy, energy policy, subsidy- and tax-regimes, efficacy of R&D programs and their associated benefits, assessment of energy-efficiency programs, and energy-market forecasts [14]. The first version of MARKAL model was developed in the late seventies at Brookhaven National Laboratory New York in collaboration under the auspices of the International Energy Agency's Energy Technology and Systems Analysis Program (ETSAP) and United States Department of Energy. Since then, the model has been bettered continuously and validated by the user community. It computes energy balances at all levels of an energy system: Primary resources, secondary fuels, final energy, and energy services. The function of the model is to identify energy services at minimum global cost by simultaneously making decisions on investments in equipment and on operating decisions and primary energy supply. The model selects that combination of energy technologies that minimize the total cost of the energy system over the projected period [15].

2.2. Life cycle analysis

Life cycle analysis (LCA) is the most widely accepted process for identifying and evaluating the environmental performance of a product over its entire lifetime, i.e., extraction of raw material, its processing, manufacturing, distribution, product use, and end-of-life management. It is a popular approach for analyzing the "cradle-to-grave" consumption of resources and emissions of industrial products and processes [16,17].

Generally, LCAs can be categorized based on the source of the life cycle inventory (LCI) data, and the set-up of the system's boundaries: Bottom-up- and top-down-approaches. The former approach relies on detailed inventory of the inputs and emissions of selected processes [18]. These data usually represent average industrial numbers for a selected geographical region and manufacturing process. Therefore, it is called as process LCA. However, using an often arbitrary boundary can introduce significant errors into the LCA results [19,20], so constituting a major obstacle in the wider use of process LCA. An alternative approach is an economic input–output LCA (EIO-LCA). In this top-down approach, the flows typically are quantified in monetary terms and the flow between economic sectors of a region is determined. An important advantage of the latter is that it considers the entire economy and, unlike the process LCA, avoids defining an arbitrary boundary around selected processes [21]. However, data representing each sector must be tightly aggregated to maintain computational tractability. Hybrid analysis compromises the weakness of both the process LCA and the EIO-LCA [22]. In addition, there is an extensive version of EIO-LCA, viz., the Ecological LCA (ECO-LCA) that encompasses the contribution of natural capital to economic input–output models so to capture the analyses at the ecosystem scale [23,24]. Some researchers prospectively discussed the approach to analyze the consequence of changes in marginal energy-technologies [25,26]. However, most of these tools usually do not consider directly the environmental impacts caused by changes in energy policies and potential technological progresses, such as their efficiency, the introduction of new technologies, and retirement of old ones.

2.3. Combined approach

A combination of both MARKAL and LCA is promising because it will incorporate the strength of both methods. Some previous