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Review

Energy consumption during cooking in the residential sector of developed nations: A review

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ABSTRACT

Residential cooking is essential for the enhancement of safety and quality of a substantial number of food products, but the energy requirements for cooking can be prodigious and individual household energy use varies considerably. This review evaluates the current state of energy efficiency during household cooking in developed countries and identifies potential policy changes that may have an impact on reducing energy consumption. The primary factors affecting energy consumption include: (1) the production and transport efficiency of fuel sources (electricity, natural gas, wood, etc.); (2) the appliance (or end-use) efficiency; and (3) the behavior of the consumer during cooking. Regarding appliance efficiencies, some improvements are plausible and policies should be directed towards reducing or alleviating stand-by energy consumption in new products. However, the most promising energy conservation tactic is consumer behavior modifications since individual cooking practices can reduce expenditures by as much as 95%; thus, policies should be directed towards consumer education to have the most marked effect on household energy consumption. Although cooking is only one aspect of food production, it is a universal requisite for food safety in the residential sector and implementing policies that reduce energy consumption during cooking may have an impact on global energy demands.

Introduction

Cooking is an important part of daily food preparation in commercial and residential settings. The application of heat alters the composition of food products to enhance taste, texture, digestibility and shelf-life (Lund, 1975). Additionally, cooking is essential to reduce food-borne illnesses that afflict an estimated 9.4 million Americans annually (Scallan et al., 2011). However, residential cooking can require substantial amounts of energy—approximately 7 MJ/kg food product (Dutilh and Kramer, 2000). In American households, cooking utilizes as much as 6.9×10^8 GJ/year (Heller and Keoleian, 2000).

In the US, as well as other developed nations, the energy required to produce food products is still significantly greater than the energy provided by the end-product (Heller and Keoleian, 2000) and constitutes 8–16% of the total national annual energy consumption (Cuellar and Webber, 2010). From a policy perspective, improvements in all aspects of global food production (from agriculture good to final consumer product) are necessary to realize sustainable energy practices. Although cooking is only one aspect of food production, it is essential for the safety of many food products and contributes to the palatability and acceptability of foods (Pimentel and Pimentel, 2008). The purpose of this review is to (1) summarize the efficiencies of various modern energy sources used for cooking, (2) present specific residential food practices that reduce energy expenditures, (3) compare the energy requirements and sources of current residential cooking appliances and (4) identify specific policy changes that may reduce household energy consumption during cooking.

Cooking methods and mechanisms of application of heat

Depending on the method of application of heat and duration, cooking is a broad heat-treatment term that is generally categorized as baking, roasting, broiling, boiling, frying, and stewing (Lund, 1975). A description of each type of cooking, the mechanism of heating (conduction, convection, or radiation), and the typical uses are listed in Table 1. Other cooking methods, such as microwave and radio frequency, generate heat within the food by electromagnetic waves (Fellows, 2009).

Energy sources and efficiency during cooking

The conversion of one form of energy to another by a device is never 100% due to inevitable losses in the conversion process (Radovic and Schobert, 1997). When burning fossil fuels, only a fraction of the chemical energy contained in the fuels is

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Table 1
The general categories of cooking and heating mechanisms. From: Lund (1975) and Fellows (2009).

Category	Description	Heat transfer mechanism	Uses
Baking	Food in oven: 100–300 °C	Convection (air); radiation (oven walls); conduction (pan)	Flour-based foods; fruits
Roasting	Food in oven: 100–300 °C	Convection (air); radiation (oven walls); conduction (pan)	Meats; nuts
Broiling	Food in oven: up to 300 °C	Primarily radiation (burner); some convection (air); Some conduction (pan)	Meats
Frying	Food submerged in hot oil (deep-frying) or cooked in a thin layer of fat (pan-frying)	Deep-frying: conduction (pan); convection (liquid) Pan-frying: conduction (pan)	Meats; vegetables
Stewing/boiling	Food cooked in boiling/simmering water	Conduction (pan); convection (liquid)	Meats; vegetables; grains; pastas

transformed into usable heat. Generically, the efficiency (η) of a process can be defined by the ratio of the useful energy output to the energy input. When comparing the efficiency of devices powered by different sources of energy, determining the overall efficiency is a more comprehensive approach than reporting solely the efficiency of the device. Therefore, the overall efficiency or system efficiency (η_s) is the product of (1) the production and transport efficiency of the fuel and (2) the appliance (or end-use) efficiency (Fig. 1).

The efficiency of power plants depends on the technology and the type of fuel. Coal-fired plants have typical efficiencies around 30% and plants with superheating (where steam is heated above its saturation temperature before coming to the turbine) can boost the efficiency to 40% (Cocks, 2009). Modern natural gas combined-cycle power plants may reach efficiencies up to 60% (Boyce, 2001) while most nuclear plants have efficiencies of approximately 32% (Cocks, 2009). Modern hydroelectric plants have efficiencies as high as 90% (U.S. Department of the Interior, 2005).

The determination of efficiency during cooking is challenging due to variations in individual appliances as well as methods for determining and reporting efficiency. For example, the size of the burners and the diversity of pots used for cooking complicate the determination of the appliance efficiency because stoves have burners of different sizes and heating occurs with pots of various size and composition adding more terms to the efficiency equation (Fig. 1), thereby reducing the overall efficiency in most cases. Furthermore, for the determination of energy efficiency of cooking appliances, studies often determine only the end-use or appliance efficiency at accomplishing a specific task (i.e. boiling water); however, as indicated previously, there are widely varied production and transport efficiencies of fuel sources, so the most appropriate determinant of efficiency is the overall system efficiency.

To further complicate the issue, the tests used to determine the end-use efficiency are diverse. They all evaluate the energy input at the site of the appliance required to heat a test load to a specific temperature but the composition of the test load varies with each test. The most common tests are: (1) the water boiling test (WBT) which is often used for microwaves, wood stoves and solar cookers, but is also used for modern stoves; (2) a wet brick test that utilizes a standardized, wet porous brick (HIPOR) to evaluate ovens, (3) the aluminum and anodized aluminum block test for stoves and ovens, respectively; and (4) the carbon steel block test which is used as an alternative to the aluminum block test in the evaluation of induction stoves (Datwyler and McFadden, 1992; DOE, 1996; U.S. Office of the Federal Register, 1997; DEFRA, 2012b). The latter two tests utilize aluminum or steel blocks with precise dimensions that are fitted with a thermocouple (for internal temperature monitoring) while WBTs, which may also include a lid fitted with a thermocouple, are not universally standardized and may be conducted with various water volumes or pan compositions (Datwyler and McFadden, 1992; DOE, 1996; U.S. Office of the Federal Register, 1997). The block and brick tests are standardized and reproducible, but reporting the thermal of efficiency for metal blocks is dissimilar to heating food products; thus, arguably, the use of the water boiling test is a more accurate depiction of practical efficiency for consumers. Ultimately, for precise comparisons of appliance efficiency, the block tests are superior, but the use of an internationally standardized WBT is more appropriate. Currently, there is a standardized WBT established by the American Society for Testing and Methods for all domestic gas and electric stoves (European Commission, 2010), but widespread use seems to be limited. Additionally, the European Union (EU) and various non-EU countries have developed their own WBT standards for energy efficiency evaluations of domestic cooking appliances (European Commission, 2010). In spite of the diversity of tests and possible discrepancies in energy efficiency determination, the following discussions attempt to reconcile the data to present a comprehensive understanding of the efficiencies of many of the traditional cooking methods currently used in society.

Impact of consumer behavior on cooking energy requirements

The conduct of the consumer can play a significant role in the energy usage during cooking. In a study comparing "patient" cooks

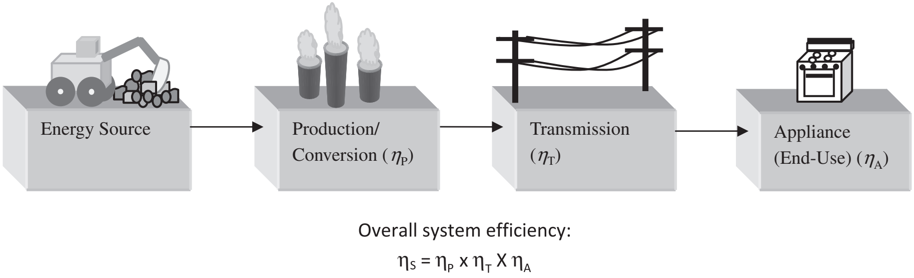

Fig. 1. Diagrammatic representation of the overall cooking efficiency (η_S) as the product of the production/conversion, transmission, and end-use of the energy source. The production/conversion efficiency is determined by a variety of factors during energy processing such as the turbine, boiler, and generator efficiency.