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Energy issues in microwave food processing: A review of developments and the enabling potentials of solid-state power delivery

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ABSTRACT

The enormous magnitude and variety of microwave applications in household, commercial and industrial food processing creates a strong motivation for improving the energy efficiency and hence, sustainability of the process. This review critically assesses key energy issues associated with microwave food processing, focusing on previous energy performance studies, energy performance metrics, standards and regulations. Factors affecting energy-efficiency are categorised into source, load and source-load matching factors. This highlights the need for highly-flexible and controllable power sources capable of receiving real-time feedback on load properties, and effecting rapid control actions to minimise reflections, heating non-uniformities and other imperfections that lead to energy losses. A case is made for the use of solid-state amplifiers as alternatives to conventional power sources, magnetrons. By a full-scale techno-economic analysis, including energy aspects, it is shown that the use of solid-state amplifiers as replacements to magnetrons is promising, not only from an energy and overall technical perspective, but also in terms of economics.

KEYWORDS

Microwave food processing; energy and economics; sustainability; solid-state power sources; emerging processing technologies; food preservation

1. Introduction

The significant rise in consumer demand for minimally-processed, microbiologically-safe and chemical additive-free foods, demands continuous innovation in food processing. As traditional thermal processing systems are limited by low heat transfer rates, and hot wall with cold centre effects, rapid, volumetric heating methods are desirable for delivering safe foods of high nutritional and sensory quality. Microwave heating is a promising technology in this regard, finding increasing application in a wide variety of domestic, commercial and industrial food processing operations, globally. As at 2014, about 92% of UK households have microwave ovens, mainly for food (ONSUK 2017, – Fig. 1). A market penetration rate of 101% (some households have multiple microwave ovens), was reported in the UK in 2016 (Euromonitor International 2017). Over 70 million microwave ovens are sold annually worldwide, with about 14.5 million unit shipments into the United States; while the global number of microwave ovens in operation is in the order of 1 billion (Osepchuk 2013). In Europe only, reports suggest that domestic microwave ovens consume about 12.4 TWh of energy per year, with relatively poor overall efficiency (electricity-to-heat) of 50% or less (HEECS 2010). A screening life cycle analysis LCA on microwave ovens by Samsung Electronics Inc. (Kim et al. 1996) concluded that the energy consumption in the use-phase has the highest environmental impact, compared to the raw material extraction, production, distribution and after-use phases. In addition to all these, industrial and commercial applications of microwave heating in food processing, is on the rise, for instance in tempering of frozen meat and poultry products, and precooking of bacon for foodservice and cooking of sausages.

Other applications include drying, heating, pasteurisation and sterilisation of fast food, cooked meals, and other foods (Schiffmann 2001; Ahmed and Ramaswamy 2007; Stanley and Peterson 2017; Gaukel et al. 2017). Given the widespread end-use, any energy savings in microwave food processing would have a large positive impact on sustainability.

Although faster and more volumetric than conventional heating, microwave heating suffers from non-uniform volumetric temperature distribution due to the uneven distribution of dielectric and thermal properties across most foods, as well as microwave standing wave and finite penetration depth phenomena. This results in the formation of cold spots which define the limits of food microbial safety, and hot spots, associated with the degradation of vital product sensory and nutritional quality attributes. One significant contributor to energy losses is the use of higher than optimal temperature-time combinations to guarantee microbial safety at the cold spots. The existence of these non-uniformities can be translated to inefficient energy distribution per unit volume of the product. A perfect energy distribution would be one that results in uniform heat load per-unit volume across the entire product. A more uniform distribution would enable the process to be steered to operate within tight constraints which would promote energy efficiency. Improving temperature uniformity is thus an important issue for energy efficiency. This is a challenging problem, relevant to a wide variety of solid/multi-phase foods such as fresh and frozen meat and fish products, fruits and vegetables, grains, etc. of various geometries, and to a lesser extent, liquid foods like fruit juices and dairy. The problem and possible solutions of non-uniformity in various microwave

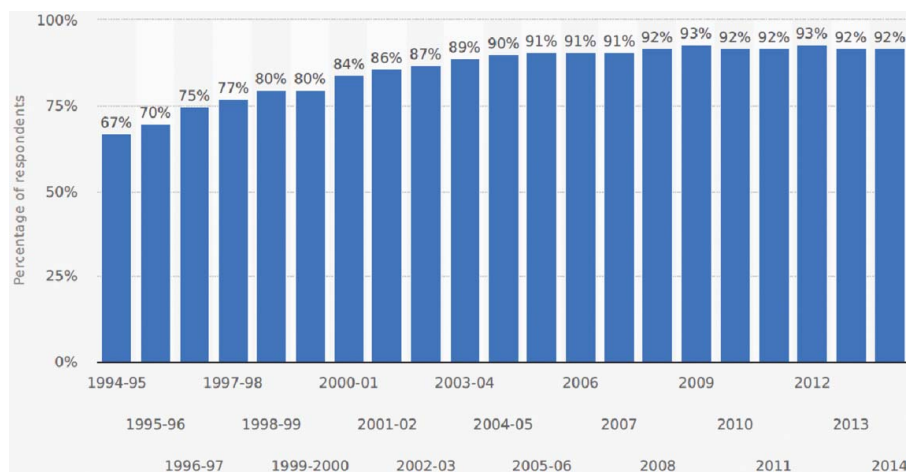


Figure 1. Percentage of households with microwave ovens in the United Kingdom from 1994–2014.

heating applications have been reviewed by several authors e.g. Vadivambal and Jayas (2010); Li et al. (2011); and Wäppling-Raaholt and Isaksson (2017).

Recently, reviews on diverse other areas of microwave food processing have appeared in the literature. Salazar-Gonzalez et al. (2012) reviewed the microwave heating of various fluid foods and their dielectric properties. Chandrasekaran et al. (2013) reviewed microwave mechanisms, food dielectric properties and their measurement methods as well as various stand-alone microwave food processes like cooking, blanching, pasteurisation, sterilisation, drying and drying-based combination operations such as microwave-assisted freeze drying. Guo et al. (2017), performed similar studies with more recent examples. Ekezie et al. (2017) focussed on combination microwave operations such as microwave-assisted ultrasonic, infrared and ohmic operations, concluding that most of these technologies are still at experimental phases, with hardly any report on pilot or industrial-scale facilities. Datta and Rakesh (2013) detailed the practical principles of microwave combination heating. Tang et al. (2015) examined the basic microwave properties relevant to heating uniformity, presenting a historical overview on the development of microwave-assisted thermal sterilisation and pasteurisation systems in research laboratories and used in food plants. Emphasis was on bridging the gap between academic research and industrial implementation. Kubra et al. (2016) presented research results on the use of microwaves in the drying of spices and herbs as well as the extraction of essential oils and bioactive components from them. Jiang et al. (2017a), reviewed the effects of microwave processing on the various food components. Kumar and Karim (2017) analysed recent advances in microwave-convective drying, identifying pressing future research needs to include improving heating and moisture uniformity, as well as developing high-fidelity drying kinetic models. Atuonwu and Tassou (2017) reviewed microwave food processing quality assurance issues such as process lethality, product degradation mechanisms, non-uniform heating and volumetric temperature sensing; showing the energy cost implications of non-uniform heating and proposing the use of solid-state devices for improved quality. The purpose of the current article is to critically analyse the issue of energy consumption in domestic, commercial and industrial microwave food processing systems, bringing together a

representative number of related studies. Areas of focus include energy consumption analysis of various microwave food processes; energy performance indices and metrics; energy standardisation and labelling issues; factors affecting energy efficiency and finally, the possibilities and challenges from an energy perspective, of using solid-state devices instead of the currently-deployed magnetrons for microwave power delivery.

2. Principles, features and applications

2.1. Background

Microwaves are electromagnetic waves in the frequency range of 300 MHz to 300 GHz. Originally deployed in telecommunication systems, the idea of using microwaves for food processing was accidentally discovered in 1945 by Percy Spencer of the Raytheon Company on observing the melting of candy bars in his pocket by radar waves. Subsequent experiments showed that microwaves could raise the internal temperature of many foods far more rapidly than conventional ovens. The first patent, describing an industrial conveyor belt microwave system, was issued in 1952 (Spencer, 1952), however its first application did not start until about 10 years later (Shaheen et al. 2012). Nowadays, microwave heating systems are usually restricted to certain frequencies, within the so-called industrial, scientific, and medical (ISM) band. The most-commonly used frequencies are 896 MHz (in the UK) and 915 MHz (in the Americas and China), for industrial applications; and 2450 MHz, for commercial, domestic and industrial uses in most countries. 5800 MHz is available for exploratory purposes. Microwave heaters are characterised by non-requirement of ancillary equipment, like boilers and their associated infrastructure; absence of hot surfaces, burn-on, fouling and flavour taints in processed foods; thus reducing cleaning times and frequencies, chemical use in cleaning operations and the volume of waste water.

2.2. Constructional features and operational principles

Figure 2 shows a basic schematic of a generalised microwave heating system (with provision for hybrid or combination operation). It consists essentially of a power supply system

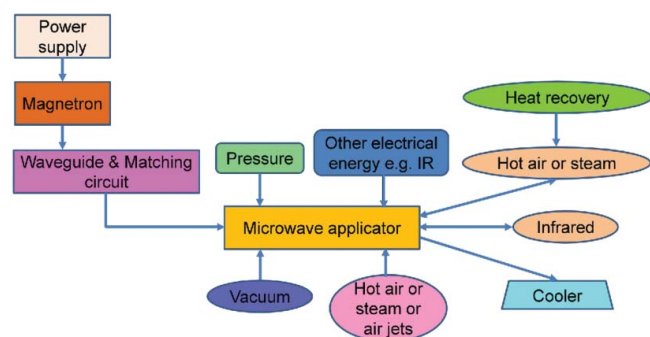


Figure 2. Schematic of basic generalised microwave heating system (adapted from Metaxas, 1991).

(transformers and power conditioning electronic circuits), microwave power source, usually a magnetron with its radiating antenna, a waveguide, and an applicator/heating cavity. The mains voltage is stepped up initially by the mains transformer. It is increased further by a voltage multiplier electronic circuit, which also acts as a rectifier/filter, converting the transformer output to a pulsed DC voltage. The high DC voltage is then applied between the cathode and anode of the magnetron. The filament transformer on the other hand, steps down the mains voltage to a few Volts AC, which is applied to a filament, concentric with, and housed within the cathode of the magnetron. The magnetron, which is a vacuum tube, is the heart of the microwave system as it generates the microwave energy. As shown in Fig. 3 (I), it consists essentially of the cathode, anode and a static magnetic field source (permanent magnet). The cathode, is made up of a hollow cylinder of emissive material surrounding the heating filament and located in the centre of the anode structure, while the anode is made of a highly conductive material, machined to have cavities. Different anode cavity configurations exist as shown in Fig. 3 (II): the slot-type (a), vane-type (b), rising-sun-type (c) and the hole-and-slot-type (d). Of these, the vane type is commonly used for microwave power heating applications. The parallel (or near-parallel) tip sides form a capacitor, while the continuous rear walls form a one-turn inductor coil. Hence, each cavity can be represented by a parallel inductance-capacitance (LC) tuned circuit (Fig. 3 (III)).

Initially, the cathode, by means of the filament voltage, is heated up indirectly via the filament to emit electrons by a process known as thermionic emission. The electrons are then accelerated towards the anode by the high-power supply DC voltage. The magnetic field due to the permanent magnet is at right angles to the electron-accelerating electric field, and

interacts with it, producing a Lorentz force on the electrons. This force deflects the electrons from their normal straight paths, so they follow circular or cycloidal paths. This leads to bunching of the electrons in a pattern that resembles the spokes in a spinning wheel (Fig. 3(I)), commonly referred to as the space-charge wheel. As this electron cloud approaches a cavity gap, they give off a small part of energy to the cavities. This energy tends to repel negative charges present in the nearby anode segment, causing them to flow round the inductive loop. The inductive current establishes a magnetic field which subsequently establishes a charging current to the capacitive part. A capacitive charge-discharge cycle and corresponding inductive magnetic field build up-collapse cycle is set up, which establishes alternating electric and magnetic fields in that segment of the anode.

Similar processes occur in all the segments and corresponding LC circuits. By the right-hand screw rule, the alternating magnetic field is perpendicular to the alternating electric field. This is the condition for electromagnetic wave generation in the third mutually-perpendicular direction. The microwaves thus generated are tapped via an output coupling loop, and channelled via the waveguide to the heating cavity, through the applicator, for onward interactions with the processed product. In general, part of the microwave energy is absorbed by the product, the magnitude of which depends on its dielectric properties. The rest is reflected towards the magnetron (usually trapped by circulators). A microwave processing system may be operated in batch or continuous mode. In batch mode, the product is placed in the heating cavity and processed until the processing time elapses. The heating cavity is usually equipped with a turntable and/or wave stirrer to promote uniformity of heating. In continuous mode, the product is fed continuously into the heating cavity using either a conveyor belt (for solids) or through a microwave-transparent pipe (for liquids and slurries).

3. Energy issues in microwave food processing

3.1. Review of energy performance studies in microwave food processes

The enormous magnitude and variety of microwave applications in consumer, commercial and industrial settings creates a strong motivation for improving the energy efficiency of the process. The rapid, selective and volumetric heating capabilities of microwaves are widely acknowledged and often advanced as reasons for their superior energy performance over conventional heaters.

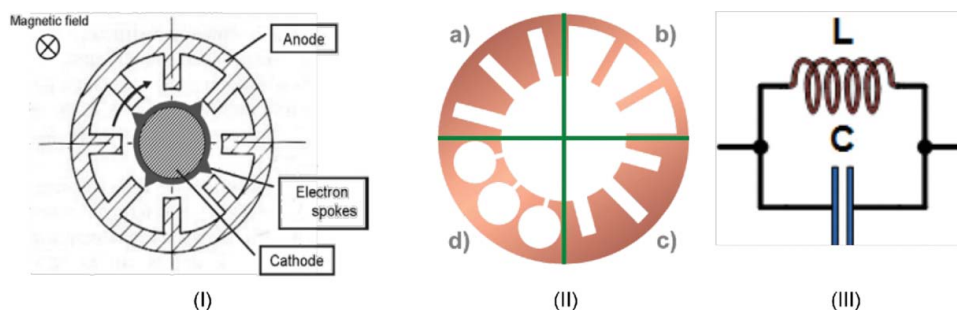


Figure 3. (I) Structure of the magnetron – Carter, 2013 (II) different configurations of an anode cavity – Wolff, 2017 (III), equivalent circuit of each cavity.

Surprisingly, the energy efficiency of microwave-assisted heating processes is still not well-explored (Hoogenboom et al. 2009). Some energy studies on small-scale chemical systems (not more than a few 100 ml or g); e.g. Hoogenboom et al. 2009; Devine and Leadbeater 2011; Moseley and Kappe 2011; Morschhäuser et al. 2012; Bermudez et al. 2015 conclude that the energy efficiency of microwave heating systems increase with scale, approaching a saturation value. In the food processing domain, very few energy performance studies on microwave systems are available in the literature. Extensive Scopus and Google Scholar searches featuring the keywords “microwave xxx” and “energy”, where xxx refers to various food processes like pasteurisation, sterilisation, cooking, baking, thawing, tempering, frying, etc., hardly reveals any article dedicated to the energy performance of these processes. Few works exist, such as Lakshmi et al. (2007) who analysed energy consumption in the cooking of rice by microwaves, and James et al. (2017) who examined the heating performance of domestic microwave ovens in terms of real power delivery, its variability (uniformity) and repeatability. A significant exception to this trend relates to the area of food drying where many relevant studies have been conducted on microwave stand-alone or combination processes. A summary of a representative number of these is presented on Tables 1 and 2. Almost all the studies are concerned with domestic systems of less than 2000 W capacity, operating at around 2450 MHz. A semi-industrial multiple-feed conveyor belt system (Jindarat et al. 2011), with rather large cavity dimensions, consisting of 12 magnetrons operating at 2450 MHz, each of which is rated 800 W, with only 6 used in the study, is an exception. The most-significant exception is the 25 kW capacity, 915 MHz industrial-type system used for one-pass drying of rough rice (Olatunde et al. 2017). Evidently, more research is needed for industrial-scale systems, particularly at 915 (or 896 MHz), where the penetration depth (which due to a phenomenon analogous to the “skin effect” in electrical conductors, is a near-linear function of wavelength = $1/f$), is about thrice that of 2450 MHz systems. Aggregating the findings of the various works, it can be observed that in general, microwaves, when used alone or in combination with other energy sources, improve overall energy efficiency. Microwave energy performance is maximum at the beginning of drying where the product water loading is maximum, and so, receive maximum power from the microwaves to ensure very fast drying. As drying proceeds, the drop in water loading means more of the incident power will not be absorbed, but reflected (unmatched condition), leading to increased energy losses. At the same time, the reduction in water loading as drying proceeds, implies the transition of drying from a constant-rate to a falling-rate period (occasioned by tighter binding of water to the food matrix). This also reduces energy performance.

Most of the studies at variable microwave output power (e.g. Aghilinategh et al. 2015; Alibas 2007a; Ding et al. 2012; Jafari et al. 2017; Wang et al. 2009; Sharma and Prasad, 2006; Zarein et al. 2015) show that energy performance is improved as microwave power increases, at constant processing mass. An exception is noted in Motevali et al. (2016), where for a microwave power variation from 200W to 900W (in steps of 100W), the energy performance improves up until 400W, after which, it declines. Similar trends are seen in Alibas (2007b); and Lule and Koyunku

(2017). A possible explanation for these is that for any given initial moisture content, the proportion of incident microwave power absorbed increases with incident power until a maximum is reached, beyond which reflections dominate (unmatched condition), leading to reduced energy performance. This reasoning is strictly applicable to microwave-only systems. In combination systems, where extra degrees of freedom are added, the situation is no longer as straightforward as extra variables influence system performance. A similar logic can be applied to explain the apparent conflicts in trends observed in systems where for constant microwave power, the load mass is changed. In Gollei et al. (2009); as mass increases (at constant microwave power), energy performance drops. In Darvishi et al. (2012); energy performance increases with loaded mass (at constant microwave power) until a maximum is attained after which it drops. In Wang et al. (2015a), there is a monotonic increase in energy performance within the mass range of interest (34–200g) at power level 1000W, and likewise in Soysal et al. (2006) in the range 64.3–128.57g at pulsed power level of 900W and 50% duty cycle. Intermittent power delivery is also shown to improve energy performance in some cases (Yongsawatdigul and Gunasekaran 1996; Aghilinategh et al. 2015) or worsen it in other cases (e.g. Jindarat et al. 2013). Product properties (e.g. moisture distribution, and form – for instance as bound or free water) would also have profound effects on energy delivery efficiency. Kurjak et al. (2012) using an imaging technique observed water loss in liquid state, in addition to normal evaporation during the microwave drying of potatoes, apples and onions. This observation, in addition to measured material temperatures, higher than could be derived from heat balances, led the researchers to postulate the existence of what they term a “non-thermal” microwave drying effect (owing to wave pressure build-up), which improves drying rate particularly in the early stages of drying. Overall, mechanistic models are needed to improve understanding of the complex interactions between product properties, processing parameters and efficiency of energy delivery in microwave food drying systems. Also, the general absence of detailed energy studies on the wide variety of microwave food processing applications such as baking, thawing, tempering, pasteurisation, sterilisation, reheating and frying, implies the need for research effort in this area, especially in relation to food quality and safety aspects.

3.2. Energy performance indices of microwave heating systems

The energy performance of microwave heating systems is usually quantified either in terms of the specific energy consumption or the energy efficiency. The specific energy consumption is the energy consumption per kg of processed material in processes other than drying (Lakshmi et al. 2007), or per kg of water evaporated in drying studies (Darvishi et al. 2014). The overall energy efficiency of microwave heating systems is defined by Lakshmi et al. (2007) as the product of the microwave generation efficiency η_{gen} and the microwave absorption

Table 1. Microwave food drying applications in literature: Part 1.

Ref.	Food	System type	Cavity size	Frequency	Power range	Air & other conditions	Specific energy; Energy efficiency
Aghili-nategh et al. (2015)	Apples	Microwave-convective	300 × 380 × 260 mm	2465 MHz	200–600W duty cycle 16.7–50%	Air conditions 1.2m/s; 40–80°C	Best energy use @ 600W, 22.32% duty cycle, 40°C, 1.78m/s
Alibas (2007a) Alibas (2007b)	Nettle leaves Pumpkin slices	Batch microwave- only Microwave- only & convective- assisted	327 × 370 × 207 mm 327 × 370 × 207 mm	2450 MHz 2450 MHz	500, 650, 750, 850W 160, 350W	1m/s, 50, 75°C	0.05 kWh (total, at 850W) Stand-alone most-efficient (0.23kWh) @ 160W
Darvishi et al. (2014)	White mulberry	Batch microwave- only	327 × 370 × 207 mm	2450 MHz	100–500W		3.97 – 6.73 MJ/kg, 31.85–55.56%
Darvishi (2012)	Potato slices	Batch microwave- only	350 × 350 × 240 mm	2450 MHz	Power density 5, 10, 5, 20W/g		21.38 – 53.54%, with maximum @ 15W/g
Ding et al. (2012)	Daylily	Microwave- only	350 × 350 × 240 mm	2455 MHz	60, 120, 180, 240W		High microwave power, lower energy use
Fang et al. (2009)	Jujube	Microwave- convective (hot air, then later, microwave)	350 × 350 × 240 mm	2455 MHz	45, 65, 90W	Air 60°C, 0.75m/s product moisture 30, 40, 50%	Energy savings 55% compared to hot air-only. Put ON microwave at higher moistures
Gollei et al. (2009)	Wheat	Microwave- only & convective- assisted		2450 MHz	800W	30 m3/h, 22, 45, 65°C 2kg, 4kg loading	Best: Hybrid 22.68MJ/kg @ 0.2 W/g & 15.4MJ/kg @ 0.4 W/g
Hazer-vazifeh et al.(2017)	Apple Slices	Batch microwave-only	400 × 370 × 230 mm	2450 MHz	500, 1000, 1500, 2000W		Best drying efficiency 6.8% @ 2000W. > that of hot air drying
Holtz et al. (2010)	Swede, Potato, bread	Batch microwave-convective		2450 MHz	300 W	50C; 4.5 m/s	SEC 15–18 MJ/kg-electrical (for all products)
Wang et al. (2015a)	Cotton stalks	Batch microwave- only		2450 MHz	1000W	Different loading: 34–200g	Drying efficiency 7.52–19.78% Specific energy 12.49–35.9MJ/kg (best @ 200g)
Jafari et al. (2017)	Paddy	Semi- continuous microwave- only		2450 MHz	90, 270, 450W	6, 9, 18mm bed thicknesses	Higher microwave power, lower energy use
Jiang et al. (2017b)	Okra snack	Freeze drying+ microwave- vacuum		2450 MHz	1536W pulsed 66.7% duty cycle	1 st freeze dry, 10 hrs @ 70kPa to 80% water	71.92% energy savings relative to normal freeze drying
Jindarat et al. (2011)	–	Continuous belt microwave-convective	90 × 45 × 270 cm	2450 MHz	8000W X 6 = 4800W	0.5m/s; 30, 50, 70°C	Energy Efficiency = 40%

Table 2. Microwave food drying applications in literature: Part 2.

Ref.	Food	System type	Cavity size	Frequency	Power range	Air & other conditions	Specific energy, Energy efficiency
Jindarat et al.(2013)	Tea Leaves	Double-feed microwave+vacuum		2450 MHz	800, 1600W continuous & pulsed (50% duty cycle)	Vacuum: 71.3 & 51.3kPa	Optimal @ 800W continuous 51.3 kPa
Khoshta- ghaza et al. (2015)	Soya- bean kernel	Microwave + fluidized bed hot air		2450 MHz	200–500W	80–140°C 1.8–4.5 m/s	Optimal @ 500W 80C,4.5m/s
Kurjak et al. (2012)	Potato, apple, onion	Batch microwave- only		2450 MHz	456, 523 W		Microwave energy for Onion> Apple> Potato Best @ 160W 23.63 kWh/kg
Lule and Koyuncu (2017)	Nettle leaves	Batch microwave- only		2450 MHz	90, 160, 350W		
Motevali et al. (2011)	Mush-room slices	Batch microwave-only µwave-vacuum	230 × 320 × 360 mm	2450 MHz	130, 260, 380, 450W	20, 40, 60,80kPa	Best: 0.28 kWh @ 450W & 0.14kWh @450W, 20kPa
Motevali et al. (2016)	Chamo- mile	Batch microwave-convective	Cylinder 90 × 380 mm	2450 MHz	200–900W (steps of 100W)	0.5m/s, 50° C	18.93–28.15 MJ/kg @ 400W; 8.25–13.07%
Mousa and Farid (2007)	Banana slices	Batch microwave vacuum	330 × 350 × 240 mm	2450 MHz	600W pulsed 28% duty cycle	Vacuum: 101, 50 & 30kPa	100–40% with vacuum; 100–20% without
Olatunde et al. (2017)	Rough rice	Continuous belt microwave- only		915 MHz	3000- 25000W	96–480 kg; 100–500cm bed thicknesses	4810 kJ/kg @ 500cm, 15kW 5985 kJ/kg @ 100cm, 5kW
Sharma and Prasad (2006)	Garlic cloves	Batch microwave-convective		2450 MHz	10, 20, 30, 40 W		70% energy savings @ 40W
Soysal et al. (2006)	Parsley	Batch microwave- only		2450 MHz	900W pulsed 50% duty cycle	Loading: 64.3–128.57g	9.5% rise in drying efficiency with mass
Varith et al. (2007)	Longan	Microwave- convective	215 × 350 × 330 mm	2450 MHz	100, 180, 300, 450W	40, 50, 60°C 0.7mls	48.2% energy savings @ Optimal: 40°C, 450W for 1.7h then 60°C & 300W for 3.3h
Wang et al. (2009)	Jujube	Microwave- only		2455 MHz	45, 90, 135W		Energy optimal @ 135W
Yongsa- watdigul and Gunasekaran (1996)	Cran- berries	Continuous microwave-vacuum	350 × 350 × 240 mm	2450 MHz	Continuous (250,500W) Pulsed 250W @ varied duty cycles	Vacuum 10.67, 5.33 kPa	Optimal 2.66 MJ/kg pulsed (250W) at 16.7% duty cycle & 5.33kPa
Zarein et al. (2015)	Apple slices	Batch microwave- only		2450 MHz	200, 400, 600W		Max: 54.34% @ 600W; Min 17.42% @ 200W

efficiency η_{abs} ,

$$\eta = \eta_{gen} \eta_{abs} \quad (1)$$

where (for $P_{out,micr}$ = microwave output power; $P_{in,elect}$ = input electrical power; P_{heat} = thermal power delivered),

$$\eta_{gen} = \frac{P_{out,micr}}{P_{in,elect}} \quad (2)$$

$$\eta_{abs} = \frac{P_{heat}}{P_{out,micr}} \quad (3)$$

Generation efficiency largely depends on the quality of the microwave power source (i.e. magnetron), while absorption efficiency depends on the degree of impedance matching between the source and the processed food (load) – which also depends on the load's dielectric properties. When calculating efficiencies (2) and (3), it is important that the microwave output power is based on real-time measurements rather than prior manufacturers' ratings and settings. This is because the magnetron output power delivery declines with age and related factors – which will lead to overestimation of generation efficiencies and underestimation of absorption efficiencies. Output drops by as much as 33% have been reported after 5–10 years of operation (Anantheswaran 1999). Even within 30 minutes of continuous operation, transient output drops in the order of 15% are common in domestic microwave ovens (Swain et al. 2006). Little wonder, electrical-to-microwave conversion efficiencies as low as 50–60% are common (Lakshmi et al. 2007; Wang et al. 2015b), even though quoted magnetron efficiencies are often higher (over 70% for 2450MHz, and 88% for 915MHz systems). The effects of any error in microwave power estimation are cancelled out in the overall efficiency computation (1). However, care must be taken to subtract standby power consumption obtained by performing no-load tests (Gollei et al. 2009; Wang et al. 2015b) from the total power drawn from the mains, when the entire system is on. The standby power is the power consumed when the system and all auxiliary components like coolers, fans, etc. are switched on, but the magnetron is off.

3.3. Energy performance indices of microwave drying systems: The need for unification and standardisation

Microwave drying processes are different from other microwave heating processes in that the incident power is deliberately converted not only to sensible heat, but latent heat of evaporation. Energy performance is maximum at the beginning of drying, declining as the water load diminishes; and hence, are normally expressed as time-averaged values. Most of the studied works on energy performance of microwave-based drying systems have expressed specific energy consumption as total electrical energy consumed (including those of auxiliaries like fans, belt drives and pumps) per kg of water evaporated. Some studies (e.g. Yongsawatdigul and Gunasekaran 1996; Aghilinategh et al. 2015), have however expressed it in terms of thermal energy only. The energy (thermal) efficiency of microwave drying systems (from the studies detailed in Tables 1 &

2), have in general, been expressed as

$$\eta_{micrD, thermal} = \frac{Q_{sens} + Q_{lat}}{Q_{micr,out} + Q_{comb}} \quad (4)$$

where Q_{sens} is the sensible heat used in heating up the product (and the water therein) to the evaporating temperature, and $Q_{lat} = mH_v$, evaporated moisture energy, evaluated at the evaporating temperature (m is the cumulative evaporated mass of water). The denominator constitutes the total thermal energy input, where, $Q_{micr,out}$ is the output microwave power integrated over operating time; and Q_{comb} , the thermal equivalent energy consumed by the assisting or combination process(es), where they exist. A related term “drying efficiency” (Soysal et al. 2006; Wang et al. 2015a), sometimes used interchangeably with “thermal or energy efficiency” discounts the sensible heat term from (4) that is:

$$\eta_{micrD, drying} = \frac{Q_{lat}}{Q_{micr,out} + Q_{comb}} \quad (5)$$

The conventional drying literature however has slightly different meanings for the terms “energy or thermal efficiency” as well as “drying efficiency”. Thermal efficiency is usually defined in the traditional drying literature (Kudra 2004; Menshutina et al. 2004; Atuonwu et al. 2012) as the ratio of latent heat delivered (evaluated at feed temperature) to the total thermal energy input. Comparing this with the equation for the same term, in the microwave drying literature (equation 4), it is observed that the sensible heat term Q_{sens} is missing, from the conventional drying expression. Hence, a major difference exists in the way thermal efficiency is evaluated for microwave and conventional dryers in the literature. However, as temperature rises, the specific latent heat of evaporation H_v of water drops. Since in conventional dryers the specific latent heat is evaluated at feed temperature; but at a higher temperature (evaporating temperature) in microwave dryers, the specific latent heat H_v in the latter is less. The addition of the sensible heat term Q_{sens} in equation (4) tends to compensate for this reduction, so the overall thermal efficiency of the two becomes roughly equivalent in form, but not the same. The thermal efficiency in the conventional drying literature is about the same as the “drying efficiency” (equation (5)) in the microwave drying literature, but with the latent heat evaluated at the evaporating temperature in the latter case. Drying efficiency in the traditional drying literature (Kudra 2004; Menshutina et al. 2004) however discounts the energy of the dryer exhaust air from the total thermal energy input (the denominator), and so, is considerably different from “drying efficiency” as defined in microwave drying systems. A unification of energy performance indices is thus recommended across the board, to facilitate comparison.

3.4. Energy standards and regulations

The microwave power outputs of domestic 2450MHz microwave ovens (shown in labels), have traditionally been calibrated based on the IEC 60705 standards (equivalent to the EN

60705). The calorimetry-based calibration method (IEC 60705, 1999) involves heating $1000 \text{ g} \pm 5 \text{ g}$ of water, inside a cylindrical borosilicate glass container (external diameter 190mm, height 90mm), from $10^\circ\text{C} \pm 1^\circ\text{C}$ to $20^\circ\text{C} \pm 2^\circ\text{C}$. The microwave power output is then calculated as

$$P_{out, micr} = \frac{4.187 m_W (T_2 - T_1) + 0.55 m_C (T_2 - T_0)}{t} \quad (6)$$

where m_W is the mass of the water; m_C , the mass of the container; T_0 , the ambient temperature; T_1 and T_2 , the initial and final temperatures of the water, respectively. The corresponding energy consumption W_{in} (electrical input power aggregated over time t), is measured, from which the microwave generation efficiency is determined as $P_{out, micr} t / W_{in}$. The choice of the operating conditions in the calorimetric experiments, is based on minimising heat loss and container heat capacity effects (IEC 60705, 1999), as well as obtaining a matched load condition for maximum microwave power transfer to heat (without reflections). $P_{out, micr}$ is thus good as a standard against which thermal energy delivery to any load, can be compared, to determine absorption efficiency (equation 3). The corresponding mains power W_{in} is however not indicative of system energy consumption under actual normal usage conditions – variable loads (shape & mass) and much higher temperature differentials. FSP (2007), for instance, classified all kinds of heating done in microwave ovens into 6 categories (from simple reheating of light ready meals, to the cooking of heavy meals from raw state)-See Table 3. In all these, the required temperature rise, ranged from a minimum of 30°C to a maximum of over 125°C , as against the 10°C used in the IEC standards. A more usage-reflective standard energy consumption indicator was thus required. To tackle this challenge, it was advocated in HEECS (2011) to

- Create a method that is representative of a real use of the microwave function in microwave ovens that is, reheating readymade food portions, beverages/liquids defrosting food and preparing meals from raw states.
- Ensure the use of an easy-to-find test load whose properties are identical and independent of geographical

location and season of the year. The weight and shape of this test load shall have a good correlation to real use.

- The method must fulfil requirements of repeatability and reproducibility (crucial for energy measuring purposes), and allow for differentiation in terms of energy consumptions amongst products.

It was suggested to use water test loads as before, but in three different masses, in different-shaped containers, and two temperature rises (both in the order of 50°C). The measured energy usage in these different cases will be weighted and averaged, to approximate true usage conditions. This was implemented in the latest Standards IEC 60705, 2010 (same as BS EN 60705 2015). Three masses of water ($1000 \text{ g} \pm 1 \text{ g}$, $350 \text{ g} \pm 1 \text{ g}$, and $275 \text{ g} \pm 1 \text{ g}$), were used in cylindrical containers of capacities 2000 ml (diameter $190 \text{ mm} \pm 1 \text{ mm}$, height $90 \text{ mm} \pm 1 \text{ mm}$), 900 ml (diameter $140 \text{ mm} \pm 1 \text{ mm}$, height $76 \text{ mm} \pm 1 \text{ mm}$) and 600 ml (diameter $125 \text{ mm} \pm 1 \text{ mm}$, height $90 \text{ mm} \pm 1 \text{ mm}$), respectively. Each was heated from $10^\circ\text{C} \pm 0.5^\circ\text{C}$ to between 60 and 65°C in the first case, and then to between 55 and 60°C in the second. The overall measured energies for the 1000 g , 350 g and 275 g cases were then weighted in the ratio 3:6:2, based on research findings on domestic loads, which show a statistical bias towards the 350 g range. Detailed descriptions of the method and the formulae used is presented in BS EN 60705 (2015). The final result is designated as W_{50} , the “energy consumption of a cooking cycle to reach a temperature increase of 50 K ”. Such standards, specific to industrial microwave heaters (896 or 915 MHz) systems are not yet available in the literature.

To encourage energy-efficiency, energy labelling schemes have widely been employed for a wide variety of energy-related products or appliances. While this is true for microwave ovens in some countries, like Brazil, China and Japan (see Tables 4, 5 and 6), the same cannot be said for the European Union (EC 2017). It is however expected that the improved microwave oven energy consumption and efficiency test methods (as detailed in the foregoing), would enable future energy labelling for microwave ovens in the European Union, being more

Table 3. Categories of microwave heating of various foods at typical final temperatures FSP (2007).

Category	Food item	Type	Starting temperature ($^\circ\text{C}$)	Final temperature range ($^\circ\text{C}$)
1	Crackers	Light product	Room temp.	49 – 66
	Bread		Room temp.	
	Sandwich	Heavy product	Room temp.	
2	Muffins or cake		Room temp.	54 – 82
	Waffles	Light product	Frozen ≤ -18	
	Pancakes		Frozen ≤ -18	
3	Broccoli	Heavy product	Frozen ≤ -18	71 – 96
	Cauliflower		Frozen ≤ -18	
	Cinnamon rolls	Light product	Frozen ≤ -18	
4	Melting cheese		Refrigerated ≤ -4	77 – 104
	Pizza	Heavy product	Frozen ≤ -18	
	Pre-cooked hamburger patties		Frozen ≤ -18	
5	Pre-cooked pork sausage	Light product	Frozen ≤ -18	77 – > 121
	Melting butter or margarine		Refrigerated ≤ -4	
	Lasagne	Heavy product	Frozen ≤ -18	
6	Macaroni and cheese		Frozen ≤ -18	77 – > 121
	Melting chocolate squares	Light product	Room temp.	
	Vegetables with cheese sauce	Heavy product	Frozen ≤ -18	
6	Melting caramels	Light product	Room temp.	77 – > 121
	Sliced bacon	Heavy product	Refrigerated ≤ -4	

Table 4. Energy labelling of microwave ovens, Brazil, based on IEC 60705 (1999)-HEECS (2011).

Class	Energy efficiency indices
A	Efficiency $\geq 54\%$
B	$49\% \leq \text{Efficiency} < 54\%$
C	$45\% < \text{Efficiency} < 49\%$

Table 5. Energy labelling of microwave ovens, China, based on IEC 60705 (1999)-HEECS (2011).

Energy-efficiency grades	Efficiency values (%)
1	62
2	60
3	58
4	56
6	54

representative of actual usage conditions than the standard IEC power calibration tests.

3.5. Factors affecting energy-efficiency

From equations (1) – (3), the overall energy efficiency (1) is affected by

- The source side (microwave generator to the transmitting waveguide), which determines the generation efficiency (equation 2)
- The load side (the processed food and the cavity housing it), which determines the absorption efficiency (equation 3)
- The matching between the source and load sides (affecting equation (3)).

Since the inception of the use of microwaves in heating applications some seven decades ago, they have always been powered by vacuum electronic devices such as magnetrons, klystrons and gyrotrons. Of these, magnetrons constitute the vast majority being the cheapest and most-efficient (Edgar and Osepchuk 2001). They have a maximum generation efficiency (equation 2) of about 70% (at 2450MHz), and 88% (at 915MHz). The absorption efficiency is however determined by the degree of impedance matching between the source and load. The load impedance varies with time, as the food temperature changes. It also varies

with space due to the inhomogeneity in thermal & dielectric properties as well as the non-uniform spatial temperatures. As a result of these, mismatch is bound to occur, leading to reflections and reduced absorption efficiency. Overall efficiencies (equation 1) are therefore usually in the order of 25–55%, depending on load size (Wang et al. 2015b). Non-uniform heating implies that for the coldest spots to reach the optimal temperature necessary for food safety, higher than optimal temperatures must be delivered to the hottest spots, incurring both quality and energy penalties. Atuonwu and Tassou (2017) analysed the energy implications of non-uniform heating, deriving equations connecting the maximum percentage energy savings associated with improving the heating uniformity of microwave processes. Depending on specific processing conditions, energy savings in the order of 20% were shown to be possible for pasteurisation and sterilisation processes, while about 85% savings are achievable for thawing processes where the non-uniformity is severe. From the foregoing, it becomes necessary to have a means of controlling the source and load variables to minimise reflections (or maximise absorption efficiency). Magnetrons fail in this, due to their poor flexibility and feedback controllability. Solid-state microwave power generators on the other hand, have proved capable of receiving feedback on the dynamic states of the load and controlling the source power delivery to match with the needs of the load, using control inputs like phase, frequency and power amplitude. These capabilities are further enhanced in systems with multiple generators. Therefore, the next sections of this article will focus on the possibilities and challenges (from energy and cost perspectives), of deploying solid-state sources as alternative to magnetrons.

4. Solid-state power delivery for process energy-efficiency

4.1. Principle of operation

A solid-state power microwave heating system as shown in Fig. 4 consists of a microwave small-signal generator, a high power amplifier (which replaces the magnetron), with its heat sink, and a power supply system. The small-signal generator is essentially an oscillator that generates a low-amplitude microwave signal, which is sent to the input of the power amplifier, to which a DC power supply has been applied. The DC power supply consists of

Table 6. Energy labelling of microwave ovens, Japan, based on the “Top Runner” program -MOE (2015).

Category				
Function	Heating method	Internal volume	Category name	Standard energy consumption efficiency (%)
Single-function microwave (with no oven function)	—	—	A	60.1
Microwave with oven function (oven ranges)	With an exposed heater (excluding those with hot air circulation heating)	<30 litres	B	73.4
	Without an exposed heater (excluding those with hot air circulation heating)	≥ 30 litres	C	78.2
		<30 litres	D	70.4
	With hot air circulation heating	<30 litres	E	79.6
		—	F	73.5

a step-down transformer which reduces the mains AC voltage to the required value, a rectifier circuit which converts the AC to a pulse of single polarity, and a filter circuit which converts the pulsed signal to pure DC (in the order of 50V). The power amplifier, in receiving the DC power, converts the input low-amplitude microwave signal to a higher amplitude microwave signal at the same frequency (RF_{out}), which is then channelled to the heating cavity. This power amplifier is essentially a power transistor (semi-conductor device consisting of three semiconductor materials, joined together in two junctions). From these three semiconductor materials, three terminals are drawn out for connection to an external circuit. The three semiconductor materials are P-type and N-type materials, hence, based on material composition, there are PNP and NPN transistors. P-type materials are formed by adding impurities (called dopants) to pure semiconductor materials like silicon or germanium, to create electron deficits, while N-type materials are doped to have electron excess. There are different types of transistor constructions, the most popular being the bipolar junction and field effect transistors. An in-depth discussion on transistors has been provided by Bahl (2009). Fig. 5 shows a block diagram and circuit configuration of the simplest commonly-used transistor circuit form: an NPN transistor in common-emitter mode. As long as a small signal voltage (RF input, with any necessary biasing), applied at the base of the transistor is able to drive it into the so-called active region of its characteristics, the resultant small current flowing through the base is amplified by an amplification factor β (sometimes as high as 200). Also, the voltage is amplified approximately by $\beta R_c / R_b$ where R_c = collector circuit output resistance and R_b = base circuit input resistance. The power gain $\beta^2 R_c / R_b$ from RF input to RF output is therefore very high. The output voltage is limited by the power supply voltage V_{cc} , while the output current is a measure of the AC current drawn from the mains. Hence, while the microwave power output is much larger than the microwave power input, it does not exceed the DC power applied (and by extension, the AC power drawn from the mains). The power conversion is commonly quantified by the drain and power-added efficiencies, given respectively by

$$\eta_D = \frac{RF_{out}}{P_{dc,in}} \quad (7)$$

$$\eta_{PA} = \frac{RF_{out} - RF_{in}}{P_{dc,in}} = \frac{G}{G - 1} \eta_D \quad (8)$$

where the decibel power gain G_{dB} is

$$G_{dB} = 10 \log (G) = 10 \log \left(\frac{RF_{out}}{RF_{in}} \right) \approx 10 \log (\beta^2 R_c / R_b) \quad (9)$$

The power-added efficiency is essentially the efficiency of power conversion from mains electricity to microwaves (for unity power supply efficiency).

4.2. Solid-state versus classical magnetrons

Solid-state power amplifiers are more advantageous than magnetrons, primarily because of their ability to receive feedback

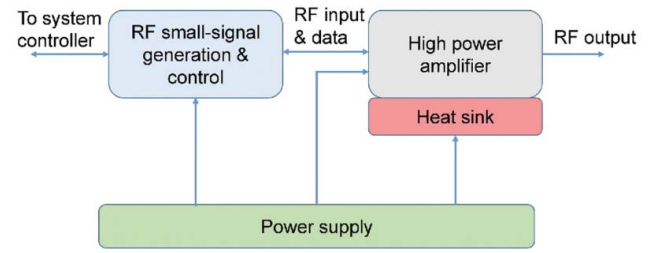


Figure 4. Block diagram of solid-state microwave generator system (Werner, 2015).

on the dynamic states of the processed food, and control same, using different degrees of freedom like frequency, phase and power amplitude – sometimes, using multiple generators. Atuonwu and Tassou (2017) itemised (with details), the advantages of solid-state over magnetrons to include:

- i. Accessibility to feedback and process optimisation algorithms
- ii. Possibility of multiple power feeds with independent control
- iii. Frequency accuracy and stability
- iv. Frequency control
- v. Phase control
- vi. Power amplitude control
- vii. Repeatability and reproducibility of product quality
- viii. Reliability and lifetime – 15 years continuous operation as against about 500 hours in magnetron-powered household ovens, and one year of continuous use in commercial and industrial environments (Wesson 2015).
- ix. Size and operational voltages – about 50V or less compared to the 4–20 kV of magnetrons, at least, 10 times lighter for the same wattage
- x. Improved compatibility with other electronic circuitry, and the *Internet-of-Things* in the future (Jerby 2016).

Frequency, phase and power amplitude control as well as multi-source power delivery have all been individually shown to improve heating uniformity in several studies (Bows 1999; Antonio and Deam 2005; Gunasekaran and Yang 2007; Dominguez-Tortajada et al. 2007; Liao et al. 2016; Bae et al. 2017). When combined effectively in solid-state systems, significant improvements in uniformity are even more likely. Electronic control over the frequency and magnitude of the signal, in combination with multiple feeds providing excitation of diverse modes in the ISM frequency range, indeed seems to open the horizon for practical techniques resolving the issue of intrinsic non-uniformity of microwave heating and making the process energy efficient (Yakovlev 2016). Moreover, by taking advantage of relevant optimisation algorithms, the system can be steered to minimise reflections, and hence attain absorption efficiencies, close to 100% as shown in a simulation study (Korpas et al. 2013).

4.3. Techno-economic analysis of solid-state versus magnetron options

Acquisition costs and energy-efficiency issues have in the past, hindered the adoption of solid-state technology in microwave

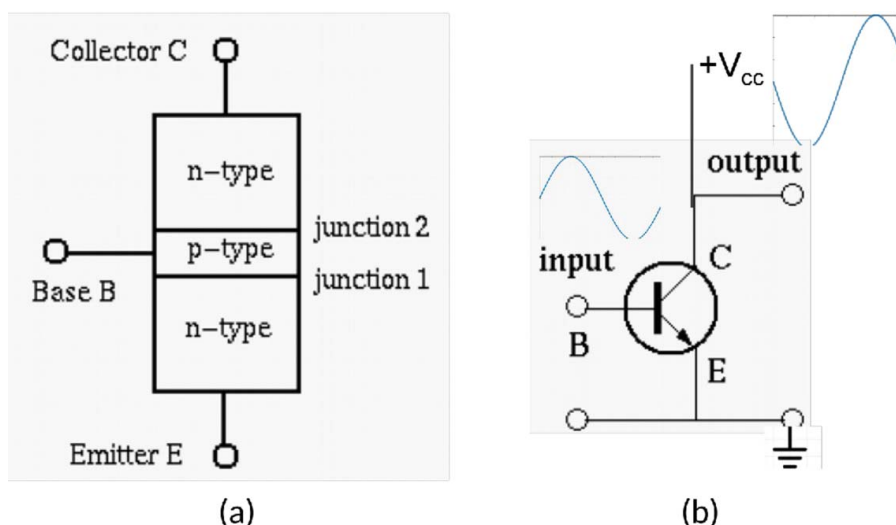


Figure 5. Block schematic (a) and basic circuit configuration of a power-amplifying transistor.

heating applications (Schwarz et al. 2006). As at 2006, when that article was written, the maximum power output of the cheapest solid-state devices (Laterally Diffused Metal Oxide Silicon LDMOS technology) was about 180W, with power-added efficiencies of about 46% at 2450MHz. Other technologies such as Gallium Arsenide (GaAs), Silicon Carbide (SiC) and Gallium Nitride (GaN), in packaged, chip and Monolithic Microwave Integrated Circuit (MMIC) were and are still significantly more expensive and sometimes with lower energy performances. The power outputs and efficiencies have however increased tremendously in recent years as shown in Table 7 (a representative summary of currently available solid-state power generators, with power output and drain efficiencies, at least 200W and 50%, respectively, operating within the frequency ranges relevant for food processing). As can be seen in the Table, power levels of 1000W are possible (for 896/915MHz operation), and 300W (for 2450MHz operation). Power-added efficiencies of 69% as also possible at both frequencies. This is comparable to what can be obtained with magnetrons at 2450MHz, and gradually approaching the 88% attainable with magnetrons at 896/915MHz. When multiplied by the absorption efficiencies (see equations 1, 2 & 3), the electricity-to-heat energy efficiency of solid-state systems is expected to be higher than that of magnetron-based systems, especially at 2450MHz. For the more cost-effective LDMOS technology, an efficiency (generation) of 61% at 206W is possible at 2450MHz. The current rate of efficiency improvement, which has been valid over the last decade, is about 3% every 2–3 years (Wesson 2016). Based on this and other information on typical experimentally-obtained absorption efficiencies for magnetron- and solid-state-based systems, plots are produced (Fig. 6) to compare the different aspects of energy efficiency over a period of years. Two scenarios are considered for 2450MHz systems:

- i. The evolution of solid-state and magnetron system energy efficiencies, from the past decade is used to project into the next 15 years, to predict possible break-even points
- ii. Given that solid-state- and magnetron-based microwave processing systems are put into service, simultaneously

at year zero, energy-efficiency projections are made over the next 15 years, taking into consideration, possible energy performance reductions that have been observed to occur over time, with usage.

To achieve this, the following reasonably valid assumptions are made:

- a. The average absorption efficiency of magnetron-based systems is taken as 65%, based on Wang et al. (2015b), while that of the solid-state system is 88.4% (Durnan 2016).
- b. The current rate of efficiency improvement (3% every 2–3 years), which has been valid over the last decade, (Wesson 2016), is assumed to remain valid over the next 15 years.
- c. The generation efficiency of magnetron-based microwave ovens drops by up to 33% after about 5–10 years of usage (Anantheswaran 1999). Actual depreciation depends on the duty cycle (the length of time over which an oven is used over this period), with commercial (e.g. fast-food outlet) systems depreciating much faster than household systems (which are hardly used more than 10 minutes per day). Here, the upper limit (10 years) is assumed, as well as a linear reduction of efficiency with time. Solid-state systems are assumed to maintain their initial generation efficiencies, throughout their service life (Wesson 2016).

The results of these projections are presented in Figs. 6(a) – (d). From Fig. 6(a), it is seen that solid-state microwave generation efficiencies, have been steadily increasing since 2006. Although still less than that of the magnetron, a break-even point is expected at about 2024, all things being equal. The lower generation efficiency is, however, more than compensated for, by the significant increase in absorption efficiency, offered by the solid-state system. Consequently, the evolutionary overall energy efficiency as shown in Fig. 6(b), is already higher than that of a magnetron-based system, having broken even about 2009. Assuming a solid-state- and magnetron-based system are put into service today, by 2021 (as seen in Fig. 6(c)), the generation efficiency of the magnetron system is expected

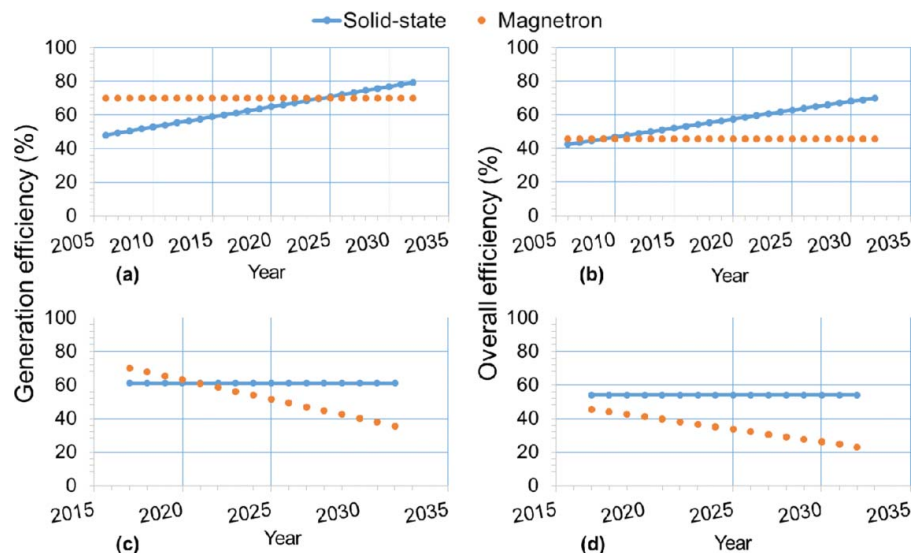
Table 7. List of currently-available solid-state microwave generators in the frequency ranges relevant to industrial and domestic food processing operations.

Part number	Manufacturer	Process	Min.freq. (GHz)	Max.freq. (GHz)	Output power (W)	Gain (dB)	Supply voltage (V)	Drain efficiency (%)	Power-added efficiency (%)
MMRF1312GSR5	NXP	LDMOS	0.9	1.215	1000	17.3	52	54.00	52.99
MMRF1312HSR5	NXP	LDMOS	0.9	1.215	1000	17.3	52	54.00	52.99
MMRF1312HR5	NXP	LDMOS	0.9	1.215	1000	17.3	52	54.00	52.99
MRF13750HSR5	NXP	LDMOS	0.7	1.3	750	19.3	50	67.10	66.31
MRF13750HR5	NXP	LDMOS	0.7	1.3	750	19.5	50	67.10	66.35
PRF13750HR9	NXP	LDMOS	0.7	1.3	750	19.5	50	63.00	62.29
BLF988	Ampleon	LDMOS	0.5	1	600	20	50	58.00	57.42
BLF988S	Ampleon	LDMOS	0.5	1	600	20	50	58.00	57.42
BLF0910H6LS500U	Ampleon	LDMOS	0.9	0.93	500	18	50	61.00	60.03
BLA8H0910LS-500U	Ampleon	LDMOS	0.9	0.93	500	19	50	62.50	61.71
BLF0910H6L500U	Ampleon	LDMOS	0.9	0.93	500	18	50	61.00	60.03
BLA8H0910L-500U	Ampleon	LDMOS	0.9	0.93	500	19.5	50	62.50	61.80
MHT1002GNR3	NXP	LDMOS	0.915	0.915	387	20.7	48	66.90	66.33
MHT1002NR3	NXP	LDMOS	0.915	0.915	387	20.7	48	66.90	66.33
MRF8VP13350NR3	NXP	LDMOS	0.7	1.3	350	20.7	50	67.50	66.93
MRF8VP13350GNR3	NXP	LDMOS	0.7	1.3	350	20.7	50	67.50	66.93
T1G2028536-FL	Qorvo	GaN	0	2	285	18	36	65.60	64.56
T1G2028536-FS	Qorvo	GaN	0	2	285	18	36	65.60	64.56
BLF6G13L-250P	Ampleon	LDMOS	0.005	1.3	250	17	50	56.00	54.88
BLF6G13LS-250P	Ampleon	LDMOS	0.005	1.3	250	17	50	56.00	54.88
A2V09H300-04NR3	NXP	LDMOS	0.72	0.96	223	19.7	48	55.90	55.30
BLF647PSJ	Ampleon	LDMOS	0	1.4	200	18	32	70.00	68.89
BLF647PS	Ampleon	LDMOS	0	1.4	200	18	32	70.00	68.89
BLF647P	Ampleon	LDMOS	0	1.4	200	18	32	70.00	68.89
BLC2425M8LS300P	Ampleon	LDMOS	2.4	2.5	300	17	32	58.00	56.84
MRF24300NR3	NXP	LDMOS	2.4	2.5	300	13.1	32	60.50	57.54
MHT1004NR3	NXP	LDMOS	2.45	2.45	280	15.2	32	57.90	56.15
MHT1004GNR3	NXP	LDMOS	2.45	2.45	280	15.2	32	57.90	56.15
MHT1003NR3	NXP	LDMOS	2.45	2.45	263	15.9	32	59.00	57.48
BLF2425M7LS250P	Ampleon	LDMOS	2.4	2.5	250	13	28	55.00	52.24
BLF2425M7L250P	Ampleon	LDMOS	2.4	2.5	250	15	28	51.00	49.39
MRF7S24250NR3	NXP	LDMOS	2.4	2.5	250	14.7	32	54.80	52.94
BLF2425M7L250P	Ampleon	LDMOS	2.4	2.5	250	13	28	55.00	52.24
BLC2425M9LS250Z	Ampleon	LDMOS	2.4	2.5	250	18.5	32	61.00	60.14
MHE1003NR3	NXP	LDMOS	2.45	2.45	206	14.1	26	63.50	61.03
T1G4020036-FL	Qorvo	GaN	0	3.5	200	18.1	50	68.66	67.60
T1G4020036-FS	Qorvo	GaN	0	3.5	200	18.1	50	69.68	68.60

to start dropping below that of the solid-state system, owing to the linear reduction of output with time. The overall efficiency of the solid-state system is however already higher than that of the magnetron-based system, owing to the vastly improved absorption efficiency brought about by the solid-state system

(Fig. 6(d)). The difference is expected to increase with time. Hence, even for initially-higher acquisition costs, it is possible to break even economically, with a short payback period.

In terms of acquisition costs, solid-state generators are still more expensive. For the cheapest technology LDMOS, \$0.25/W,

**Figure 6.** Energy efficiencies of solid-state- and magnetron-based systems under different scenarios.

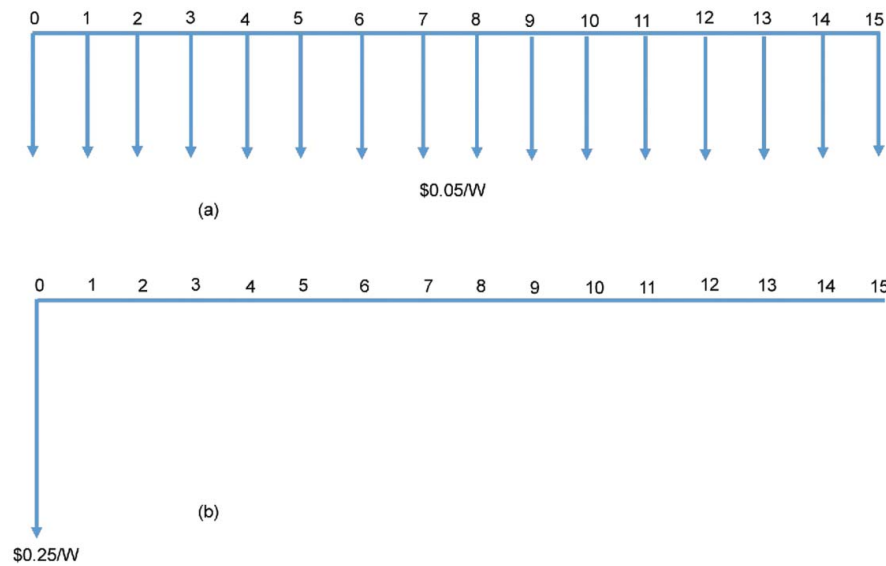


Figure 7. Cash flow diagrams for magnetron (a) and solid-state (b) – based systems.

is now achievable in some cases as against $> \$1.00/W$ in the past (compare Fitzpatrick 2013 and Schwartz et al. 2006). Magnetrons cost $\$0.01/W$ to $\$0.1/W$ (Edgar and Osepchuk 2001). It is however noteworthy that magnetron-based commercial/industrial systems have a limited lifetime of 1 year. We estimate the overall economic impact of this situation using the “Net Present Value” metrics. Negative cash flows are assumed to be made at the end of every year, for the magnetron-based system, to cater for replacement costs (a value of $\$0.05/W$ is assumed, each year), while for the solid-state system, there are no replacements for 15 years. The cash flow diagrams for both cases are presented in Figs. 7(a) & (b). The net present value is then calculated using the relation

$$NPV = \sum_{t=0}^N \frac{R_t}{(1+i)^t} \quad (10)$$

where R_t is the net cash flow at year t (see Fig. 7(a) & (b)), $N = 15$ the total number of years under consideration, and $i = 10\%$, the discount rate. The results, shown in Fig. 8, indicate that after about 5 years, the net magnetron cash flow becomes more negative than the solid-state case. This is equivalent to the

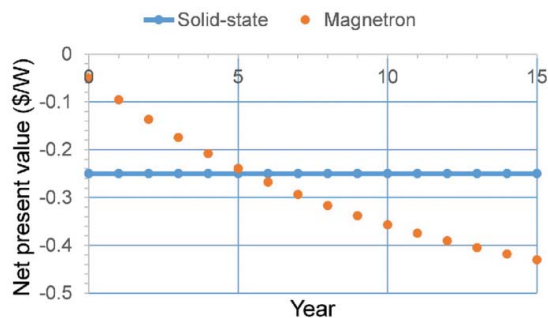


Figure 8. Net present value results for magnetron (a) and solid-state (b) – based systems.

payback period, neglecting other solid-state advantages like energy savings and quality improvements, which usually minimise product wastage and recycling costs. It can therefore be inferred that the use of solid-state amplifiers as replacements to magnetrons is promising, not only from an energy and overall technical perspective, but also in terms of economics.

Conclusions

Key energy issues associated with the microwave processing of foods have been reviewed and critically accessed, from which the following conclusions can be drawn:

- With the exception of microwave and microwave-assisted food drying operations, not much is available in the literature on studies dedicated specifically to energy consumption analysis of microwave food processes.
- Of the drying-related studies, the majority are at the domestic scale, with perhaps only one study in the 915MHz frequency range.
- Microwaves are capable of improving energy performance, compared to conventional drying, provided the microwave power level is properly chosen to match the moisture loading and overall characteristics of the processed food material, minimising reflections. In combination operations, additional degrees of freedom are introduced which improve energy optimisation possibilities.
- The energy performance indices “thermal efficiency” and “drying efficiency”, as currently used in the microwave drying literature have significantly different definitions from those used in the conventional drying literature. A unification of definitions is suggested to facilitate comparison.
- From an energy standards and regulations perspective, it is important to implement energy labelling schemes for microwave heaters in the European Union, which is currently not the case. Such labelling, should take advantage of the recently-implemented European Standards metric:

the “energy consumption of a cooking cycle to reach a temperature increase of 50 K”, as this is more indicative of actual food processing conditions than the standard 1000g, 10K temperature rise power calibration measurements.

- Factors affecting energy-efficiency are categorised into source, load and source-load matching factors. This highlights the need for highly-flexible and controllable power sources capable of receiving real-time feedback on load properties, and effecting rapid control actions to minimise reflections, heating non-uniformities and other imperfections that lead to energy losses.
- From results of a techno-economic analysis, it can be concluded that solid-state amplifiers are promising replacements to magnetrons as microwave power sources not only from an energy and overall technical perspective, but also in terms of economics.

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