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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).

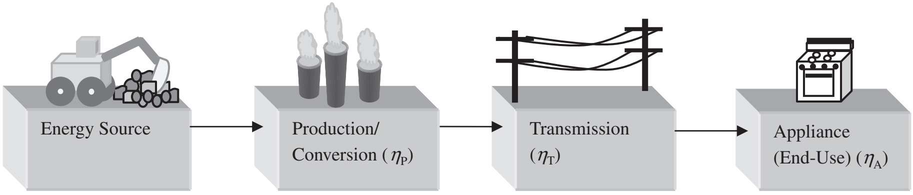
The efficiency of power plants depends on the technology and the type of fuel. Coal-fired plants have typical efficiencies around 30% and plants with superheating (where steam is heated above its saturation temperature before coming to the turbine) can boost the efficiency to 40% (Cocks, 2009). Modern 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



Overall system efficiency:

$\eta_S = \eta_P x \eta_T X \eta_A$

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.

with "hurried" cooks (that did not bother to control cooking parameters), the "patient" cooks used 1746–2326 MJ and the "hurried" cooks used 4061–4637 MJ to prepare the same meal (DeMerchant, 1997). In summary, the behaviors of the consumer can double the energy demands for cooking if the consumer is unaware of energy saving techniques. Over the past three decades (due to the emphasis on energy conservation during the 1970s), many studies have evaluated consumer practices that are important for saving energy during cooking and these techniques are summarized in Table 2.

Just the use of a lid on a pot with water maintained at 100 °C can reduce energy requirements 8-fold, according to Newborough and Probert (1987), since the use of the lid reduces the loss of latent heat during evaporation. Furthermore, the heating efficiency increases as the volume of fluid in the pot increases and the pan size increases (Table 2). For example, when only 20% of a particular pot is filled, the water-boiling efficiency is almost half of the efficiency when using it at capacity (100%) (Newborough and Probert, 1987). Similarly, Oberascher et al. (2011) demonstrated that there is a negative linear relationship between increasing water volume and the specific energy consumption (or energy per volume of water) to heat water to 90 °C under a variety of conditions (electric kettle, pots, microwave, etc.). Since water-boiling efficiency increases with pan size and volume of fluid, encouraging consumers to cook food in larger volumes, when possible, would reduce the amount of cooking energy required per mass of cooked food (J/kg food).

Although it may require some additional time to attain the final product, partly cooking a product and then allowing it to continue cooking only with the residual heat—passive cooking—also reduces energy requirements (Table 2) (Amann et al., 2007). Additionally, controlling temperature during cooking by monitoring the temperature of the food, the cooking medium, or the pan also plays an important role in energy conservation (Table 2). As a result of the benefits of controlled cooking, newer models of stoves are actually fitted with temperature or infrared sensors and microprocessors to regulate cooking temperatures automatically for consumers (Thim, 2009). Even educating consumers to avoid yellow flames on gas stoves—indicative of inefficient gas burning—could improve energy use (Amann et al., 2007).

The composition, size and shape of the cookware influence energy consumption (Table 2) with thermally inefficient pots reducing efficiency by as much as 30% (Carlsson-Kanyama and Bostrom-Carlsson, 2001). For example, pans comprised of metals (particularly with copper bases), due to the high thermal diffusivity, can be heated on the stove more efficiently than ones with less conductive properties (i.e. glass and ceramics) (Newborough and Probert, 1987; Amann et al., 2007). In contrast, since radiation is the primary heating mechanism in the oven, glass and ceramic dishes can be significantly more efficient than all metallic cookware during baking/roasting due to the low emissivity (or reflective nature) of metal pans (Newborough and Probert, 1987; Amann et al., 2007).

Residential food cooking: fuel sources and appliances

The energy used for household storage and preparation of food in developed countries can generally be categorized as energy for cooking (~20% of the total), refrigeration (>40% of the total), and the generation of hot water for washing dishes (~40% of the total) (Heller and Keoleian, 2000). The two most common forms of cooking are surface (stove-top) and oven cooking. Although ranges (units that combine stoves and ovens) are also available, for discussion purposes, the stove and oven portions will be considered

Table 2
Potential energy savings associated with various cooking techniques.

Techniques	Reduction in energy[a] (%)	Reference
Cooking method		
Simmering (~90 °C) rather than boiling (100 °C)	69–95[b]	Brundett and Poultney (1979)
Steaming rather than boiling	9–56	Warthesen et al. (1984)
Passive cooking[c]	17–23	Carlsson-Kanyama and Bostrom-Carlsson (2001)
Simmer with a pot lid	50–85[d]	Brundett and Poultney (1979)
Bake at lower temperatures	4–13	Scarisbrick et al. (1991)
Cookware		
Using a pan with a diameter larger than the heat source	31–40	Newborough and Probert (1987)
Using non-distorted, flat pans	42–68	Probert and Newborough (1985)
Using insulated materials to retain heat (e.g. brew and retain heat of coffee for 120 min)		Oberascher et al. (2011)
Using a larger pot size (based on the ratio of the energy-to-volume)	42–63	Newborough and Probert (1987)
Food volume		
Filling pot to capacity	20–49	Newborough and Probert (1987)
Cooking larger quantities (based on the energy-to-mass ratio)	78–83[e]	Oberascher et al. (2011)
Baking more than one portion at a time (based on the energy-to-mass ratio)	43–75[e]	Carlsson-Kanyama and Bostrom-Carlsson (2001) and Scarisbrick et al. (1991)
Monitoring product		
Monitoring internal temperature	19–50	Das et al. (2006)
Stirring	3–14[f]	Newborough and Probert (1987)
Soaking		
Soaking prior to cooking (for certain foods)	3–19[g]	Das et al. (2006) and Roy et al. (2004)

[a] Calculated from total energy data presented by the authors: % Reduction = 100 − [$(E_s/E_t) * 100$], where E_s is the energy required for the energy conservation method and E_t is the energy required for the typical/traditional method.

[b] Largest reduction achieved by the use of the pan lid.

[c] The use of residual heat after termination of the heat source to finish cooking the product.

[d] At 100 °C, the differences were negligible.

[e] Percent reduction in the specific energy (or energy required divided by the mass of the product).

[f] This is the percent reduction in time to cook at the same temperature with and without stirring. Energy usage was not reported; however, energy savings should be comparable since the temperature was constant.

[g] Values reported only for rice.

isolated entities and referred to individually (as "stove" or "oven"). In the US, the primary residential energy sources for cooking are electricity (63% of the population) and natural gas (35%); however, the use of natural gas appliances in the US is greater as household size and income increase (EIA, 2009). There is a small portion (5%) of the population that utilize propane or LPG as well as kerosene (<0.3%) and wood (<1.5%) (EIA, 2009). In Europe, most cooking appliances are electric with only a small fraction of the appliances utilizing gas—ovens (~16%) and stoves (~36%) (DEFRA, 2012a).

Since 1990, the average energy consumption of residential cooking appliances in developed countries has decreased approximately 31% due to improved technology (Thim, 2009); however, additional improvements are still possible and documentation by the UK Department of Environment, Food, Rural Affairs (DEFRA) suggest that "ecodesign" regulations should be introduced to further reduce the primary energy consumption of ovens and stoves by 10% and 24%, respectively, by 2020 (DEFRA, 2012b).

Stove-top cooking

Gas stove-tops

European regulations require typical gas stove conversion efficiencies of at least 52% (European Commission, 2010) and manufacturers are currently generating niche market appliances with thermal efficiencies as high as 69% (Shein, 2010); however, the average gas stove top cooking efficiency in the US is only ~40% (DOE, 2008). According to Ramanathan and Ganesh (1994), the end-use efficiency of LPG and natural gas for cooking is typically only 50% while the end-use efficiency of electricity is approximately 80% (although this is not specific to stove-top cooking) (Fig. 2). In the few studies comparing the efficiency of cooking specific foods, it is still not clear if cooking with natural gas or LPG is more efficient (Table 3).

For gas stoves, the most prominent source of wasted energy is standing pilot lights (DOE, 1996), but these are becoming less common in modern gas stoves. Other features of a gas stove (natural gas and LPG) that can be modified to enhance end-use energy efficiency are listed in Table 4. However, the use of sealed burners (Tables 4 and 5) remains controversial. According to the DOE, sealed burners may enhance efficiency (DOE, 1996, 2008); however, according to Datwyler and McFadden (1992) sealed burners decreased the efficiency of gas stoves (Fig. 3).

Electric stove-tops

The heat sources for traditional modern electric stoves consist of (1) suspended concentric metallic resistance rings/coils, (2) glass–ceramic surfaces, or (3) solid plate elements (Table 5); however, solid plate elements are primarily utilized as individual portable hotplates (European Commission, 2010). Induction stoves are also considered electric stoves, but heating by differs greatly from traditional electric stoves and will be discussed in more detail in 'Induction stoves' section. According to the DOE, the average end-use efficiency of all electric stove tops (smooth and coil tops) is 74% (DOE, 2008); however, due to the large variations in the categories of electric stove-tops, the efficiencies can vary greatly. Using steel block and water boiling tests, Datwyler and McFadden (1992) evaluated efficiencies of various electric stoves (Fig. 3). The most efficient was halogen (under glass–ceramic), but there was large variation between appliances.

Various studies and reports indicate that solid disk elements are the least efficient of the electric stove-tops (DOE, 2008; Datwyler and McFadden, 1992; Amann et al., 2007). In contrast, however, Carlsson-Kanyama and Bostrom-Carlsson (2001), reported that the glass–ceramic stove-tops were up to 20% less efficient than the solid hotplate surfaces. Furthermore, for coiled stove-tops, reflective trays beneath the electric coils are considered important for energy efficiency and can reduce heating times by 20% (Probert and Newborough, 1985). While the DOE (1996) also recognized the importance of the trays, they reported the inclusion of reflective trays only minimally increases energy efficiency (by approximately 1%) and soiling of the trays can diminish cooking efficiency and heat transfer (Carlsson-Kanyama and Bostrom-Carlsson, 2001). In conclusion, more work may be necessary to determine which stove elements are the most efficient.

Oven cooking

Although essential for many applications such as bakery products (i.e. pastries and bread), oven cooking—baking and roasting—generally consumes more energy than surface cooking (Table 3) (Rhee and Drew, 1977; Carlsson-Kanyama and Bostrom-Carlsson, 2001). When unavoidable, however, broiling (rather than traditional roasting) may save considerable energy during cooking (Table 3) (Rhee and Drew, 1977). Furthermore, due to the size of the oven space, the energy requirements to attain

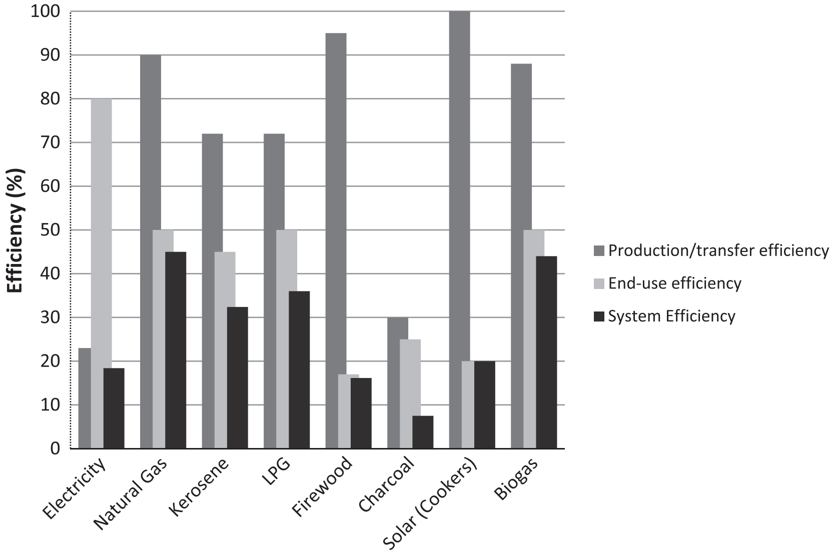


Fig. 2. Energy sources for cooking with conversion and transport efficiencies, end-use efficiency, and total system efficiencies as summarized from Ramanathan and Ganesh (1994).

Table 3
Comparison of modern cooking appliance efficiencies for specific foods.

Product (quantity)	Stoves			Ovens			Pressure		
	Electric[a]	NG	LPG	Electric	NG	LPG	Microwave	Cooker	Reference
Barley (4 serv.)	180 kJ/serv.	–	–	–	–	–	270 kJ/serv.	–	Carlsson-Kanyama and Bostrom-Carlsson (2001)
Beef patty (1)	343–373 kJ	569–654 kJ[b]	795–917 kJ[b]	B: 1416–1936 kJ R: 2283–2107 kJ	B: 2608–3519 kJ[b] R: 3851–5387 kJ[b]	B: 2842–3484 kJ[b] R: 4492–6631 kJ[b]	154 kJ	–	Rhee and Drew (1977)
Boiling water (250 mL)	1112 kJ/kg[c]; 1145 kJ/kg[d]						760 kJ/kg	–	Oberascher et al. (2011)
Boiling water (1000 mL)	551 kJ/kg[c]; 565 kJ/kg[d]						745 kJ/kg	–	Oberascher et al. (2011)
Broccoli (4 serv.)	2380 kJ[4]	–	–	–	–	–	490 kJ	E: 482 kJ ES: 788 kJ	Warthesen et al. (1984)
Navy beans (4 serv.)	1004.4 kJ[c]	–	–	–	–	–	1238 kJ	E: 522 kJ ES: 889 kJ	Warthesen et al. (1984)
Potatoes (2000 g)	991.4 kJ[c]; 2369 kJ[d]	–	–	Steam oven: 1697 kJ[f]	–	–	–	1283 kJ[f]	Oberascher et al. (2011)
Potatoes (4 serv.)	300 kJ/serv.	–	–	1300 kJ/serv.[g]	–		510 kJ/serv.[g]	–	Carlsson-Kanyama and Bostrom-Carlsson (2001)
Potatoes (4 serv.)	2088 kJ[c]	–	–	4493 kJ[g]	–	–	796 kJ[f]	ES: 1357 kJ E: 1465 kJ	Warthesen et al. (1984)
Rice (300 g)	–	–	–	–	–	–	4200 kJ/kg	LS: 4000 kJ/kg	Lakshmi et al. (2007)
Rice (1 serv.)	340 kJ/serv.[e]	–	–	–	–	–	630 kJ/serv.	–	Carlsson-Kanyama and Bostrom-Carlsson (2001)
Rice (4 serv.)	120 kJ/serv.e[e]	–	–	–	–	–	230 kJ/serv.	–	Carlsson-Kanyama and Bostrom-Carlsson (2001)
Rice (296 g)	2880 kJ	–	2098 kJ	–	–	–	–	E: 1620 kJ LS: 1180 kJ	Das et al. (2006)

Serv.: Serving; B: Broiling; R: Roasting; E: Electric; ES: Electric Stove; LS: LPG Stove.

[a] Induction stoves are not included.

[b] Values reported as cubic feet; energy contents of the gases were estimated at normal temperature and pressure (NTP) with conversion values of 33 MJ/m^3 and 108 MJ/m^3 for NG and LPG, respectively (Engineering Toolbox, 2012).

[c] With lid on the pot.

[d] Without lid on the pot.

[e] Hotplate.

[f] Boiled/steamed potatoes.

[g] "Baked" potatoes.

and maintain high temperatures indicate that oven cooking is more suitable for large portions than small ones (Table 3) (Carlsson-Kanyama and Bostrom-Carlsson, 2001). Although not an option for certain products such as breads, cakes, or similar baked goods, the use of the oven during pre-heating can have a considerable impact on the energy consumption (Rhee and Drew, 1977). Additionally, the use of fans (i.e. convection ovens) to increase the convective heat flow during cooking can increase cooking efficiency because (1) they need less time for pre-heating and (2) they cook at lower temperatures than conventional ovens (Table 4) (Amann et al., 2007; Probert and Newborough, 1985).

In addition to traditional ovens, self-cleaning ovens are gaining consumer popularity since manual cleaning is difficult and often involves undesirable chemicals. The two types of self-cleaning ovens are pyrolytic and catalytic (Table 5) (Probert and Newborough, 1985). Currently, the most common self-cleaning oven is the pyrolytic version which is less costly to manufacture due to the relatively high cost of the catalysts (Palmisano et al., 2009). Since the catalytic (continuous) self-cleaning ovens do not require high temperatures for extended times like the pyrolytic ones, theoretically, they utilize less energy during the self-cleaning process; however, more work is necessary to compare the energy requirements of the two types of ovens.

Self-cleaning ovens (specifically pyrolytic versions) are more efficient than standard ovens due to the greater wall insulation density designed to withstand the high temperatures for self-cleaning (DOE, 1996, 2008); thus, theoretically, fitting standard ovens with insulation of the same density of the self-cleaning ovens should improve the efficiency of standard ovens (Table 4) (DOE, 1996, 2008). In addition, conducting the self-cleaning cycle immediately after the oven has been used decreases the overall energy required for self-cleaning because less energy will be required to reach the proper temperatures (Amann et al., 2007).

Another proposed modification of gas and electric ovens includes the potential modification of vent tubes (that exhaust smoke from the oven) (Table 4) (DOE, 1996), but there are some limitations to their alteration. Due to the possible accumulation of smoke with the very high temperatures employed during roasting (or baking) of foods, especially foods with high lipid content, vent tubes include a catalyst to assist in the removal of malodorous, hazardous and discoloring components (Fries, 1956; Valle et al., 1999). Although somewhat controversial, the most recent report by the DOE indicates reducing the vent rate may still be a design option to increase efficiency (for both electric and gas ovens) (DOE, 1996, 1998, 2008).

Electric ovens

In the US, the average electric oven utilized ~1.6 GJ/year, according to the Energy Information Administration (EIA) in 2001 (EIA, 2001), with average cooking efficiencies of 12.15% and 13.79% for standard and self-cleaning electric ovens, respectively (DOE, 2008). The viable appliance alterations to potentially increase appliance efficiency are listed in Table 4.

Gas ovens (natural gas and liquid petroleum)

The US DOE reported that the average standard and self-cleaning gas oven cooking efficiencies are 5.92% and 7.13%, respectively (DOE, 2008). Likewise, Probert and Newborough (1985) reported

Table 4
Features or modifications that may enhance efficiency of various cooking appliances.

Modification	Effect of modification	Fuel source	References
Stoves			
Greater pan-to-stove contact to enhance heat conduction	Amann et al.: ↓ energy requirements up to 50% (for pasta); DOE: ↑ efficiency by 4.3%	Electric	Amann et al. (2007) and Probert and Newborough (1985)
Use of halogen elements (compared to solid disk elements)	↑ Efficiency by 1.5%	Electric	DOE (2008)
Sealed burners	DOE: ↑ efficiency by 4.8% (NG); Datwyler and McFadden: ↓ efficiency by 5–8% (NG); Adams: NS	NG	DOE (1996), Datwyler and McFadden (1992) and Adams (2008)
Greater flame control (i.e. very low simmer option)	NS	NG	Adams (2008)
Alter burner configuration/shape	NS	NG	Adams (2008)
Ovens			
Improve insulation	↑ Efficiency by 4.9% (NG) or 0.52% (Electric)	Electric, NG	DOE (1996, 2008)
Improve door seals	↑ Efficiency by 1% (NG)	Electric, NG	DOE, 2008
Use of convection fans	Probert and Newborough: ↓ energy use up to 30% (for various foods); DOE: ↑efficiency by 4.8% (NG)	Electric, NG	DOE (2008), Amann et al. (2007) and Probert and Newborough (1985)
Reduce vent tube size of standard ovens (to the size of self-cleaning)	↑Efficiency by 0.5% (NG)	Electric, NG/LPG	DOE (1996, 2008)
Radiant burners	NS	NG/LPG	DOE (1996, 2008)
Microwaves			
Improved power supply	↑ Absolute baseline efficiency by 2.9%	Electric	DOE (2008)
Improved fan	↑ Absolute baseline efficiency by 0.23%	Electric	DOE, 2008
Use of reflective surfaces	↑ absolute baseline efficiency by 0.5%	Electric	DOE (2008)
Improved magnetron	↑ absolute baseline efficiency by 0.9%	Electric	DOE (2008)

NS: Not specified.
↑: Increase; ↓: Decrease.

Table 5
Modern stove and oven appliance options.

Appliance	Power	Description	Reference
Stoves			
Coiled element	Electric	Suspended concentric metallic resistance rings/coils	
Glass–ceramic element (halogen/radiant)	Electric	A heat source directly below a solid surface—glass with a ceramic-like crystalline structure—designed to withstand dramatic temperature changes (low coefficient of thermal expansion)	Pannhorst (1997)
Solid disk element	Electric	Coiled electric resistance wires embedded within an encasing (typically ceramic) beneath the surface of a metal plate	Hurley (1988) and Hurko (1974)
Induction	Electric	High frequency (25 kHz) alternating current applied to a coil (inductor) just below the cooking surface producing a changing magnetic field that generates heat within metal cookware	DOE (1996), Acero et al. (2010) and Thim (2009)
Sealed burner	Gas	Surface of the cooker acts as a drip pan with the flame flush against the burner and a cap placed at the center of the burner	DOE (1996, 2008)
Ovens			
Self-cleaning—pyrolytic	Electric/gas	Oven surface comprised of material that can withstand extremely high temperatures (500 °C) for long durations (2 h) in order to generate ash from residual food to facilitate easy cleaning	Probert and Newborough (1985)
Self-cleaning—catalytic (continuous)	Electric/gas	Porous oven surface embedded with catalysts which oxidize residual food at typical cooking temperatures so the cleaning (conversion to ash) is conducted during normal product cooking	Palmisano et al. (2009)

that gas oven end-use efficiency was less than electric oven due to the ventilation required for gas ovens; however, taking into account the production and transport efficiency of gas and electricity in the UK at the time of the publication, the overall system efficiency of the electric oven was significantly less than gas ovens. Ramanathan and Ganesh (1994) also showed similar disparities in end-use and system efficiencies for cooking with gas and electric (Fig. 3). Data on enhancing the efficiency of ovens specifically designed to burn natural gas or LPG is minimal (Table 4) and the current US standards only indicate that there should be no standing pilot lights in newly manufactured appliances (DOE, 2008).

Microwave

The microwave has become more ubiquitous in American households over the past 25 years, according to the EIA (2009), with 88% of homes owning a microwave in 2005 compared to 8% in 1977. Microwave ovens are designed to emit electromagnetic waves in the microwave range (2.45 GHz for typical household microwaves) that induce polar compounds within a product to move rapidly which generates heat via molecular friction and not by typical heating mechanisms—conduction, convection, or radiation (Venkatesh and Raghavan, 2004). The average cooking efficiency of a microwave is reportedly 55.7–60.2% (depending on the class of microwave) (DOE, 2008), but potentially as high as 98% (Sadhu et al., 2010); however, Probert and Newborough (1985) indicate that microwaving efficiencies can be as low as 35% and Lakshmi et al. (2007) reported theoretical microwave cooking efficiencies as low as 16% for rice. The large discrepancies in the reported efficiencies of microwave ovens are not surprising due to the lack of a standardized and reproducible efficiency test that is suitable for all models of microwaves. The irreproducibility of test results and controversy over the use of water as the representative food load eventually resulted in a repeal of the US DOE test procedures for active mode microwave oven efficiency in 2010 with no viable replacement protocols to date (DOE, 2010a).

Pimentel et al. (2009) determined from published data that daily cooking of 2500 kcal with a microwave as opposed to an oven could conserve as much as 5.8 GJ/person/year. Cooking various vegetables in a microwave reduced energy use up to 65% compared

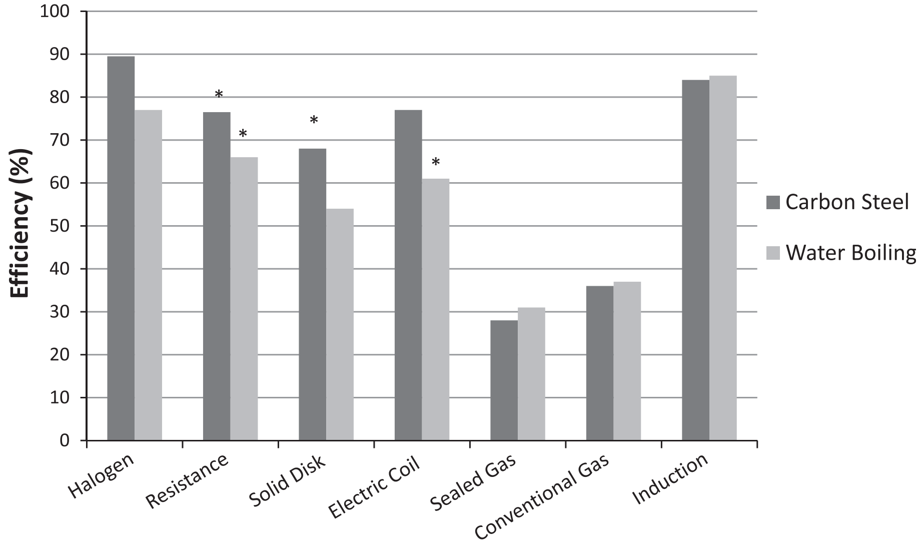


Fig. 3. End-use efficiencies of various electric and natural gas stoves as determined by the carbon steel block and water-boiling tests. Adapted from data presented in Datwyler and McFadden (1992). Values for halogen and resistance (under glass) appliances were averaged; however, according to the authors, the data may be slightly skewed since values were dramatically different indicating significant variation in efficiencies of individual appliances. *Values within the same test are not statistically different.

to boiling on the stove while simultaneously reducing cooking time (Table 3) (Warthesen et al., 1984; Pimentel et al., 2009). This is not true for all foods, however, since microwaving certain grains and other dry products (such as rice and navy beans) is not nearly as energy efficient as other cooking methods (Table 3) (Lakshmi et al., 2007; Warthesen et al., 1984). This may be attributed to the greater energy (up to 4-fold) required to simmer products in the microwave (Carlsson-Kanyama and Bostrom-Carlsson, 2001).

Furthermore, the energy efficiency of microwave cooking is affected by the volume of fluid or mass of the food product. As observed in Table 3, rice (Carlsson-Kanyama and Bostrom-Carlsson, 2001), beef patties (Rhee and Drew, 1977), and water (Oberascher et al., 2011), were more efficiently prepared by stovetop than microwave when multiple servings were prepared whereas single servings were more efficiently cooked by microwave.

In conclusion, microwave cooking generally conserves more energy than other forms of cooking but the efficiency is highly dependent on the food product and conditions. In addition, due to the physical and chemical changes that occur during microwave cooking, it affects foods differently than other traditional cooking methods and can have deleterious effects on the quality of certain vegetables (Warthesen et al., 1984) and meats (Ehrcke et al., 1985). However, new microwave technologies are emerging that utilize infrared radiation and convection or jet-impingement to improve food quality while simultaneously reducing cook time (Amann et al., 2007; Datta et al., 2005). For example, baked food product qualities (such as Maillard browning, texture, and surface moisture content) can be improved by the use of the hybrid microwave (Sevimli et al., 2005; Walker and Li, 1993).

Induction stoves

Induction stoves are unique stove-top appliances that do not generate heat on the surface of the stove, but utilize an electromagnetic field to generate heat within the pan (Table 5 and Fig. 4) (Thim, 2009; Sadhu et al., 2010). One study reported a thermal transfer efficiency of 84% (using the steel block test method with a ferro-magnetic material attached at the base to enable heating of the block by induction) (Fig. 3) (Datwyler and McFadden, 1992), but end-use efficiencies may be as high as 90% (Sadhu et al., 2010). Depending on the meal, induction stoves reportedly utilized 28–79% of the energy required to prepare the same meal with traditional electric stoves (Probert and Newborough, 1985). Unlike other stoves, however, the composition of the pan can significantly influence the efficiency during cooking (with steel or iron cookware being the most efficient) (Amann et al., 2007).

Other electric heating devices (slow cookers, rice cookers, etc.)

Appliances with specified end-uses are ideally suited for their specific application and may be a considerable source of energy savings when used regularly. For example, brewing an 8-cup serving of coffee with a traditional glass jug coffee maker required 40 kJ/100 mL while brewing manually (by boiling water on a stove-top) required 69 kJ/100 mL (Oberascher et al., 2011). Electric rice cookers, also, consistently utilized less energy than all other rice cooking methods (Das et al., 2006; Lakshmi et al., 2007). Similarly, an egg cooker consistently required 30–50% less energy than a lidded pot on an electric stove (Oberascher et al., 2011). Even boiling 1 L of water with an electric kettle required only 35–37 kJ/100 g whereas a pot (with a lid) and a microwave required as much as 55 kJ/100 g and 75 kJ/100 g, respectively (Oberascher et al., 2011). In fact, the electric kettle is a highly efficient device. Carlsson-Kanyama and Bostrom-Carlsson (2001) demonstrated that, when water is heated to 100 °C in an electric kettle, the change in specific energy consumption with increasing temperature [J/(kg °C)] is virtually equivalent to the specific heat of water.

Alternative cookers—pressure cookers and slow cookers—may also reduce energy requirements during cooking. The energy required to cook a variety of products with pressure cookers is significantly less than the energy required to cook products by stove-top and, in many cases, less than microwaves (Table 3) (Warthesen et al., 1984; Das et al., 2006; Lakshmi et al., 2007); however, one study (Oberascher et al., 2011) observed that the use of a lid with a conventional pot may be comparable or use less energy than pressure cookers. According to Amann et al. (2007), using a slow cooker (or crock-pot) for specific foods that require extensive cooking times may save a significant amount of energy (i.e. a meatloaf cooked in the oven requires three times more energy than a meatloaf cooked with a slow cooker). Thus, educating consumers on the

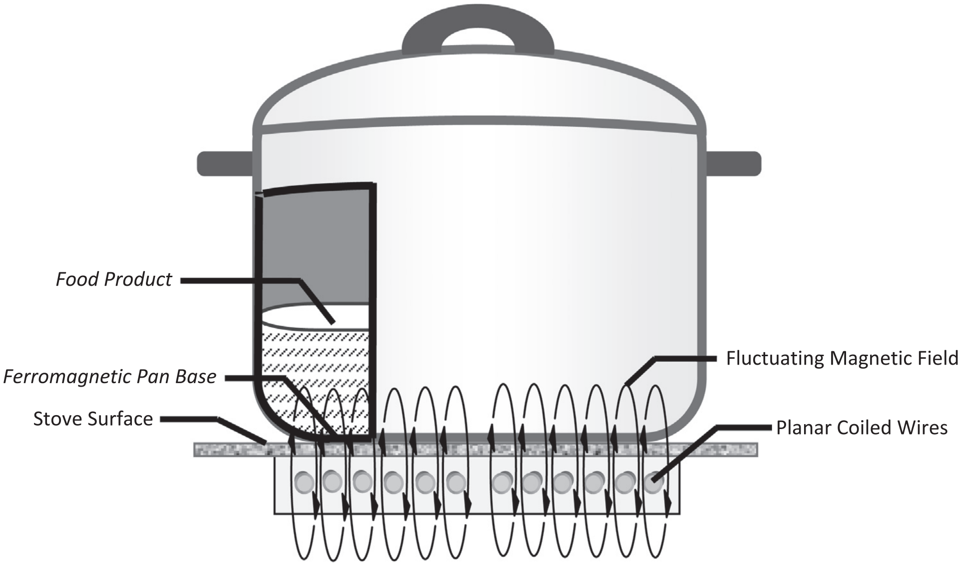


Fig. 4. Diagram demonstrating the basic concepts of an induction stove with the components subject to heating during cooking (resulting from the eddy currents generated within the pan) denoted with italics. Modified from Thim (2009).

value of using small appliances or alternative cookers as well as promoting their uses may reduce energy use.

Policy recommendations

Consumer education

Consumer education will be the most valuable source of energy conservation. When comparing the potential energy savings associated with behavioral modifications (Tables 2 and 3) with the potential savings attributed to appliance modifications (Table 4), the most fundamental need is to ensure the consumer is cooking under proper conditions. In fact, one field study of households in the UK demonstrated that energy usage during cooking was reduced by as much as 20% by informing them of energy-saving practices and providing them with a meter that displayed real-time energy-consumption (Wood and Newborough, 2003).

Programs to promote enhanced appliance efficiency

As evidenced by the success of various energy rating and labeling programs—the Energy Star program in the US with non-cooking appliances (Sanchez et al., 2008); the EnerGuide labeling program in Canada (Natural Resources Canada, 2009); and other international programs (European Commission, 2010)—to assist consumers in making informed decisions, policies that enhance the knowledge of consumers can increase the demand for efficient appliances. Greater demand for efficient products will likely draw more manufacturers to produce more economical and efficient models. In addition, implementing policies that incentivize or otherwise encourage the production of more efficient appliances could further motivate manufacturers. For example, for gas cooking appliances, Japan's Top Runner program encourages competitiveness and uses the top tier model as the platform on which new potential efficiency targets are based (Kimura, 2010). It has been a highly effective program since adoption in 1998; however, the efficacy is primarily attributed to the Japanese market and culture (in which manufacturers prefer to avoid government reprimands and strive to meet efficiency expectations) and may not be universally applicable (Kimura, 2010).

Policies that promote the use of labeling with "full-fuel-cycle" data, which integrates all aspects of energy conversion, transport and usage with emissions data (DOE, 2010b), may also be a solution to the complications attributed to transport, production, and end-use efficiencies. With the integration of this data and the advancement of technology for increased efficiency in modern appliances, consumers will likely be able to determine which appliance is the most energy efficient and environmentally acceptable.

Since cooking is a rudimentary need at all income levels, it is important to recognize that appliances with lower efficiencies may also be more affordable to low-income consumers and implementation of efficiency requirements may reduce affordability. In spite of the success of the program, one of the criticisms of the Japanese Top Runner program is the lack of life-cycle payback analyses that reigns in the cost to consumers (Kimura, 2010). As policymakers, it is essential that the environmental goals be reasonable, particularly when they may interfere with the health and well-being of individuals that may be incapable of affording appliances with additional features (that reduce energy consumption). Minimum Energy Performance Standards (MEPSs) have been set for various appliances, including cooking appliances, in many countries (European Commission, 2010) and the policies have effectively eliminated the least efficient products on the market; however, eliminating the least efficient appliances may also reduce affordability and new MEPS policies should be implemented cautiously. Even the US DOE recognizes there are cost limitations to the inclusion of many of the features reportedly enhancing the efficiency of modern appliances (DOE, 1998). In fact, replacing appliances may or may not have ecological benefit due to waste generated by the removal and disposal of older appliances that are considered usable.

Regulations for stand-by energy mode

For more than a decade, due to the rise in number of consumer electronics and appliances in households, the international community has become aware of the significant energy wasted in stand-by and off-mode (IEA, 2007). Based on a 2005 study of households in Australia, the average stand-by energy consumption was 92.2 W/household—an estimated 10% of total national energy consumption in the residential sector (Energy Efficient Strategies, 2006). Since the technology and modifications required to reduce stand-by energy consumption is regarded as economically feasible (European Commission, 2008; IEA, 2007), policies to address appliance stand-by energy consumption are reasonable.

In 1999, the International Energy Agency encouraged participating countries to aggressively strive for a maximum stand-by energy mode energy consumption of 1.0 W per appliance by 2010 (known as the "1-Watt Plan") (IEA, 2007). An example of a policy with such guidelines is the eco-design regulations by the European Commission that requires all appliances with an electronic display to use ⩽1.0 W for reactivation and stand-by mode by 2013 (European Commission, 2008, 2010). In the US, federal appliance purchases must comply with the 1-W standby energy consumption maximum (IEA, 2007). The measurement of the stand-by energy of microwaves will likely be required in the future (DOE, 2011). Ultimately, policies should be in place for all cooking appliances—microwaves, stoves, ovens, and small appliances—in stand-by and off-mode that can be a considerable waste of energy. The policies could entail maximum energy consumption limits (based on the IEA standards or otherwise) or simply require manufacturers to label products with stand-by energy consumption for consumer reference. In either case, the reduction in stand-by energy consumption is a key policy area that can reduce household cooking energy usage.

Incentives to encourage the use of alternative cookers (biogas and solar)

In agricultural communities, the use of alternative energy sources may also reduce energy usage for cooking. Although not as common in developed countries, biogas cookers and solar cookers, utilize renewable energy sources that would reduce reliance on traditional fuels. For example, the use of biogas–gases derived from the anaerobic fermentation of animal waste (Pimentel et al., 2008)—is gaining popularity in developed countries to mitigate the effects of pollution and over-fertilization from the abundance of livestock manure generated on modern farms (Holm-Nielsen et al., 2009). Biogas stoves could easily be promoted as a viable cooking fuel option since they are economical and practical with efficiencies comparable to natural gas stoves (when the gas is used directly as the source of fuel) (Fig. 2) (Ramanathan and Ganesh, 1994; Bhattacharya and Salam, 2002; Kurchania et al., 2010; Chandra et al., 1991). With evidence that the fertilizer (by-product) generated during the fermentation process is more profitable for the production of various agricultural products (Holm-Nielsen et al., 2009), there are significant advantages to the use of biogas.

Similarly, solar cookers may also reduce reliance on fossil fuel-derived energy sources for cooking. Solar cookers are specially designed to directly cook food products from the solar energy that reaches the earth's surface (1.08×10^8 GJ/s) (Thirugnanasambandam et al., 2010). Although technology is continually progressing and the energy is utilized directly (with no losses due to energy conversion or transport), most publicly-available solar cookers are relatively inefficient at converting solar energy into thermal energy for cooking food (with an overall efficiency of $\sim$20%) (Fig. 2) (Ramanathan and Ganesh, 1994). However, actual conversion efficiencies vary with the type and brand of cooker. Although limited in capacity and heating efficiency, in certain regions of developed countries where sunlight is abundant, the use of solar cookers to supplement traditional methods may reduce overall energy use for cooking (Wentzel and Pouris, 2007). In conclusion, even in developed nations, promotion of these alternative fuels may reduce household energy consumption.

Conclusions

With the rise in use of non-renewable energy sources over the last half-decade (EIA, 2009), the need to implement energy efficient practices in all aspects of the industrial and residential sectors is extremely important and household cooking is no exception. Since residential cooking for many products is more inefficient that industrial cooking (Carlsson-Kanyama and Bostrom-Carlsson, 2001), significant improvement in many aspects of cooking within the household are important and, theoretically, quite feasible. The fuel sources for cooking are widely varied and the energy required to properly cook foods varies considerably with the fuel source, appliance and consumer behavior. The most extreme effects in energy consumption, however, are due to the choices of the individual preparing and cooking the food so education should be the major focus of policies in developed countries. Although challenging, the implementation of policies to reduce energy usage during cooking can have an impact on total energy consumption due to the frequency and prevalence of residential cooking.

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