Induction Cooking Technology Design and Assessment

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ABSTRACT

Induction cooking is often considered one of the most efficient cooking technologies. With this technology, up to 90% of the energy consumed is transferred to the food, compared to about 74% for traditional electric systems and 40% for gas. This technology has become popular in Europe, but its adoption in the US has been less enthusiastic. Several market barriers exist for this technology, including high first cost, the requirement of magnetic cookware, and lower perceived reliability. This paper presents findings from a technical assessment of induction cooking performed by the Electric Power Research Institute (EPRI) for the California Energy Commission (CEC). This assessment evaluated the cooking efficiency of induction technology and estimated its energy savings potential. Total cost of ownership is considered, as well as market barriers and non-energy benefits offered by induction cooking technology. The findings of this study demonstrate that induction cooking is not always more efficient that conventional electric (resistive) technology. The energy savings potential of induction cooking is found to be greatest when used with small cookware. The impact of these findings on standard test procedures is discussed, and recommendations for improvement are suggested. Finally, a prototype cooker design is presented, with a discussion of the limitations of current designs that prevents their operation with non-magnetic cookware.

Introduction

Induction cooking is often considered one of the most efficient technologies for stovetop cooking. This technology relies on the principle of magnetic induction, in which eddy currents are excited in a ferromagnetic cookware when in the presence of an oscillating magnetic field. These induced currents dissipate heat by the Joule effect, generating the heat for cooking directly in the cooking vessel. As such, less heat is lost in inefficient thermal conduction between heating element and cookware.

A typical induction cooker is composed of a switching power electronics circuit that delivers high-frequency current to a planar coil of wire embedded in the cooking surface. The cookware is magnetically coupled to the coil by the oscillating magnetic field, analogous to the coupling between primary and secondary coils of a transformer. Current flows in the cooking vessel due to the low resistance of the metal, with power dissipation given by I^2R. The resistance of the vessel is dependent on the magnetic permeability (μ) and resistivity (ρ) of the cookware, as well as the frequency of excitation.

To generate sufficient heat for cooking, cookware must be used that has relatively high permeability and resistivity. Typical induction cookers operate at switching frequency between 25 kHz and 50 kHz. In this regime, induction cookers are only able to couple with ferromagnetic cookware, such as cast iron and some alloys of stainless steel. Thus, modern induction cooking technology is not compatible with cookware made from copper, aluminum and non-magnetic alloys of stainless steel.

Standard Cooking Efficiency Test Procedures

It is important to follow a standard test procedure when evaluating efficient products so that their performance can be compared with other devices in an unbiased way. The primary test procedure for measuring the efficiency of consumer cooking appliances in the U.S. is specified by the Department of Energy (DOE) (US National Archives and Records Administration 2012). In its procedure, DOE specifies the heating of a solid aluminum test block on maximum power until its temperature has increased by 144° F (80° C). At this point, power is reduced to 25% ±5% of maximum and held for 15 minutes. Cooking efficiency is calculated as the ratio of thermal energy absorbed by the block divided by the energy consumed by the device as it heated the block. Because this procedure specifies that an aluminum test block be used as the cooking load, it cannot be applied to induction cooking products.

To address this limitation, DOE proposed an amendment to its test procedure in 2013 that would allow induction technology to be tested alongside conventional cooking technologies. The proposal specifies that a "hybrid test block" composed of two pieces be used in place of the aluminum test block. The body of the test block would remain aluminum, but the aluminum block would fit inside of a base made of ferromagnetic stainless steel. This two-piece block would be used in testing all cooking technologies, including conventional electric and gas.

Apart from DOE's test procedure, two test procedures used by the food service industry provide an alternate method for evaluation the efficiency of cooking appliances. One of these test procedures is specified by the American Society for Testing and Materials (ASTM) in its standard F1521, which is applicable to both gas and electric ranges and cooktops (ASTM 2012). The cooking efficiency component of this test procedure calls for the heating of 20 pounds (9.07 kg) of water in a 13" (33 cm) aluminum stock pot. The water is heated from 70° to 200° F (21° to 93° C), with efficiency calculated as the change in thermal energy of the water divided by the energy consumption of the device.

The ASTM test procedure is very similar to that specified by the American National Standards Institute (ANSI) standard Z83.11 for food service equipment, specifically gas ranges and broilers (FSTC 2003). The primary difference between the two is that ANSI specifies aluminum stock pots of different sizes to be used based on the size of the burner tested. Namely, ANSI specifies a 9.5" stock pot be used with burners less than 15,000 Btu/h, a 13" pot for burners between 15,000 and 25,999 Btu/h, and 16" for burners greater than 26,000 Btu/h. Water load is specified as 4" deep, which leads to weights of approximately 10 pounds (4.5 kg), 19 pounds (8.6 kg), and 29 pounds (13.2 kg), respectively. For reference, residential cooking appliances are not typically equipped with burners rated at more than 18,000 Btu/h.

Table 1. Equivalent power of electric heating element for typical gas burner heat rates.

	Typical Gas Burner Heat Rate (Btu/h)	Equivalent Electric Element Power (W)
Small	5,000	800
Medium	9,000	1,400
Large	12,000	1,900
Extra-Large	15,000	2,400
Commercial ("Pro-sumer")	≥18,000	≥2,900

The rated power of natural gas-fueled appliances is specified by heat rate in terms of British thermal units per hour, or Btu/h, rather than kW. This is a measure of the chemical energy of the gas consumed per hour and cannot directly be converted to kW due to the efficiency of combustion of the fuel. Table 1 approximates the equivalent electric power for typical gas heat rates (assuming 40% and 74% efficiency, respectively, reported by DOE [LBNL 1998]).

Laboratory Testing by EPRI

Because each of the major cooking efficiency test procedures used in the U.S. specifies an aluminum stock pot be used for testing, no standard test procedure is compatible. Yet vendors often claim cooking efficiency as high as 90%. With few third-party evaluations of induction cooking available, EPRI undertook a technical evaluation of induction cooking technology, including laboratory testing of induction side-by-side with conventional technologies. This work was performed for the California Energy Commission (CEC) with funding provided under its Public Interest Energy Research (PIER) program.

To evaluate the cooking efficiency of induction cooking technology, EPRI developed a test procedure that was compatible with the technology and representative of actual cooking performance. Based on ASTM F1521 and ANSI Z83.11, the procedure developed by EPRI calls for 10 pounds (4.54 kg) of water to be heated from 70° to 200° F (21° to 93° C) in a 9.5" (24 cm) stainless steel stock pot. Cooking efficiency is calculated as the amount of energy delivered to the water divided by the total energy consumption by the appliance.

For a direct comparison of cooking technologies in the laboratory, EPRI selected two low-cost, standalone (countertop) induction cooking products for evaluation. These products were chosen to represent the induction technology most commonly used in residential cooking applications. A natural gas range and a conventional electric (coil) range were selected to represent baseline (conventional) cooking technologies.

Figure 1. Standalone induction cookers tested by EPRI. *Source:* CEC 2014.

Figure 1 shows the two induction cooking products tested by EPRI. These cookers, hereafter referred to as "induction cooker A" and "induction cooker B", were rated for 120-V (60 Hz) operation with maximum power of 1500 W and 1800 W, respectively. These products are widely available and can be purchased for around $70 and $130, respectively. Although induction cooking technology is available in more conventional form factors, such as multi-unit, built-in cooktops, and ranges (stovetop and oven combination), these standalone devices were selected for their low cost and wide availability.

Figure 2. Conventional cooking appliances tested by EPRI for side-by-side comparison of cooking efficiency. *Source:* CEC 2014.

Figure 2 shows the conventional electric and gas ranges chosen to represent baseline technologies in this side-by-side evaluation. The electric range has four resistive heating elements with exposed resistive coils, the largest of which is 8" and 2 kW. The natural gas range has burners of various heat rates: one 5,000 Btu/h, two 9,500 Btu/h and one 12,000 Btu/h. The large burner/element of each range was evaluated for a fair comparison of units of roughly equivalent sizes and heat rates.

Results of Cooking Efficiency Testing

EPRI tested each of the consumer cooking appliances according to the induction-compatible test procedure it developed, involving the heating of water from 70° to 200° F (21° to 93° C). As specified by the procedure, three test runs were performed with each device at both half power and full power, with efficiency calculated as the average of the three runs. The results of cooking efficiency testing performed by EPRI are shown in Table 2.

Table 2. Cooking efficiency results measured according to EPRI test procedure

	Large Vessel		Small Vessel	
	Half Power	Full Power	Half Power	Full Power
Induction Cooker A	74.9%	77.6%	76.5%	77.4%
Induction Cooker B	75.7%	77.2%	75.6%	75.1%
Electric Coil	81.6%	83.4%	48.2%	41.5%
Natural Gas	41.7%*	35.2%*	-	30.2%*

*Natural gas range tested at 50° F (10° C).

Due to infrastructure limitations, the natural gas appliances were tested at ambient temperature of 50° F (10° C). Yet all electric technologies—both conventional and induction—

were tested at 70° F (21° C) in a controlled environment. It can be reasonably expected that the cooking efficiency of the gas range measured at 50° is somewhat lower than if tested at 70° F. As such, the results of gas efficiency testing should not be directly compared with the electric technologies. However, these results are useful for illustrating the relative efficiency of gas technology.

The results of initial testing showed that conventional electric coil technology was significantly more efficient (82%-83%) compared to the efficiency reports by DOE (74%). It is theorized that this difference is due to the difference in the diameter of the cooking vessel, which in this testing is large enough to completely cover the coil elements. Thus, testing was repeated with a smaller cooking vessel to investigate the impact of vessel size on cooking output. This testing (labeled "Small Vessel" in Table 2) made use of a 6" (15 cm), 1.5-quart (1.4 L) sauce pan with a water load of 3 pounds (1.36 kg).

These results demonstrate that induction cooking is not necessarily more efficient than conventional electric technology. In fact, the conventional electric coil was found to be 6% more efficient than induction cooking when measured with the large cooking vessel. Yet the efficiency of conventional technology was shown to be highly dependent on the size of the cookware used. The full-power efficiency of conventional electric technology fell from 83% to 42% when testing the electric coil with the small cooking vessel. This demonstrates the impact of contact area on the efficiency of conductive heat transfer between the heating element and cooking vessel. When operated with small cookware, a greater portion of heat created by conventional technologies is radiated outward as losses. On the other hand, induction cooking was found to maintain high efficiency regardless of cookware size.

Because the efficiency of baseline technology depends so strongly on cookware size, the energy savings potential of induction cooking is dependent on the prevalence of cooking with vessels smaller than the electric element. It is unclear how often users cook with cookware that is smaller in diameter than the cooking element. Average cooking efficiency of conventional electric technology lies somewhere between the 42% and 83% measured in this testing. But without market data regarding the rate of incidence of cookware mismatch in home cooking, the average efficiency of conventional cooking appliances cannot be calculated.

Induction cooking was measured to have full-power cooking efficiency of 76% to 77%. In this way, it offers an efficiency gain of between -6% (an increase in energy consumption) and 34% over conventional electric technology, depending on the prevalence of cooking with small cookware. Assuming that typical users employ cookware of varied sizes, it is likely that induction offers slightly higher efficiency on average. But without any data on user behavior, it cannot be concluded that induction cooking necessarily would reduce overall cooking energy consumption.

Opportunity for Standard Metric Improvement

Standard procedures for testing the efficiency of consumer cooking products do not consider that users may choose to use cookware that is smaller in diameter than the heating element or burner. Instead, cooking efficiency is tested using a single cooking vessel that is sized to match the element / burner. In this manner, standard test procedures typically report a relatively high value for the cooking efficiency of conventional technologies, showing little opportunity for energy savings with induction cooking. Anecdotal evidence suggests than many users do not consider the size of the cookware when selecting which burner / heating element to use. This would lead to additional cooking losses that are not captured by standard cooking efficiency test procedures. Furthermore, such test procedures do not credit induction cooking for the reduction of cooking losses that it offers with small cookware.

To better capture the losses of cooking with mismatched cookware, a standard test procedure could call for testing with multiple vessels for each burner / element. Such a procedure would specify a number of typical cookware sizes, such as 6” (15 cm), 8” (20 cm), and 10” (25 cm) vessels, for example. Each heating element would be evaluated with a vessel that completely covers the heating element, followed by a test run with the next smallest vessel. Cooking efficiency would be reported as the average of both test runs. In this way, the standard test procedure would capture both the maximum efficiency and a non-ideal thermal coupling that is likely to be more representative of user behavior. More detailed consumer usage data is required to accurately model the thermal coupling between cookware and cooking element typical for residential cooking.

Energy Use and Payback

DOE estimates that the energy consumption of the stovetop portion (heating elements) of a conventional electric range is 128 kWh annually, and for a natural gas range 720 kBtu (DOE 2009). The equivalent energy consumption of induction technology can be computed by its efficiency, assuming an equal amount of cooking energy is delivered by each technology. As an exaggerated example, Table 3 shows the equivalent energy consumption of each technology in the improbable case that the user only cooks with small cookware. Note that DOE does not make this assumption in calculating the cooking energy delivered by residential products. Energy costs are calculated using U.S. average residential energy costs of $0.12 per kWh and $10 per thousand cubic feet of gas.

Table 3. Annual energy consumption of cooktop technologies using only small cookware

Technology	Efficiency	Annual Energy Consumption	Cooking Energy	Energy Cost
Conventional Electric	42%	128 kWh	54 kWh	$15.36
Induction	76%	71 kWh	54 kWh	$8.49
Natural Gas	30%	720 kBtu	216 kBtu	$7.05

The annual energy consumption calculated in Table 3 shows the maximum energy savings potential of induction technology. Yet even in this exaggerated scenario, natural gas provides the lowest cost solution to the user. In this case, induction cooking reduces energy use by 45% over conventional electric, for annual savings of 57 kWh and $6.87 for the user. A market study performed by EPRI of residential cooktop appliances found induction technology to be at least $300 more expensive than comparable electric cooktop products. This yields a simple payback of 44 years, more than double the expected lifetime of typical consumer appliances. Thus, it can be concluded that induction cooking does not offer a cost-effective method of energy savings at this time.

Non-Energy Benefits and Grid Impacts

Apart from energy savings, induction cooking offers a number of non-energy benefits to the user. First, nearly all induction cooking products are equipped with an automatic shutdown feature that powers-off the product when the cooking vessel has been removed. Thus, induction cooking products are much less likely to cause fires or burn-related injuries than conventional technology, because no heat is created without a cooking vessel present. In addition, the surface of induction cookers remains somewhat cooler than smooth electric cooktops because heat is not generated in or beneath the cooktop. While an induction cooker does get hot during use, it cools much more quickly than conventional cooktops and poses a reduced risk of burns to the user.

One feature of induction cooking that is often overlooked is the level of control that it offers at low power settings. Unlike conventional electric technology, which can only cycle off and on at full power, induction cooking is able to provide continuous heat at less than rated power. Of the products evaluated by EPRI, continuous power could be sustained down to 30% to 50% of the products' maximum settings. To supply lower levels of heat the induction cookers cycle at their lowest continuous power rating in roughly 10-second intervals.

Further, induction cooking offers some of the response of natural gas that causes many users to prefer gas over electric appliances. With heat generated directly in the cookware and excellent low-power control, induction cooking allows much greater controllability than conventional electric technology, enabling precise cooking techniques practiced by advanced chefs. For example, it is very challenging to quickly change from a high-heat sauté to a simmer with a conventional electric cooktop. This is due to the high thermal mass of the heating element and glass surface of smooth-top devices. With heat generated directly in the cookware, induction cooking allows much faster response, similar to gas.

Apart from energy consumption, the impact of any consumer electronics device on the power quality of the grid should be considered. Evaluation by EPRI (CEC 2014) found the current harmonics of induction cooking technology to be relatively low, below 6% THD (of current) for all load levels. In addition, power factor was measured at 0.98 and above. This performance is unlike that of switching power supplies, which draw current in large spikes. Although induction cooking makes use of high-frequency switching power electronics, these devices do not naturally exhibit poor power factor like switch-mode power supplies because their voltage is unregulated. Rather, power flow is controlled by varying the switching frequency of the resonant converter driving the magnetic coil.

Table 4. Field strength limits permitted by FCC Part 18 for induction cooking appliances

Operating Frequency	Field Strength Limit (μV/m)	Distance (m)
<90 kHz	1,500	30
≥90 kHz	300	30

An additional consideration when using induction cooking is the high-frequency electromagnetic interference (EMI) emitted from the device. The radiated emissions from these products are regulated by the Federal Communications Commission (FCC) under Part 18 of federal code, which specifies limits for industrial, scientific, and medical devices as well as residential induction and microwave cooking appliances. Table 4 shows the maximum field strength permitted under FCC Part 18 for induction cooking appliances (U.S. National Archives and Records Administration 1998).

Market Barriers

The greatest market barrier to adoption of this technology is its cost, which was found to add a minimum of $300 over of the cost of comparable electric cooktops (multi-unit products). This added cost was shown to require 44 years to recoup using best-case energy savings scenario. Yet this calculation did not consider the cost of induction-compatible cookware that is required for some users. A consumer that uses cookware made of aluminum, copper, and non-magnetic stainless steel would be required to replace this cookware with induction-compatible products. This could cost several hundred dollars, depending on the cooking requirements of the user, adding a substantial added cost on top of the premium incurred by induction technology. Furthermore, anecdotal evidence suggests that the compatibility of stainless steel is highly sensitive to its alloy composition, causing pans within the same cookware set to exhibit varying degrees of compatibility with induction and creating additional consumer frustration towards cookware compatibility.

To address this barrier, a prototype induction cooker was developed in conjunction with the Future Energy Electronics Center at the Virginia Polytechnic Institute and State University (Virginia Tech) that is compatible with non-ferrous cookware. This prototype employed wide-bandgap, gallium nitride (GaN) transistors to achieve the high switching frequency required for operation with non-magnetic material. The prototype was successfully demonstrated to operate at 60 kHz with non-ferrous stainless steel—a feat accomplished by some commercially-available products already—with cooking efficiency of 84%.

However, the prototype was not able to deliver sufficient power for cooking when used with aluminum cookware. This was due to losses in the magnetic coil of the cooker at high frequency. At high frequency, losses in the magnetic coil increased to unsustainable levels due to electromagnetic effects in the wire. Even when extremely thin (#54 Litz) wire is used, these losses prohibited sufficient power be delivered for cooking. Therefore, it was concluded that the development of aluminum-compatible designs would not be possible in the foreseeable future without a significant innovation in induction cooker design.

Conclusion

Results of this study show that induction cooking is not always the most efficient method of cooking. When tested with a large cooking vessel, the efficiency of conventional electric technology was measured to be higher (83%) than that of induction cooking (77%). Yet the efficiency of conventional cooking appliances was shown to be highly dependent on the size of the cooking vessel. This study measured the efficiency of conventional electric technology to fall to 42% when used with small cookware. Induction cooking technology was found to maintain high efficiency regardless of cookware size. Yet it is unclear what the overall energy savings potential of induction is without market data showing the frequency of cooking with mismatched cookware. To better estimate potential energy savings, follow-up work could analyze real-world usage patterns in detail. Moreover, it is recommended that future research evaluate the efficiency of smooth electric cooktops using both conventional and induction technology, as these products are most directly comparable.

Further, standard cooking efficiency test procedures do not measure the impact of cooking vessel mismatch on the efficiency of cooking technologies, assigning a single efficiency measurement that may represent optimal operation. Such a procedure does not capture additional losses that may be common in actual use. Given the strong dependence of the efficiency of conventional technologies on cooking vessel size, it is recommended that standard test procedures be amended to assess the efficiency drop characteristic of typical usage.

Even in its best-case scenario, induction cooking was not found to offer a cost-effective means of energy saving. To recoup the minimum $300 cost added by induction over comparable cooktops would require 44 years of energy savings, more than twice the typical lifetime of consumer electronics. When the cost of replacement cookware is considered, it is clear that induction cooking is not the most economical cooking technology. Yet it was shown to offer additional benefits of safety and controllability that may prove attractive to consumers.

Finally, this study found that the development of aluminum-compatible induction cooking technology remains a significant challenge. Given the widespread use of aluminum cookware in the U.S., this has remained one of the most significant market barriers to the technology apart from cost. Even with the use of wide bandgap semiconductors, induction cooking could not be operated with sufficient power for cooking. As such, it is not expected the aluminum-compatible induction products will be available in the near future without a major innovation in the design of the technology.

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