Environmental impact of the main household cooking systems—A survey

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REVIEW ARTICLE

Abstract

The food cooking energy may represent the primary hotspot in the cradle-to-grave life cycle of several foods and drinks. It is mainly affected by the type of food and its cookery method, cooking appliance and the fuel selected as well as the number of portions to be cooked. The primary aim of this survey was to demonstrate the basic characteristics of the main cooking methods, appliances, and fuels as well as energy required for some key foods. The secondary aim was to assess the environmental impacts of a generic cooking system as a function of few household cookers fueled by different fuels (i.e., firewood, charcoal, coal, natural gas, liquefied petroleum gas, kerosene and biogas) and electricity in the Italian scenario by using the ReCiPe 2016 and product environmental footprint (PEF) standard methods and Ecoinvent v. 3.7 database. A functional unit equal to per capita useful energy delivered to the pot for cooking (1.41 gigajoule [GJ]) in 27 European Union countries in 2019 was used as the basis of comparison. The use of natural gas resulted in minimum impact in nine of the 18 mid-point impact categories of ReCiPe 2016 method and two damage categories (human health and ecosystem quality) with a minimum overall weighted damage score ($OWDS_R$) of ~5 Pt. Thus, such a cookstove appeared to be more apt to minimize both indoor and outdoor air pollution. Even if the electric cookstove yielded a greater $OWDS_R$ (8.6 Pt) because the Italian electricity grid mix was mainly based on fossil sources, it was possible to forecast that new-generation, smart cooktops driven by hydro- and wind-power electricity would minimize $OWDS_R$ to as low as 0.9 and 1.4 Pt, respectively, thus not only avoiding the consumption of any fossil energy source but also improving people's health.

Keywords: clean cooking, cooking appliances, cooking fuels, cooking systems, environmental impacts, life cycle assessment, PEF standard method, ReCiPe 2016 standard method

Introduction

Nowadays, cooking of food has become mandatory for humans (Wrangham and Conklin-Brittain, 2003). Its associated energy requirements represent the preponderant share of energy used in the cradle-to-grave life cycle of several foods and drinks, as in the case of vegetal products with low to medium degree of processing (Carlsson-Kanyama and Boström-Carlsson, 2001), dry pasta (Bevilacqua *et al.*, 2007; Cimini *et al.*, 2019, 2021a, 2021b) and coffee brewing (Cibelli *et al.*, 2021). Energy use for cooking is largely affected by the food type and its cookery method, and the cooking appliance selected. Energy utilization reduces as the number of portions cooked increases (Carlsson-Kanyama and Boström-Carlsson, 2001).

About one-third of the human population (that is 2.5-billion people), generally living in low- and middle-income countries, still relies on solid biomass fuels (i.e., firewood, crop residue, charcoal and dung) for cooking, while the remaining 5-billion people rely on fossil energy, such as coal, natural gas (NG), kerosene, liquefied petroleum gas (LPG) and electricity (Wright *et al.*, 2020).

The combustion products emitted by solid fuels give rise to by far higher levels of indoor air pollution than those recommended by the World Health Organization (WHO, 2018), especially in poorly ventilated dwellings. These harmful emissions have been associated with respiratory diseases and other health problems (i.e., lung cancer, chronic obstructive pulmonary disease [COPD], pneumonia, tuberculosis, cardiovascular events, low birth weight and cataracts; Fullerton *et al*., 2008), and are responsible for as many as 4 million premature deaths per year globally (WHO, 2021). WHO is thus committed to attaining the so-called 'Sustainable Development Goals' (SDG) on health (SDG 3) and energy (SDG 7) as scheduled by the United Nations Development Program (UNDP, 2021) in order to improve the health and well-being of the people still using polluting technologies and fuels not only for cooking but also for heating and lighting. So far, numerous programs have been implemented globally to introduce cleaner and more efficient cooking technologies. All the attempts to improve the performance of biomass-burning stoves have until now caused limited health benefits, while the use of other cleaner fuels (i.e., LPG, ethanol and biogas) has offered not only greater health benefits but also smaller greenhouse gas (GHG) emissions (Rosenthal *et al*., 2018). In particular, the replacement of solid biofuels with LPG was quite successful in several countries, such as Brazil (Wright *et al*., 2020), Ecuador (Martínez-Gómez *et al*., 2016), Ghana (Afrane and Ntiamoah, 2011, 2012), Indonesia (Thoday *et al*., 2018), India (Gould and Urpelainen, 2018; Jungbluth *et al*., 1997; Singh *et al*., 2014), and a few countries of the Indo-Chinese Peninsula (Aberilla *et al*., 2020) for at least two reasons: (i) lower GHG emissions compared to burning solid fuels, and (ii) lower infrastructure requirement compared to NG and electricity (Wright *et al*., 2020). Unfortunately, although use of such a clean cooking technology improves people's health conditions, it still relies on fossil energy sources. A long-term sustainable cooking should alternatively rely on renewable energy sources only (i.e., solar or wind energy, biogas and bioethanol; Aro, 2016).

Several life cycle assessment (LCA) studies have so far dealt with cooking appliances, such as cookstoves fired by different fuels (Aberilla *et al*., 2020; Afrane and Ntiamoah, 2011, 2012; Jungbluth *et al*., 1997; Singh *et al*., 2014), induction and gas hobs (Favi *et al*., 2018) and electric and gas ovens (Landi *et al*., 2019) in the Italian context as well as induction hobs with different electronic boards (Elduque *et al*., 2014), using diverse life cycle impact assessment (LCIA) methods, some of which, unfortunately, use old databases.

The primary aim of this survey was to review the basic characteristics of main cooking methods, appliances and fuels as well as energy requirements for some key foods. The secondary aim was to account for a generic cooking system capable of delivering the useful per capita energy transferred to the cooking pot in 27 European Union (EU) countries in 2019 (Eurostat, 2021a). The final goal of this study was to assess its life cycle environmental impacts by using the well-known ReCiPe 2016 (Huijbregts *et al*., 2016) and product environmental footprint (PEF) (European Commission [EC], 2018b) LCIA methods and Ecoinvent v. 3.7 database (Ecoinvent, 2020). By using different fuels (i.e., firewood, charcoal, coal, NG, LPG, kerosene, and biogas) and electricity used in the Italian scenario, it was possible to identify the cooking system with overall minimum environmental impact and, thus, prospect promising new eco-smart household cooktops.

Basic Characteristics of Main Cooking Methods

Cooking makes food as more edible, easily digestible and relishing. In this way, cooked foods exhibit quite significant variations in their physical aspect, structure, composition and nutritional value. Any food-cooking operation is characterized by a heating element (i.e., open flame etc.) and a heat transfer medium that allows cooking by:

1. *expansion* if the hot medium is made of water or oil, and
2. *concentration* if the heating element transmits heat to food through a pan, plate or grill.

Mixed cooking methods include both modes. Generally, the first part of cooking is carried out by concentration, while the second one by expansion, thanks to the addition of a liquid. Alternatively, the dry heat cookery methods (i.e., baking, steaming, grilling and roasting) can be discriminated from the moist heat cookery ones (i.e., boiling, stewing, shallow frying, deep frying and basting). In the former, the heating element conveys heat directly to the food (which in turn is cooked in its own juice and the steam generated by the evaporation of water added to the food during its preparation) mainly by means of convection and/or irradiation. On the contrary, in the moist heat methods a liquid medium (i.e., water, milk, coconut cream, molted butter, oil etc.) is heated before or after the food to be cooked is placed in the cooking pan.

Table 1 briefly describes both basic cooking methods and some combined and microwave cooking methods by pointing out heat propagation media, range of cooking temperature and main heat transfer modes.

Table 1. Main food cooking methods (Hager and Morawicki, 2013; McGee, 2004).

Main cooking methods	Cooking system	Description	Heat propagation medium	Cooking temperature (°C)	Heat transfer mode	Uses
Dry heat cooking	Baking	Food is put in an oven.	Air	140–250	Air convection + wall radiation + pan conduction	Cereal-based foods
	Grilling	Food is placed on a grill tray, which is heated by burning charcoal and gas, or by electricity.	Air	220–250	Air convection + grill conduction + grill or flame radiation	Meat, vegetables, cheeses, and marshmallow
	Steaming	Food is cooked by the hot steam rising from an underlying pot filled with water.	Steam at ambient or steam pressure	100–120	Vapor convection and condensation	Meat and filled pastas
	Roasting in an oven	Food is flavored, tied with strings and placed in a saucepan containing a very hot fatty substance to wet the external surface of the food and avoid its drying.	Air and fats	200–220	Air convection + wall radiation + pan conduction	Meat and nuts
	Roasting on a spit	Pieces of food are skewered, salted and flavored to be heated by wood, charcoal, coal, electricity and gas.	Air	250	Air convection + burner radiation + spit conduction	Poultry and meat
	Cooking au gratin	Food is placed in a shallow oven-proof container and baked or cooked under an overhead grill with a topping of seasoned breadcrumbs, grated cheese, egg, or butter.	Air	250–300	Air convection + grill radiation + pan conduction	Vegetables and pastas
	Barbequing	Food is variously cooked over live fire from glowing firewood, charcoal or coal and smoke using direct or indirect heating with several national and regional differences.	Smoke	200–250	Smoke convention + flame radiation	Meat, vegetables and breads
Moist heat cooking	Boiling	A water-filled pot is used to cook food over the fire. Except for rice and meat, the cooking water is thrown away at the end of cooking.	Water	≤100	Water convection	Pastas, rice, meat and vegetables
	Stewing	Food is chopped, diced and cubed, and added to a pot partially filled with a liquid. Stewed food is served with the thickened liquid.	Water and oil	≤100	Vapor condensation + liquid convection + pan conduction	Meat, vegetables and grains
	Deep frying	Food is submerged in hot boiling oil contained in a deep pan till it turns brown on the outside. A piece of brown paper helps soaking up any oil from the food before it is served.	Oils and fats	150–200	Convention + pan conduction	Meat, vegetables and dough
	Pan or shallow frying	Food pieces are stirred around a few times in a frying pan coated with a small amount of oil and fat, and must be properly heated to prevent cooked foods from becoming too oily, greasy or burnt outside and uncooked inside.	Oils and fats	150–200	Oil and pan conduction	Meat, vegetables and dough

		Description	Medium	Temperature	Heat transfer	Food
	Basting	Meat is cooked in its own juices, or a sauce or marinade in an oven using a lidded oven-pan. Any juice is often spooned over the outer part of the meat to avoid its drying during cooking. Use of a closed oven-bag traps evaporating moisture, the condensation of which forming the real cooking juice of food.	Air, steam oils, and fats	100–120	Pan conduction + liquid convection + wall radiation	Meat
Mixed cooking	Braising	Food is first browned at a high temperature, and then simmered in a lidded pot in a cooking liquid (i.e., wine, broth, coconut milk and beer). It differs from stewing for about 3/4 of the product being submerged by the cooking liquid.	Air, steam, oils and fats	~150	Pan conduction + liquid convention	Meat, vegetables and grains
	Cooking in a casserole	Small and tender pieces of meat are salted, placed over finely chopped vegetables sprinkled with melted butter in a lidded oven-pot, and cooked in the oven on a very low flame.	Air, oils and fats	150–220	Pan conduction + liquid convection + wall radiation	Meat and vegetables
Microwave cooking		Electromagnetic radiation at a frequency of 915 or 2,450 MHz is used to heat directly and rapidly the only polar molecules of foods, while the oven air and nonpolar container materials (i.e., glass, stoneware and plastic) are heated by the food itself as it heats up. While infrared energy is almost entirely absorbed at the food surface, microwaves can penetrate food to a depth of about 2.5 cm.	Polar molecules	Variable	Microwave radiation	Meat and vegetables

Main cooking appliances

Open wood fires were used for cooking by humans for approximately two million years (Wrangham, 2009). The energy performance and resulting emissions from biomass cookstoves depend on various factors, such as the stove design, fuel feeding practice, lighting, and combustion temperature (Okino *et al*., 2021; Rasoulkhani *et al*., 2018). Generally, traditional biomass stoves, largely used indoor in developing nations, are improperly ventilated, which leads to a significant increase in indoor levels of particulate matters ($PM_{2.5}$) and carbon monoxide that cause lung inflammation and lead to chronic obstructive pulmonary disease. Excessive consumption of biomass fuels has led to natural forest degradation and deforestation, as already observed in South Italy during period of Roman Empire, as well as shortage of firewood for cooking in some areas of Africa even today (Okino *et al*., 2021). In order to improve the efficiency of cooking energy and thus reduce the biomass consumption of the so-called *three-stone fire stove*, quite numerous improved stoves have been developed (Okoko *et al*., 2018; Wikipedia, 2021a). For instance, Darlami *et al*. (2019) reported that the thermal efficiency (η_{CS}) of a traditional Nepalese cookstove increased from 18.0% to 25.6% when it was modified with mud, while Okino *et al*. (2021) improved the thermal efficiency (η_{CS}) of a cooking stove insulated with sawdust from 13–21% to 19–35% with the use of a few indigenous wood fuels available in Uganda. Nevertheless, a recent review has found that the use of such improved cookstoves has so far had a small mitigating effect on the health results of household air pollution and called for more initiatives and policies to favor the adoption of cleaner fuels and improved cookstoves in households (Pratiti *et al*., 2020). In fact, more than 2.5-billion people in developing countries are still relying on quite polluting cooking fuels, such as wood, crop residues, animal dung, charcoal, coal and kerosene.

For instance, wood and coal burning cookstoves are still manufactured by the Amish in Lancaster County (PA, USA) to satisfy not only cooking and baking requirements but also heating and hot water requirements. In India (Jungbluth *et al*., 1997) and Nigeria (Anozie *et al*., 2007), kerosene stoves replaced most of the traditional biomass cookstoves, thanks to governmental fuel subsidies to prevent deforestation for cooking fuels. Cheaper and more efficient gas stoves fueled by NG and LPG started to disseminate once a distribution network for gas pipeline and bottled LPG transport was available. This allowed their increasing diffusion either in Europe or the United States since the beginning of the 20th century. Gas ignition was originally done by matchsticks. Then it became possible with a pilot light, a continuously burning gas flame under the cooktop to immediately light the gas leaving the burner if the stove was

turned on. Nowadays, gas stoves have electronic ignition to avoid any gas consumption when the stove is not used, a flame failure device to stop gas flowing without igniting and prevent from accidental explosion, and an extractor hood to evacuate fumes and minimize indoor air pollution (Wikipedia, 2021b).

By the end of the 19th century, several electric stoves were patented in Canada, the United States and Australia, even though their diffusion in household kitchens was conditioned by the extension of urban and rural electrification. Whereas gas cooktops heat food with flame and disperse much of the heat in the air, electric cooktops mainly transfer heat to the cooking surface and thus are more efficient than gas cooktops. Electric cooktops include both open coil and smooth (or radiant) cooktop types. The former is made of resistive wires encased in hollow metal tubes arranged in a spiral to directly support the cookware, and thus is quite affordable and durable. On contrary, smooth and radiant types consist of a hotplate surface or a smooth glass-ceramic surface heated locally via electrical heating coils or halogen lamps. The latter guarantees less heat loss with easier cleanability but, unfortunately, higher stretchability and breakability. Nowadays, in such cooktops, the maximum temperature of the heating element is controlled thermostatically while power supply is regulated either discretely or continuously between minimum and maximum heat settings (Wikipedia, 2021c). Different studies have indicated that hotplates are least efficient among electric stoves (Hager and Morawicki, 2013), even if the glass–ceramic cooktops are found to be up to 20% less efficient than hotplate surfaces (Carlsson-Kanyama and Böstrom-Carlsson, 2001). Moreover, reflective trays beneath electric coils in coiled cooktops appeared to increase the energy efficiency and reduce heating period by 20% (Hager and Morawicki, 2013). Induction stoves are *de facto* the latest version of electric stoves. In fact, these use electricity to generate electromagnetic induction in just ferromagnetic cookware, which is thus directly heated instead of being heated by beneath smooth surface of glass–ceramic. Such cooktops are not only highly safe but also the most energy-efficient appliances. Their accurate control of cooking temperature could be improved by using a low-cost, open-source electronic platform pilotable via smartphone, as in the case of the novel home eco-sustainable pasta cooker previously developed by Cimini *et al.* (2020).

Among the diverse renewable fuel stoves, it is worth citing the biogas, ethanol and solar stoves.

Biogas stoves resemble the conventional NG and LPG stoves with just some modifications in burner design to maximize their combustion effectiveness and reduce unburned methane and soot from incomplete combustion (International Renewable Energy Agency [IRENA], 2017).

Alcohol burning stoves are like existing kerosene stoves, their main differences being related to the use of stainless steel to minimize corrosion and fuel type used. Interest for such stoves is mainly due to the use of bioethanol, its combustion practically providing pollutant-free emissions. Unfortunately, such stoves are expensive and suffer from the costs of bioethanol supply chain. In the EU, such stoves are used for marine and mobile leisure applications in conjunction with an aqueous mixture of 85% (v/v) ethanol. Their use was extended to a few developing countries, especially in Brazil, where the above mixture is available as a biofuel (Benka-Coker *et al.*, 2018; Stokes and Ebbeson, 2005; Zuzarte, 2007). In order to avoid using such an inflammable mixture, other safer prototypes were developed in India and South Africa to utilize diluted ethanol mixtures at 50% (v/v) (Rajvanshi *et al.*, 2004) or enriched with colorants and thickeners (i.e., calcium acetate) and flavoring agents (*Greengel*; Climate Technology Center & Network [CTCN], 2017; Okusanya *et al.*, 2019), respectively.

Solar cooking appliances started to be commercialized in the 1980s as 100% emission-free devices capable of concentrating solar thermal energy to cook foods. Each one consists of three components: concentrator, absorber and retainer. The first one, being made of shiny materials, such as silver, chromium or aluminum, allows the sunlight to be concentrated at a fixed point, where it is absorbed by a black-painted cookware to cook food. To minimize heat loss, the cookware is to be properly insulated and lidded. Four types of solar cookers are currently available (Pandey *et al.*, 2021), as shown in Table 2. The *box cooker* simply consists of a box inside another one and is the cheapest type of solar cooker. The transparent cover on the top of the outer box allows entrance of the sunlight, where it is absorbed by the black-painted inner box. A mirror in the inner side of the outer box helps in reflecting the heat energy radiated from the inner black box. The *panel solar cooker* has a large flat panel, which mainly reflects and focuses the sunlight falling vertically on the cooker for cooking. Owing to the instability of panel to high wind, such a solar cooker is not used frequently. The *parabolic solar cooker* collects the solar radiation in the central focus point of a collector dish, where a pressure cooker with black-painted bottom is placed. In this way, temperatures as high as those causing the burning of food can be achieved. Finally, the *vacuum-tube solar cooker* entails two tubes, one inside the other. The inner tube contains food to be cooked and is black painted to maximize heat absorption, while the outer one is transparent. Vacuum is created in the space between these tubes to minimize heat loss and trap the heat absorbed for a longer period. Such type of cooker is highly efficient (Pandey *et al.*, 2021).

Table 2. Main types of cookstoves and performances together with cooking fuels used, some typical models, fuel availability and cookstove efficiency (η_{cs}).

Category	Fuel type used	Some typical models	Fuel availability	η_{cs} (%)	References
Traditional biomass stove	Firewood		Usually, easily available *in situ*	11 13.5 14 17 20 13–21	Aberilla *et al.*, 2020 Singh *et al.*, 2014 Afrane and Ntiamoah, 2011, 2012 Hager and Morawicki, 2013 Benka-Coker *et al.*, 2018 Okino *et al.*, 2021
	Crop residues		Usually easily available *in situ*	11	Singh *et al.*, 2014 Aberilla *et al.*, 2020
	Charcoal		Supply chain required	14 17.5 18 23 24–32	Aberilla *et al.*, 2020 Singh *et al.*, 2014 Afrane and Ntiamoah, 2011, 2012 Benka-Coker *et al.*, 2018 Okoko *et al.*, 2018
Coal stove	Coal		Supply chain required	15.5	Singh *et al.*, 2014
Improved biomass stove	Firewood		Usually, easily available *in situ*	25.0–42.8	Mehetre *et al.*, 2017
Modern fossil fuel stove	Kerosene		Supply chain required	35 40 45 46 47 42–64	Afrane and Ntiamoah, 2012 Benka-Coker *et al.*, 2018 Hager and Morawicki, 2013 Aberilla *et al.*, 2020 Singh *et al.*, 2014 Jungbluth *et al.*, 1997
	LPG		Supply chain required	24–34 45 46[*] 49 50 56 57 60–72	Cimini and Moresi, 2017 Afrane and Ntiamoah, 2012 Cimini and Moresi, 2017 Aberilla *et al.*, 2020 Hager and Morawicki, 2013 Benka-Coker *et al.*, 2018 Singh *et al.*, 2014 Afrane and Ntiamoah, 2011 Jungbluth *et al.*, 1997
	Natural gas		Supply infrastructure required	50	Hager and Morawicki, 2013
Electric stove	Electricity	Generic electric stove	Supply infrastructure required	55 59 65 70 80	Benka-Coker *et al.*, 2018 Aberilla *et al.*, 2020 Afrane and Ntiamoah, 2012 Singh *et al.*, 2014 Hager and Morawicki, 2013
		(a) Hotplate hob		42–50 57[*]	Cimini and Moresi, 2017
		(b) Coil stove		49	Wollele, 2020
		(c) Induction cooktop		27–39 65[*] 45–59[§] 66–68[#]	Cimini and Moresi, 2017 Cimini *et al.*, 2020
Renewable fuel stove	Biogas		Supply chain required	55 50	Singh *et al.*, 2014 Aberilla *et al.*, 2020 Afrane and Ntiamoah, 2011, 2012
	Ethanol	(a) Low-grade ethanol stove (b) Ethanol-gel stove	Supply chain required	43–45 55 43	Rajvanshi *et al.*, 2004 Benka-Coker *et al.*, 2018 Okusanya *et al.*, 2019
	Solar	(a) Box cooker (b) Panel cooker (c) Parabolic cooker (d) Vacuum tube cooker	Weather-dependent	20 26.6	Hager and Morawicki, 2013 Arenas, 2007 Xu *et al.*, 2015

[*] As referred to dry pasta cooking with a water-to-pasta ratio (WPR) of 10 L/kg when using the environmentally sustainable cooking practice set up by Cimini and Moresi (2017).
[#] As referred to dry pasta cooking with WPR = 10 L/kg when using the home eco-sustainable pasta cooker (Cimini *et al.*, 2020).
[§] As referred to dry pasta cooking with the minimum WPR of 2–4 L/kg when using the home eco-sustainable pasta cooker (Cimini *et al.*, 2020).

Table 2 provides an overview of main cooking stoves in use together with the cooking fuels used, fuel availability and cookstove efficiency (η_{CS}).

Besides the cooking stoves mentioned above, useable for the so-called *surface* (or stovetop or cooktop) *cooking*, oven cooking, must also be considered, since it is essential for cooking quite numerous food products (i.e., bread, cakes, biscuits and various meat products) requiring diverse cooking methods, such as baking, grilling, roasting etc. (Table 1). An oven is a device liable to expose foods to a hot environment. It consists of a hollow chamber that can be heated in a controlled manner using a burning gas, electricity or microwaves. When an oven is combined with cook-tops (*range*), the fuel used for the oven may be the same as, or different from, that used for the burners on the stovetops. Generally, the food placed in an oven is heated from below, as in the case of baking and roasting. It can be also heated from the top, as in the case of broiling and grilling. In a *conventional oven*, the air is naturally circulated in the oven chamber, while in *a convection oven*, air recirculation is assisted by a small fan, thus resulting in faster and more energy-efficient cooking of food. Such ovens make use of a thermostat for on and off mode in order to maintain about constant the temperature selected, and a timer to turn off the oven automatically after selected period. The so-called *smart ovens* may use computer-based controls to program quite different cooking modes and even the possibility of automatically shutting it off when the minimum core temperature of the food has been attained. Moreover, self-cleaning ovens are earning an increasing popularity among consumers, their manual cleaning being complicated and asking for critical cleaning chemicals. There are two types of self-cleaning ovens (Barratt, 2021; Hager and Morawicki, 2013):

(i) *Pyrolytic ovens*, which feature a self-cleaning mode that heats the oven to about 500°C for as long as 2 h to convert food and fat residues into a white ash that can be wiped away easily.
(ii) *Catalytic ovens*, their porous surfaces being embedded with catalysts, which oxidize residual food by converting it into ash during cooking of food.

Currently, the pyrolytic version of self-cleaning ovens is not only that most widespread since it needs no expensive catalyst (Hager and Morawicki, 2013), but also because it is more thermally efficient due to greater wall insulation density required to withstand the high self-cleaning temperatures used. Generally, the thermal efficiency (η_{CS}) of well-insulated conventional electric ovens ranges from 10% to 15%, while that of gaseous counterparts ranges from 6% to 7% because of the higher air flows and electric glow-bar that run continuously to reignite the gas flame should it blow out (Barratt, 2021; Hager and Morawicki,

2013). The energy requirements of convection ovens are less than those of conventional ovens by 20–30% (Barratt, 2021). Finally, the mean efficiency of a microwave oven was reported to range between 56% and 60% depending on the class of microwave (Hager and Morawicki, 2013), although efficiency of as low as 35% was reported by Probert and Newboroug (1985).

In addition to the above oven types, it is necessary to acknowledge wood-fired ovens, which are used globally in restaurants, rotisserie shops and bakeries. For instance, about 6,400 pizza restaurants are operating in the city of São Paulo in Brazil and using about 48 megagram (Mg)/year of wood as fuel in their pizza ovens. These are responsible for an average emission factor of $PM_{2.5}$ = 0.38 g per kg of wood burned (Lima *et al.*, 2020). The average $PM_{2.5}$ concentration at the exit of their chimneys was quite high (6,171 $\mu g/m^3$), while indoor, it was about two orders smaller in magnitude (68 $\mu g/m^3$) (Lima *et al.*, 2020), although it definitely exceeded the indoor 24-h mean level of 15 $\mu g/m^3$ of $PM_{2.5}$ recommended by WHO (2018). In order to limit such a high $PM_{2.5}$ emission in Delhi (India), it was proposed to replace coal-fired with electric- and gas-fired appliances in all restaurants with a seating capacity of more than 10 persons (Apurva, 2016). Also, San Vitaliano, a town with a population of 5,000 people located near Naples (Italy), banned the use of wood-fired ovens in restaurants and bakeries during the cold season unless their chimneys were equipped with pollution-reducing filters (Singh and Highway, 2016). However, wood-fired ovens are specifically used to bake the well-known *Pizza Napoletana* (TSG), registered as a traditional specialty guaranteed by the EC (2010) Regulation No. 97/2010. Such ovens consist of a base of tuff bricks covered with a circular cooking floor over which is built a dome made of refractory materials to minimize heat dispersion. Their appropriate geometric dimensions (i.e., mouth of an having a width of 45–50 cm and a height of 22–25 cm, a cooking floor with a diameter of 105–140 cm and a vault height of 40–45 cm) allow the temperature of the dome and cooking floor maintained at about 485 °C and 430 °C, respectively; this ensures the baking quality of the Pizza Napoletana TSG (EC, 2010).

The thermal efficiency (η_{CS}) of such ovens should be like that of conventional gas ovens. According to Igo *et al.* (2020), the thermal efficiency of a metal fired-wood oven to heat 20 liters of water from 35 to 90°C was found to be of ~19%, about 55% of the energy consumed being lost by hot fumes and 26% dispersed through the oven walls. Alternatively, the specific consumption of two types (indirect and semi-direct) of bakery ovens resulted in 0.55 and 0.90 kg of wood used per kg of wheat flour baked, respectively (Manhiça *et al.* 2012). This was equivalent to an estimated oven efficiency of 3–5% when assuming an increment in temperature from 25 to 150°C

for dough having a moisture content of 36.5% (w/w) and the lower heating value of firewood as shown in Table 3.

Cooking fuels

According to Eurostat (2021a), the final energy consumption in households in EU-27 in 2019 amounted to about 10.3×10^{18} J, 63.6% of which was used for space heating, 14.8% for water heating, 14.1% for lighting and appliances, 6.1% for cooking devices and 0.4% for space cooling. The share of energy consumption for cooking ranged from 1% in Finland to as much as 36% in Portugal, while it was 6.5% in Italy. The cooking energy consumption in EU-27 was mainly supplied by electricity (49.8%), gas (31%), oil and petroleum products (13%), renewables and wastes (5.7%) and solid fuels (0.6%). In Italy, it was primarily supplied by gas (69.2%), then by electricity (15.8%), oil and petroleum products (10.2%) and renewables and wastes (4.8%).

The specific energy consumption for cooking was thus estimated by referring the overall cooking energy consumed in 2019 (628.67 petajoule [PJ]) by EU-27 population (~447 million) (Eurostat, 2021b), and it amounted to about 1.41 gigajoule [GJ] (i.e., 391 kWh) per capita/year.

The main characteristics of the cooking fuels used globally are shown in Table 3.

Biomass fuel

The use of biomass as a fuel in thermal and electrical applications is related to the fact that its combustion is CO_2 neutral that is, CO_2 released into the air equals to that absorbed during photosynthesis. The ultimate composition of wood biomass is slightly dependent on species. Roughly, it is made of 50% carbon, 6% hydrogen, 44% oxygen and 0.1–0.5% nitrogen (Vassilev *et al.*, 2010). Such composition may vary in other agricultural residues (i.e., rice husk, straw, cotton stalk and grasses), mainly because of higher hemicellulose and ash contents (Shen *et al.*, 2010). Ash is an inorganic fraction of biomass fuel that remains after its burning, and it includes calcium, potassium, sodium, magnesium and other elements. The heating value of biomass is often expressed as the higher (HHV) and lower (LHV) heating values, provided the heat released by its complete combustion leading to the production of water vapors includes or does not include the latent heat of water condensation. Such values decrease as the initial moisture content of biomass increases. These can be determined experimentally via an adiabatic bomb calorimeter or predicted based on the weight fraction of carbon (x'_C), hydrogen (x'_H), oxygen (x'_O) and moisture content (x_M) of the biomass under

Table 3. Characteristics of the main cooking fuels: density, moisture (x_M), elemental composition (C, H, O, N, S) and ash (x_A) content on a dry matter (DM) basis; raw formula; CO_2 generated per kg of burned fuel (CFR); and higher heating value (HHV) and lower heating value (LHV) (EPA, 1998; Singh *et al.*, 2014).

Fuel type	Density (kg m^{-3})	x_M (g/100 g)	x'_C	x'_H	x'_O	x'_N	x'_S	x'_A	Raw formula	CFR (kg/kg)	HHV (MJ/kg)	LHV (MJ/kg)
					(g/100 DM)							
Firewood	450–980[1] 300–450[2]	22.4	46.00	5.80	44.87	0.30	0.01	3.02	$CH_{1.513}O_{0.732}N_{0.006}S_{0.002}$	1.74	15.84	13.95
Crop residues	200–400[3]	14.0	42.10	6.30	48.37	0.36	0.17	2.70	$CH_{1.796}O_{0.862}N_{0.007}S_{0.002}$	1.59	14.62	12.84
Charcoal	180–220	1.7	80.00	1.80	10.00	0.74	0.06	7.40	$CH_{1.513}O_{0.270}N_{0.094}S_{0.000}$	3.17	27.86	27.41
Coal	640–930[4]	10.0	39.00	4.00	15.00	1.50	0.50	40.00	$CH_{1.231}O_{0.288}N_{0.033}S_{0.005}$	2.38	16.30	15.14
Natural gas	0.57–0.72	0.0	72.38	23.58	1.37	2.66	0.01	0	$CH_{3.909}O_{0.014}N_{0.032}S_{0.0005}$	2.65	58.25	52.92
LPG	508–573	0.0	82.29	17.70	0.00	0.00	0.01	0.00	$CH_{2.581}$	3.02	53.37	49.37
Kerosene	780–810	0.0	85.90	13.80	0.05	0.05	0.20	0.00	$CH_{1.928}S_{0.001}$	3.15	48.97	45.85
Biogas	0.85–0.93	0	56.50	11.90	27.86	3.47	0.27	0.00	$CH_{2.527}O_{0.37}N_{0.053}S_{0.002}$	2.07	31.28	28.59
Ethanol	785–794	4[5]	52.17	13.04	34.78	0	0	0	$CH_{3}O_{0.5}$	1.91	26.8–29.7	21.4–26.9

[1] Density at 13% moisture content (Francescato *et al.*, 2008).
[2] Bulk density of wood logs at 15% moisture content (Francescato *et al.*, 2008).
[3] Bulk density of agricultural residues at 7–11% moisture content (Makavana *et al.*, 2018).
[4] Bulk density (https://www.tapcoinc.com/images/uploads/Tapco_Catalog_09_p88-94.pdf).
[5] Water content of the ethanol mixture used by CleanCook ethanol stove (Appropedia, 2008; Benka-Coker *et al.*, 2018).

study on dry basis using one of the mathematical models available in literature (Vargas-Moreno *et al.*, 2012). In this work, HHV and LHV (expressed in MJ/kg) were calculated as follows (Mukunda, 2009):

$$HHV = 33.823\, x'_C + 144.249\, (x'_H - x'_O/8) + 9.418\, x'_S, \quad (1)$$

$$LHV = HHV - 22.604\, x'_H - 2.581\, x_M. \quad (2)$$

Table 3 shows the elemental composition and moisture content of typical firewood and crop residues (Singh *et al.*, 2014), together with their estimated raw formula, theoretical amount of CO_2 produced by the overall combustion of a unitary mass of biofuel, and higher and lower heating values calculated using Equations (1) and (2), respectively.

The heating value of anhydrous wood biomass varies between 18.5 MJ/kg and 19 MJ/kg, whatever be the wood species examined. Owing to their higher lignin, resin, wax and oil contents, the heating value of conifers is about 2% higher than that of broad leave trees. The calorific value of anhydrous lignin (26–27 MJ/kg) is higher than that of cellulose (17.2–17.5 MJ/kg) or hemicellulose (16 MJ/kg). Further variability in the heating value is due to slight variation in hydrogen content and especially to diverseness in ash and moisture contents (Francescato *et al.*, 2008).

Several crop residues (i.e., rice husk, wheat straw, cotton stalk, corn stover etc.), which are mostly left on fields after harvesting, and forestry residues (i.e., branches, leaves, bark etc.) are usually collected and burned by households. These are characterized by low bulk density and heating values in the range of 12–20 MJ/kg, depending on their ash and moisture contents. Most of the woody biomass free from leaves and needles has an ash content of less than 2%, while in some agricultural residues, it could be as high as 21% as in the case of rice husk (Shen *et al.*, 2010).

Table 3 shows the ultimate composition of a typical mixture of crop residues used in India (Singh *et al.*, 2014). Emissions in the air resulting from the combustion of typical firewood and crop residues as shown in Table 4 are derived from Singh *et al.* (2014). The resulting ash contents are generally disposed of in landfills. The theoretical CO_2 emissions shown in Table 3 were greater than those obtained under conditions of real combustion, probably because of an inappropriate mass ratio of air to the solid fuel used.

Charcoal

Charcoal (CHC) is a high-carbon solid fuel obtained from the carbonization of wood and wood wastes, which

Table 4. Emissions to air and waste generated by the combustion of typical cooking fuels (EPA, 1998; Singh *et al.*, 2014).

Emissions to air/waste	Firewood (g/kg)	Crop residues (g/kg)	Charcoal (g/kg)	Coal (g/kg)	Natural gas (g/STPm³)	Kerosene (g/kg)	LPG (g/kg)	Biogas (g/kg)
CO_2 (biogenic)	326	1,302	625	0	0	0	0	1,450
CO_2	1,032	0	1,979	1,559	1,918.5	2,943	3,085	0
CO	69	65.6	275	49	1.3	62	14.9	1.88
CH_4	4.2	6.8	7.9	4.69	0.04	0.74	0.074	0.43
NO	0.41	0.54	0.62	0.55	1.60	0.58	0.98	0.38
NO_2	0.35	0.54	0.51	0.45	0.00	0.52	0.78	0.24
N_2O	0.09	0.05	0.08	0.08	0.04	0.09	0.015	0.009
Non-methane volatile organic compounds (NMVOC)	7.35	8.2	10.3	10.5	0.09	13.2	10.59	0.56
$PM_{2.5}$	3.3	7.5	0.4	12.2	0.12	1.9	0.32	0.66
PM_{10}	4.34	7.54	0.43	17.9	0.00	0.52		0.66
Total suspended particulate (TSP)	1.04	0.63	2.19	1.3	0.00	0.7	0.51	0.52
Black carbon	0.6	0.51	0.2	5.42	0.00	0.16	0.01	0.01
Organic carbon	0.95	1.46	1.18	6.75	0.18	0.12	0.02	0.02
SO_2	0.32	0.27	0.34	2.67	0.01	2.56	2.12	0.85
Formaldehyde	0	0	0.03	0	0	0	0	0
Ash	30.2	27	74	400.0	0	0	0	0
Digested slurry	0	0	0	0	0	0	0	1060.0

are heated under limited aeration to remove water and volatile components. Such a process can be carried out in traditional earth mound kilns with a yield of about 14%, or in closed retorts with yields as high as 25–40%, thanks to the heat recovered from the combustion of volatile components baked off (Singh *et al.*, 2014; Wikipedia, 2021d). Generally, the carbon content of charcoal ranges from 0.68 to 0.82 kg per kg of charcoal, which upon combustion gives rise to 2.5–3 kg of biogenic CO_2 (Table 3). The main disadvantage of this process is the emission of unburnt methane, combustion gases, and particulates harmful to human health and the environment (Table 4).

Coal

Coal (CO) is a common resource of energy and chemicals. It is a complex heterogeneous solid composed of organic and inorganic matter with quite different chemico-physical properties. It is generally ranked on the basis of its carbon content into four types, namely, (1) *anthracite* with 86–97% carbon content (x'_C) and the highest heating value, (2) *bituminous coal* with x'_C = 45–86%, (3) *sub-bituminous coal* with x'_C = 35–45% and (4) *lignite* with x'_C = 25–35%. Table 3 shows the ultimate composition of a typical sub-bituminous coal generally used for cooking purposes. Its combustion gives rise to the emissions to air as listed in Table 4, and to coal ash usually disposed in landfills like that resulting from biomass fuels.

Kerosene

Kerosene (KER) is a combustible hydrocarbon liquid obtained from the fractional distillation of petroleum between 150 °C and 275 °C. It is mainly used as aviation fuel and indoor cooking fuel. Its typical physico-chemical properties are shown in Table 3, while main emissions after its combustion are shown in Table 4. Even in this case, the theoretical CO_2 emissions (Table 3) were greater than those obtained under the real combustion conditions of this liquid fuel (Table 4).

Natural Gas

Natural gas is a nonrenewable mixture consisting of methane (85–96% mol/mol), other alkanes (1.9–7.4% mol/mol) and inert compounds (i.e., carbon dioxide, nitrogen and hydrogen sulfide) (Florida Power & Light Co., 2003).

Table 3 shows typical properties and composition of NG. It is used as a fuel for generating electric and thermal energy, household heating and cooking, in vehicles as well as a chemical feedstock for manufacturing

plastics and organic chemicals. It is primarily transported in its gaseous form using specific gas transmission network in industrialized countries. It can also be compressed and cooled into a liquid form and transported by sea. Emissions to the air resulting from its combustion are listed in Table 4 (US Environmental Protection Agency [EPA], 1998).

Liquified Petroleum Gas

Liquified petroleum gas is a fossil fuel mixture consisting of propane (C_3H_8) and butane (C_4H_{10}) with smaller percentage of isobutene and propylene. Its composition may range from 100% propane to 20% propane and 80% butane depending on the local winter and summer weather conditions, respectively. LPG can be manufactured during the refining of crude oil or extracted from petroleum or NG streams. It can be used as a fuel gas for heating and cooking, and in vehicles. To this end, it can be stored in portable steel cylinders, barbecue gas bottles and larger tanks. It is considered a clean cooking fuel because it gives rise to by far smaller indoor air pollution than biomass fuels. For this reason, LPG supply chains have been developed in several countries (e.g., Brazil, India, Indonesia, Bangladesh, Ethiopia, Haiti, Burundi, Mozambique etc.) to convert people in rural and urban areas to cleaner and healthier cooking solutions because its supply chain requires no investment in infrastructure as in the case of electricity grid and NG network (Rosenthal *et al.*, 2018; Wright *et al.*, 2020).

Table 3 shows the typical properties and composition of LPG, while Table 4 reports the main emissions to air as resulting from LPG cookstoves. Beyond the fact that LPG is ideal for users living in areas not accessible to NG lines, it has the advantage of a greater calorific value of 93.2 MJ/m^3 against 38.7 MJ/m^3 for NG. Moreover, because of the easier regulation of mass ratio of air to LPG, the CO_2 emitted during real burning is near to the theoretical amount shown in Table 3.

Biogas

Biogas (BG) is obtained from the process of anaerobic digestion of organic wastes, such as agricultural waste, manure, municipal waste, sewage, green waste and food waste, in anaerobic digesters (Bedoić *et al.*, 2020). It mainly comprises methane (50–75% v/v), carbon dioxide (25–45% v/v) and nitrogen (0–10% v/v). It also contains small amounts of oxygen, ammonia, hydrogen and hydrogen sulfide, each being less than 1% v/v, and siloxanes. Its moisture varies from 2% v/v at 20 °C to 7% v/v at 40 °C. It is regarded as a renewable energy source, since its combustion practically releases the CO_2 absorbed from

the atmosphere in the growth of primary bio-resource. It can be used for different purposes, such as electricity and heat generation, cooking etc. A greater percentage of household-scale biogas digesters are installed in China and India. Economic governmental subsidies are provided to encourage rural population in Asia, Africa and South America to produce and use biogas at household levels, and thus avoid health problems associated with the use of biomass cookstoves (Wright *et al*., 2020).

Table 3 shows the typical properties and composition of biogas, while Table 4 reports the main emissions to air resulting from biogas cookstoves.

Bioethanol

Bioethanol is a renewable fuel used as a low-carbon alternative to fossil-derived fuels. It is the main fermentation product of yeast (e.g., *Saccharomyces cerevisiae*) or bacteria (e.g., *Zymomonas mobilis*) cultured on the media rich in simple sugars under anaerobic conditions. The so-called *first-generation* bioethanol stems from sugar-based raw materials (i.e., sugarcane, corn, sweet sorghum and cassava), while the *second-generation* bioethanol is derived from lignocellulose raw materials (such as straw, corn stover, wood trimmings, sawdust, bamboo, citrus peels etc.), which are presented for preliminary enzymatic treatment to hydrolyze cellulose (Kang *et al*., 2014). Brazil and the United States currently cover ~85% of global supply of bioethanol by utilizing sugarcane and corn as substrates, respectively (Bertrand *et al*., 2016).

Numerous life cycle assessment studies attempted to estimate the environmental impact of bioethanol from different substrates with contradictory results. According to Jeswani *et al*. (2020), if no land-use change is involved, only bioethanol from sugarcane can meet the EU Renewable Energy Directive (EC, 2018a) of 60% reduction in GHG emissions relative to petrol, while lignocellulosic bioethanol from agricultural and forest residues appears to have a greater mitigation effect. Among the several initiatives aiming at testing the use of ethanol cookstoves, it is worth citing the case of Gaia Association in Addis Ababa (Ethiopia), where the stoves are fed with 96% (v/v) technical ethanol, which cannot be used as power ethanol for vehicles and is denatured with a bitter additive and dyed blue to make it unpalatable for drinking and unmistakable for water (Appropedia, 2008).

Table 3 shows the typical properties and composition of bioethanol. No information was found in the literature about the emissions in the air generated by ethanol cookstoves, although several studies monitored emissions to air resulting from the combustion of different

ethanol-gasoline mixtures in spark-ignition engines (Iodice *et al*., 2018; Manzetti and Andersen, 2015). The ethanol blend of 85% (v/v), generally used as a vehicle fuel in Brazil, generated 90%, 15% and 50% less particulates, CO and NO_X, respectively, or benzene and 1,3-butadiene with respect to 100% gasoline, but almost 3.5 times higher carbonylic compound emissions were noted, mainly acetaldehyde (Costagliola *et al*., 2013).

Electricity

The use of electric energy (EL) for cooking results in no indoor emissions and smoke, and thus is a minimum health risk source. Nevertheless, such use affects ambient air pollution and climate change in a smaller or greater manner, especially if the electricity is made from wind turbines and solar photovoltaic panels or coal, respectively. Globally, about 26,603 TWh of electricity was generated in 2018, about 38% of which being made from coal, 23% from NG, 10% from nuclear power plants and 25.5% from renewables (International Energy Agency [IEA], 2019). In industrialized countries, where electrification rates are very high, about 50% and 61% of the cooking energy consumption in the EU-27 (Eurostat, 2021a) and the United States (IEA, 2018) is supplied by electricity whereas 31% and 33% by NG, respectively. Nevertheless, cooking devices consume about 6% of the overall energy consumption in the EU-27 and the US households, while the energy consumption for noncooking purposes (e.g., space and water heating, lighting and air conditioning) is by far dominating (Eurostat, 2021a). In low- and middle-income countries, use of electricity for cooking is limited, being even lower than the electricity access rate, for its high specific cost (Wright *et al*., 2020).

Food Cooking Energy Requirements

Several studies have attempted to measure the energy required to cook some food items in single or multiple portions using different cookstove or oven types, cooking fuels, and methods, and in some cases to assess the resulting GHG emissions (Carlsson-Kanyama and Boström-Carlsson, 2001; Foster *et al*., 2006; Frankowska *et al*., 2020; Martinez-Gómez *et al*., 2016; Nielsen, 2003). Many of these studies pointed out different thermal energy efficiencies of the main cooking systems used.

As an example, Table 5 shows the specific life cycle energy use (LCEU) and cooking time (t_C) of a few food items as a function of different appliances and cooking modes, number of portions, including mass of food and water used, as interpreted by Carlsson-Kanyama and Boström-Carlsson (2001). For instance, these authors demonstrated that boiling water in an electric kettle or

Table 5. Specific life cycle energy use (LCEU) and cooking time (t$_c$) of a few food items as a function of different appliances and cooking modes used, number of portions, including the overall masses of food and water used (Carlsson-Kanyama and Boström-Carlsson, 2001).

No.	Food Item	Appliance & cooking mode	No. of portions	Food mass (g)	Water mass (g)	t$_c$ (min)	LCEU (MJ/kg)
1	Wheat	Hotplate	4	180	350	17	1.8
2	Wheat	Hotplate	1	45	88	15	11.3
3	Wheat	Microwave oven	4	180	350	15	2.1
4	Wheat	Microwave oven	1	45	85	12	14.9
5	Barley	Hotplate	4	160	700	23	2.3
6	Barley	Hotplate	1	40	175	30	16.5
7	Barley	Microwave oven	4	160	700	26	2.9
8	Barley	Microwave oven	1	40	160	23	23.8
9	Couscous	Electric kettle	4	240	300	1.00	4.0
11	Couscous	Hotplate	4	240	300	2.42	4.2
12	Couscous	Hotplate	1	80	100	2.00	13.8
13	Boiled potatoes	Hotplate	4	800	1,000	32.4	1.1
14	Boiled potatoes	Hotplate	1	190	600	28.3	6.8
15	Boiled potatoes	Hotplate[1]	4	800	1,000	32.4	1.1
16	Boiled potatoes	Hotplate[1] method	1	190	600	28.3	6.3
17	Baked potatoes	Microwave oven	4	1,200	-	28.0	1.2
18	Baked potatoes	Microwave oven	1	300	-	7.0	5.0
19	Baked potatoes	Conventional oven	4	1,200	-	65.0	1.8
20	Baked potatoes	Conventional oven	1	300	-	65.0	20.0
21	Mashed potatoes	Electric kettle	4	140	650	4.25	7.1
22	Mashed potatoes	Electric kettle	1	35	175	2.25	28.6
23	Mashed potatoes	Hotplate	4	140	650	1.83	7.9
24	Mashed potatoes	Hotplate	1	35	175	0.83	34.3
25	Swedish-made pasta	Hotplate	4	280	2,500	18	4.3
26	Italian-made pasta	Hotplate	4	280	2,500	18	4.6
27	Swedish-made pasta	Hotplate	1	70	1,000	14	21.4
28	Italian-made pasta	Microwave oven	1	70	1,000	14	22.9
29	Fresh pasta	Microwave oven	4	520	2,500	12	3.5
30	Fresh pasta	Microwave oven	1	130	1,000	8	16.2
31	Rice	Hotplate	4	240	600	20	4.2
32	Rice	Hotplate	1	60	150	20	21.7
33	Rice	Microwave oven	4	240	600	17	5.0
34	Rice	Microwave oven	1	60	150	17	25.0

[1] Energy-saving method.

baking a single portion of potatoes in a microwave oven was by far more energy-efficient than a hotplate or conventional oven. Moreover, Lakshmi *et al.* (2007) observed that an electric rice cooker was more energy-efficient than a pressure cooker or microwave cooker. Similarly, Martinez-Gómez *et al.* (2016) analyzed several cooking parameters for eight typical Ecuadorian meals when cooked using LPG-, coil- or induction-stoves. For example, the energy requirements to cook four hard-boiled eggs or grill 400-g chicken reduced from about 0.44 to

0.29 or 0.2 kWh. This clearly indicated that induction stove was more efficient thermally than other stoves examined.

According to Frankowska *et al.* (2020), the cooking of vegetables (e.g., cabbage, carrots, cauliflower, onions and potatoes) and meat and fish accounts for around 61% and 8–27% of total GHGs emitted during their overall life cycle, respectively. Similarly, home cooking of 1 kg of conventional dry pasta in 10 L of boiling water laced

with 70 g of table salt consumed as much as 2.8 kWh/kg, which represented about 50% of the cradle-to-grave carbon footprint, while wheat-milling and pasta-making and packaging or durum wheat cultivation covered 24.8% and 21.7% of total GHG emissions respectively (Cimini *et al*., 2020). By using the innovative Arduino®-based eco-sustainable pasta cooker, operating with a water-to-dry pasta ratio of 3 ± 1 L/kg and consuming just 0.6 ± 0.1 kWh/kg (Cimini *et al*., 2020), the cradle-to-grave carbon footprint of dry pasta reduced by 27% (Cimini *et al*., 2020). In the case of brewing of a cup of coffee using different coffee makers, the use phase represented the secondary hotspot (12.5–18.2% of cradle-to-grave carbon footprint), coffee bean cultivation and green coffee production phase embodying 59–70% of total GHG emissions (Cibelli *et al*., 2021).

The cooking of lamb and beef is highly energy-intensive in consequences of their long cooking period (>1 h) as in the case of roasting in an oven. Nevertheless, the contribution of their cooking to the total GHGs emitted was found to be lower than 10% because their cradle-to-grave carbon footprint was by far higher than that of vegetables. Under these circumstances, it would be much more environment-friendly to reduce the consumption of lamb and beef than to improve the energy efficiency of cooking method of choice (Frankowska *et al*., 2020).

Table 6 summarizes the specific energy requirements for cooking different food items using either a few ordinary moist (e.g., boiling, and frying), dry (grilling) and combined (microwave) heat cookery methods, as interpreted by Foster *et al.* (2006).

Description of the Cooking Systems Studied

A cooking system does not entail just the cookstove and oven but it accounts for the stove technology, cooking fuels and their supply chains, cookware, food materials as well as all the stages involved in the process of cooking from collection, handling, transportation and use of raw materials, extraction and/or refining, transportation to consumers, cooking, as well as post-consumer

Table 6. Specific energy requirements for cooking different food items using a few ordinary cookery methods (Foster *et al*., 2006).

Cookery methods	Specific energy required (MJ/kg of raw food)
Boiling	3.5
Frying	7.5
Grilling	8.5
Microwave cooking	0.34

waste disposal. Its system boundary is sketched in Figure 1.

If the per capita cooking energy consumption per year is known as (E_C), the mass of cooking fuels consumed (m_{CF}) and the electric energy absorbed from the national grid (E_{EE}) can be estimated as follows:

$$m_{CF} = \frac{E_C}{LHV\,\eta_{CS}}, \qquad (3)$$

and

$$E_{EE} = \frac{E_C}{\eta_{CS}(1-\eta_{EG})}, \qquad (4)$$

where LHV is the lower heating value of each cooking fuel (see Table 3), η_{CS} is the average thermal efficiency of cookstove, and η_{EG} is the average loss of electric grid. While the range of values for η_{CS} is shown in Table 2, the latter was about 5.8% for the Italian grid in 2020 (Terna, 2020).

Specific emissions into the air, water and solid wastes resulting from the use of different cooking fuels are reported in Table 4. In Italy, electricity is produced mainly from fossil fuels (52% of total, that is, 43% from NG, 4.3% from coal and 1.0% from petroleum products etc.), and from renewable energy sources (37.6% of total, that is, 15.3% from hydroelectric sources, 8.3% from solar, 6.0% from wind and 1.94% from geothermic power, and 6.3% from biofuels) (Terna, 2020).

Methodology

The life-cycle analysis (LCA) was carried out according to specific international standards (International
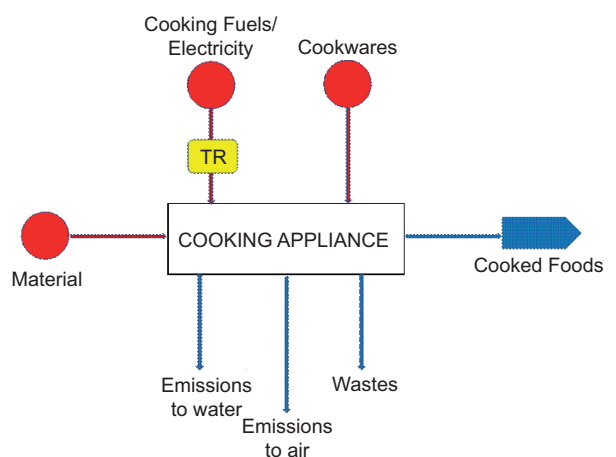
Figure 1. Schematic of a generic cooking system, including the transportation stage (TR) of cooking fuels.

Organization for Standardization [ISO], 2006a, 2006b), and included the following stages: Goal and scope definition, inventory analysis, impact assessment and interpretation of results.

Goal and scope definition

The goal of this study was to determine the potential life cycle environmental impacts of different cooking fuels (i.e., firewood, charcoal, kerosene, NG, LPG, biogas and electricity) in Italy using the LCA software Simapro 9.2.0.2 (Prè Consultants, Amersfoort, NL) with embedded background Ecoinvent v. 3.7 database. The cooking energy requirements depend not only on the thermal efficiency (η_{CS}) of the cookstove used but also on the type and energy (LHV) value of each fuel, as shown in Tables 2 and 3. For a valid comparison between different cooking systems, the production of useful EU-27 per capita cooking energy consumption of 1.41 GJ/yr, as transferred to the cooking pot after the combustion of each fuel in the cookstove, was used as the functional unit. In this way, differences in the fuel energy values and efficiencies of end-use cookstoves were accounted for.

As suggested by the guidelines established by the Publicly Available Specification (PAS) 2050 standard method (British Standards Institution [BSI], 2011), the production of capital goods (cookstoves, cookware etc.) as well as their cleaning and disposal (Section 6.4.4; BSI, 2011), was not included in the system boundary. Such assumption was also corroborated by a few LCA analyses which confirmed that the use phase was responsible for the greatest environmental impact in several impact categories in the case of mud stoves for firewood (Afrane and Ntiamoah, 2012), gas and induction hobs (Favi *et al*., 2018), electric and gas ovens (Landi *et al*., 2019) as well as domestic induction hobs equipped with different electronic boards (Elduque *et al*., 2014). Additionally, the lifespan of each cookstove was, in general, more than 10 years, this being the average life of the appliances installed in Italy (Favi *et al*., 2018). In addition, the production and transportation of food materials, as well as the transportation and disposal of food wastes, were excluded from the system boundaries, as they were assumed to be the same for all the cookstoves examined.

Inventory analysis

The production processes of all cooking fuels, as well as electricity drawn from the Italian grid mix, were extracted from the Ecoinvent v. 3.7 database (Table 7).

Solid (i.e., firewood, charcoal and coal) and liquid (i.e., kerosene and LPG) cooking fuels were distributed by road using Euro5 lorries with a load capacity of 3.5–7.5 Mg for an average distance of 50 km. Kerosene was packed in 20-L high-density polyethylene tanks weighing 0.75 kg each and LPG was filled into 10-kg steel bottles, weighing 11 kg each. Finally, gaseous fuels (i.e., NG and biogas) were distributed by 50-km pipelines, while electricity was drawn from the Italian grid mix.

Pollutants from cookstoves are mainly derived from incomplete combustion processes. They included biogenic and/or fossil CO_2, carbon monoxide, methane, oxides of nitrogen (NO_X), non-methane volatile organic compounds (NMVOC), particulate matter (PM), black carbon, organic carbon compounds and sulfur dioxide. These pollutants are of great concern because of their harmful effects on human health. Electric cookstoves have no direct indoor emissions but a more or less severe indirect environmental impact depending on the electric power supply.

Emissions and solid wastes resulting from the combustion of fuels (Singh *et al*., 2014) are shown in Table 4, as referred to 1 kg of cooking fuel or 1 standard temperature and pressure (STP) m³ of NG. The effective mass of cooking fuels burnt and electricity drawn from the electric grid were calculated by using Equations (3) and (4), respectively.

Finally, solid wastes (wood and coal ash) from cookstoves were disposed of in landfills.

Impact assessment

The impact assessment was carried out using the ReCiPe 2016 (Huijbregts *et al*., 2016), and PEF (EC, 2018b; Manfredi *et al*., 2012; Sala *et al*., 2017, 2018) standard methods, all these methods being embedded in the software SimaPro 9.2.0.2.

Any generic impact category (IC_j) was estimated by summing up release into the air, water and soil (ψ_i, expressed in mass, energy, and mass-km basis) associated to the system boundaries times its corresponding characterization factor ($F_{i,j}$) as:

$$IC = \sum_i (\Psi_{i,j} F_{i,j}) \qquad (5)$$

The updated ReCiPe 2016 method (Huijbregts *et al*., 2016) included the following 18 midpoint impact categories; the reference substance of each is indicated in parentheses: global warming (kg CO_{2e}); stratospheric

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Table 7. Production processes for the cooking fuels used in this work (extracted from the Ecoinvent v. 3.7 database).

Cooking fuels	Ecoinvent v. 3.7 database	Description
Firewood	Wood pellet, measured as dry mass (RoW)| wood pellet production| cut-off, S	Wood pellets are produced in a wood pellets factory, which uses wood residue from sawmills and woodchips as raw materials. The raw materials are first pre-treated and dried; then comminuted, mixed, pelletized, cooled and bagged. 20% of the production was packed in 15-kg bags, while the remaining 80% was sold unpacked.
Charcoal	Charcoal (GLO)| production| cut-off, S	Charcoal with an average carbon content of 80% (w/w) is produced from hardwood from forest plantations.
Coal	Hard coal (Europe, without Russia and Turkey)| market for hard coal| cut-off, S	This activity starts at the hard coal preparation plant with coal ready to be loaded on rail, truck, barge or conveyor. The activity ends with the unloading of hard coal at domestic consumers or export hubs. The inventory refers to the average transport distance specific to the domestic market of hard coal in Europe without Russia and Turkey.
Natural gas	Natural gas, high pressure (IT)| import from RU| cut-off, S	This dataset represents the extraction of NG in the Russian Federation and includes the following activities: exploration, production, processing, underground storage of NG, and feeding of produced gas in the pipeline for transport to the country where it is consumed. The leakages of production and processing of the raw gas are included. This dataset describes the transport required for the export of Russian NG to Italy (expressed in Mg km). Gas losses and emissions during seasonal storage are included. An average distance of 6,400 km is estimated for the export.
LPG	Liquefied petroleum gas (Europe without Switzerland)| liquefied petroleum gas production, petroleum refinery operation| cut-off, S	This dataset describes the operation of a representative average petroleum oil refinery in Europe without Switzerland. It includes the following activities: crude oil and product storage on refinery grounds and energy provision, refinery infrastructure, wastewater treatment, freshwater supply (from nature), refined petroleum products leaving the refinery. Its sulfur content was 1.03%.
Kerosene	Kerosene (Europe without Switzerland)	kerosene production, petroleum refinery operation| cut-off, S	This dataset describes the operation of a representative average petroleum oil refinery in Europe without Switzerland. Activity starts with crude oil entering the petroleum refinery. Wastewater treatment, freshwater supply (from nature), refinery infrastructure, crude oil and product storage on refinery grounds and energy provision are included. Electricity requirements are met by the on-site generation mix. Activity ends with refined petroleum products leaving the refinery.
Biogas	Biogas (RoW)| anaerobic digestion of manure| cut-off, S	This activity produces biogas and digestate from manure and includes the following activities: input of livestock manure (cattle slurry, pig slurry and cattle manure) to incoming storage at the biogas plant, storage of the substrates, anaerobic fermentation, and storage of digestate after fermentation. The activity ends with the biogas and digestate being available at the biogas plant. The calorific value of the biogas only accounts for the methane content excluding the presence of H_2S in it.
Electricity	Electricity, low voltage (IT)| market for| cut-off, S	This dataset describes the electricity available on the low-voltage level in Italy in 2017 as well as grid losses. It includes electricity inputs produced in this country and from imports and transformed to low voltage, the transmission network over aerial lines and cables, direct emissions to air (SF_6 from the insulation gas in the high-voltage level switchgear are allocated to the electricity demand on medium voltage), and electricity losses during transmission.
	Electricity, low voltage (FR)| market for| cut-off, S	This dataset describes the electricity available on low-voltage level in France in 2017. It includes electricity inputs produced in France from imports and transformed to low voltage, the transmission network, direct emissions to air (SF_6 from the insulation gas in the high-voltage level switchgear are allocated to the electricity demand on medium voltage), and electricity losses during transmission. This dataset excludes electricity losses during transformation from high to medium voltage or medium to low, as these are included in the dataset for transformation, leakage of insulation oil from cables and electro technical equipment, SF_6 emissions during production and deconstruction of the switchgear, as these are accounted for in the transmission network dataset.
	Electricity, low voltage (PL)| market for| cut-off, S	This dataset describes the electricity available on low-voltage level in Poland in 2017. It includes electricity inputs produced in Poland and from imports and transformed to low voltage, the transmission network, direct emissions to air (SF_6 from the insulation gas in the high-voltage level switchgear are allocated to the electricity demand on medium voltage level), electricity losses during transmission. This dataset excludes electricity losses during transformation from high to medium voltage or medium to low, as these are included in the dataset for transformation, leakage of insulation oil from cables and electro technical equipment (transformers, switchgear and circuit breakers) because this only happens in case of accidental release, SF_6 emissions during production and deconstruction of the switchgear, as these are accounted for in the transmission network dataset.

Table 7. Continued

Cooking fuels	Ecoinvent v. 3.7 database	Description
	Electricity, high-voltage (IT)| electricity production, hydro, reservoir, alpine region| cut-off, S	This dataset represents the production of high-voltage electricity at grid-connected reservoir hydropower plants in Italy in 2012. Net average electrical efficiency, including pipe losses, is 78%. This dataset starts from the power plant ready to produce electricity, i.e., the reservoir filled with water, and ends with 1 kWh of high-voltage electricity produced at the power plant and arrived at the busbar. This dataset doesn't include land use for access roads to the reservoir, emissions of carbon dioxide, raw materials extraction, decommissioning and waste treatment as these activities are already included in the infrastructure datasets, transformation of the electricity produced.
	Electricity, high-voltage (IT)| electricity production, wind, 1–3-MW turbine, onshore| cut-off, S	This dataset represents the production of high-voltage electricity at on-shore grid-connected wind power plants with a capacity between 1 MW and 3 MW in Italy in 2005–2020. It includes operation and maintenance expenditures as well as infrastructure inputs.
	Electricity, low-voltage (IT)| electricity production, photovoltaic, 570-kWp open ground installation, multi-Si	cut-off, S	This dataset represents the production of grid-connected low-voltage electricity with a 570-kWp open ground photovoltaic plant in Italy in 2008–2020. An inverter is used to convert the low-voltage DC power into AC power. Use of tap water for cleaning the module and its treatment is included.

FR - France; GLO, global; IT - Italy; PL - Poland; RoW - Rest of world; RU - Russia, S - system.

ozone depletion (kg trichlorofluoromethane or freon-11, CFC-11$_e$); ionizing radiation (kBq ^{60}Co$_e$); fine PM formation (kg PM$_{2.5e}$); ozone formation-human health, and ozone formation-terrestrial ecosystems (kg NO$_{xe}$); terrestrial acidification (kg SO$_{2e}$); freshwater (kg P$_e$) and marine (kg N$_e$) eutrophication; terrestrial, freshwater, and marine ecotoxicity (kg 1,4-Dichlorobenzene [DCB]); human carcinogenic and noncarcinogenic toxicity (kg 1,4-DCB); land use (m^2 annual crop$_e$); mineral (kg Cu$_e$) and fossil (kg oil$_e$) resource scarcity; and water consumption (m^3). Finally, the PEF method accounted for the following 16 impact categories, the reference substance of each is indicated in parentheses: climate change (kg CO$_{2e}$), ozone depletion (kg CFC-11$_e$), ionizing radiation-human health (kBq ^{235}U$_e$), photochemical ozone formation (kg NMVOC$_e$), PM (diseases included), human toxicity, noncancer (Human Comparative Toxic Unit, CTU$_h$); human toxicity, cancer (CTU$_h$), acidification (mol H^+_e), freshwater eutrophication (kg P$_e$), marine eutrophication (kg N$_e$); terrestrial eutrophication (mol N$_e$), freshwater ecotoxicity (ecotoxicity Comparative Toxic Unit, CTU$_e$), land use (point [Pt]), water scarcity (m^3 depriv.), resource use-fossils (MJ), and resource use-mineral and metals (kg Sb$_e$).

Both standard methods combine the above-mentioned environmental impacts into one point value. More specifically, the ReCiPe 2016 method groups the aforementioned impact categories into the following three endpoint indicators: (i) damage to *human health* (HH), expressed in DALY, that is, the number of years of life lost as a result of premature mortality and/or disability after an exposure to toxic chemicals; (ii) damage to *ecosystem quality* (EQ), expressed in loss of species during a year;

and (iii) damage to *resource availability* (RA), expressed in US\$ 2013 to quantify the extra costs involved for future mineral and fossil resource extraction. Such damage categories are then normalized with respect to the global population and aggregated using specific weights. Finally, the three damage categories may be grouped into individualistic, hierarchic, or egalitarian perspective, according to the 'Cultural Theory' (Thompson *et al.*, 1990). In this study, hierarchic perspective was used to estimate the *overall weighted damage score* (OWDS$_R$), since such a perspective is regarded as the most balanced one between future and present impacts, and risks and benefits (Huijbregts *et al.*, 2016). Thus, the midpoint ReCiPe-Hierarchic (H) version-Europe was used to characterize the results of LCIA, while the environmental impacts were calculated according to the ReCiPe endpoint - Hierarchic (H) version-Europe H/A - with the average weighting set (A), both methods being encoded in the LCA software SimaPro 9.2.0.2.

Concerning the PEF method, any impact category was normalized with respect to its corresponding global impact as recommended by Sala *et al.* (2017), weighted as suggested by Sala *et al.* (2018), and finally summed up to yield another *overall weighted score* (OWS$_P$).

Sensitivity analysis

Uncertainty in the outputs of the above-mentioned LCA models was mainly apportioned to the range of variations in thermal efficiency (η_{CS}) of the cooking fuels used (see Table 2) and to the electric power supply (i.e., the French or Polish grid mix, hydro, solar photovoltaic and

wind power). In particular, the French electricity mix is largely dominated by the nuclear power, while coal governs the power sector of Poland (www.iea.org/countries). Once the default triangular and/or normal distribution uncertainty range for η_{CS} was accounted for, it was possible to resort to the well-known Monte Carlo analysis (Theodoridis, 2015).

Results and Discussion

Mid-point environmental profile of the cooking systems examined

Environmental impacts of the cooking fuels examined in this work at the first stage of cause–effect chain are shown in Table 8, depicted according to the ReCiPe 2016 and PEF standard methods.

According to the ReCiPe 2016 method, the use of coal appeared to have the maximum impact in 12 of the 18 categories (i.e., global warming, fine PM formation, ozone formation affecting human health and terrestrial ecosystems, terrestrial acidification, freshwater and marine eutrophication and ecotoxicity, human carcinogenic and noncarcinogenic toxicity, and fossil resource scarcity). The use of charcoal, electricity and firewood largely affected three impact categories (namely, stratospheric ozone depletion, land use and water consumption), two impact categories (e.g., ionizing radiation and mineral resource scarcity), and one (terrestrial ecotoxicity) impact category, respectively. In contrast, the use of NG gave rise to the minimum impact in 9 of the 18 categories (i.e., ionizing radiation, fine PM formation, terrestrial acidification, freshwater eutrophication, terrestrial, freshwater and marine ecotoxicity, human noncarcinogenic toxicity, and land use). The use of biogas, LPG and kerosene minimized the impact of four impact categories (i.e., global warming, ozone formation affecting human health and terrestrial ecosystems, and fossil resource scarcity), four impact categories (namely, stratospheric ozone depletion, marine eutrophication, human carcinogenic toxicity, and mineral resource scarcity) and one impact category (water consumption), respectively.

In addition, with the PEF method, the use of coal appeared to have the maximum impact in 10 of the 16 categories (i.e., climate change, photochemical ozone formation, PM, acidification, freshwater, marine and terrestrial eutrophication, freshwater ecotoxicity, resource use, that is, fossils and mineral and metals). The use of charcoal, NG and electricity had the maximum impact on four impact categories (namely, human noncancer and cancer toxicity, land use, and water scarcity), one impact category (ozone depletion), and one impact category (ionizing radiation), respectively. In agreement with the other LCIA method, the use of NG led to minimum impact in 10 of the 16 categories (i.e., ionizing radiation, photochemical ozone formation, PM, noncancer and cancer human toxicity, acidification, eutrophication freshwater, ecotoxicity freshwater, land use, and resource use, that is, -mineral and metals). The use of kerosene and biogas exerted minimum impact on the remaining three (i.e., marine, terrestrial eutrophication, and water scarcity) and three (namely, climate change, ozone depletion, and resource use, that is, fossils) impact categories, respectively.

Whereas the PEF method refers to the 100-year time horizon global warming potentials (Myhre *et al*., 2013), in the ReCiPe 2016 method, the characterization factors for global warming differ from the former because climate–carbon feedback for non-CO_2 GHGs is included (Huijbregts *et al*., 2017). Therefore, scores of the global warming category, as estimated using both methods, resulted to be slightly different. These ranged from as high as 1,210 kg CO_{2e} in the case of coal cookstoves to as low as 153 kg CO_{2e} in the case of biogas cookstoves. Except for charcoal cookstoves (which emitted about 607 kg CO_2), all other cookstoves emitted 188–256 kg CO_{2e} per person per year. By contrast, thanks to the model developed by van Zelm *et al.* (2016), it was possible to assess maximum formation of fine PM if using coal, firewood and charcoal cookstoves (i.e., 7.5, 2.3 and 0.46 kg $PM_{2.5e}$ per person per year, respectively), and minimum formation of fine PM if using NG cookstoves (~0.1-kg $PM_{2.5e}$). LPG and kerosene cookstoves emitted about 0.15–0.27 kg $PM_{2.5e}$ per person per year. These results were similar to those obtained with the PEF method, despite this method estimates the impact of such a category in terms of disease incidence using the United Nation Environment Program (UNEP) model (Fantke *et al*., 2016).

End-point environmental profile of the cooking systems examined

The ReCiPe 2016 standard method groups its 18 mid-point impact categories into three damage categories (DC) to highlight the environmental compartments damaged by any cooking system during its life cycle. In particular, the impact categories of global warming and water consumption exerted their damage to both human health and ecosystem quality compartments. By contrast, the categories of stratospheric ozone depletion, ionizing radiation, fine PM and ozone formation affecting human health, and human carcinogenic and noncarcinogenic toxicity affected the human health compartment only, while categories of ozone formation affecting terrestrial ecosystems, terrestrial acidification, freshwater and marine eutrophication, terrestrial, freshwater and marine

Table 8. Environmental profile at the first stages of the cause–effect chain of different cooking systems used, as provided by the mid-point impact categories of the ReCiPe 2016 and product environmental footprint (PEF) standard methods per person per year.

Impact category	Cooking fuels								Unit
	FW	CHC	CO	NG	LPG	KER	BG	EL	
ReCiPe 2016									
Global warming (GW_{100})	2.28E+02	6.07E+02	1.21E+03	2.35E+02	1.88E+02	2.27E+02	1.53E+02	2.56E+02	kg CO_{2e}
Stratospheric ozone depletion	6.57E-04	1.75E-03	5.89E-04	1.27E-04	6.11E-05	1.24E-04	3.34E-04	1.59E-04	kg CFC-11$_e$
Ionizing radiation	8.22E+00	2.82E+00	9.71E+00	2.71E-01	1.77E+00	2.07E+00	1.87E+00	2.75E+01	kBq $^{60}Co_e$
Fine particulate matter formation	2.30E+00	4.63E-01	7.50E+00	9.73E-02	1.46E-01	2.73E-01	2.53E-01	2.67E-01	kg $PM_{2.5e}$
Ozone formation, human health	1.75E+00	1.58E+00	3.07E+00	3.44E-01	3.31E-01	3.79E-01	1.91E-01	4.37E-01	kg NO_{xe}
Ozone formation, terrestrial ecosystems	2.23E+00	2.12E+00	3.72E+00	3.56E-01	3.97E-01	4.82E-01	2.00E-01	4.45E-01	kg NO_{xe}
Terrestrial acidification	8.49E-01	5.94E-01	2.81E+00	2.79E-01	4.01E-01	4.67E-01	7.48E-01	7.77E-01	kg SO_{2e}
Freshwater eutrophication	4.70E-02	2.80E-02	7.89E-01	1.55E-03	1.83E-03	2.08E-03	2.41E-02	6.25E-02	kg P_e
Marine eutrophication	8.64E-03	1.08E-02	4.90E-02	2.06E-04	1.87E-04	2.26E-04	1.68E-03	4.57E-03	kg N_e
Terrestrial ecotoxicity	4.75E+02	3.02E+02	3.64E+02	7.32E+00	1.41E+02	1.14E+02	9.60E+01	2.88E+02	kg 1,4-DCB
Freshwater ecotoxicity	9.70E+00	8.44E+00	5.75E+01	2.02E-01	3.12E-01	3.44E-01	1.86E+00	2.18E+01	kg 1,4-DCB
Marine ecotoxicity	1.34E+01	1.19E+01	7.90E+01	2.83E-01	5.85E-01	6.24E-01	2.47E+00	2.69E+01	kg 1,4-DCB
Human carcinogenic toxicity	1.04E+01	5.53E+00	7.50E+01	2.41E+00	1.51E+00	1.66E+00	4.06E+00	1.16E+01	kg 1,4-DCB
Human noncarcinogenic toxicity	3.11E+02	3.10E+02	3.89E+03	3.81E+00	1.03E+01	1.13E+01	5.33E+01	1.69E+02	kg 1,4-DCB
Land use	2.65E+02	4.11E+02	1.49E+01	9.66E-02	3.14E-01	3.32E-01	5.68E+00	6.40E+00	m^2 annual crop$_e$
Mineral resource scarcity	2.54E-01	1.18E-01	3.57E-01	5.00E-02	4.28E-02	5.19E-02	9.00E-02	4.51E-01	kg Cu_e

(*continued*)

Table 8. Continued

Impact category	Cooking fuels								Unit
	FW	CHC	CO	NG	LPG	KER	BG	EL	
Fossil resource scarcity	3.67E+01	2.05E+01	3.79E+02	8.54E+01	6.43E+01	7.62E+01	1.38E+01	7.78E+01	kg oil$_e$
Water consumption	7.64E-01	5.99E+00	8.57E-01	3.82E-02	3.85E-02	2.55E-02	1.67E-01	3.62E+00	m³
PEF									
Climate change (GW$_{100}$)	2.36E+02	6.17E+02	1.26E+03	2.36E+02	1.89E+02	2.34E+02	1.59E+02	2.56E+02	kg CO_{2e}
Ozone depletion	1.03E-05	8.05E-06	1.87E-05	6.64E-05	4.52E-05	5.36E-05	2.96E-06	3.47E-05	kg CFC-11$_e$
Ionizing radiation, human health (HH)	1.18E+01	5.01E+00	1.51E+01	3.82E-01	1.25E+01	1.48E+01	2.61E+00	3.01E+01	kBq $^{235}U_e$
Photochemical ozone formation, HH	5.25E+00	5.56E+00	9.14E+00	3.94E-01	8.62E-01	1.35E+00	4.41E-01	5.65E-01	kg NMVOC$_e$
Particulate matter (PM)	6.08E-04	4.14E-05	2.13E-03	3.22E-06	7.12E-06	3.49E-05	2.90E-05	4.50E-06	disease inc.
Human toxicity, noncancer	1.84E-06	6.46E-05	3.56E-05	2.59E-07	1.18E-06	4.81E-06	4.35E-06	1.79E-06	CTU$_h$
Human toxicity, cancer	6.85E-08	2.25E-07	1.77E-07	1.39E-08	1.45E-08	1.43E-08	4.09E-08	8.66E-08	CTU$_h$
Acidification	1.38E+00	9.79E-01	4.26E+00	4.52E-01	5.85E-01	6.69E-01	1.12E+00	1.14E+00	mol H^+_e
Eutrophication freshwater	4.70E-02	2.80E-02	7.89E-01	1.55E-03	1.82E-03	2.07E-03	2.41E-02	6.24E-02	kg P$_e$
Eutrophication marine	4.05E-01	3.16E-01	9.57E-01	1.27E-01	8.71E-02	8.26E-02	9.18E-02	1.81E-01	kg N$_e$
Eutrophication terrestrial	4.36E+00	3.28E+00	9.39E+00	1.38E+00	9.53E-01	9.03E-01	3.38E+00	2.01E+00	mol N$_e$
Ecotoxicity freshwater	2.78E+03	2.72E+03	2.92E+04	3.77E+02	1.42E+03	1.71E+03	2.39E+03	3.04E+03	CTU$_e$
Land use	3.07E+04	4.668E+04	2.54E+03	6.26E+01	3.36E+02	3.91E+02	7.93E+02	1.21E+03	Pt
Water scarcity	2.20E+01	2.530E+02	1.71E+01	1.23E+00	9.78E-01	3.46E-01	4.41E+00	1.32E+02	m³ depriv.
Resource use, fossils	1.72E+03	9.337E+02	1.69E+04	3.51E+03	2.78E+03	3.29E+03	6.31E+02	3.78E+03	MJ
Resource use, mineral and metals	6.75E-04	2.050E-04	1.26E+03	1.61E-05	3.93E-05	4.08E-05	2.14E-04	2.38E-03	kg Sb$_e$

FW: firewood; CHC: charcoal; CO: coal; NG: natural gas; LPG: liquified petroleum gas; KER: kerosene; BG: biogas; EL: electricity; CTU$_e$: comparative toxic unit of ecotoxicity; NMVOC: non-methane volatile organic compounds.

ecotoxicity, and especially land use distressed the ecosystem quality compartment. Finally, the categories of mineral and fossil resource scarcities limited the resource availability compartment.

Table 9 shows single scores of the three damage categories for any cooking system examined, which were first normalized and then aggregated to complete assessment to the end-point approach.

The use of coal appeared to have maximum impact on two of the three damage categories (i.e., human health and resource availability). The use of charcoal affected maximum the other damage category (ecosystem quality). In contrast, the use of NG exerted the least impact on human health and ecosystem quality, while the use of biogas had a minimum impact on resource availability. The resulting single score ($OWDS_R$) was maximum in the case of coal cookstoves (118 Pt) and minimum in the case of LPG cookstoves (~5 Pt). The contribution of damage to human health ranged from 91% to 98% of $OWDS_R$ in the case of charcoal and coal cookstoves, respectively. Moreover, the overall weighted damage score for NG, biogas, kerosene and electricity cookstoves were 5.2, 5.7, 7.0 and 8.6 Pt, respectively; these scores confirmed their suitability for being included in the category of the so-called clean cooking fuels (IEA and the World Bank, 2014).

As suggested by the PEF method, all mid-point impact categories were normalized with respect to their corresponding global impact and weighted to obtain another single score (OWS_P). Even with this method, the overall environmental impact of coal cookstoves was maximum (425 millipoint [mPt]), while that of LPG cookstoves was minimum (12.6 mPt). Higher scores characterized the NG (12.9 mPt), biogas (14.2 mPt), kerosene (19.7 mPt) and electricity (21.8 mPt) cookstoves, while the overall environmental impact of firewood and charcoal cookstoves represented just 27% and 11% of OWS_P of coal cookstoves (Table 9). It also confirmed the predominant contribution of PM on OWS_P for coal (75%) and firewood (79%) cookstoves; it was minimum in the case of electric (3%) and NG (4%) cookstoves. It is worth pointing out that such a contribution grew to 13%, 27% and 31% in the case of charcoal, kerosene and biogas cookstoves (Table 9).

Sensitivity analysis

Figure 2 shows how the environmental single scores, $OWDS_R$ and OWS_P, of cooking systems under study were affected by uncertainty of thermal efficiency (η_{CS}) of the cooktops used (Table 2). Such mean values were derived

from the Monte Carlo analysis (using a fixed number of 2,000 runs) and characterized by standard deviations ranging from ~3% (in the case of biogas cookstove) to 19% (in the case of charcoal cookstove). Moreover, at a probability level of 0.05, there was no statistically significant difference between the overall scores for NG and LPG cookstoves. Under these circumstances, both cooking fuels appeared to be less damaging to the compartments of human health and ecosystem quality, and thus more apt to minimize both indoor and outdoor air pollution. As shown in Figure 2, $OWDS_R$ increased from a minimum value of ~5 Pt to 6 Pt, 7 Pt and 9 Pt if biogas, kerosene and electric cookstoves are used, respectively. Quite similar results were obtained by comparing the overall weighted scores OWS_P according to the PEF method (Figure 2).

In the case of electric cookstoves, both single scores were related to different primary energy sources producing electricity in Italy. To point out the effect of different nonrenewable and/or renewable sources used to generate electricity, it was assumed to draw electricity from the French and Polish grid mix, or from hydro, solar photovoltaic and wind power plants. Table 10 shows the mean values and standard deviations for damage categories of human health, ecosystem quality and resource availability, as such or normalized, as well as the overall weighted score $OWDS_R$ and OWS_P for the electric cooking system examined.

If using the Italian grid mix, which uses about 52% fossil sources (mainly NG) and 37.6% renewable ones (mainly hydroelectric and wind power) (Terna, 2020), $OWDS_R$ was equal to about 8.7 Pt and was practically controlled by damage to ecosystem quality. By contrast, large use of electricity from nuclear power in France had positive effects of reducing $OWDS_R$ to about one-third (3.1 Pt); however, this being predominantly affected by damage to human health. Such a damage enhanced up to 28.8 Pt when using the electricity produced by coal power plants as in Poland, while the total environmental score $OWDS_R$ amounted to ~30 Pt (Table 10). By using renewable energy sources only, $OWDS_R$ reduced to as low as ~0.9 Pt if hydropower electricity was used. It slightly increased to 1.4 and 2.8 Pt if electricity was generated through wind and solar photovoltaic plants, respectively (Table 10).

According to the PEF method, the single environmental score OWS_P was maximum in the case of Polish grid mix (59 mPt) but almost indifferent in the case of Italian and French grid mix (21−22 mPt). It reached a minimum value if electricity from wind was used (1.8 mPt) but increased to 6.3 mPt and 8.4 mPt if electricity was used from hydropower and solar energy, respectively.

Table 9. Endpoint characterization of the environmental profile of cooking systems examined according to the ReCiPe 2016 and PEF standard methods: single and weighted damage scores of each damage category (DC), and overall weighted scores (OWDSR, and OWSP).

Parameter	Cooking fuels								Unit
	FW	CHC	CO	NG	LPG	KER	BG	EL	
ReCiPe 2016									
Single DC score									
Human health (HH)	1.77E-03	9.59E-04	6.98E-03	2.88E-04	2.73E-04	3.91E-04	3.27E-04	4.89E-04	DALY
Ecosystem quality (EQ)	3.51E-06	5.85E-06	5.18E-06	7.65E-07	6.67E-07	8.04E-07	6.84E-07	1.07E-06	Loss of Species yr
Resource availability (RA)	1.01E+01	6.11E+00	4.11E+01	3.05E+01	2.89E+01	3.43E+01	2.42E+00	2.32E+01	US$2013
Weighted DC score									
Human health (HH)	2.95E+01	1.60E+01	1.16E+02	4.81E+00	4.56E+00	6.52E+00	5.46E+00	8.15E+00	Pt
Ecosystem quality (EQ)	9.49E-01	1.58E+00	1.40E+00	2.07E-01	1.80E-01	2.17E-01	1.85E-01	2.91E-01	Pt
Resource availability (RA)	7.24E-02	4.36E-02	2.93E-01	2.18E-01	2.07E-01	2.45E-01	1.73E-02	1.66E-01	Pt
OWDS$_R$	30.5	17.6	118.0	5.2	5.0	7.0	5.7	8.6	Pt
PEF									
OWS$_P$	116.0	46.2	425	12.9	12.6	19.7	14.2	21.8	mPt
Particulate matter score	91.6	6.23	320	0.49	1.07	5.25	4.36	0.68	mPt

FW: firewood; CHC: charcoal; CO: coal; NG: natural gas; LPG: liquified petroleum gas; KER: kerosene; BG: biogas; EL: electricity. OWDS$_R$: overall weighted damage score; OWS$_P$: overall weighted score.
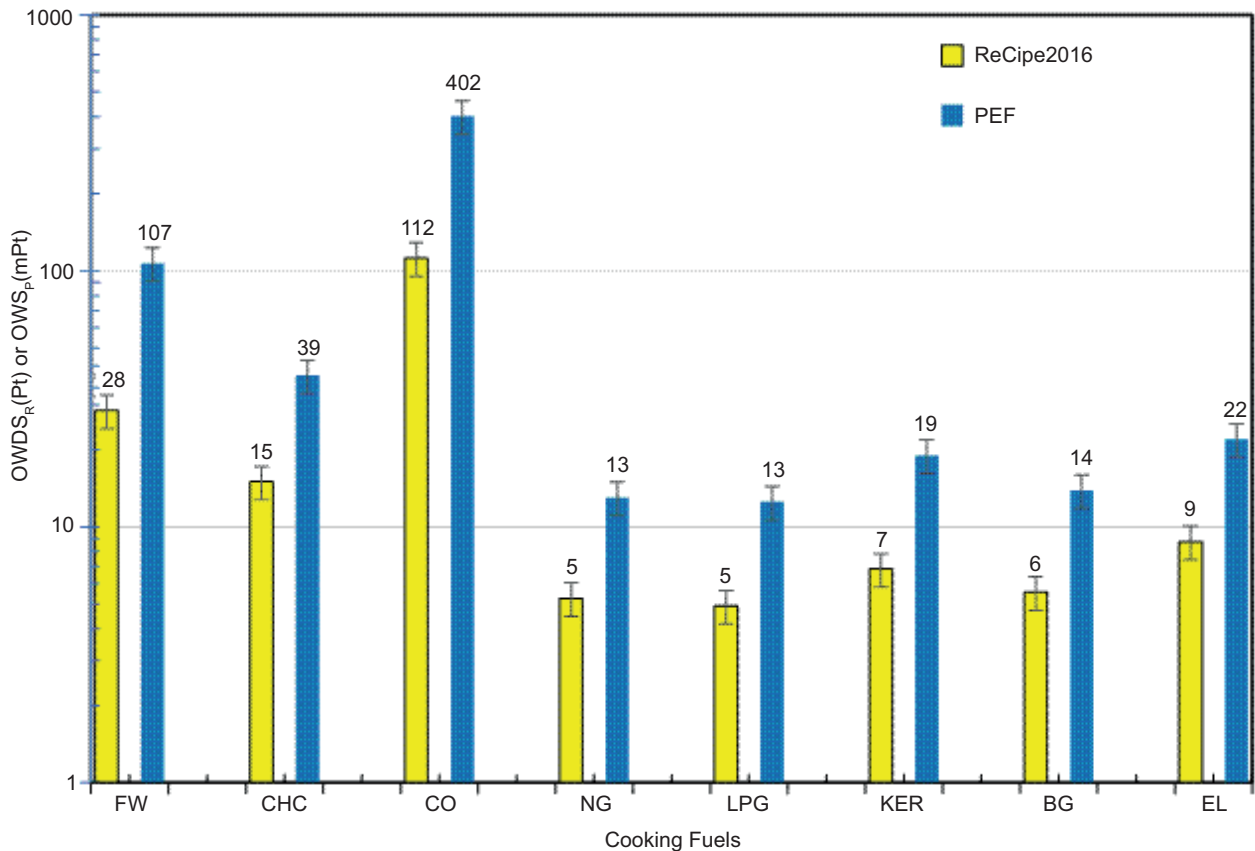
Figure 2. **Comparison of environmental impact of different cooking systems examined using the overall weighted scores OWDS$_R$ and OWS$_P$ as estimated according to the ReCiPe 2016 end-point—Hierarchic (H) version—Europe H/A and PEF standard methods, respectively: FW, firewood; CHC, charcoal; CO, coal; NG, natural gas; LPG, liquified petroleum gas; KER, kerosene; BG, biogas, and EL, electricity.**

Discussion of results and the future perspectives

The main results of this LCA study pointed out quite similar environmental effects despite the different life cycle impact assessment methods used, and can be summarized as follows:

1. Among the cooking fuels used in the Italian context, the lowest environmental impact was associated with the use of NG and LPG if using the ReCiPe 2016 method, their overall weighted damaged scores being not statistically different at 5% probability level. Such impact was, in turn, significantly smaller than that induced by burning biogas at 95% Confidence Level (CL) despite the fact that use of such a biofuel exerted just 8% of the damage to resource availability induced by other fossil fuels accounted for (Table 10). This was further corroborated by the fact that the database used excluded the infrastructure required to distribute biogas to final users (Table 7). According to the PEF method, LPG cookstoves exerted a lesser impact than that derived from NG and biogas cookstoves, probably because the average distance travelled by LPG bottles was assumed as short as 50 km.

2. When using solid fuels derived from fossils (coal) and renewable (firewood and charcoal) sources, damage to the human health compartment increased by approximately 25 or six and three times, respectively, with respect to that caused by the cooking fuels mentioned above. This was similar to the previous findings from a few LCA studies relative to other countries, such as India (Singh *et al*., 2014), Ghana (Afrane and Ntiamoah, 2011, 2012) and remote communities in the Southeast Asia Pacific region (Aberilla *et al*., 2020) despite different LCIA methods used. Likewise, a recent meta-analysis of 50 studies from Africa, Asia, South and Latin America confirmed that indoor PM$_{2.5}$ concentrations were very low if cooking is done with LPG and electricity (Pope *et al*., 2021). Finally, the LCA study of cooking fuel systems in India, China, Kenya and Ghana pointed out the primary requirement to reduce indoor PM formation, especially in China (its cooking fuel mix includes 31% LPG, 29% coal, 15% firewood and 12% crop residues) and India (its cooking fuel mix being

Table 10. Endpoint characterization of the environmental profile of cooking systems supplied with different electricity grid mixes according to the ReCiPe 2016 and PEF standard methods: single and weighted damage scores of each damage category (DC), and overall weighted scores (OWDS$_R$, and OWS$_P$).

Parameter	EL-IT	EL-FR	EL-PL	EL-HY	EL-SP	EL-WI	Unit
ReCiPe 2016							
Single DC score							
Human health (HH)	$(4.94 \pm 0.49) \times 10^{-4}$	$(1.78 \pm 0.18) \times 10^{-4}$	$(1.72 \pm 0.17) \times 10^{-3}$	$(5.13 \pm 0.51) \times 10^{-5}$	$(1.61 \pm 0.16) \times 10^{-4}$	$(7.98 \pm 0.80) \times 10^{-5}$	DALY
Ecosystem quality (EQ)	$(1.09 \pm 0.11) \times 10^{-6}$	$(3.25 \pm 0.32) \times 10^{-7}$	$(3.40 \pm 0.33) \times 10^{-6}$	$(6.48 \pm 0.64) \times 10^{-8}$	$(3.70 \pm 0.37) \times 10^{-7}$	$(5.73 \pm 0.57) \times 10^{-8}$	Species yr
Resource availability (RA)	23.5 ± 2.3	5.97 ± 0.59	12.7 ± 1.24	$(1.86 \pm 0.18) \times 10^{-1}$	2.82 ± 0.28	$(8.71 \pm 0.87) \times 10^{-1}$	US$2013
Weighted DC score							
Human health (HH)	0.29 ± 0.03	2.97 ± 0.29	28.8 ± 2.8	$(8.56 \pm 0.85) \times 10^{-1}$	2.69 ± 0.27	1.33 ± 0.13	Pt
Ecosystem quality (EQ)	8.24 ± 0.81	$(8.80 \pm 0.86) \times 10^{-2}$	$(9.19 \pm 0.90) \times 10^{-1}$	$(1.75 \pm 0.17) \times 10^{-2}$	$(1.00 \pm 0.10) \times 10^{-1}$	$(1.55 \pm 0.16) \times 10^{-2}$	Pt
Resource availability (RA)	0.17 ± 0.02	$(4.27 \pm 0.42) \times 10^{-2}$	$(9.09 \pm 0.89) \times 10^{-2}$	$(1.33 \pm 0.13) \times 10^{-3}$	$(2.01 \pm 0.20) \times 10^{-2}$	$(6.22 \pm 0.62) \times 10^{-3}$	Pt
OWDS$_R$	8.71 ± 0.86	3.10 ± 0.31	29.8 ± 2.90	0.88 ± 0.09	2.81 ± 0.28	1.35 ± 0.14	Pt
PEF							
OWS$_P$	22 ± 2	21 ± 2	59 ± 6	6.3 ± 0.6	8.4 ± 0.8	1.8 ± 0.2	mPt

EL-IT: Italian electricity grid mix; EL-FR, French electricity grid mix; EL-PL, Polish electricity grid mix; EL-HY, electricity from hydropower plants; EL-SP, electricity from solar photovoltaic power plants; EL-WI, electricity from wind power plants.
OWDS$_R$: overall weighted damage score; OWS$_P$: overall weighted score.

formed by 49% firewood, 25% LPG, 11% dung and 9% crop residues), and secondarily to replace traditional stoves with improved ones so as to allow the use of traditional cooking fuels in more appropriate forms and thus enhance their thermal efficiency and limit their environmental burden (Morelli *et al.*, 2017). For instance, in China, substituting conventional honey-comb coal briquettes with coal powder would reduce the impact of climate change and PM formation by about 70% and 97%, respectively (Morelli *et al.*, 2017).

3. Electric cookstove accounted for more than 174% of overall weighted damage score of NG hob. This reflects the environmental impact of two typical cooking appliances, induction hob vs. gas hob and electric oven vs. gas oven, in Italian kitchens, as assessed by Favi *et al.* (2018) and Landi *et al.* (2019), respectively. Obviously, such unfavorable comparison stems from the nature of electricity grid mix in the Italian scenario, which is mainly based on fossil sources (Terna, 2020). Alternatively, use of French electricity grid mix, mainly established from nuclear energy, had the advantage of reducing damage to human health, ecosystem quality and resource availability by about 66%, 49% and 21%, respectively. More favorable environmental impact would arise by using renewable electricity from hydro and wind plants. In this way, electric cooking would not only improve people's health but also avoid the consumption of any fossil energy source.

4. Electricity is currently the only means of cooking suitable for developing new-generation, energy-efficient home smart cookers. In fact, the prospective diffusion of low-cost, open-source platforms would in all probability reduce their selling price and thus promote their market penetration. Such platforms would, for instance, keep the selected cooking temperature practically constant or variable according to specific cooking programs, and shut the cooktop after preset period or as soon as the minimum core temperature is achieved. In this way, it would be possible to minimize both food cooking period and energy requirements. As an example, it is worth citing the eco-sustainable pasta cooking system developed by Cimini *et al.* (2021b). It consisted of a commercial 2-kW induction-plate hob, an induction stainless steel cooking pot, a stainless steel rod mixer piloted by a direct current electric motor welded to pot lid, a digital temperature sensor to monitor temperature of cooking water and a current sensor to register consumption of electric energy. All operations were accomplished via Arduino® platform and an application installed in a smartphone with android system. It allowed short and long dry pastas to be cooked even at lower temperatures than the water boiling point at ambient pressure with as low as 2.7–3.2 L of cooking water per kg of dry pasta. Although the cooked pasta

did not differ from that conventionally cooked at 100 °C with 10-L water per kg of dry pasta in terms of chemico-physical quality parameters and ultrastructure, the pasta cooking energy requirement reduced from the default value of 2.8 kWh/kg to 0.45 kWh/kg, and the overall GHG emissions reduced to about one-sixth of those resulting from the use of average European home appliances.

5. Finally, even if the energy used for cooking represents just 6% of a household's typical energy consumption in the United States and EU-27 countries, such a percentage is quite high in some European, Asian and African countries. Above all, reduction of indoor and outdoor household air pollution and personal exposure to health damaging pollutants, such as PM and carbon monoxide, is a top-priority environmental goal.

Conclusions

After reviewing the basic characteristics of main cooking methods, appliances and fuels, and assessing environmental impact of a few household cookers fired by different fuels and electricity in the Italian scenario in compliance with the ReCiPe 2016 and PEF standard methods, it is pointed out that NG cookstove generates minimum indoor and outdoor air pollution. This finding was comforting, because the Italian cooking energy requirements are predominantly fulfilled by gas (69.2%), although such cookers still rely on fossil energy sources.

To avoid finishing such sources and concurrently improving people's health, household cooking appliances must be replaced by new-generation smart-cooktops driven by hydropower or wind-power electricity, of course, on condition that global electricity generation from renewable energy sources is accelerated faster than done ever before.

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