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System dynamic modeling of energy savings in the US food industry

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ABSTRACT

In the United States, the food industry alone accounts for approximately 19% of the total energy consumed. The objective of this study is to forecast the food-related energy consumption and evaluate policy alternatives for reducing food related energy consumption in the medium and long term. Influential factors of energy consumption in the food industry include population growth rate, GDP, agriculture's share of GDP, food waste, technologies, and agricultural investment. Based on the life cycle of the food industry, five life stages were considered: agricultural production, industrial processing and packaging, transportation, wholesale and retail, and household. In this study, based on the causal relationships and feedback loops between these factors and the energy consumed for each life stage, a system dynamics (SD) model was designed to simulate the situation for the US food industry. Policy options of reducing waste percentage and improving industrial energy productivity are incorporated for building the energy use mitigation scenarios. By implementing the integrated mitigation scenarios, a 9.43% reduction in total food system energy consumption can be attained in 2030.

1. Introduction

Owing to oil shortage, air pollution and climate change, energy savings and emission reductions are important issues with global attention. The food industry, which accounts for 30% of the global energy consumption and 20% of greenhouse gas emissions has been increasingly recognized for its potential for energy savings (Monforti-ferrario et al., 2015). From the production of crops and livestock, to the processing, packaging, distributing, storing, preparing, serving and disposing of food products, energy plays an important and necessary role for every stage of the food industry. In the United States, the food industry takes a 10% share of the US GDP (Egilmez et al., 2014) and around 17.3 million full- and part-time jobs are related to agriculture—about 9.3 percent of total US employment (Glaser and Morrison, 2016). Although the food industry is neither energy nor emission intensive compared with other industries such as iron or steel, it is still an important energy consumer due to its massive scale. Overall, the food industry accounts for approximately 19% of the total primary energy consumed in the US, and each American requires nearly 2000 l/year in oil equivalents to supply their food (Pimentel et al., 2008). Additionally, in order to accommodate a growing population the industry has consequentially grown in recent years. The average annual growth rate of US food-related energy use was about 23 percent (Azzam, 2012). Therefore, it is necessary to seek energy saving approaches for the food industry.

The food industry includes several important components—such as regulation, education, research and financial services–which are beyond the scope of our interest here because they represent very little energy consumption. We are actually modeling the food system. The food system includes all the processes involved in feeding a population: agricultural production, food manufacturing (formulation, food processing, and packaging), transportation and distribution, wholesale and retail, and food preparation and disposal in the home. Based on the life cycle of the food system, five life stages were considered: agricultural production, industrial processing and packaging, transportation, wholesale and retail, and household (Minn and Seager, 2009). In addition to the rapid population growth, several other factors also influence energy consumption throughout the US food system, such as GDP growth rate, agriculture's share of GDP, food waste, technologies, and agricultural investment. These factors were chosen because they were always used in previous literature for analyzing the food system or building SD models for other industries (Ansari and Seifi, 2012; Canning et al., 2010; Minn and Seager, 2009; Wallgren and

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Mattias, 2009).

In this study, based on the causal relationships and feedback loops between these factors and energy consumed for each life stage of the food system, an SD model integrated with life cycle analysis (LCA) was built to capture the constant shifts and changes occurring in the US food system. The model was validated on data from 1980 to 2014 and used to predict the trends of total US food energy consumption through 2030. The objective here is to estimate potential energy consumption in the future and to assess the effects of two potential policy approaches for saving energy in the US food industry: specifically, reducing the percentage of food waste and improving industrial energy productivity.

Many papers have discussed energy conservation in the food industry in different parts of the world, but none has comprehensively examined the energy conservation status in all of the five life stages in the food system. This paper addresses the following important issues:

- the impacts of population and GDP growth on food demand;
- the inherent structures of energy consumption under diverse scenarios for each life stage and the whole food system;
- the impact of investments in public agricultural research and development (R&D) on agricultural energy intensity;
- the impact of agriculture's share of GDP on agriculture energy use; and
- analysis of potential energy savings attained by two policies: reducing waste percentage and improving energy productivity in industrial processing.

The rest of this paper is organized as follows: Section 2 presents literature relevant to this study and how this research is derived; Section 3 discusses the methodology, the modeling framework of this study and the model validation; Section 4 develops the sensitivity analysis, the policy analysis and the result discussion; and Section 5 provides the conclusion and the limitations of this paper.

2. Literature review

Much research has analyzed food related topics, especially issues like food security (Godfray et al., 2010; Maxwell, 1996; Schmidhuber and Tubiello, 2007) and food quality (Cen and He, 2007; Grunert, 2005). Since the food industry is not an energy-intensive industry and cost for energy inputs is only approximately 3% of the total cost of production (Muller et al., 2007), much less literature deals with energy consumption in the food industry. Energy conservation in the food industry has been studied by several authors in different parts of the world, such as the US (Azzam, 2012; Canning et al., 2010; Specht et al., 2014), China (Lin and Xie, 2015, 2016; Ma et al., 2012), the UK (Hall and Howe, 2011), France (Seck et al., 2013, 2015), the Netherlands (Ramírez et al., 2006), Switzerland (Muller et al., 2007), Portugal (Nunes et al., 2014, 2016), and Sweden (Wallgren and Mattias, 2009).

Ramírez et al. (2006) developed feasible indicators to monitor energy efficiency developments in the food industry based on physical production data at the company level. To our knowledge, this was the first time that energy usage per unit of physical output was examined in a non-energy intensive industry at a high level of aggregation. Hall and Howe (2011) analyzed the influence of improving different kinds of energy intensive technologies on energy savings for the food processing industry. Azzam (2012) answered the question of how much of US energy consumption goes to the US food system by compiling diverse previous research findings into a table and provided several energy efficient actions. Specht et al. (2014) introduced an environmentally friendly building named Zfarming for future urban food production promising resource savings and energy efficiency. In other efforts to increase energy efficiency and save energy, Nunes et al. (2014) devised a predictive tool for assessing the energy performance of cold storage in agrifood industries, and Seck et al. (2013, 2015) developed a bottom-up model to analyze the impact of heat recovery using heat pumps in industrial processes. Lin and Xie (2015) studied the substitution relationships between energy and other input factors like capital and labor and the rebound effect of the food industry in China. Most of this research provides tools for measuring energy efficiency development in a single stage of the food industry. However, we are unaware of any study that has comprehensively examined the energy conservation status in all of the five life stages in the food system.

Energy conservation or carbon emission reductions have always been a hot topic for researchers focusing on diverse industries. Methods employed in such studies can be divided into three main categories: top-down, bottom-up, and hybrid approaches. The top-down approach, such as Stochastic Frontier Analysis (SFA) and Data Envelopment Analysis (DEA), refers to the decomposition of a scenario into a set of equations. DEA has been applied in the transport sector (Park et al., 2016), the power industry (Hampf and Rødseth, 2015), and the iron and steel industry (Yang et al., 2016). SFA has been used in the electricity sector (Chen et al., 2015), the chemical industry (Lin and Long, 2015), and the thermal power industry (Lin and Long, 2015). Bottom up approaches, such as conservation supply curve (CSC) and regression, analyze the global impacts associated with an industry by assembling the various local disaggregated influences. Chen et al. (2017) applied CSC to analyze the costs and the potential of energy conservation in China's coal-fired power industry. CSC has also been used in India's cement, iron and steel industries by Morrow et al. (2014). A hybrid approach combines both bottom-up and top-down approaches.

For the food industry, Gowreesunker and Tassou (2015) summarized many different approaches for modeling the food energy flow, including life cycle analysis (LCA), MARKAL model, regression analysis, input-output (IO) analysis and SD model. Among them, LCA, MARKAL model and regression analysis belong to bottom-up approaches, but IO analysis and SD model are top-down approaches. MARKAL is a demand-driven model used to compare multi-period energy-related systems at the national level to represent its evolution. It is often used to determine the trade-offs between different objectives such as costs and environmental indicators (Gowreesunker and Tassou, 2015). Regression is a simple model to reflect the causal relationships between the dependent and independent variables in the food system. Using statistical methods or empirical observations to determine suitable influential variables is especially important for regression analysis (Mendenhall and Sincich, 2012). Among these five methods, LCA and IO analysis are the most popular quantitative approaches. IO is a technique that represents the interdependencies between different branches of economic sectors. Food-energy IO analysis is usually used at a product specific level. This method always needs a wide range of data presented in tabular form and can be attained from national statistical offices on a yearly basis. Canning et al. (2010) employed the IO model to analyze the energy flow in the US food system between 1997 and 2007, and Zhang et al. (2012) built a multi-regional IO model to track the use of energy for various sectors in China in 2007. LCA, also known as cradle to grave analysis, is a technique for evaluating environmental impacts associated with all the processes or activities throughout the life cycle of a product. LCA analysis was developed in the 1960s. Since then, more and more researchers have used LCA to monitor energy flows in the food industry, including Monforti-ferrario et al. (2015) and Dutilh and Kramer (2000). Another powerful approach to model a complex system is SD, a computer aided approach to