CalNEXT
ENERGIZING CALIFORNIA'S FUTURE

Industrial Microwave Technologies Market Study

Final Report

ET23SWE0070

Prepared by:

Colin Lee Alternative Energy Systems Consulting, Inc.

Daniela Grassi Alternative Energy Systems Consulting, Inc.

November 1, 2024

Acknowledgements

We would like to thank our industry partners and interviewees for collaborating and answering our questions for this report.

Disclaimer

The CalNEXT program is designed and implemented by Cohen Ventures, Inc., DBA Energy Solutions (“Energy Solutions”). Southern California Edison Company, on behalf of itself, Pacific Gas and Electric Company, and San Diego Gas & Electric® Company (collectively, the “CA Electric IOUs”), has contracted with Energy Solutions for CalNEXT. CalNEXT is available in each of the CA Electric IOU’s service territories. Customers who participate in CalNEXT are under individual agreements between the customer and Energy Solutions or Energy Solutions’ subcontractors (Terms of Use). The CA Electric IOUs are not parties to, nor guarantors of, any Terms of Use with Energy Solutions. The CA Electric IOUs have no contractual obligation, directly or indirectly, to the customer. The CA Electric IOUs are not liable for any actions or inactions of Energy Solutions, or any distributor, vendor, installer, or manufacturer of product(s) offered through CalNEXT. The CA Electric IOUs do not recommend, endorse, qualify, guarantee, or make any representations or warranties (express or implied) regarding the findings, services, work, quality, financial stability, or performance of Energy Solutions or any of Energy Solutions’ distributors, contractors, subcontractors, installers of products, or any product brand listed on Energy Solutions’ website or provided, directly or indirectly, by Energy Solutions. If applicable, prior to entering into any Terms of Use, customers should thoroughly review the terms and conditions of such Terms of Use so they are fully informed of their rights and obligations under the Terms of Use, and should perform their own research and due diligence, and obtain multiple bids or quotes when seeking a contractor to perform work of any type.

Executive Summary

Industrial processes are one of the more difficult sectors for electrification and energy efficiency measures due to the high capital costs and risks of implementing new technologies. While less known, emerging microwave technologies can be a process heating solution for a variety of industrial, agricultural, medical, and food processing applications. The recent rapid development of microwave technologies has led to the commercialization of new products that can be deployed for a variety of energy efficiency and electrification measures.

This report describes the current technology readiness levels (TRLs) for industrial microwave technology applications, including metallurgy, mining, food production, chemicals, and industrial refrigeration industries. This list of industries may not be inclusive of all applications currently available. The report also identifies commercially available technologies that can produce microwaves for these applications and compares the theoretical energy performance.

Alternative Energy Systems Consulting, Inc. (AESC) interviewed manufacturers and industry experts to understand more about industrial microwave technology and market barriers, opportunities, applicable codes and standards, high value applications that can adopt these technologies, and recommendations to support market adoption. Barriers such as cost, process flow integration, knowledge and awareness, and others challenge the adoption of industrial microwave technologies. The technology opens opportunities for higher throughput, operational cost savings, and more. Customers may be interested in adopting the technology for high value applications such as gasification, mining, and food processing. Recommendations such as develop more case studies demonstrating energy efficiency improvement, improve collaboration between industry and research communities, promote carbon capture and incentive programs, further application and materials testing, and improve equipment standardization. Industrial microwave technology and industrial markets are continually evolving and, as a result, this report may not address all current issues or opportunities in the marketplace.

Abbreviations and Acronyms

Acronym	Meaning
°C	Degrees Celsius
°F	Degrees Fahrenheit
Al_2O_3	Aluminum Oxide
ALARA	As Low as Reasonably Achievable
B-field	Magnetic Field
BFS	Blast Furnace Sludge
C	Carbon
$CaCO_3$	Calcium Carbonate
CaO	Calcium Oxide
$CaSiO_3$	Calcium Silicate
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CRC	Chromium Converter Waste
Cu	Copper
EAFD	Electric Arc Furnace Dust
EE	Energy Efficiency
E-field	Electric Field
ET	Emerging Technology
ETL	Electrical Testing Laboratories
Fe	Iron
Fe_2O_3	Ferric Oxide

Acronym	Meaning
GaN	Gallium Nitride
GHG	Greenhouse Gas
GHz	Gigahertz
GPM	Gallons per Minute
H_2	Hydrogen
hrs	Hours
IOU	Investor-Owned Utility
K_2O	Potassium Oxide
kg	Kilograms
kg/h	Kilograms per Hour
km	Kilometers
kW	Kilowatts
kWh	Kilowatt-hour
m	Meters
Mg	Magnesium
MgO	Magnesium Oxide
MHz	Megahertz
min	Minutes
MJ	Megajoules
mm	Millimeters
MW	Megawatt
O_2	Oxygen
ORR	Operational Readiness Review

Acronym	Meaning
Pd	Palladium
PEF	Pulsed Electric Field
PGM	Platinum Group Metals
Pt	Platinum
R&D	Research and Development
RF	Radio Frequency
Rh	Rhodium
SiO_2	Silicon Dioxide
tCO_2	Metric Tons of CO_2
TRL	Technology Readiness Level
V	Vanadium
W	Watts
wt %	Weight %
Zn	Zinc

Table of Contents

List of Tables

List of Figures

Introduction

Surface or conventional heating can cause non-uniform heating resulting in prolonged process times and energy loss; while industrial microwaves allow for volumetric heating, thus transferring energy more efficiently and cutting processing times. Combustion-based boilers, electric resistance heaters, or heat pumps traditionally serve industrial heating. This market study investigates further how microwave technologies compare to traditional industrial heating technologies such as their decarbonization potential.

The development of microwave technologies can offer energy efficiency opportunities in sectors such as food, mining and metallurgy, chemical, and other industries as an alternative process heating solution. Within the food processing industry, industrial microwave generators are commercially available for cooking, tempering, sterilizing, drying, heating, and pasteurizing many food products (IMS, 2023). Microwave freeze drying is an emerging technology that has shown potential in a lab setting to save 34.5 percent of energy consumption and 33.3 percent of drying time compared to pure vacuum freeze-drying methods (Chen, Bo-Lin, et. al, 2023). However, there have not been any recent known market studies that understand customer acceptance or the energy efficiency impacts of these products in an industrial setting. Technological and financial elements of electrification retrofits remain unknown, particularly for this technology market segment. There are few studies on market elements to enable broad acceptance of microwave technologies. Due to the wide applicability of the technology, opportunities must be identified and documented for large industrial customers to overcome the unique challenge of custom-built, complex process systems and high temperature process loads.

This market study assesses existing opportunities and barriers for deploying industrial microwave technologies. With the wide applicability of microwave technology across a variety of industrial sectors, this project will help understand the market potential and solutions available for decarbonizing industrial processes through microwave systems.

Background

Technical Description

Microwaves are a form of electromagnetic radiation that is time reflected, transmitted, and/or absorbed by any kind of matter. Their frequencies range from 300 megahertz (MHz) to 300 gigahertz (GHz) with wavelengths between 1 millimeter (mm) and 1 meter (m). They can be used in a variety of applications from heating food to radar communications and even military weapons. Microwaves travel by line-of-sight, unlike lower frequency radio waves, and are unable to diffract around hills, limiting their visual horizon to about 40 miles (64 kilometers (km)) (Hitchcock, R. Timothy, 2004).

Microwave and radio frequency (RF) technologies can heat materials due to their dielectric loss properties. These properties allow microwaves to penetrate materials, thereby heating the full volume of the object directly and uniformly, while conventional conductive heating transfers heat from the exterior through the surface and the interior remains relatively cool in the process (Sairem, 2020). Microwave technologies bring energy into a system because of their electric and magnetic fields that can exert forces and move charges in a system to do work. As seen in Figure 1 below, energy transferred by electromagnetic waves is proportional to the square of the amplitude of the wave. Larger E-fields (electric) and larger B-fields (magnetic) can exert larger forces and do more work to a system (Urone, P.P., et. al., n.d.).

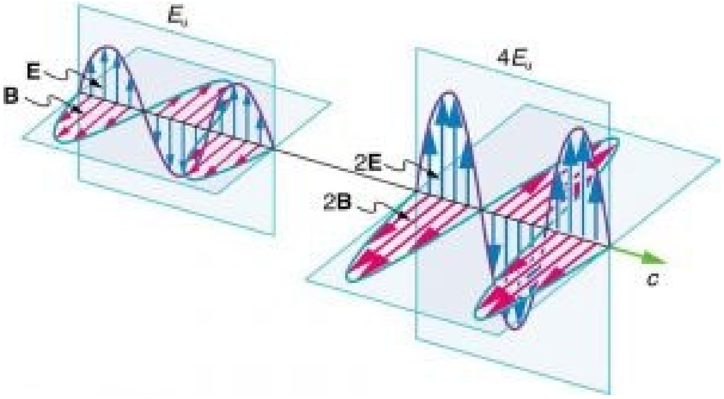


Figure 1: Energy transferred by electromagnetic waves.

Source: Urone, P.P., et. al., n.d.

Macroscopically, interactions between matter and microwaves can be described by their electrodynamic properties: electric permittivity, magnetic permeability, and electrical conductivity (Ulloa, R. Z., et. al., 2019).

- Electric permittivity — how an object responds to and electric field — is related to the polarization of a dielectric specimen such as water, wood, glass, and more. This is correlated to the number of electric dipoles and molecular polarizability of the medium and is generally anisotropic, meaning it responds differently in different directions. Electric dipoles exhibit damped oscillations at the GHz range and significantly absorb microwaves depending on their frequency (Ulloa, R. Z., et. al., 2019).
- Magnetic permeability is a material's ability to carry magnetic dipoles. A microwave's magnetic field can interact with magnetic dipoles and absorb energy because of the magnetic field's torques that can change the orientation of a rotating material with damping (Ulloa, R. Z., et. al., 2019).
- The electrical conductivity of a material offers free electrons for microwaves' electric and magnetic fields to manipulate with. The Lorentz force makes the electrons vibrate rapidly in their resistive medium, generating Joule losses and eventually heat (Ulloa, R. Z., et. al., 2019).

At the surface of obstacles, microwaves can be reflected, absorbed, refracted, or dispersed similar to other electromagnetic radiation. In general, the amount of energy transferred is dependent on the material's electrodynamic properties and frequency of the microwaves (Ulloa, R. Z., et. al., 2019).

Microwave Heating

Surface or conventional heating requires heat to flow from one source into the body or surface of another. Specific heat, thermal conductivity, density, and viscosity are all factors that can impact the heating process over time. Different surface geometries such as edges and corners can cause non-uniform heating, with outside surfaces being much hotter than the inside material. This can result in lower quality products, extended process times, and energy loss in a variety of industries. However, by using microwaves, volumetric heating can be done by transferring energy through the material electromagnetically, rather than through thermal heat flux (IMS, 2023). Figure 2 depicts the difference between microwave volumetric heating and conventional heating.

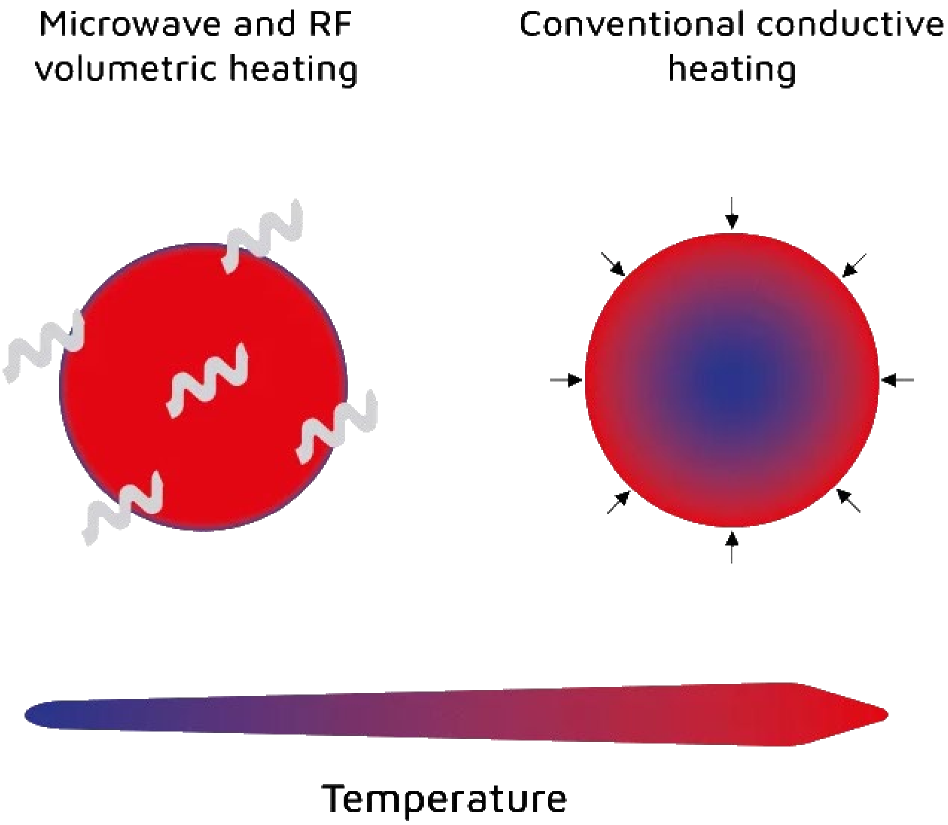


Figure 2: Volumetric heating vs. conventional heating.

Source: Sairem, 2020

Objectives

The objectives of this project are to perform a technology and market assessment to:

- Understand the potential and technology readiness for industrial microwave technologies in a variety of industries,
- Identify readily available commercial solutions,
- Identify technology and market barriers and opportunities,
- Identify any applicable codes and standards for this technology,
- Identify target customers who may be interested in adopting these technologies, and
- Recommend next steps to support market adoption.

Target stakeholders for this project include technology providers, industry experts, industrial customers, utilities, and those interested in electrification and energy efficiency efforts.

Methodology and Approach

To achieve the study’s objectives, the following methodologies and approaches were used:

1. Leverage past research and existing data to understand current technology readiness across multiple industries and identify high benefit applications and locations.
2. Outreach to manufacturers and product development teams to understand current limitations and potential of microwave technology.
3. Conduct secondary and primary research through interviews to understand product costs and market and installation barriers with manufacturers and potential customer sites.
4. Evaluate the feasibility of electrification options.
5. Identify potential customers and manufacturers who may be interested in demonstration projects.
6. Report on key findings, barriers, and next steps and strategies for utility intervention to advance adoption.

Initial Findings

Industrial Microwave Technology Applications

Industrial heating is traditionally done by incumbent technology such as combustion-based boilers, electric resistance heaters, or heat pumps. While heat pump technology is generally more energy efficient, there are limitations to their operating temperatures, with current technology capable of reaching 165°C (329°F) (Lee et. al, 2023). Figure 3 below displays temperature requirements by percentage of heat demand across eight different industries. As shown, the proportion of heat demand varies greatly from industry to industry. Approximately 35 percent of industrial heat requirements are below 165°C (329°F), which aligns with the upper limit achievable by commercially available industrial heat pumps (Rissman, 2022). However, the remaining 65 percent of industrial heat requirements must be fulfilled by other technological solutions if industrial processes are to be fully decarbonized. Microwave technology has been able to reach temperatures of up to 1550°C (2822°F) for metallurgy applications (Mizuno, et. al., 2021-a), showing the potential for the technology to decarbonize thermally demanding processes. However, limits to a material’s electrodynamic properties, as described in the previous Technical Description section, may restrict broad application of this technology.

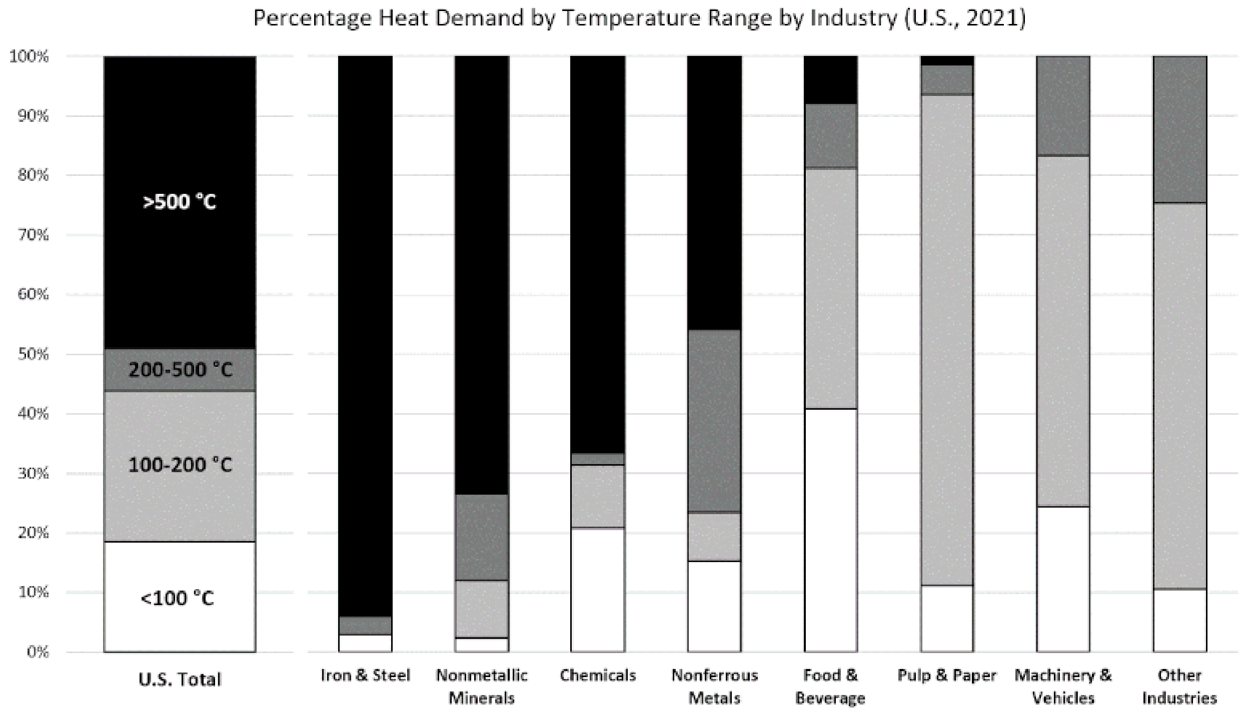


Figure 3: Percentage of heat demand by temperature and industry for the U.S.

Source: Rissman, 2022; Data Source: U.S. EIA, n.d.

The technology readiness level (TRL) is a metric used to determine the maturity of a particular technology, where TRL 1 is the lowest and TRL 9 is the highest maturity. While there are variations of this scale, the United States (U.S.) Department of Energy definition was used to estimate the maturity of industrial microwave technologies across multiple industries for this report (U.S. Department of Energy, 2015). See Table 3 in Appendix A: Supplemental Information for the descriptions of TRLs. The sections below describe the current TRLs for a variety of potential industrial microwave technology applications. This list of industries may not be inclusive of all applications currently available.

Metallurgy

Mizuno, et. al. recently published a review of microwave-based extractive metallurgy to obtain pure metals which summarizes recent technological developments within the metallurgical industry. The study reviews the extractive metallurgical approaches for obtaining pure metals by subjecting virgin materials and waste materials to the microwave heating method for producing virgin metals, such as iron and steel, and recycled metals (Mizuno, et. al., 2021-a). Details of the specific processing steps can be seen in the sections below.

Iron oxides have been the main focus of microwave heating approaches in the metallurgy field due to the permittivity and magnetic permeability of hematite and magnetite (Mizuno, et. al., 2021-a). It is still unknown whether other non-ferrous metallic materials can be used. High recovery rates of over 90 percent of iron (Fe) were observed, showing the potential for magnetite ore to be used as a new raw material within the steel industry (Mizuno, et. al., 2021-a). Compared to conventional technology, microwave-based heating for smelting and recycling was seen to have over a 50 percent reduction in activation energy (Mizuno, et. al., 2021-a). This shows that microwave technology has the potential to reduce chemical reaction times, resulting in fewer product impurities within the metallurgy industry. Currently, all of the evaluated systems are at the laboratory scale, which corresponds to a TRL of 3 or 4.

IRON AND STEEL

In industrial pig iron and steel making processes, the most common methods use a blast furnace and converter furnace to allow for continuous steelmaking with high efficiency. The blast furnace is used to chemically reduce the ore to a liquid metal state. Iron ore, coke, and limestone are inserted, and a blast of hot air is blown into the bottom. Coke is made from baking coal and its impurities until it transforms to carbon. Coke is used as a fuel source and a reducing agent for smelting iron ore. (Federal Steel Supply, 2016). Figure 4 illustrates a basic blast furnace schematic.

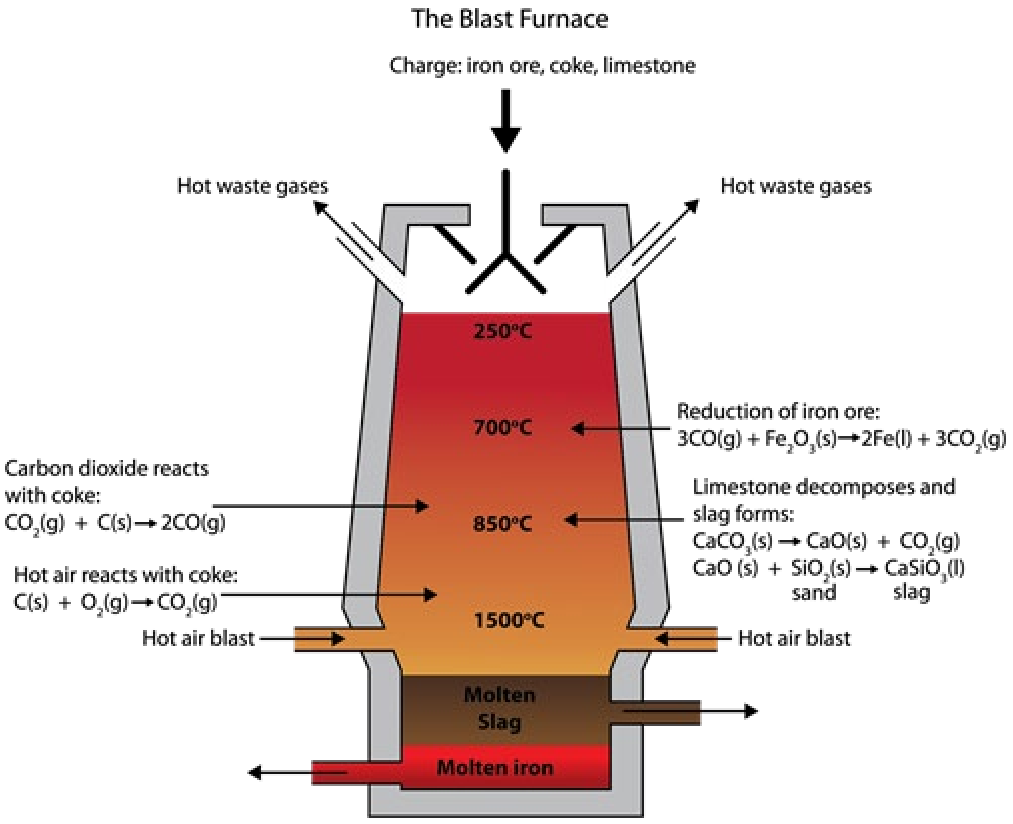
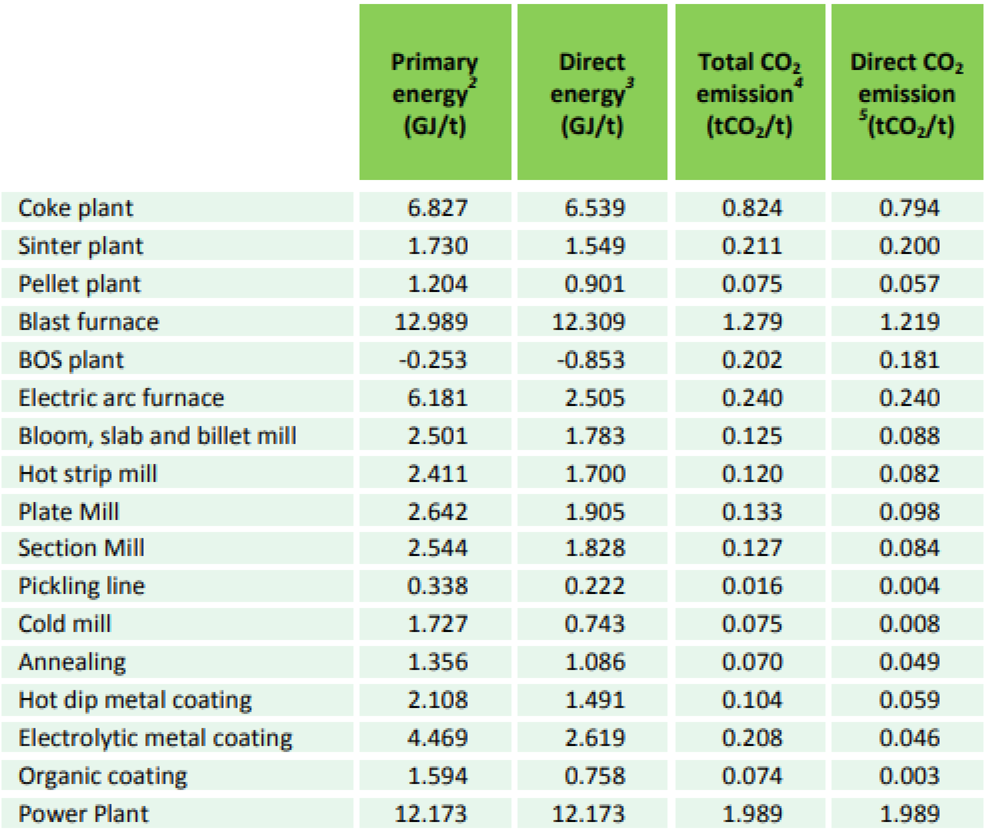


Figure 4: Blast furnace schematic.

Source: YaClass, n.d.

Furthermore, coke production and combustion in the blast furnace are a major producer of greenhouse gas (GHG) emissions, producing 1.2 metric tons of carbon dioxide (tCO_2) per ton of iron produced. See Figure 5 below for the specific energy consumption and CO_2 emissions per ton for iron and steel production in Europe (Pardo, N., et. al., 2012).



	Primary energy[2] (GJ/t)	Direct energy[3] (GJ/t)	Total CO_2 emission[4] (tCO_2/t)	Direct CO_2 emission [5](tCO_2/t)
Coke plant	6.827	6.539	0.824	0.794
Sinter plant	1.730	1.549	0.211	0.200
Pellet plant	1.204	0.901	0.075	0.057
Blast furnace	12.989	12.309	1.279	1.219
BOS plant	-0.253	-0.853	0.202	0.181
Electric arc furnace	6.181	2.505	0.240	0.240
Bloom, slab and billet mill	2.501	1.783	0.125	0.088
Hot strip mill	2.411	1.700	0.120	0.082
Plate Mill	2.642	1.905	0.133	0.098
Section Mill	2.544	1.828	0.127	0.084
Pickling line	0.338	0.222	0.016	0.004
Cold mill	1.727	0.743	0.075	0.008
Annealing	1.356	1.086	0.070	0.049
Hot dip metal coating	2.108	1.491	0.104	0.059
Electrolytic metal coating	4.469	2.619	0.208	0.046
Organic coating	1.594	0.758	0.074	0.003
Power Plant	12.173	12.173	1.989	1.989

Figure 5: Estimated specific energy consumption and specific CO_2 emissions per ton of product of the current pathways for iron and steel production in Europe.

[2] Primary energy: Actual energy content (lower heating value) together with the upstream energy used to produce a material e.g., energy to produce the electricity.

[3] Direct energy: energy use of a specific installation only.

[4] Total CO_2 emission: Direct CO_2 emission to air due to use of a material together with the upstream emissions (emitted by suppliers) of a limited list of materials.

[5] Direct CO_2 emission: Only CO_2 emission to air of a specific installation.

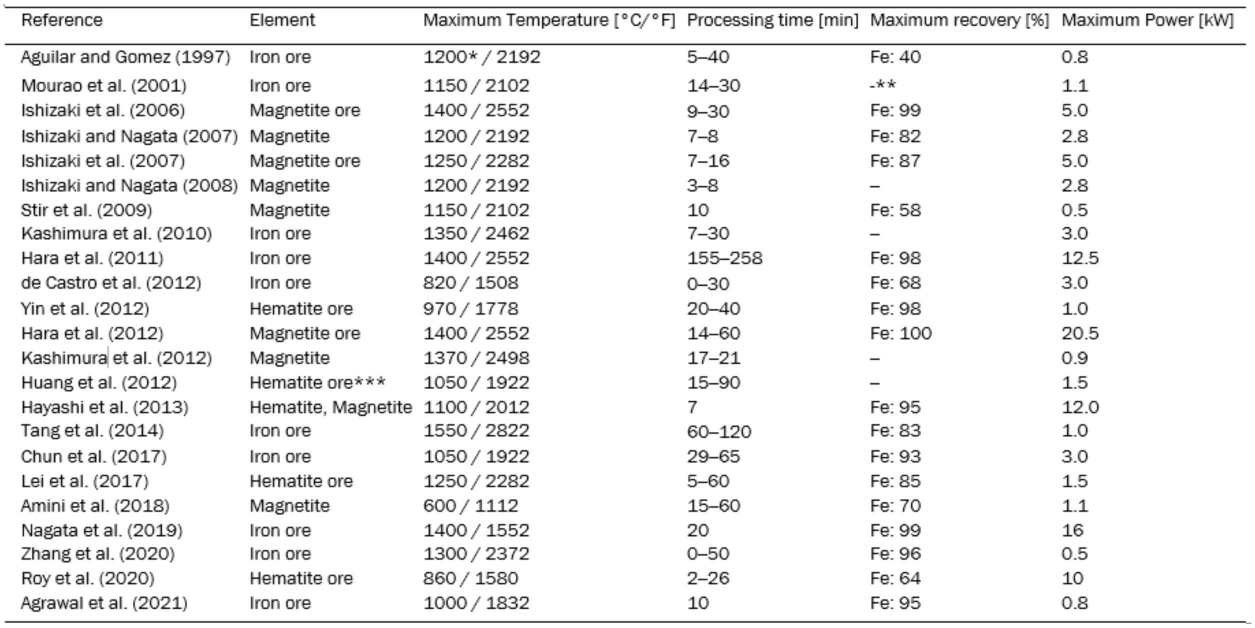
Source: Pardo, N., et. al., 2012

A variety of studies have investigated microwave-based reduction approaches for iron and steel processing. Earlier studies have found that using microwave-based approaches are feasible at the laboratory scale. In one study by Hara et al. (Hara et. al., 2012), natural iron ore powders were used as samples in addition to iron oxide powder samples. The study used a 20.5 kilowatt (kW) microwave furnace at 2.45 GHz, resulting in a 100 percent recovery rate for pig iron when irradiated for 30 minutes at 1400°C (2552°F). The high intensity of electromagnetic energy at this scale resulted in less phosphorus and silicon contamination compared to the conventional furnace-based reduction approach for pig iron.

Practical studies have found that the utilization of microwaves as a heating source can mitigate environmental burdens and remove impurities in a continuous reduction approach. Kashimura et al. was able to develop a prototype microwave-based continuous furnace with a maximum power of 3.0 kW and 2.45 GHz. Theoretically, this could reduce the carbon emissions by half due to a shorter processing time. Additionally, the controllability of the furnace could increase, the iron purity could improve, and other processes for pollution removal could potentially become unnecessary. It was determined that approximately seven minutes at 3.0 kW of power was needed to process the iron, which represents only two percent of the processing time of the conventional blast furnace approach (Kashimura et al., 2010).

Using non-carbonaceous reductants instead of coke in microwave heating conditions was also investigated to reduce CO_2 emissions. Amini et al. used gaseous hydrogen (H_2) as a reductant in the magnetite reduction approach using microwave heating of 1.1 kW maximum power at 2.45 GHz (Amini et al., 2018).

In modern conventional steelmaking processes, magnetite is generally not used as a raw material because it is difficult to reduce. However, magnetite is reactive under microwave irradiation, and a high recovery rate of more than 90 percent of iron was observed in many studies. This shows that microwave technology has the potential to allow magnetite ore to be used as a new raw material in the steel industry. Materials difficult to reduce using conventional technology can potentially be well-treated under microwave irradiation. A summary of the microwave-based reduction approaches to obtain pure iron from iron oxides can be found in Figure 6.



Reference	Element	Maximum Temperature [°C/°F]	Processing time [min]	Maximum recovery [%]	Maximum Power [kW]
Aguilar and Gomez (1997)	Iron ore	1200* / 2192	5–40	Fe: 40	0.8
Mourao et al. (2001)	Iron ore	1150 / 2102	14–30	-**	1.1
Ishizaki et al. (2006)	Magnetite ore	1400 / 2552	9–30	Fe: 99	5.0
Ishizaki and Nagata (2007)	Magnetite	1200 / 2192	7–8	Fe: 82	2.8
Ishizaki et al. (2007)	Magnetite ore	1250 / 2282	7–16	Fe: 87	5.0
Ishizaki and Nagata (2008)	Magnetite	1200 / 2192	3–8	–	2.8
Stir et al. (2009)	Magnetite	1150 / 2102	10	Fe: 58	0.5
Kashimura et al. (2010)	Iron ore	1350 / 2462	7–30	–	3.0
Hara et al. (2011)	Iron ore	1400 / 2552	155–258	Fe: 98	12.5
de Castro et al. (2012)	Iron ore	820 / 1508	0–30	Fe: 68	3.0
Yin et al. (2012)	Hematite ore	970 / 1778	20–40	Fe: 98	1.0
Hara et al. (2012)	Magnetite ore	1400 / 2552	14–60	Fe: 100	20.5
Kashimura et al. (2012)	Magnetite	1370 / 2498	17–21	–	0.9
Huang et al. (2012)	Hematite ore***	1050 / 1922	15–90	–	1.5
Hayashi et al. (2013)	Hematite, Magnetite	1100 / 2012	7	Fe: 95	12.0
Tang et al. (2014)	Iron ore	1550 / 2822	60–120	Fe: 83	1.0
Chun et al. (2017)	Iron ore	1050 / 1922	29–65	Fe: 93	3.0
Lei et al. (2017)	Hematite ore	1250 / 2282	5–60	Fe: 85	1.5
Amini et al. (2018)	Magnetite	600 / 1112	15–60	Fe: 70	1.1
Nagata et al. (2019)	Iron ore	1400 / 1552	20	Fe: 99	16
Zhang et al. (2020)	Iron ore	1300 / 2372	0–50	Fe: 96	0.5
Roy et al. (2020)	Hematite ore	860 / 1580	2–26	Fe: 64	10
Agrawal et al. (2021)	Iron ore	1000 / 1832	10	Fe: 95	0.8

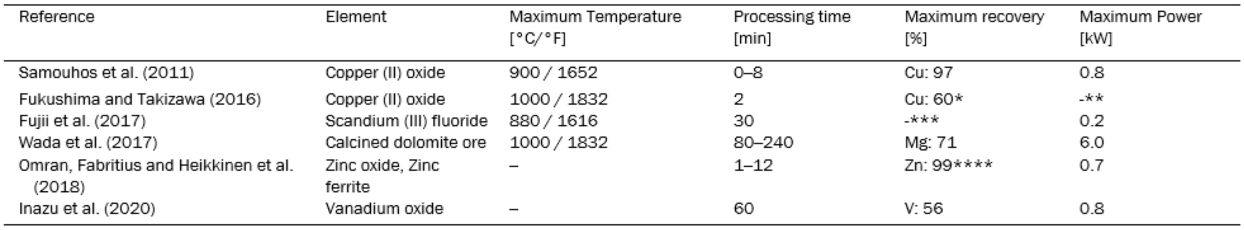
*: estimated minimum temperature rate by analyzing samples with the use of scanning electron microscopy after microwave heating.
**: only reported the reaction rate in the pellets.
***: considered by the compositions result.

Figure 6: Summary of microwave-based reduction approaches to obtain pure iron from iron oxides.

Source: Mizuno, et. al., 2021-a

NON-FERROUS METALS

Microwaves have also been tested for processing non-ferrous metals. These include microwave-based reduction approaches to purify metal oxides into pure metals such as copper, zinc, magnesium, scandium, and vanadium. A summary of studies can be seen in Figure 7.



Reference	Element	Maximum Temperature [°C/°F]	Processing time [min]	Maximum recovery [%]	Maximum Power [kW]
Samouhos et al. (2011)	Copper (II) oxide	900 / 1652	0–8	Cu: 97	0.8
Fukushima and Takizawa (2016)	Copper (II) oxide	1000 / 1832	2	Cu: 60*	-**
Fujii et al. (2017)	Scandium (III) fluoride	880 / 1616	30	-***	0.2
Wada et al. (2017)	Calcined dolomite ore	1000 / 1832	80–240	Mg: 71	6.0
Omran, Fabritius and Heikkinen et al. (2018)	Zinc oxide, Zinc ferrite	–	1–12	Zn: 99****	0.7
Inazu et al. (2020)	Vanadium oxide	–	60	V: 56	0.8

*: estimated from the results chart.
**: only reported the microwave frequency at 2.45 GHz.
***: only reported the observation of pure scandium.
****: obtained in the reduction of zinc oxide.

Figure 7: Microwave-based reduction approaches to obtain non-ferrous metals

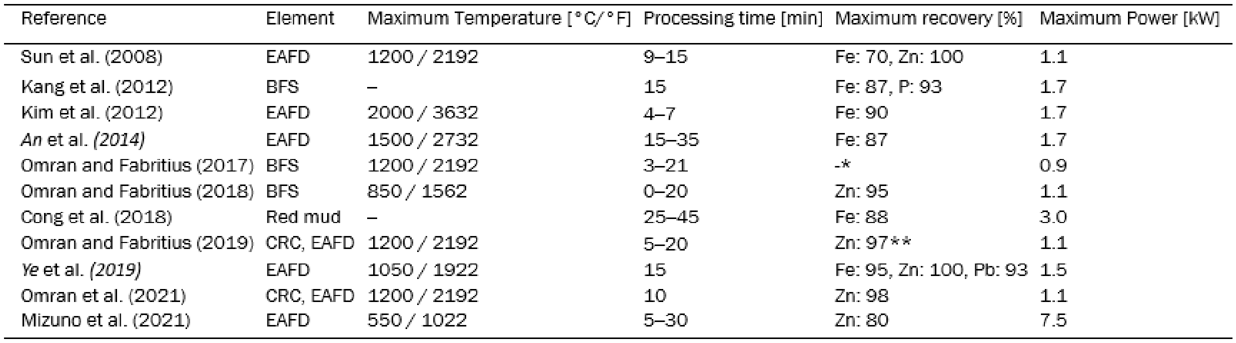
Source: Mizuno, et. al., 2021-a

PRODUCING RECYCLED METALS

Pyrometallurgical recycling methods extract metals from waste through physical and chemical transformations by providing thermal energy. These approaches are different than hydrometallurgical processes that use chemical reactions between samples and solutions or solvents (Mizuno, et. al., 2021-a).

Microwave-based pyrometallurgical processes can recycle waste such as blast furnace sludge (BFS), electric arc furnace dust (EAFD), and chromium converter (CRC) waste, and have been previously investigated in literature. From the blast furnace process described in the Iron and Steel section above, the sludge byproduct can contain useful metallic ingredients such as iron (Fe), calcium oxide (CaO), aluminum oxide (Al_2O_3), magnesium oxide (MgO), zinc (Zn), and potassium oxide (K_2O), as well as carbonaceous material that could be recycled as reductant material (Mizuno, et. al., 2021-a).

BFS applications have been proven with a maximum power of 0.9–1.1 kW at 2.45 GHz where BFS was crushed and then heated to 850°C (1562°F), yielding a recovery rate for zinc of almost 95 percent as well as the reduction of iron oxides to iron (Omran and Fabritius, 2018). For recycling materials, an electric arc furnace can be used to melt recycled or scrap metal. In iron production, an electric arc furnace recycles zinc-galvanized steel plates which generates EAFD in the process. Recent studies have reported a low-carbon microwave-based recycling process for EAFD using a maximum power of 7.5 kW at 2.5 GHz, leading to an 80 percent removal rate of zinc (Mizuno, N., Kosai, S., Yamasue, E., 2021-b). Other waste process studies using microwave-based recycling demonstrated that CRC, mixed with graphite powder, generated in the ferrochrome production process resulted in a 97 percent recovery rate of zinc (Omran et al., 2021). A summary of studies using a microwave-based pyrometallurgical recycling approach to obtain pure metals can be seen in Figure 8 below.



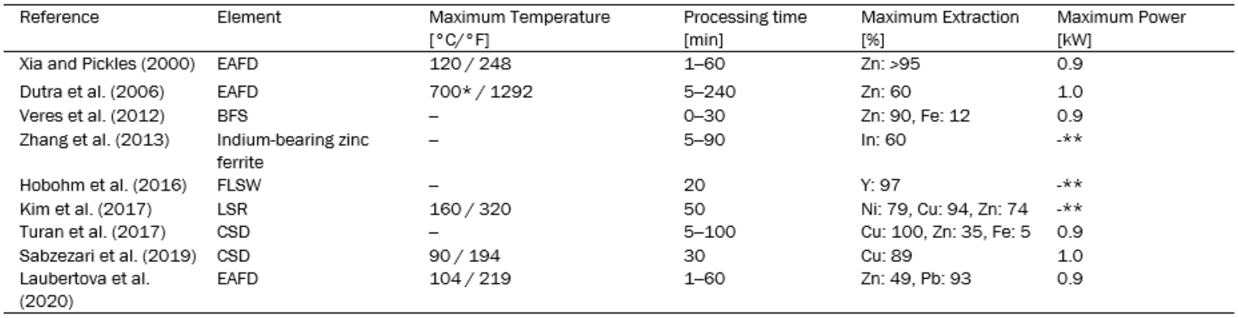
Reference	Element	Maximum Temperature [°C/°F]	Processing time [min]	Maximum recovery [%]	Maximum Power [kW]
Sun et al. (2008)	EAFD	1200 / 2192	9–15	Fe: 70, Zn: 100	1.1
Kang et al. (2012)	BFS	–	15	Fe: 87, P: 93	1.7
Kim et al. (2012)	EAFD	2000 / 3632	4–7	Fe: 90	1.7
An et al. *(2014)*	EAFD	1500 / 2732	15–35	Fe: 87	1.7
Omran and Fabritius (2017)	BFS	1200 / 2192	3–21	-*	0.9
Omran and Fabritius (2018)	BFS	850 / 1562	0–20	Zn: 95	1.1
Cong et al. (2018)	Red mud	–	25–45	Fe: 88	3.0
Omran and Fabritius (2019)	CRC, EAFD	1200 / 2192	5–20	Zn: 97**	1.1
Ye et al. *(2019)*	EAFD	1050 / 1922	15	Fe: 95, Zn: 100, Pb: 93	1.5
Omran et al. (2021)	CRC, EAFD	1200 / 2192	10	Zn: 98	1.1
Mizuno et al. (2021)	EAFD	550 / 1022	5–30	Zn: 80	7.5

*: only reported the potential of microwave as a heating source.
**: the CRC mixed with graphite powder reached the maximum recovery rate.

Figure 8: Microwave-based pyrometallurgical recycling approaches to obtain pure metals.

Source: Mizuno, et. al., 2021-a

Hydrometallurgical processes are those that extract metals from waste through chemical reactions between the materials. Acid or alkaline liquids are used as leaching reactors. When used in conjunction with microwaves for heating, the reaction time, chemical amount, and energy demand could be reduced while improving extraction efficiency. A summary of studies processing various waste products can be seen in Figure 9 (Mizuno, et. al., 2021-a). Recently, the Flemish Institute for Technological Research (VITO), an independent Flemish research organization in the area of cleantech and sustainable development, has fully optimized a microwave-assisted leaching process to platinum group metals (PGMs) from spent automotive ceramic catalysts. At the lab scale, they were able to extract at least 90 percent of palladium (Pd), platinum (Pt), and rhodium (Rh) within five to ten minutes of reaction time. (Peacoc, 2023)



Reference	Element	Maximum Temperature [°C/°F]	Processing time [min]	Maximum Extraction [%]	Maximum Power [kW]
Xia and Pickles (2000)	EAFD	120 / 248	1–60	Zn: >95	0.9
Dutra et al. (2006)	EAFD	700* / 1292	5–240	Zn: 60	1.0
Veres et al. (2012)	BFS	–	0–30	Zn: 90, Fe: 12	0.9
Zhang et al. (2013)	Indium-bearing zinc ferrite	–	5–90	In: 60	-**
Hobohm et al. (2016)	FLSW	–	20	Y: 97	-**
Kim et al. (2017)	LSR	160 / 320	50	Ni: 79, Cu: 94, Zn: 74	-**
Turan et al. (2017)	CSD	–	5–100	Cu: 100, Zn: 35, Fe: 5	0.9
Sabzezari et al. (2019)	CSD	90 / 194	30	Cu: 89	1.0
Laubertova et al. (2020)	EAFD	104 / 219	1–60	Zn: 49, Pb: 93	0.9

*: observed in the pretreatment process of sample.
**: only reported the microwave frequency at 2.45 GHz.

Figure 9: Microwave-assisted leaching approaches to obtain pure metals.

Source: Mizuno, et. al., 2021-a

Mining

Within the mining industry, microwave technology is currently in development to reduce energy associated with crushing and sorting pre blasted ore. This process, known as comminution, can consume 50 to 70 percent of the energy used in mineral processing (Hercus, C., 2023). The process can be as little as one percent efficient if unnecessary material is processed due to excess heat, vibration, and noise (Hercus, C., 2023). Since valuable sulfide minerals are very responsive to microwave irradiation compared to other gangue (less valuable) materials, thermal stress and fractures along grain boundaries can be created by microwaves, freeing the valuable minerals from the gangue matrix. This method of selective heating can result in improved mineral liberation and reduce the ore competency, leading to further energy savings downstream in the metallurgical recovery process. This application has a potential energy savings of 35 percent compared to standard comminution processes and an overall 10 to 46 percent per ton of energy savings for downstream metal production (Sepro Laboratories, n.d.). Currently, Sepro is conducting pilot-scale test work for customers using their microwave-based comminution process with a 915 MHz, 150 kW sized microwave system. Their comminution circuit modeling diagram can be seen in Figure 10 below (Sepro Laboratories, n.d.). With pilot-scale work underway for these applications, the estimated TRL is 6 to 7.

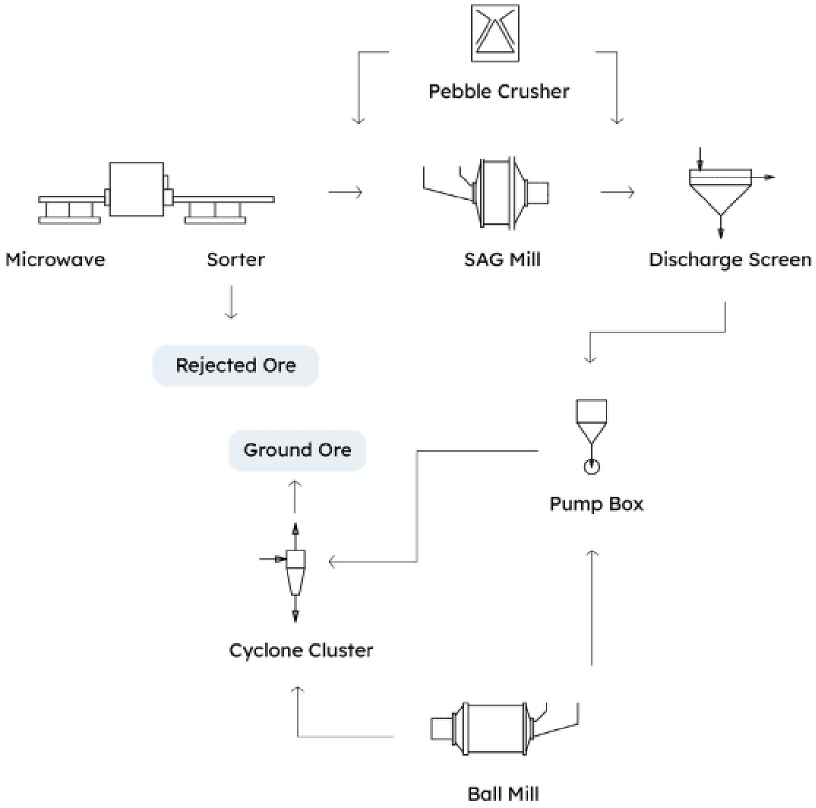


Figure 10: Comminution circuit modeling.

Source: Sepro Laboratories, n.d.

Food Production

Due to the volumetric heating benefits of microwaves, food production processes can benefit from faster throughput and energy efficiency for many processes. These processes may include drying/roasting, gelation, defrosting/thawing/tempering, cooking, pasteurization/sterilization, boost heat, and freeze drying. For more information regarding freeze-drying applications, see the Industrial Refrigeration section later in this report. Microwave systems have been used at scale to process a variety of products such as beef, chicken, fish, pork, bacon, sausage, fruit, vegetables, spices, snack foods, seeds, pulses, grains, cheeses, soy milk, pureés, surimi, peanuts, cereals, sauces, bread, slurries, and more (Ferrite Microwave Technologies, n.d.-a). Details of some of the processes can be seen in the sections below. Currently, the use of microwave technology is widespread for processing some food types such as bacon, while other applications are still in development. Microwave technology currently can operate reliably in high temperatures of up to 1000°C (1832°F) within continuous or batch processing of liquids or solids (CEng, S., et. al., 2021). The current deployment of these systems for processing foods is widespread for some products, therefore the estimated TRL is 7 to 9.

DRYING/ROASTING

Microwave drying can be used in many food production applications. The unique properties of microwaves can penetrate the food, allowing for faster processing times and uniform heating for drying purposes. This also can lead to decreased energy consumption and easier temperature management (Microwave Drying, n.d.). An example of drying/roasting can be seen in coffee beans, where TORWAVE has been able to use microwaves instead of hot air heating to reduce processing time by 80 percent. Due to the volumetric heating methods, the beans have increased bloating and porosity, increasing surface area by 20 percent and allowing more flavor development (TORWAVE, n.d.). This technology can also be used in conjunction with a vacuum or other electric heating to meet product standards. Vacuum microwave drying can be suitable for many sensitive food products such as fruits and vegetables that cannot withstand high temperatures (Microwave Drying, n.d.).

TEMPERING

Most processed meat in the world contains many frozen ingredients that must be tempered or thawed before further processing. Some products such as hamburgers, sausage, canned meats, and pet food use frozen meat exclusively that must be tempered before processing. Traditionally, air thawing and water thawing are the primary tempering mediums. Air thawing involves thawing products on pallets with air spacers between layers and can take several days depending on air temperature and velocity. Water thawing is a standard practice for fish products. These thawing methods can lead to drip loss, which is a loss of moisture and original texture from myofibrils to the extracellular space; this can be approximately five percent for boxed beef with a protein content of ten percent (Ferrite Microwave Technologies, 2021). Bacterial growth is also a concern with traditional thawing methods. Over an extended period, the surface temperature of the product can vary significantly compared to the center of the product. Figure 11 shows the temperature difference between the surface and center of a block of beef when thawing.

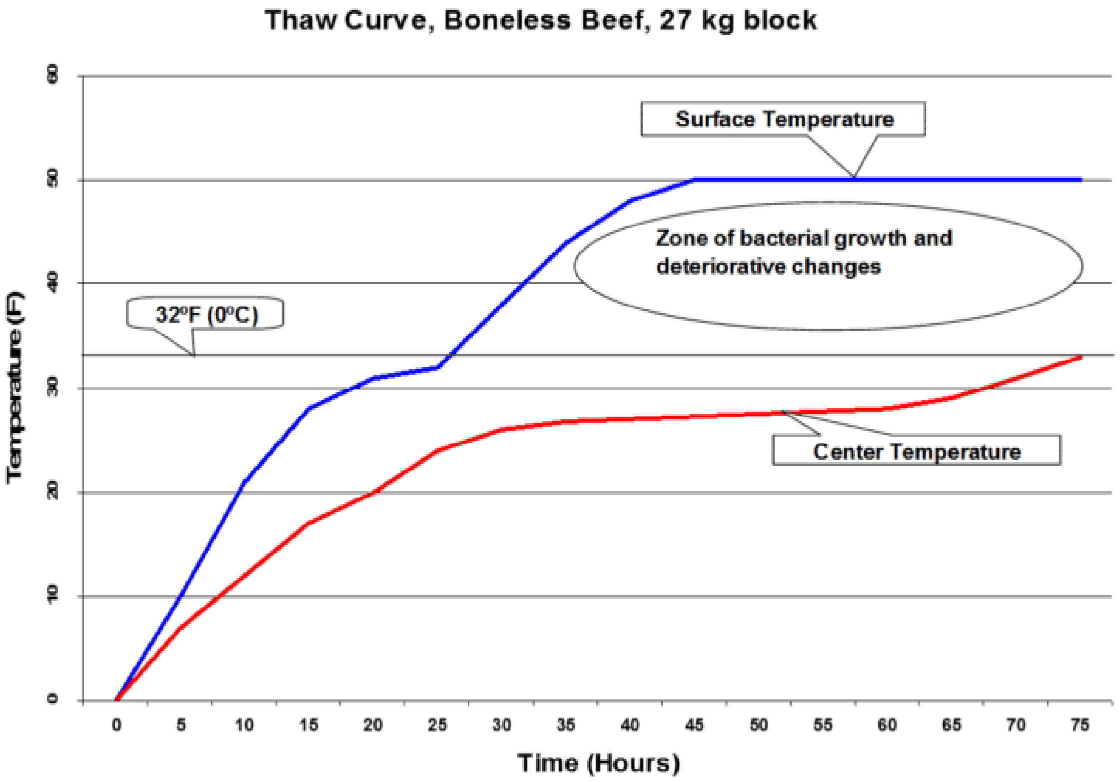


Figure 11: Example temperature difference of a beef block.

Source: Ferrite Microwave Technologies, 2021

Due to volumetric heating, microwave tempering can precisely control product temperatures from -18°C to -3°C (-0.4°F to 26.6°F) in three minutes or less. The phase change of water, however, makes it difficult to control microwave systems past that point for these applications. Microwave tempering can be used with many processes, especially those that involve slicing or grinding of ingredients (Ferrite Microwave Technologies, 2021). These systems can be installed as continuous or batch processes and boast a smaller footprint with high throughput. An example of a continuous tempering tunnel microwave oven system is shown in Figure 12.

Figure 12: MIP12 continuous tempering tunnel microwave oven system.

Source: Ferrite Microwave Technologies, 2021

COOKING

Microwaves have been used for many years to cook different foods. Using microwaves to cook bacon with industrial processes was originally introduced in the 1970s, where slicing equipment was slow at around 200 slices per minute and microwave power levels were approximately 100 watts (W). Today however, the throughput, efficiency, and power of bacon processing systems has improved drastically. Bacon can be sliced at 2,000 slices per minute with over 800 kW of power per system. Automation has also allowed all functions including slicing, cooking, and packaging to be combined into a more integrated system. This has led the pre-cooked bacon market to increase to over $4 billion in 2013 with over 44 percent of in-home bacon consumption being pre-cooked (Ferrite Microwave Technologies, n.d.-b).

Microwaves have also been used as a high-efficiency, energy saving method to produce beef jerky. The process of making beef jerky can be time consuming, requiring the beef to dry and reduce its water content from 35 percent to 10–12 percent. Traditionally, this takes a long time, requiring significant thermal energy. Compared to conventional electric resistance drying, microwaves have been reported to consume a third to a half of the amount of electricity. Due to the volumetric heating properties of microwaves, only the heated jerky absorbs microwave energy, allowing for uniform heating. drying, and sterilization. The processing speed also preserves its original color, aroma, and flavor. Depending on the product’s water content, other drying methods can be used in conjunction with microwave heating to improve efficiency. For products with a high water content, an oven or natural drying can be combined with microwave drying. An example of a microwave drying and sterilization production line can be seen in Figure 13 below. The product shown has an output microwave power of up to 60 kW and can process up to 125 kilogram (kg) per hour (Advanced Environmental Technologies Limited, n.d.-a).

Figure 13: Example microwave drying and sterilization production line.

Source: Advanced Environmental Technologies Limited, n.d.-a

PASTEURIZATION

Industrial microwaves can provide uniform, high-intensity electromagnetic energy to liquid components for pasteurization and sterilization. Through volumetric heating methods, this removes ‘hot spots’ related to traditional surface heating technologies, potentially leading to faster processing times and improved energy efficiency. An in-line microwave liquid heating system can thermally process high-value heat or shear sensitive, high viscosity, and multi-phase products including salsa, surimi, soy milk, purees, sauces, soups, drinks, and more. A microwave inert tube is designed to ensure it does not absorb electromagnetic energy while allowing the product to flow through the microwave applicator. An example system can be seen Figure 14. The system can output up to 200 kW with a maximum throughput of 10 gallons per minute (GPM) and a maximum temperature of 150°C (302°F) (IMS, n.d.-a).

Figure 14: Example microwave liquid heating system.

Source: IMS, n.d.-a

Chemicals

There are many new applications of microwave technologies to assist in the production of various chemicals. Microwave systems can be used for drying, curing, heating, reacting, sintering, catalyzing, extracting, sterilizing, and calcinating (IMS, n.d.-c). Some product examples that have used this technology for production include inks, resins, foams, plastics, binders, coatings, polymers, pigments, adhesives, composites, and fermentation media (IMS, n.d.-c). Some of these applications are more technologically mature than others. A foam manufacturer was able to use a microwave dryer for continuously poured hydrophilic polyurethane foam to reduce its moisture content to less than two percent using a 100 kW microwave system. This resulted in a 250 percent increase in drying speed in a small footprint of 18 feet, and a 96 percent absorption efficiency of microwave energy. The total system efficiency was calculated to be 81 percent with a payback period of approximately eight months (IMS, n.d.-c). Microwaves have also been used to assist in pre-heating epoxy resins from 50°C to 180°C (122°F to 356°F) using a 100 kW system. The throughput was doubled, and maintenance costs were reduced, generating a payback of less than six months (IMS, n.d.-c). For simple drying applications, the current estimated TRL is 7 to 9. However, there are some more complex chemical reactions such as pyrolysis, discussed below, with a current estimated TRL of 3 to 6.

Recently, recycling plastics through microwave-assisted pyrolysis has been gaining attention. The ability to convert polystyrene plastic into aviation fuel was shown to be successful at the lab scale, yielding a maximum of 97.67 weight (wt) percent oil yield with a pyrolysis temperature of 460°C (860°F) using a 650 W microwave (Fan, S. et. al., 2023). A pilot study of a continuous microwave assisted pyrolysis system was tested by Zhou, N., and was able to process 10 kg of plastic per hour using 5 megajoules (MJ) (1.4 kilowatt-hours (kWh)) of electrical energy per kg of plastic (high density polyethylene), resulting in an 89.6 percent energy efficiency improvement and a pyrolysis temperature of 620°C (1148°F). This yielded a 48.9 percent liquid product with 73.5 percent gasoline-range hydrocarbons rich in aromatic (45.0 percent) and isomerized aliphatic (24.6 percent) contents. The schematic of the pilot system can be seen in Figure 15 (Zhou, N., et al, 2021).

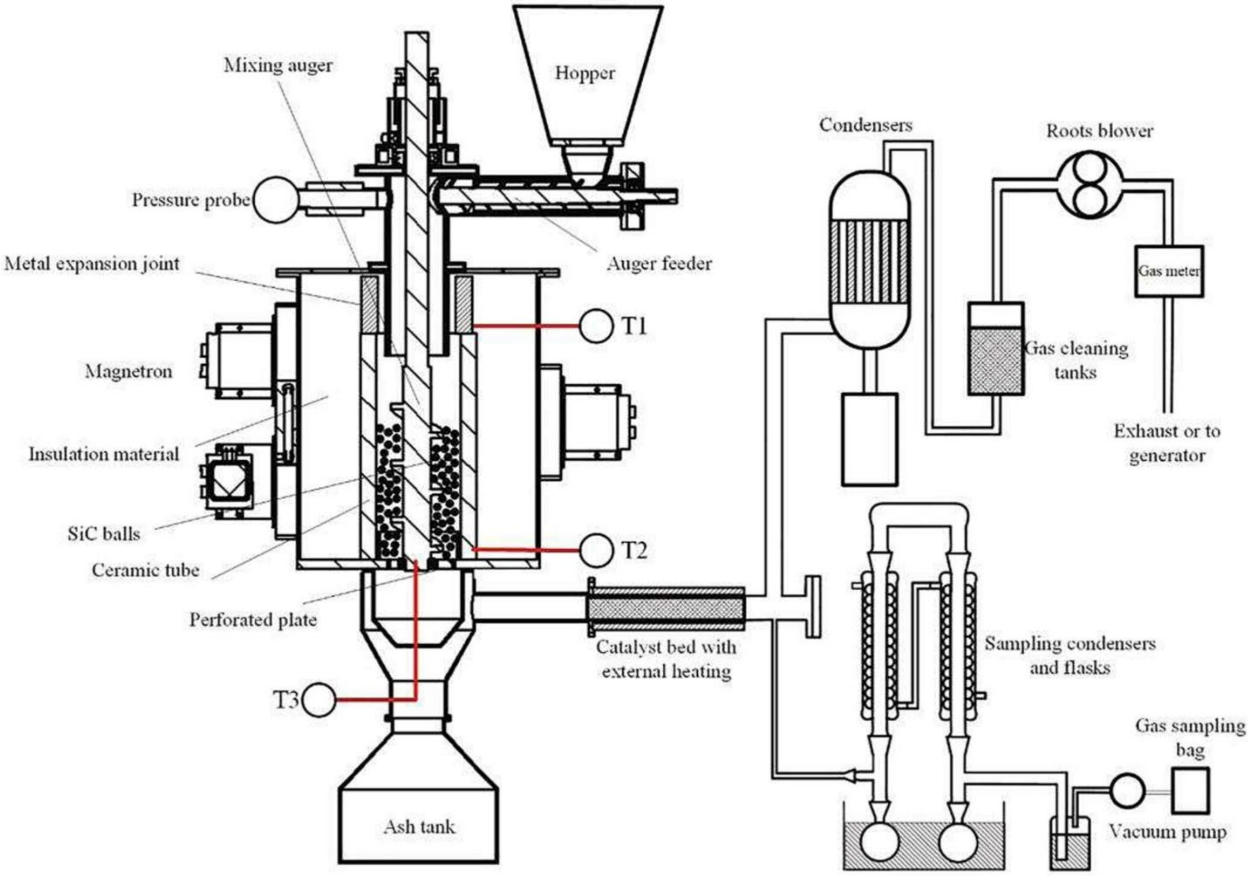


Figure 15: Schematic of a continuous microwave assisted pyrolysis pilot.

Source: Zhou, N., et al, 2021

A variety of methods of processing different plastics with microwaves have been published with some of the results summarized in the graphs below. Figure 16 shows the percent of oil yielded with different plastics and pyrolysis temperatures. Figure 17 shows the percent of oil yielded with different plastics and varying microwave power (Hu, X., et al., 2023). With this information, the maximum pilot power currently tested was a 2.5 kW microwave system, showing the potential for the technology.

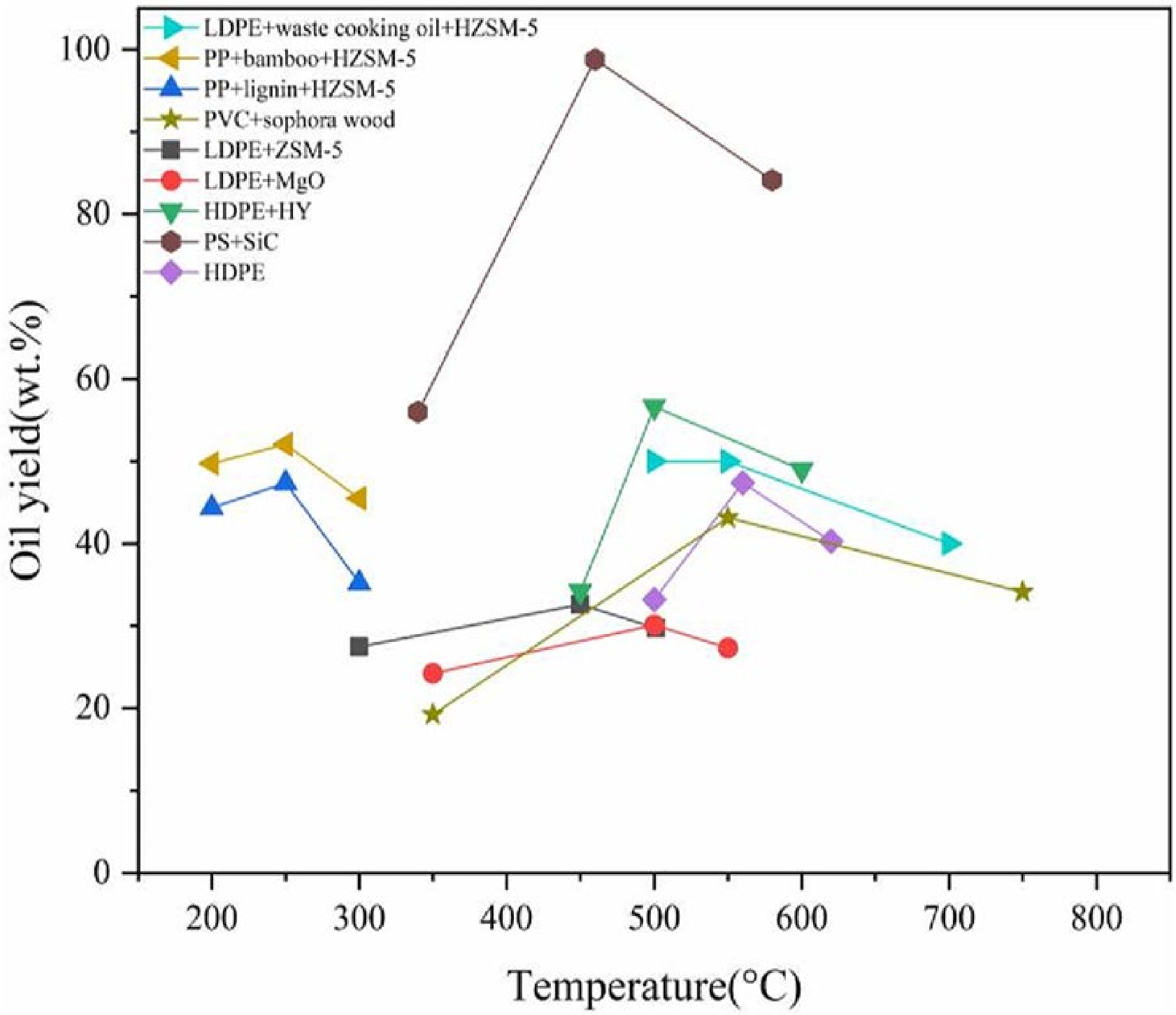


Figure 16: Oil yield and pyrolysis temperature.

Source: Hu, X., et al., 2023

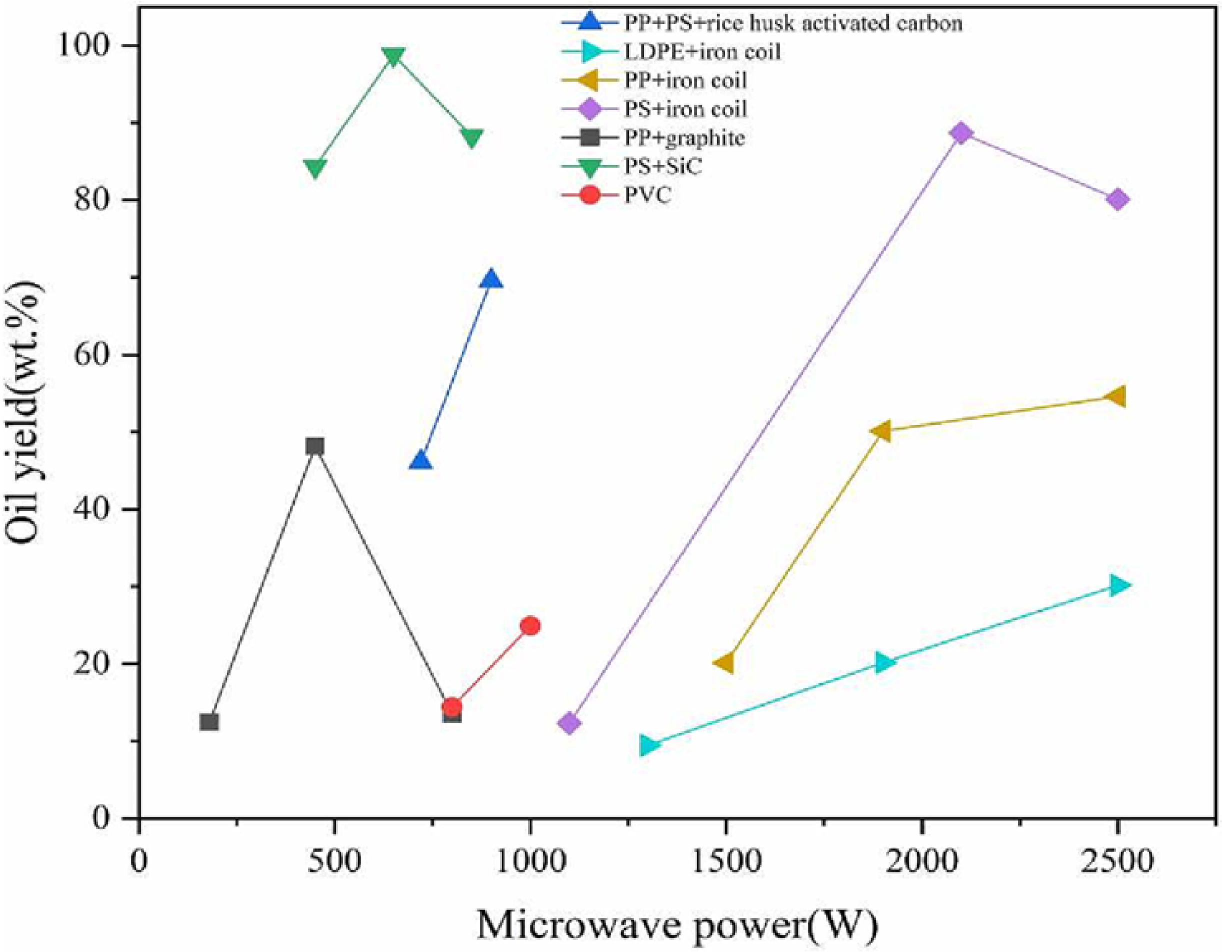


Figure 17: Oil yield and microwave power.

Source: Hu, X., et al., 2023

Industrial Refrigeration

Freeze drying, known as lyophilization or cryodesiccation. is one of the methods used to dry products or bioactive compounds that are sensitive to heat and may degrade at higher temperatures. This industrial refrigeration technique can be applied across multiple industries, including food processing, biotechnology, pharmaceuticals, taxidermy, chemical synthesis, and more. Although it is widely applicable, the traditional vacuum freeze-drying process is considered the most expensive dehydration process due to its long drying duration, excessive energy consumption, and high capital, operational, and maintenance costs (Nwankwo et. al., 2023). Generally, a freeze dryer starts by flash freezing product to as low as -80°C (-112°F) to retain product quality. Next, the water is removed under vacuum and slowly heated until the triple point — the point where water sublimates from solid to gas — is reached. This phase must be held constant, and water must be sublimated slow enough to not damage the product. In some cases, a pressure rise test is performed to ensure there is no more evaporation by sealing the chamber and checking for pressure rise. To ensure absolute dryness, the product may undergo a secondary drying phase and then be prepared for storage

(Eurotherm, n.d.). An example schematic of a traditional vacuum freeze dryer can be seen in Figure 18.

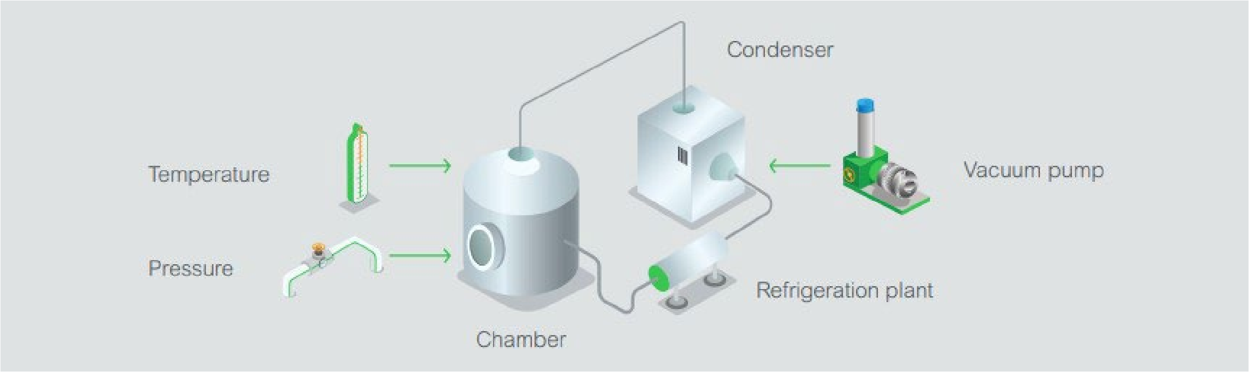


Figure 18: Basic arrangement for a traditional vacuum freeze dryer.

Source: Eurotherm, n.d.

A microwave-assisted freeze-drying process can increase the drying rate and reduce energy usage while preserving nutritional substances. There are two strategies for a hybrid microwave freeze-drying approach: simultaneous freeze drying or a two-stage drying. In the simultaneous approach, the entire process is completed under a vacuum and microwaves are used to supply heat required during the sublimation process, whereas in the two-stage approach there is freeze pre-drying followed by a microwave or microwave vacuum to finish drying (Nwankwo, C., et. al., 2023). Due to the selectivity of microwaves, the frozen bulk temperature rises, and frozen water molecules gain sufficient energy to sublimate under the vacuum, eliminating moisture from the frozen region (Nwankwo, C., et. al., 2023). An example schematic for a simultaneous microwave freeze dryer can be seen in Figure 19 with the actual machine shown in Figure 20. The systems can be modular, with a microwave power of 45 kW to 110 kW and a dehydration capacity of 90 kg/h (Advanced Environmental Technologies Limited, n.d.-b).

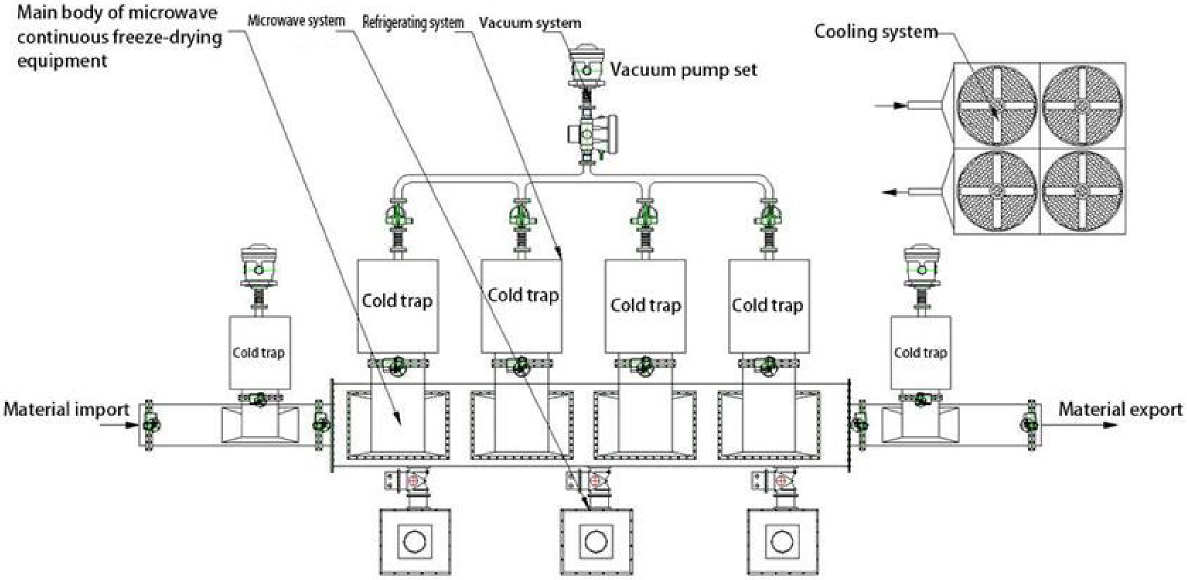


Figure 19: Example schematic for a simultaneous continuous microwave freeze dryer.

Source: Advanced Environmental Technologies Limited, n.d.-b

Figure 20: Tunnel type continuous microwave vacuum freeze dryer.

Source: Advanced Environmental Technologies Limited, n.d.-b

Currently there are a variety of products that use microwave-assisted freeze drying. Within the food processing field, microwave-assisted freeze drying has been shown to produce high quality products with reduced processing time, lower cost, and high customer satisfaction. One case study within the cannabis industry claimed up to six times more throughput with a small footprint, reducing drying times from seven days down to two hours (Enwave, n.d.). Although these products are already out on the market, there are some products that have yet to be tested for compatibility with microwave-assisted systems. With this, the current TRL is estimated to be 6 to 9.

Other Applications

Since technology is rapidly developing, the above information is not inclusive of all industrial microwave applications. There are several other industrial microwave applications that have not been evaluated as part of this report but should be mentioned, such as microwave annealing in semiconductor production (Veettil, et al., 2023), microwave plasma for synthetic diamonds (Sairem, n.d.), and emerging applications such as hydrogen production (Zhao, et al., 2023). Although the TRL was evaluated for this report, higher TRL technologies should be further evaluated for their economic feasibility to ensure market adoption.

Commercially Available Solutions

Magnetron Microwave Generators

Microwaves can be generated by a magnetron oscillator. This technology was originally developed during World War II in 1940 for radar applications (Marsh, 2018). Figure 21 shows a schematic of a magnetron and a simple breakdown of its parts. The magnetron is a high-vacuum electronic valve with a hollow copper anode that has a resonant microwave structure. This anode is surrounded by a magnet with an electron-emitting cathode (filament) in the center. An electron cloud is formed around the cathode when heated and when the anode is supplied with a high voltage, the electrons will travel from the cathode to the anode. Due to the magnetic field produced by the magnets, the electrons are forced to travel in a quasi-circular path around the cathode. As a result, the cavities in the anode will generate a resonant microwave field which is then extracted using an antenna connected to a launcher (Production Engineering, 2024). Currently, individual magnetron generators can output up to 100 kW at 915 MHz. However, since many technologies can be modular, ten of these individual generators can be combined to produce a 1 megawatt (MW) system. (IMS, n.d.-b) An example of a typical linear power supply magnetron generator design can be seen in Figure 22.

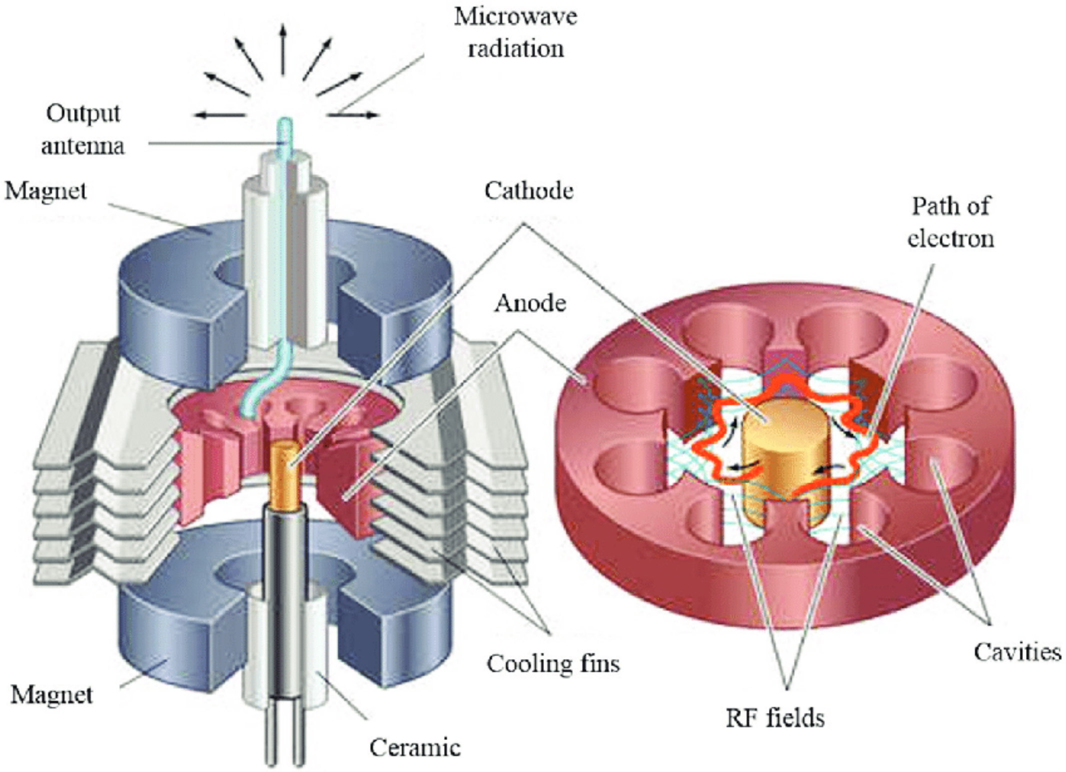


Figure 21: Schematic of a magnetron.

Source: Borrell, A. & Salvador, M., 2018

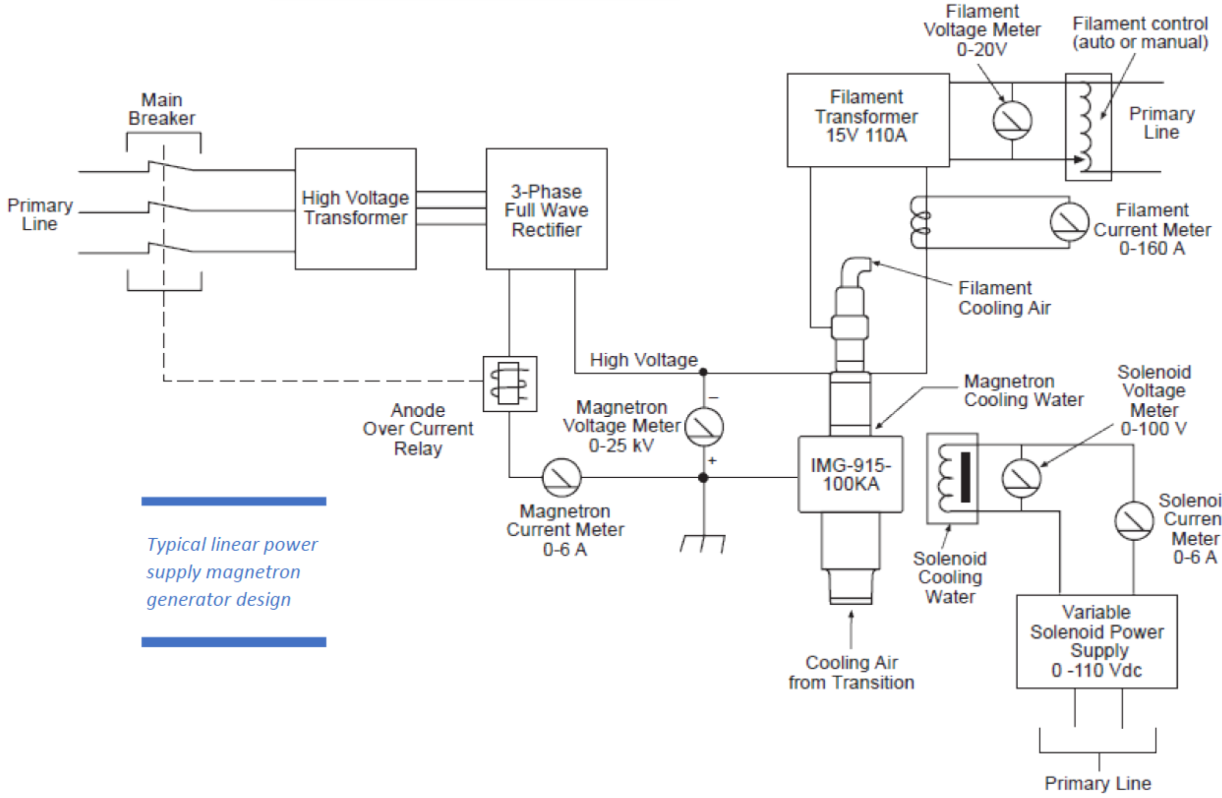


Figure 22: Linear power supply magnetron generator design.

Source : Istok. (n.d.)

Solid-State Microwave Generators

Recent innovations in telecommunications have led to the development of solid-state semiconductor devices that can generate and amplify radio frequency signals, including microwave frequencies. Compared to magnetron generators, solid-state devices can produce variable frequencies, allowing for slight changes in frequency and phase in real time. This has the potential to remove standing waves and potential hot spots to improve quality and uniform heating. However, due to cost implications, solid-state microwave generators may not be scalable for many industrial processes currently. As the technology continues to develop, the price may come down and replace traditional magnetron generators (Bayliss, D., Hooper, G., 2019). An example of a 200 kW solid-state microwave generator can be seen in Figure 23. The design architecture of a solid-state generator can be seen in Figure 24.

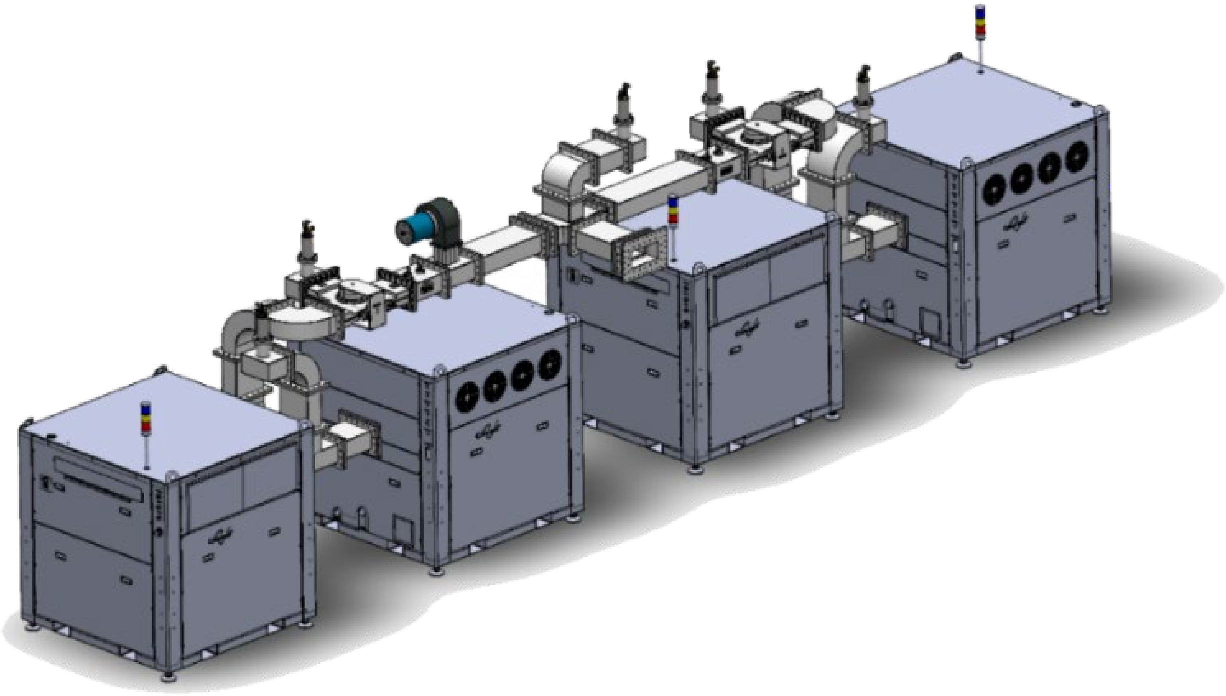


Figure 23: 200 kW, 902–928 MHz solid-state high-power system.

Source: Crescend Technologies, n.d.-a

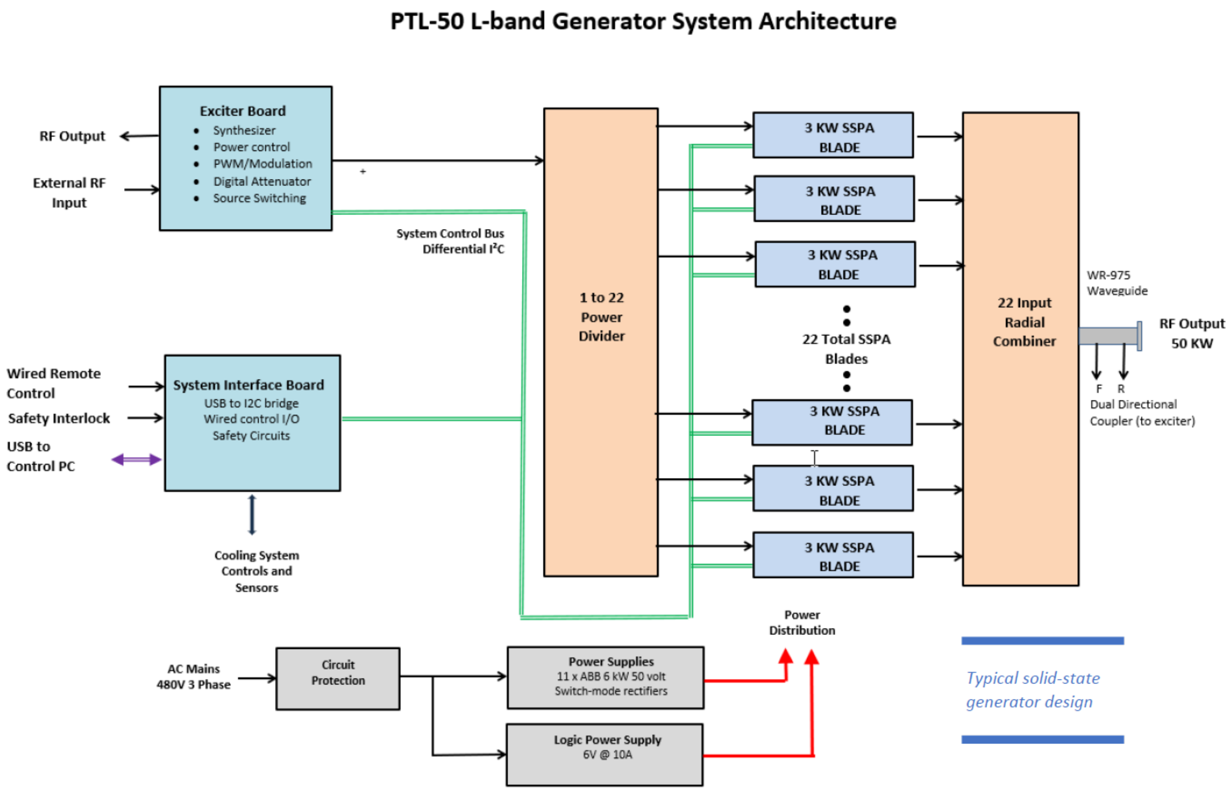


Figure 24: Solid-state generator design.

Source: Crescend Technologies, n.d.-d

Generator Comparison

Some of the main differences between high power 915 MHz solid-state and magnetron generators are highlighted in Table 1 below.

Table 1: High Power 915 MHz Magnetron and Solid-State Microwave Differences

Characteristic	Magnetron	Solid State
Maximum power per unit	75 or 100 kW, outputs cannot be combined	50 kW, outputs can be combined to deliver 100 or 200 kW
Operating frequencies	Fixed at 896, 915, or 922 MHz	Frequency agile from 902–928 MHz (896 available)
Power control range	30–90 kW or 20–75 kW	0–50 kW
Power on/off or change power level	2–10 seconds	Nearly instantaneous

Characteristic	Magnetron	Solid State
Warm-up or cool down time	10 minutes	Zero
Power control accuracy	+/- 1 kW	+/- 100 W
Automatic Load Tuning	No	Yes
Adaptive power control	No	Yes
Power and frequency stability	Moderate	Very high
Equipment cost	Moderate	More expensive
Reliability	Poor to moderate	Very high
Power element lifetime	About 6,000 hours.; warranty 3,000 hours	500,000+ hours
Serviceability	Poor	Very high
External control interface	Programmable logic controller (PLC)	PLC or computer via Ethernet
Pulse mode operation	No	Yes
Cooling	Water cooled	Water cooled
Reflected power protection	Internal circulator	Internal circulators and adaptive power control

Source: Crescend Technologies, n.d.-c

Crescend Technologies also performed an analysis of the end-use efficiency between magnetron and solid-state microwaves. Most magnetron generator manufacturers do not publish their efficiency. Stellant and Econoco tube manufacturers state an efficiency of 83–88 percent for their magnetrons (Crescend Technologies, n.d.-d). When calculating total system efficiency, other losses coming from the transformer, waveguide isolators, and load matching must be considered. Waveguide isolators can have an insertion loss which results in passive unnecessary heating of the device itself. An isolator return's loss is power that may be reflected back to the source. Generally, the higher the frequency, the greater the attenuation or insertion loss. A high-power isolator is usually needed to isolate the generator from reflected microwaves, otherwise the tube may prematurely fail. Cooling of the devices is also necessary if there are greater return losses that may lead to unnecessary heating of the device. Load matching is the ability for the produced microwave to match the ideal frequency in the load to prevent reflection of energy. Magnetrons are fixed frequency sources and generally rely on the design of the applicator to establish load impedance. Solid-state devices can use software to easily adjust specific frequencies in real time and optimize the load match with a specified operating range. Figure 25 illustrates the process from the magnetron generator to the load (Crescend Technologies, n.d.-d).

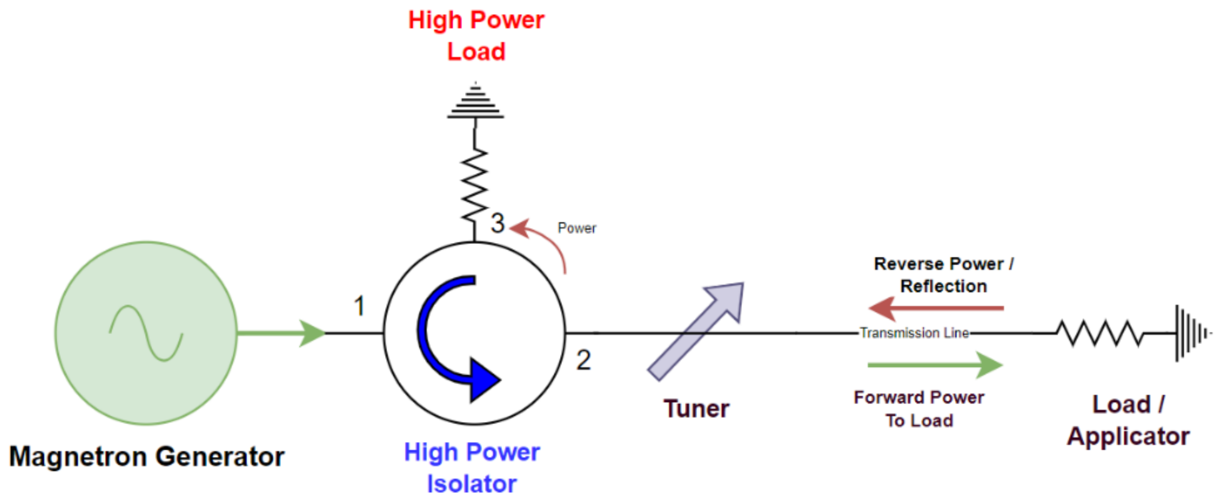
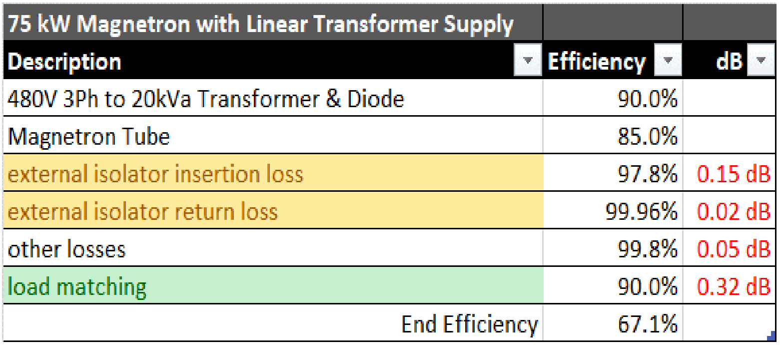


Figure 25: System schematic for a magnetron generator with load matching.

Source: Crescend Technologies, n.d.-d

NXP, one of the largest semiconductor manufacturers, produces a laterally-diffused metal-oxide semiconductor (LDMOS) transistor with a maximum efficiency of 67 percent at 915 MHz in a 750 W package. While LDMOS technology is considered mature, commercially available solid-state microwave generators still currently use this technology. Next generation gallium nitride (GaN) transistors are expected to increase efficiency in microwave generators with Ampleon advertising a 78 percent efficiency at 915 MHz for a 1.4 kW package (Crescend Technologies, n.d.-d). With this in mind, the end efficiency of a magnetron system and a solid-state system assuming GaN transistors is estimated below in Figure 26 (magnetron system) and Figure 27 (solid-state system). Figure 26 and Figure 27 demonstrate estimated examples only; the potential buyer must inquire from their manufacturer on their expected alternating current (AC) to MW efficiency. As the technology systems improve, these examples also change.

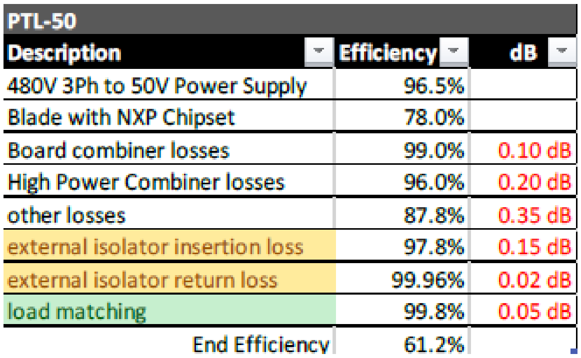


75 kW Magnetron with Linear Transformer Supply

Description	Efficiency	dB
480V 3Ph to 20kVa Transformer & Diode	90.0%	
Magnetron Tube	85.0%	
external isolator insertion loss	97.8%	0.15 dB
external isolator return loss	99.96%	0.02 dB
other losses	99.8%	0.05 dB
load matching	90.0%	0.32 dB
End Efficiency	67.1%	

Figure 26: Estimated end efficiency for a magnetron system [example only].

Source: Crescend Technologies, n.d.-d



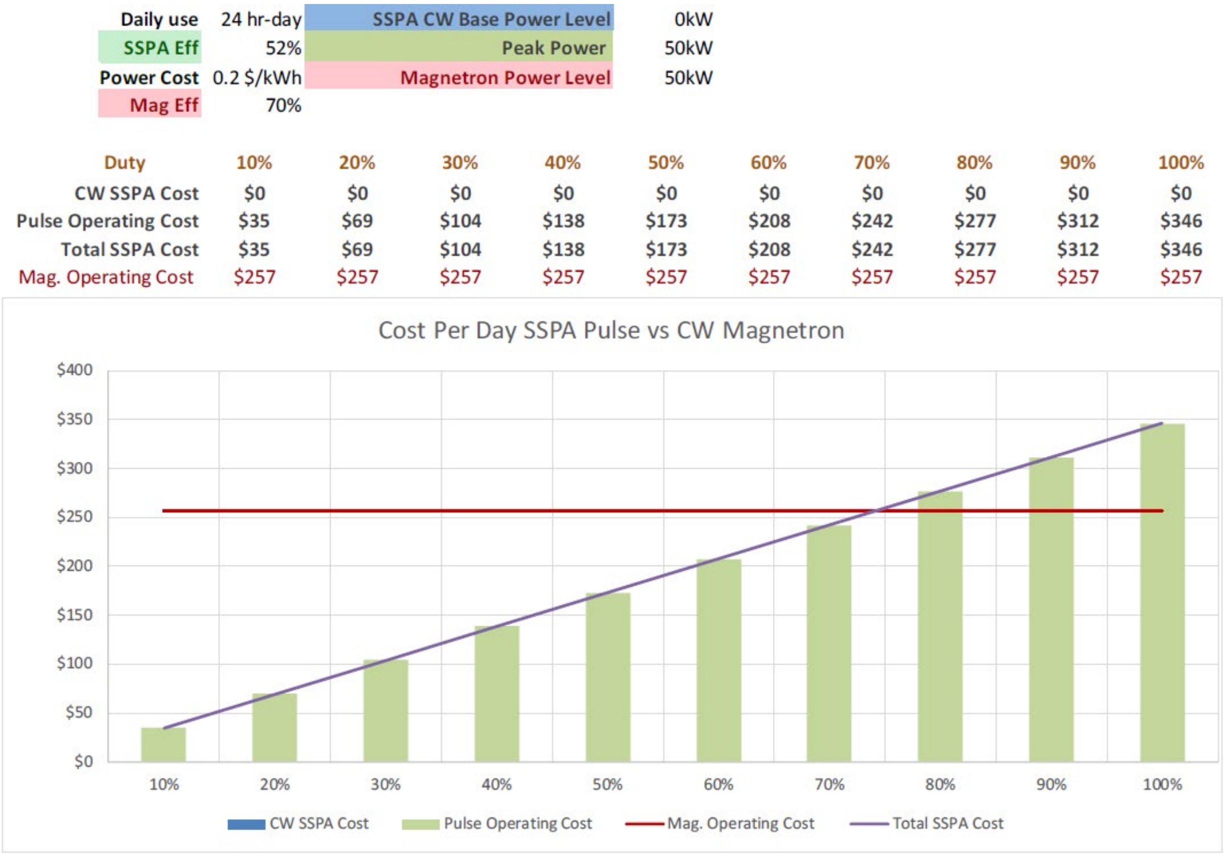
PTL-50

Description	Efficiency	dB
480V 3Ph to 50V Power Supply	96.5%	
Blade with NXP Chipset	78.0%	
Board combiner losses	99.0%	0.10 dB
High Power Combiner losses	96.0%	0.20 dB
other losses	87.8%	0.35 dB
external isolator insertion loss	97.8%	0.15 dB
external isolator return loss	99.96%	0.02 dB
load matching	99.8%	0.05 dB
End Efficiency	61.2%	

Figure 27: Estimated end efficiency for a solid-state system [example only].

Source: Crescend Technologies, n.d.-d

While the end efficiency of magnetron systems is estimated to be higher when operating, solid-state systems can benefit by operating in a pulse power mode at reduced duty cycles for different applications. This allows for a significant amount of power savings (Crescend Technologies, n.d.-d). An example model of the cost savings for solid-state power amplifiers (SSPA) vs. magnetron for varied duty cycles can be seen in Figure 28.



Daily use	24 hr-day	SSPA CW Base Power Level	0kW
SSPA Eff	52%	Peak Power	50kW
Power Cost	0.2 $/kWh	Magnetron Power Level	50kW
Mag Eff	70%		

Duty	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
CW SSPA Cost	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Pulse Operating Cost	$35	$69	$104	$138	$173	$208	$242	$277	$312	$346
Total SSPA Cost	$35	$69	$104	$138	$173	$208	$242	$277	$312	$346
Mag. Operating Cost	$257	$257	$257	$257	$257	$257	$257	$257	$257	$257

Figure 28: Cost savings for SSPA vs. magnetron for varied duty cycles [example only].

Source: Crescend Technologies, n.d.-d

Microwave System Components

There are a wide range of microwave system parts and components that can be customized for each application and facility. After the microwave generator produces microwaves, a waveguide is used to transmit the microwaves directly to the desired target/chamber. A waveguide is usually the simplest component of the system and typically made of aluminum to reduce weight and energy loss. The dimensions of the waveguide are designed to resonate with the traveling microwaves to reduce energy loss as well (Crescend Technologies, n.d.-b). An example of a section of a waveguide can be seen in Figure 29.

Figure 29: Example section of a waveguide.

Source: Crescend Technologies, n.d.-b

The applicator is the destination for microwaves. This is where the microwave meets the load and terminates. An example could be a batch or continuous oven, a vertical tank, a horizontal mixer, or a conveyor belt with microwave safe doors. Below in Figure 30 is an example of a conveyor belt oven applicator (Crescend Technologies, n.d.-b).

Figure 30: Example of a conveyor belt oven applicator.

Source: Crescend Technologies, n.d.-b

Technology and Market Barriers

As part of this report, manufacturers and industry experts were interviewed to understand more about the current industrial microwave industry and technology.

The questionnaire in Appendix B: Industrial Microwave Questionnaire was used for the discussion. The following sections use the questionnaire responses to inform industrial microwave technology and market barriers and opportunities, related codes and standards, high-value applications, and recommendations for market adoption.

Cost

While solid-state technology is more expensive than magnetron, both technologies compete with natural gas in affordability. While solid-state technology works to decrease the dollar per watt, magnetron microwaves face cost efficiency barriers, specifically modular cases in some applications. Assuming an increase in commercial availability, the economies of magnetron microwaves might appear more competitive if modular systems increased from 100 to 200 kW systems. Due to natural gas' affordability, this challenges electrification efforts unless rebates assist these efforts. While existing magnetron systems cost $1 to $1.5 per watt, solid-state systems cost $4 to $5 per watt. Manufacturers aspire to decrease the cost per watt for solid-state systems to under $3 per watt and increase efficiency to 70 percent to increase competitiveness. In payback years, manufacturers strive for three to five years maximum payback. In terms of total project cost, design, and installation of the solid-state technology, each system varies. Compared to solid-state technology, magnetron technology has economic and efficiency advantages.

Magnetron vs. Solid-State Technology Barriers

Table 2 highlights technology barrier variations between the two main technologies in the microwave industry.

Table 2: Magnetron vs. Solid-State Technology Barriers

Technology Barrier	Magnetron	Solid State
System Sizing	Need to do modular sizing for a large system e.g., building a 400 kW system with four 100 kW modules might not be cost-effective	Can do larger systems such as a 400 kW but need to factor in cost of generators
Maintenance	Working with high voltage can be difficult to maintain e.g., need to change the magnetron tube properly.	No replacing of tube
Power Factor	Not a concern above 0.95	Not a concern above 0.95
Efficiency (percent): Transfer AC to microwave energy	75 percent	50 to 60 percent
Power Output	Limited to manufacturer production (currently 100 kW module)	Waveguide limits max power, transmission line increases cost

Process Flow Integration

Customer integration causes a barrier for microwave technology because of the complexity of the equipment. The implementer needs to verify that the microwave technology truly applies to the facility's needs and whether the facility wishes for a new process or retrofit. The implementer should consider the raw material location in the facility, material handling in and out of the microwave applicator while maintaining throughput, and efficient application use from the facility's microwave energy intake. Each system fits uniquely to each facility and implementers need to study the size and power needed for the plant. The facility needs to accommodate the technology and materials such as chemicals and gases, change workflows, and implement training, standard procedures, and maintenance.

Grid Infrastructure

Industrial microwave technology can run into grid infrastructure barriers such as adding significant electrical load to the grid or not having access to the power required for the application. For example, if an industrial facility needs a MW of AC power, the facility might not have access to that. For mining, some facilities have plenty of power while those located in remote areas may not. If industrial microwaves were deployed across the U.S., there would be a considerable increase in electricity demand that the electric grid may not be ready for. Continued efforts for industrial electrification could more than double current U.S. power demand (Gimon, E., 2023).

Knowledge and Awareness

Industrial microwave technology faces lack of familiarity and knowledge among manufacturers and laboratories. The following contributes to the lack of knowledge:

Bias

Unfamiliarity with industrial microwave technology has caused bias such as radiation exposure assumptions, as well as skepticism of the efficiency and scalability. In hopes of removing these biases, industry experts shared a microwave-based methane reformer with a company in Canada currently performing demonstrations of hydrogen production. In these demonstrations, industry experts hope to see proof of energy efficiency at scale from industrial microwaves.

Lack of Demonstrations

While manufacturers and industry experts know of some current demonstrations in the U.S., they could not share more due to non-disclosure agreements. Manufacturers need to perform demonstrations to expand their knowledge of materials reactive to this technology. Industry experts also need to increase their knowledge in designing microwaves for high-temperature applications. To further pursue better economics and energy benefits, industry experts need to move away from a lab scale and increase modeling of the technology. The lack of available information on operation and benefits hinders widespread adoption of the technology.

Niche Applications and Incompatible Materials

Although industrial microwave technology can assist niche applications, it is difficult to research and develop further with visibility. Niche applications can limit the technology's customer base, require specialized products, and result in costly projects.

The lack of knowledge about materials and processing methods makes it more difficult to adopt the technology. Manufacturers have found materials that do not react with the microwaves' technology.

Since only some materials react and industry experts and manufacturers have no textbook, they must do the work to learn more about the technology.

Lack of Characterization Tools for High Temperature Applications and Lack of Standardization

Lack of characterization tools for high temperature applications contributes to the lack of knowledge barrier. For example, adding tools with the ability to take dielectric measurements at high temperatures would accelerate development of the technology. To tackle the lack of tools barrier, industry experts should install and develop their own characterization tools and make them available in-house or work with partners. Building these tools would ensure modelling accuracy before moving forward to the building stage. The lack of standardization for material testing creates a need to further understand material interaction with microwaves.

Scalability

Industry experts need to develop and research scaling plans that consider a product's capacity, performance, integration at facilities, and quality to streamline technology processes at a large scale. Methods for automation should be further investigated to improve scalability while maintaining smooth workflows and throughput. To sell the technology to large chemical producers, for example, the technology requires large scale production. At the same time, manufacturers and industry experts need to find markets for commodity chemicals at scale.

Technology and Market Opportunities

Industrial microwaves have opportunities for technological and market growth due to higher throughput, operational cost savings, corporate goals for sustainable products and reputation, and incentive program inclusion.

Higher Throughput

Volumetric heating can decrease processing times which in turn can increase throughput compared to conventional heating, thereby increasing revenue. As mentioned in the Food Production section, beef jerky production entails a large amount of thermal energy due to the time-consuming drying and baking process. Microwaves can heat the jerky uniformly and faster because of their volumetric heating properties. The faster processing times can also preserve the jerky's authentic taste. Industrial microwave application reports found microwave drying to be more energy efficient compared to conventional electrical resistance drying (Advanced Environmental Technologies Limited, n.d.-a).

Operational Cost Savings

Since many facilities are considering switching from fossil fuel consuming processes to electric processes, the commodity's price difference must be considered when evaluating cost-effectiveness. The spark spread is the difference between the price of electricity supplied to the generator and the cost of natural gas needed to produce electricity. Spark spread can vary over time and by region across the U.S. and is a key factor in determining the return on investment of fuel switching initiatives. The spark spread is defined by the following equation (EIA, 2023):

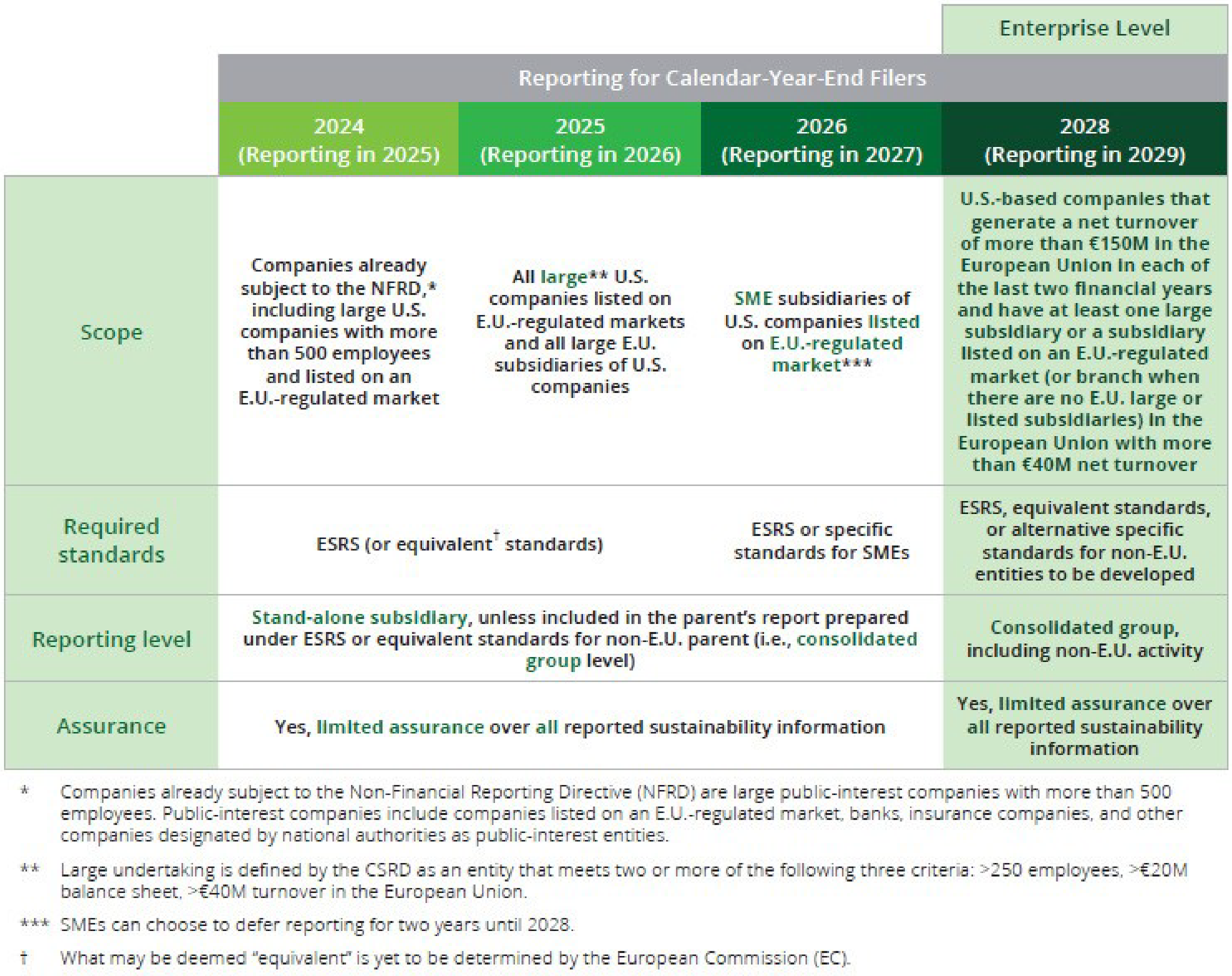
$$Spark\ Spread\left(\frac{\$}{MWh}\right) = Power\ Price\left(\frac{\$}{MWh}\right) - [Natural\ Gas\ Price\left(\frac{\$}{mmBtu}\right) * Heat\ Rate(\frac{mmBtu}{MWh})$$

A higher spark spread signifies higher electricity prices compared to natural gas prices in the region, and therefore lower cost savings when fuel switching from natural gas to electricity.

Corporate Goals for Sustainable Products and Reputation

Due to the importance of global environmental, social, and governance (ESG) impacts a corporation may have, industrial microwaves may be highly valued in industries where a reputation of sustainability adds additional value to its products. A recent study by McKinsey & Company showed that consumers are shifting their spending toward products with ESG-related claims. The study found products making ESG-related claims had a 28 percent cumulative growth over the last five years compared to 20 percent for products that made no such claims (Bar Am, J. et al, 2023). Since consumers are changing their buying behavior to value sustainable products, companies may see industrial microwaves as an attractive solution for achieving ESG goals and growing their sustainability reputation. Cosmetics and fashion are examples of consumer products where customers strongly value sustainability. Aviation fuel production is another example that places a high value on ESG reporting across multiple industries due to its impact on reported indirect (Scope 3) emissions across the corporate value chain. Some companies also have an internal price for carbon emissions savings that is not disclosed to the public. Many companies have set net-zero emissions timeline targets for their operations. These goals may be an indication of how aggressive they are willing to spend on ESG initiatives.

ESG standards are continually updating with the European Union (EU) Corporate Sustainability Reporting Directive (CSRD) being put in place for U.S. companies listed in the EU market starting in 2024. The CSRD is a new directive that requires companies to divulge climate change and environmental information such as GHG emissions, reduction targets, and climate risk assessments in publicly disclosed management reports. Figure 31 shows the expected ESG reporting calendar for U.S. companies listed on an EU market. By 2029, U.S. companies of a certain scope in the EU will have to report at the ‘Consolidated group’ level, meaning non-EU activity will have to be reported as well (Deloitte, 2023). This will contribute to an increase in public awareness of ESG impacts of companies and their products in the U.S. in the future.



				Enterprise Level
	Reporting for Calendar-Year-End Filers			
	2024 (Reporting in 2025)	2025 (Reporting in 2026)	2026 (Reporting in 2027)	2028 (Reporting in 2029)
Scope	Companies already subject to the NFRD,* including large U.S. companies with more than 500 employees and listed on an E.U.-regulated market	All large** U.S. companies listed on E.U.-regulated markets and all large E.U. subsidiaries of U.S. companies	SME subsidiaries of U.S. companies listed on E.U.-regulated market***	U.S.-based companies that generate a net turnover of more than €150M in the European Union in each of the last two financial years and have at least one large subsidiary or a subsidiary listed on an E.U.-regulated market (or branch when there are no E.U. large or listed subsidiaries) in the European Union with more than €40M net turnover
Required standards	ESRS (or equivalent† standards)		ESRS or specific standards for SMEs	ESRS, equivalent standards, or alternative specific standards for non-E.U. entities to be developed
Reporting level	Stand-alone subsidiary, unless included in the parent's report prepared under ESRS or equivalent standards for non-E.U. parent (i.e., consolidated group level)			Consolidated group, including non-E.U. activity
Assurance	Yes, limited assurance over all reported sustainability information			Yes, limited assurance over all reported sustainability information

* Companies already subject to the Non-Financial Reporting Directive (NFRD) are large public-interest companies with more than 500 employees. Public-interest companies include companies listed on an E.U.-regulated market, banks, insurance companies, and other companies designated by national authorities as public-interest entities.

** Large undertaking is defined by the CSRD as an entity that meets two or more of the following three criteria: >250 employees, >€20M balance sheet, >€40M turnover in the European Union.

*** SMEs can choose to defer reporting for two years until 2028.

† What may be deemed "equivalent" is yet to be determined by the European Commission (EC).

Figure 31: ESG reporting calendar for U.S. companies listed on an EU market.

Source: Deloitte, 2023

Incentive Programs

While manufacturers expressed interest in incentive programs to motivate the market, they have not promoted their products as part of utility programs yet. Involvement in incentive programs could further propel the technology in the market and increase competition against natural gas options. The following programs offer incentives for industrial technologies such as industrial microwaves:

Federal and State Programs

- The Industrial Efficiency & Decarbonization Office of the DOE funds projects that accelerate innovation and adoption of cost-effective technologies that assist the reduction of industrial GHG emissions. Selected participants include national laboratories, nonprofit organizations, private companies, and other entities (U.S. DOE, n.d.-a).
- The Inflation Reduction Act (IRA) of 2022 is the single largest investment in climate and energy in U.S. history, focusing on a net-zero economy by 2050. The IRA directs almost $400 billion in funding to clean energy through a mix of tax incentives, grants, and loan guarantees (McKinsey, 2022).

- The Qualifying Advanced Energy Project Credit (48C) program was recently expanded with a $10 billion investment under the IRA in 2022. This program provides tax credits for investments in advanced energy projects (U.S. DOE, 2023a).
- The Bipartisan Infrastructure Law (BIL) was passed in 2021 and expands funding for new and existing DOE programs (U.S. DOE, 2023b).
- Industrial Research and Assessment Center Implementation Grants are designed to provide up to $400 million in grants, funded by section 40521 of the BIL to small- and medium-sized manufacturers (SMMs) to implement recommendations made in Industrial Assessment Center or Combined Heat and Power Technical Assistance Partnership assessments (U.S. DOE, 2023c).
- The Office of Clean Energy Demonstrations (OCED), established in 2021, manages more than $25 billion in funding to deliver clean energy demonstration projects at scale in partnership with the private sector to accelerate deployment, market adoption, and the equitable transition to a decarbonized energy system. Funded by the BIL, $6.3 billion is allocated to support the advancement of transformational technologies needed to decarbonize the industrial sector (U.S. DOE, 2023d).
- There are some multi-state initiatives that are increasing in membership to reduce CO_2 emissions. These include the Regional Greenhouse Gas Initiative, the Western Climate Initiative, the U.S. Climate Alliance, the Governors Accord for a New Energy Future, the Pacific Coast Collaborative, and the Transportation and Climate Initiative (Center for Climate and Energy Solutions, n.d.-a).

California Initiatives

The state of California has passed the following senate bills (SB) to promote decarbonization of industrial processes:

- SB 32 aims to reduce GHG emission to 40 percent below 1990 levels by 2030.
- SB 100 ensures that California's transition to a zero-carbon electric system does not cause or contribute to GHG increases.
- 2019 California Energy Efficiency Action Plan expands SB 350, doubling energy efficiency by 2030 to include agriculture, industry, and electrification.

The California Energy Commission also releases solicitations and funding to promote technology development and demonstration projects of promising pre-commercial technologies to accelerate industrial decarbonization and increase overall energy efficiency to reach statewide goals (California Energy Commission, n.d.).

The state of California also manages its own cap-and-trade program. This is a key element used to reduce GHG emissions by creating economic incentives for investment in cleaner, efficient technologies. The California Air Resources Board (CARB) manages the program and creates allowances equal to the total amount of permissible emissions. Every year the allowance floor price increases, less allowances are created and auctioned off, creating a sustained carbon price signal to prompt action to reduce emissions (California Air Resources Board, 2023).

Related Codes and Standards

For product installation, implementers must meet regulatory codes and standards to ensure safety. The following are related industry codes and standards, but they do not cover all the standards applicable to the technology and its high value applications.

Occupational Safety and Health Administration (OSHA):

- 1910.97 – Nonionizing radiation exposure
- 1926.54 – Microwave power density exposure in construction industry (U.S. Department of Labor, n.d. -a)

UL standards for industrial equipment may apply:

- UL 508 Industrial Control Equipment
    - UL 508A – Industrial Control Panels
    - UL 508C – Power Conversion Equipment (UL, 2019)

Food protection and sanitation requirements for food processing application:

- National Sanitation Foundation (NSF)/American National Standards Institute(ANSI) 169 – Special purpose food equipment and devices (NSF, n.d.)

Standards for chemical exposure and exhaust limits:

- Department of Industrial Relations California Code of Regulations – 5515. Airborne Contaminants (Department of Industrial Relations, n.d)
    - OSHA 1910.1450 – Occupational exposure to hazardous chemicals in laboratories
    - OSHA 1926.57 – Ventilation (U.S. Department of Labor, n.d.-b)

Industrial, scientific, medical (ISM) band standards:

- The frequency bands microwave heating operate at are the 915 MHz and 2.45 GHz band (Zhao, et al., 2023), Figure 32 illustrates the 2.45 GHz band. The Institute of Electrical and Electronic Engineers (IEEE) defined the 802.11 standards. Channels 1, 6, and 11 of IEEE 802.11 are non-overlapping channels in the Americas (Air 802, 2024). The 802.15.4 specifications in Figure 32 are for low-data-rate wireless connectivity devices (IEEE, n.d.). The BLE is specific for Bluetooth low energy radio.

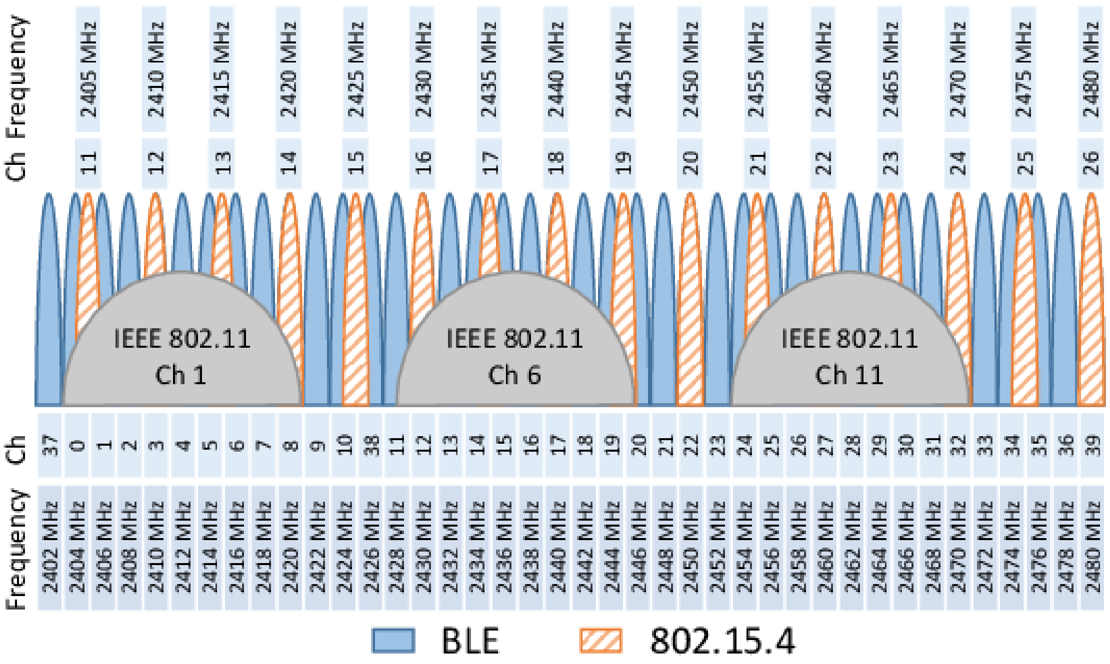
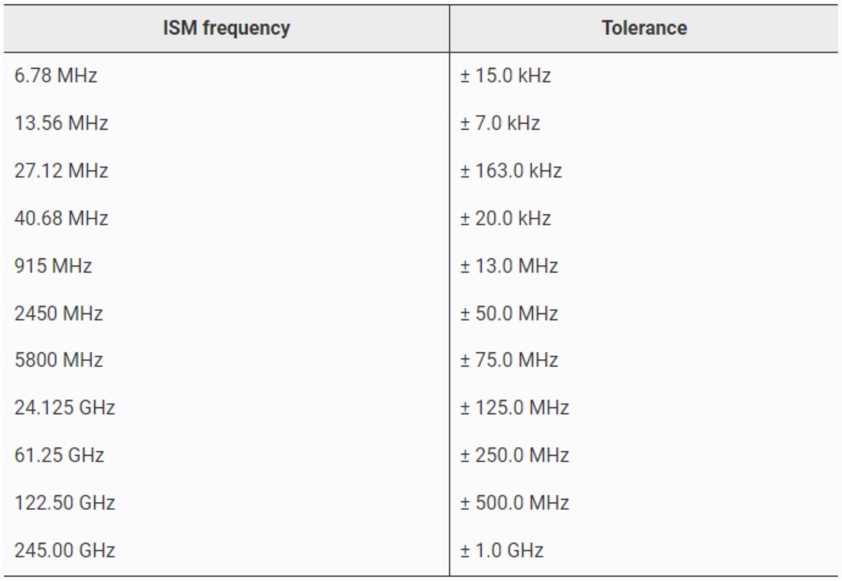


Figure 32: 2.4 GHz ISM band.

Source: Natarajan, R., et. al.,2019

- 18.301 Operating frequencies shown in Figure 33



ISM frequency	Tolerance
6.78 MHz	± 15.0 kHz
13.56 MHz	± 7.0 kHz
27.12 MHz	± 163.0 kHz
40.68 MHz	± 20.0 kHz
915 MHz	± 13.0 MHz
2450 MHz	± 50.0 MHz
5800 MHz	± 75.0 MHz
24.125 GHz	± 125.0 MHz
61.25 GHz	± 250.0 MHz
122.50 GHz	± 500.0 MHz
245.00 GHz	± 1.0 GHz

Figure 33: ISM equipment operating frequencies.

Source: National Archives, 2024

- 18.303 Prohibited frequency bands.

- Operation of ISM equipment within the following frequency bands is prohibited: 490–510 kilohertz (kHz), 2,170–2,194 kHz, 8,354–8,374 kHz, 121.4–121.6 MHz, 156.7–156.9 MHz, and 242.8–243.2 MHz. (National Archives, 2024).

High Value Applications

Customers may be interested in adopting the technology for high value applications such as niche applications, gasification, mining, food processing, and more.

Niche Applications

Industrial microwave technology presents opportunities for niche applications such as shoemaking. Microwave technology can replace other technologies to make shoe soles quickly by rapidly heating the foam to form the shoe. Industrial microwave technology can also be applied to the lab grown diamond industry. Beyond jewelry, industrial diamonds can be used for high energy or high-density applications such as developing diamond rapid charging of batteries. The government defense sector was an early adopter for lab grown diamonds, but manufacturers foresee the use of these diamonds outside of defense applications. Manufacturers hope to see an increase in demand for lab grown diamonds which could increase the need for industrial microwaves. In addition to shoemaking and diamonds, microwave manufacturers also hope to increase interest in other markets with industrial processes heat needs.

Gasification Application

Reported hydrogen production methods mainly involve fossil fuel steam conversion and natural gas-based conversion. Microwave heating can return an expeditious, selective, and volumetric heating process, providing benefits traditional heating methods cannot. Benefits can include a higher conversion and selectivity with a decreased system temperature needed. Industrial microwave technology has potential for environmentally sustainable solutions in hydrogen production. Microwave technology can use methanol or ammonia as carrier material for hydrogen, then the microwave could decompose the chemical back to hydrogen. Microwave reactors can work as an external energy supply to reform low-carbon alcohols at low temperatures such as methanol made of only carbon-hydrogen bonds. The hydrogen production can be processed at a low temperature of about 200–300°C. Storage and transportation challenge hydrogen production. With ample resources and high hydrogen content of low-carbon alcohols, these materials may be suitable for on-demand hydrogen production. As a result, hydrogen can be stored in non-gaseous compounds and released only when needed (Zhao, et al., 2023). If the hydrogen economy continues to grow where various sources of hydrogen are required, such as hydrogen fuel, then industrial microwaves might be a better fit in terms of throughput and convenience.

The industrial microwave experts interviewed always track energy efficiency energy savings as a metric in their technology development studies. For example, they found using microwaves for methane reforming increased energy efficiency. Currently, methane reforming uses a steam method to produce hydrogen which also produces a large amount of CO_2. The process of electrolysis uses electricity to split water into hydrogen and oxygen which results in high energy consumption (U.S.

DOE, n.d.-b). Microwave heating can rapidly and selectively heat a catalyst to promote reactions, increasing energy efficiency compared to water electrolysis.

Mining and Metallurgy

In mining processes, selective heating can save energy in the metallurgical recovery process via advancing mineral liberation and diminishing the ore competency. Selective heating can potentially save 35 percent of energy compared to traditional ore breaking processes and save 10–46 percent per ton of energy for future metal production overall (Sepro Laboratories, n.d.).

The global steel industry annually utilizes 900 million tons to over half of seaborne iron ore from the mines in the Pilbara region of Western Australia. China produces more than half of the world's steel and imports most of their iron ore from the Pilbara mines. A company based in Australia called RioTinto searches for low-carbon steelmaking processes for Pilbara iron ores. Through these efforts, an advanced technology called BioIron that uses sustainable biomass and microwave energy instead of coal to convert ores into iron was created. With the technology, RioTinto estimates potential CO_2 emission reduction up to 95 percent compared to the blast furnace method (Farry, S., 2024).

Food Processing

Due to the volumetric heating benefits of microwaves, food production can benefit from higher throughput and energy efficiency for various processes. In an interview with a manufacturer, they shared an example of using hydrocarbon-based heating sources to dry California walnuts after seasoning. Unfortunately, the manufacturer could not share more about the case due to non-disclosure agreements. The following examples highlight higher throughput and energy efficiency. Rather than using hot air heating, microwaves can decrease 80 percent of processing time and improve the quality of the product in drying/roasting coffee beans (TorWave, n.d.). In freeze-drying processes, the use of microwaves can shorten processing time, reduce cost, improve product quality, and increase customer approval. A case study in cannabis drying claimed decreased processing time from seven days to two hours due to microwaves' higher throughput (Enwave, n.d.).

Chemical Processing

Microwave systems can be used for the following processes: drying, curing, heating, reacting, sintering, catalyzing, extracting, sterilizing, and calcinating (IMS, n.d.-c). A pilot study of a continuous microwave assisted pyrolysis system demonstrated better plastic (high density polyethylene) processing times, resulting in an 89.6 percent energy efficiency improvement and a pyrolysis temperature of 620°C (1148°F) (Zhou, N., et al, 2021).

The application of sintering oxide and non-oxide ceramics for materials such as aluminum oxide, silicon carbide, titanium diboride, and boron carbide can also take advantage microwave heating. Microwave sintering can produce improved uniform heating, greater property quality of the product, and higher throughput, thus reducing plant size and increasing energy efficiency, compared to conventional sintering. Since microwave technology allows volumetric heating, less time is needed to heat the component to sintering temperature than the time to dispense heat from the exterior. Rapid sintering could result in smaller grain size at a given density with improved mechanical properties (National Academies of Sciences, Engineering, and Medicine, 1994).

Recommendations for Market Adoption

Recommendations to support market adoption of industrial microwave technology are included in the following sections.

Demonstrations

Manufacturers and industry experts should develop more case studies demonstrating energy efficiency, potential energy savings, operation of the technology, materials reactive to the technology, and economics to streamline market adoption. Experts can also investigate renewable energy coordinated with electric microwave-based systems for carbon emissions reduction potential, such as in the iron and steel industry. Manufacturers frequently work with start-ups on lower powered pilot-scale systems but emphasized the need to engage at all levels even if the development takes time.

Industry Collaboration

Industry experts recommended the need for more projects between the industry and research communities. Industry experts expressed that, with a good industrial partner, there can be a more coordinated approach to solving problems, such as what to do with the chemicals produced and where to collect raw material for processes. Ideally, both the industrial and research partner would develop the technology from its foundations, allowing the industrial partner to grow the product into the market. The collaboration from the product’s foundations could improve market adoption for the product. Additionally, more industry interest or start-up engagement would allow for more technology demonstrations and increase market adoption.

Decarbonization and Incentive Promotions

A price of carbon attached to the technology’s processes would assist with electrification. Promotions of carbon capture and incentive programs could also further market adoption. From interviews conducted as part of this study, manufacturers advised that any program that would incentivize or subsidize the company’s technology would expedite the development process and shorten the timeline for commercialization.

Application Development

The development of more applications and materials testing can increase technology awareness and streamline market adoption. The development of solid-state technologies could further research on improving technology efficiency and economics, resulting in more competition to magnetron technology. With two competitive technologies in the market and both technologies testing new applications that show decarbonization and energy saving results, it could expand the market for industrial microwaves.

Technology Development

Solid-state manufacturers aspire to create more efficient and cost-effective systems as more systems enter the industrial markets. For example, researching and developing new, more efficient transistors such as gallium nitride (GaN) could enable improved processes, resulting in more efficient systems. Manufacturers aspire to replace the existing technology over time when new and more efficient technology develops.

Current solid-state technology power output is limited by waveguide materials and microwave generators. Manufacturer production, currently at a 100 kW module, limits the power output of magnetron technology. Higher power output can lead to higher throughput in microwave systems, presenting market opportunities.

Equipment Standardization

Most equipment is engineered for custom or niche applications which makes the systems more expensive. Industry experts hope to build a database of the materials that react to the technology to overcome the lack of knowledge of material and processing. The database would need to include efficiency calculations, indicate clearly how the experts measured the material, and document the overall procedure or demonstration of the system. The development of characterization tools can also improve equipment standardization of the equipment. With standardization, manufacturers can achieve economies of scale and reduce installation costs.

References

Advanced Environmental Technologies Limited. (2023). Pulsed Electric Field Processing, PEF Machine. https://www.envcare.net/pulsed-electric-field-processing.html

Advanced Environmental Technologies Limited. (n.d.-a). Microwave Beef Jerky Drying Machine, Tunnel Drying. https://www.envcare.net/microwave-beef-jerky-drying-machine.html

Advanced Environmental Technologies Limited. (n.d.-b). Tunnel type of microwave freeze drying equipment. https://www.envcare.net/freeze-dry-machine-microwave-tech.html

Air 802, (2024). IEEE 802.11 standards, Facts & Channels. https://www.air802.com/ieee-802.11-standards-facts-amp-channels.html

Amini, A., Ohno, K., Maeda, T., Kunitomo, K., (2018). Effect of the ratio of magnetite particle size to microwave penetration depth on reduction reaction behaviour by H2. Sci. Rep. 8, 1–7, 15023.

Badlam, J., et al. (2022). The Inflation Reduction Act: Here's what's in it. McKinsey & Company. https://www.mckinsey.com/industries/public-sector/our-insights/the-inflation-reduction-act-heres-whats-in-it

Bar Am., J., et al. (2023). Consumers care about sustainability-and back it up with their wallets. McKinsey & Company. https://www.mckinsey.com/industries/consumer-packaged-goods/our-insights/consumers-care-about-sustainability-and-back-it-up-with-their-wallets/

Bayliss, D., Hooper, G. (2019). Solid-state microwaves – the future? Campden BRI. https://www.campdenbri.co.uk/blogs/solid-state-microwaves.php

Borrell, A. & Salvador, M. (2018). Advanced Ceramic Materials Sintered by Microwave Technology. 10.5772/intechopen.78831.

California Air Resources Board. (2023). Cap-and-Trade Program. https://ww2.arb.ca.gov/our-work/programs/cap-and-trade-program/about

California Energy Commission. (n.d.). Solicitations. https://www.energy.ca.gov/funding-opportunities/solicitations

Ceng, S., et. al. (2021). Microwave Processing – Beyond Food. November 2021. Issue 865. https://www.thechemicalengineer.com/features/microwave-processing-beyond-food/

Center for Climate and Energy Solutions. (n.d.-a) Multi-State Initiatives. https://www.c2es.org/content/multi-state-initiatives/

Chen, Bo-Lin, et. al., (2023). Microwave-assisted freeze drying of pineapple: Kinetic, product quality, and energy consumption, Case Studies in Thermal Engineering, Volume 41, 2023, 102682, ISSN 2214-157X, https://doi.org/10.1016/j.csite.2022.102682

Crescend Technologies (n.d.-a) 200 kW 902-928 MHz High Power System. https://crescendrf.com/microwave-generators-systems/solid-state-products/200kw-l-band-902-928-mhz-solid-state-high-power-microwave-generator-system/

Crescend Technologies (n.d.-b) System Components. https://crescendrf.com/microwave-generators-systems/system-components/

Crescend Technologies (n.d.-c) Why Choose Solid State Technology? https://crescendrf.com/microwave-generators-systems/why-solid-state/

Crescend Technologies (n.d.-d) Practical, real-world efficiency comparison between L-Band magnetron and SSPA microwave sources. Work Paper

Deloitte. (2023). Frequently Asked Questions About the E.U. Corporate Sustainability Reporting Directive (August 17, 2023). https://dart.deloitte.com/USDART/home/publications/deloitte/heads-up/2023/csrd-corporate-sustainability-reporting-directive-faqs

Department of Industrial Relations (n.d.). 5155. Airborne Contaminants. https://www.dir.ca.gov/title8/5155.html

Environmental Waste International (2023). Microwave Information. https://www.ewi.ca/microwave-information.html

Enwave. (n.d.). Case Studies. https://www.enwave.net/case-studies/

Eurotherm. (n.d.). Freeze Drying Overview. https://www.eurotherm.com/life-sciences-hub/the-freeze-drying-process/

Fan, S., et al. (2023). Conversion of Polystyrene Plastic into Aviation Fuel through Microwave-Assisted Pyrolysis as Affected by Iron-Based Microwave Absorbents. ACS Sustainable Chemistry & Engineering 2023 11 (3), 1054-1066 DOI: 10.1021/acssuschemeng.2c05880

Farry, S. (2024). How will we decarbonize our steelmaking processes? Rio Tinto. https://www.riotinto.com/en/news/stories/how-will-we-decarbonise-our-steelmaking-processes

Federal Steel Supply (2016). How does coke and coal play into steel making? https://www.fedsteel.com/insights/how-does-coke-and-coal-play-into-steel-making/

Ferrite Microwave Technologies. (2021). The Benefits of Microwave Tempering. https://ferriteinc.com/benefits-microwave-tempering/

Ferrite Microwave Technologies. (n.d.-a). Food Processing Microwave Systems. https://ferriteinc.com/industrial-microwave-systems/food-processing/

Ferrite Microwave Technologies. (n.d.-b). Bacon Processing Microwave Systems. https://ferriteinc.com/industrial-microwave-systems/bacon-processing/

Gimon, E., (2023). Full industrial electrification could more than double US power demand. Here's how renewables can meet it. https://www.utilitydive.com/news/industrial-electrification-renewable-climate-energy-innovation/651572/

Hara, et. al., (2012). Pig Iron Making by Focused Microwave Beams with 20 kW at 2.45 GHz. ISIJ International. 2012 Volume 52 Issue 12 Pages 2149-2157. https://doi.org/10.2355/isijinternational.52.2149

Hercus, C. (2023). Microwave Processing of Ore. Canadian Mining Journal. https://www.canadianminingjournal.com/featured-article/microwave-processing-of-ore/

Hitchcock, R. Timothy (2004). Radio-frequency and Microwave Radiation. American Industrial Hygiene Assn. p. 1. ISBN 978-1931504553.

Hu, X., et al. (2023) Microwave-assisted pyrolysis of waste plastics for their resource reuse: A technical review, Carbon Resources Conversion, Volume 6, Issue 3, 2023, Pages 215-228, ISSN 2588-9133, https://doi.org/10.1016/j.crcon.2023.03.002.

IEEE. (n.d.). IEEE SA - IEEE standard for low-rate wireless networks. IEEE Standards Association. https://standards.ieee.org/ieee/802.15.4/7029/

IMS (2023). Industrial Microwaves 101. https://industrialmicrowave.com/industrial-microwaves-101/

IMS. (n.d.-a). 100kW Liquid Heating Microwave System | 915 MHz. https://industrialmicrowave.com/microwave-systems-liquids-fluids-heating/100kw-microwave-system/

IMS. (n.d.-b). 1 Megawatt Microwave Generator | GET-MAX. https://industrialmicrowave.com/industrial-microwave-generators/915-mhz/1-megawatt-generator/

IMS. (n.d.-c). Industrial Microwave Chemical Heating. https://industrialmicrowave.com/industrial-microwave-applications/chemical-heating/

Istok. (n.d.). Istok Technical Data. Istok IMG-915-100KA Industrial Magnetron. https://frank.pocnet.net/sheets/164/i/IMG915100KA.pdf

Janahar, J., Jin, Z., Balasubramaniam, V. (2022). Pulsed Electric Field Processing Applications in the Food Industry. Agriculture and Natural Resources. FST-FABE-1002. https://ohioline.osu.edu/factsheet/fst-fabe-1002

Jin, T., Guo, M., & Zhang, H. Q. (2015). Upscaling from benchtop processing to industrial scale production: More factors to be considered for pulsed electric field food processing. Journal of Food Engineering, 146, 72–80. doi.org/10.1016/j.jfoodeng.2014.08.020.

Kashimura, et. al. (2010). Concept of Furnace for Metal Refining by Microwave Heating: A Design of Microwave Smelting Furnace with Low CO2 Emission. Materials Transactions. 2010 Volume 51 Issue 10 Pages 1847-1853. https://doi.org/10.2320/matertrans.M2010026

Lee, C., et al. (2023). Industrial Heat Pump Market Study. CalNEXT. ET23SWE0036. https://calnext.com/wp-content/uploads/2023/12/ET23SWE0036_Industrial-Heat-Pump-Market-Study_Final-Report.pdf

Manning, C. (2023). Technology Readiness Levels. NASA. https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/

Marsh, A (2018) From World War II Radar to Microwave Popcorn, the Cavity Magnetron Was There. IEEE Spectrum. https://spectrum.ieee.org/magnetron

Microwave Drying. (n.d.). Microwave Drying Introduction. https://www.microwavedrying.net/solution/microwave-food-drying-technology.html

Mizuno, N., Kosai, S., Yamasue, E. (2021-a) Microwave-based extractive metallurgy to obtain pure metals: A review, Cleaner Engineering and Technology, Volume 5, 2021, 100306, ISSN 2666-7908, https://doi.org/10.1016/j.clet.2021.100306

Mizuno, N., Kosai, S., Yamasue, E. (2021-b). Microwave-based approach to recovering zinc from electric arc furnace dust using silicon powder as a non-carbonaceous reductant. J. Occup. Med. 73 (6), 1828–1835.

Natarajan, R., et. al. (2019). Analysis of coexistence between IEEE 802.15.4, BLE and IEEE 802.11 in the 2.4 GHz ISM band - Scientific Figure on ResearchGate. https://www.researchgate.net/figure/24-GHz-ISM-band-IEEE-802154-BLE-and-IEEE-80211-channels_fig1_312114413

National Archives (2024). Title 47, 18.301 Operating frequencies. Code of Federal Regulations. https://www.ecfr.gov/current/title-47/chapter-I/subchapter-A/part-18/subpart-C/section-18.301

National Academies of Sciences, Engineering, and Medicine. 1994. Microwave Processing of Materials. Washington, DC: The National Academies Press. https://doi.org/10.17226/2266.

Nwankwo, C., et. al. (2023). Recent Developments in the Hybridization of the Freeze-Drying Technique in Food Dehydration: A Review on Chemical and Sensory Qualities. Foods 2023, 12, 3437. https://doi.org/10.3390/foods12183437

NSF, (n.d.). NSF Food Equipment Standards. https://www.nsf.org/nsf-standards/standards-portfolio/food-equipment-standards

Omran, M., Fabritius, T. (2018) Improved removal of zinc from blast furnace sludge by particle size separation and microwave heating. Miner. Eng. 127, 265–276.

Omran, M., Fabritius, T., Yu, Y., Chen, E.P., Heikkinen, G., Kacar, Y., 2021. Improving zinc recovery from steelmaking dust by switching from conventional heating to microwave heating. Journal of Sustainable Metallurgy 7, 15–26.

Pardo, N., et. al., (2012). Prospective Scenarios on Energy Efficiency and CO2 Emissions in the EU Iron & Steel Industry. European Commission. JRC Scientific and Policy Reports. https://publications.jrc.ec.europa.eu/repository/bitstream/JRC74811/ld1a25543enn.pdf

Peacoc (2023). Improving Metal Extraction Using Microwave Assisted Leaching. https://www.peacoc-h2020.eu/news/improving-metal-extraction-using-microwave-assisted-leaching/

Production Engineering (2024). Microwave Theory. https://www.productionengineering.com/industrial-microwave-rf/microwave-theory.html

Rissman, J (2022). Decarbonizing Industrial Heat via Heat Pumps. https://www.industrialheating.com/articles/97313-decarbonizing-industrial-heat-via-heat-pumps

Sairem (2020). Our heating and drying technologies for food industry. https://www.sairem.com/solutions-for-food-and-industry/our-food-and-industrial-heating-technologies/

Sairem (n.d.). Lab grown diamonds by CVD. https://www.sairem.com/growing-of-diamonds-by-cvd/

Sepro Laboratories (n.d.) Microwave Treatment of Ores. https://labs.seprosystems.com/services/microwave-treatment-of-ores/

TorWave. (n.d.). Coffee Roasting. https://www.torwave.co.uk/coffee

US Department of Energy (2015). Technology Readiness Assessment Guide. DOE G 413.3-4A. https://www.directives.doe.gov/directives-documents/400-series/0413.3-EGuide-04a-admchg1/@@images/file

U.S. DOE (n.d. -a). “IEDO Project Database | Department of Energy.” Office of Energy Efficiency & Renewable Energy. www.energy.gov/eere/iedo/iedo-project-database.

U.S. DOE (n.d. -b). “Hydrogen production: Electrolysis | Department of Energy.” Office of Energy Efficiency & Renewable Energy. https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis

U.S. DOE (2023a). Qualifying Advanced Energy Project Credit (48C) Program. Office of Clean Energy Infrastructure. https://www.energy.gov/infrastructure/qualifying-advanced-energy-project-credit-48c-program

U.S. DOE (2023b). Bipartisan Infrastructure Law. Grid Deployment Office. https://www.energy.gov/gdo/bipartisan-infrastructure-law

U.S. DOE (2023c). Industrial Research and Assessment Center Implementation Grants. Office of Manufacturing and Energy Supply Chains. https://www.energy.gov/mesc/industrial-research-and-assessment-center-implementation-grants

U.S. DOE (2023d). The Office of Clean Energy Demonstrations (OCED). https://www.energy.gov/oced/office-clean-energy-demonstrations

U.S. Department of Labor (n.d. -a). Radiofrequency and Microwave radiation – Standards. Occupational Safety and Health Administration. https://www.osha.gov/radiofrequency-and-microwave-radiation/standards

U.S. Department of Labor (n.d. -b). 1926.57 - Ventilation. Occupational Safety and Health Administration. https://www.osha.gov/laws regs/regulations/standardnumber/1926/1926.57

U.S. EIA (U.S. Energy Information Administration) (n.d.). Annual Energy Outlook 2023. https://www.eia.gov/outlooks/aeo/tables_ref.php

U.S. EIA (U.S. Energy Information Administration) (2023). Today in energy. https://www.eia.gov/todayinenergy/prices.php

UL (2019). Industrial Control Equipment – UL 508. https://www.ul.com/sites/default/files/2019-05/Industrial-Control-Equipment_us.pdf

Ulloa, R. Z., et. al. (2019). The Interaction of Microwaves with Materials of Different Properties. Electromagnetic Fields and Waves. DOI: 10.5772/intechopen.83675. https://www.intechopen.com/chapters/66294

Urone, P. P., et. al. (n.d.). College Physics: Openstax. 24.4 Energy in Electromagnetic Waves. https://pressbooks.bccampus.ca/collegephysics/chapter/energy-in-electromagnetic-waves/

Veettil, Binesh Puthen, et al. (2023). Microwave annealing of silicon solar cells. Appl. Phys. Lett. 3 April 2023; 122 (14): 142101. https://doi.org/10.1063/5.0127896

YaClass (n.d.). Smelting Process. https://www.yaclass.in/p/science-state-board/class-10/periodic-classifications-of-elements-11437/metallurgy-of-aluminium-copper-and-iron-10978/re-2fee56ed-b0db-4ff1-9c83-b41283c86b07

Zhao, J., Wang, D., Zhang, L., He, M., Ma, W., Zhao, S. (2023). Microwave-enhanced hydrogen production: a review. RSC Adv. 2023 May 18;13(22):15261-15273. doi: 10.1039/d3ra01898a. PMID: 37213333; PMCID: PMC10194329.

Zhou, N., et al. (2021) Catalytic pyrolysis of plastic wastes in a continuous microwave assisted pyrolysis system for fuel production, Chemical Engineering Journal, Volume 418, 2021, 129412, ISSN 1385-8947, https://doi.org/10.1016/j.cej.2021.129412.

Appendix A: Supplemental Information

Table 3: U.S. Department of Energy Technology Readiness Levels

Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
System Operations	**TRL 9**	Actual system operated over the full range of expected mission conditions.	The technology is in its final form and operated under the full range of operating mission conditions. Examples include using the actual system with the full range of wastes in hot operations.
System Commissioning	**TRL 8**	Actual system completed and qualified through test and demonstration.	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental testing and evaluation of the system with actual waste in hot commissioning. Supporting information includes operational procedures that are virtually complete. An Operational Readiness Review (ORR) has been successfully completed prior to the start of hot testing.
	TRL 7	Full-scale, similar (prototypical) system demonstrated in relevant environment	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Examples include testing full-scale prototype in the field with a range of simulants in cold commissioning[1]. Supporting information includes results from the full-scale testing and analysis of the differences between the test environment, and analysis of what the experimental results mean for the eventual operating system/environment. Final design is virtually complete.
Technology Demonstration	**TRL 6**	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. This represents a major step up in a technology's demonstrated readiness. Examples include testing an engineering scale prototypical system with a range of simulants.[1] Supporting information includes results from the engineering scale testing and analysis of the differences between the engineering scale, prototypical system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. TRL 6 begins true engineering development of the technology as an operational system. The major difference between TRL 5 and 6 is the step up from laboratory scale to engineering scale and the determination of scaling factors that will enable design of the operating system. The prototype should be capable of performing all the functions that will be required of the operational system. The operating environment for the testing should closely represent the actual operating environment.
Technology Development	**TRL 5**	Laboratory scale, similar system validation in relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Examples include testing a high-fidelity, laboratory scale system in a simulated environment with a range of simulants[1] and actual waste[2]. Supporting information includes results from the laboratory scale testing, analysis of the differences between the laboratory and eventual operating system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. The major difference between TRL 4 and 5 is the increase in the fidelity of the system and environment to the actual application. The system tested is almost prototypical.

Technology Development	**TRL 4**	Component and/or system validation in laboratory environment	The basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of ad hoc hardware in a laboratory and testing with a range of simulants and small scale tests on actual waste[2]. Supporting information includes the results of the integrated experiments and estimates of how the experimental components and experimental test results differ from the expected system performance goals. TRL 4-6 represent the bridge from scientific research to engineering. TRL 4 is the first step in determining whether the individual components will work together as a system. The laboratory system will probably be a mix of on hand equipment and a few special purpose components that may require special handling, calibration, or alignment to get them to function.
Research to Prove Feasibility	**TRL 3**	Analytical and experimental critical function and/or characteristic proof of concept	Active research and development (R&D) is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative tested with simulants.[1] Supporting information includes results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. At TRL 3 the work has moved beyond the paper phase to experimental work that verifies that the concept works as expected on simulants. Components of the technology are validated, but there is no attempt to integrate the components into a complete system. Modeling and simulation may be used to complement physical experiments.
Basic Technology Research	**TRL 2**	Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies. Supporting information includes publications or other references that outline the application being considered and that provide analysis to support the concept. The step up from TRL 1 to TRL 2 moves the ideas from pure to applied research. Most of the work is analytical or paper studies with the emphasis on understanding the science better. Experimental work is designed to corroborate the basic scientific observations made during TRL 1 work.
	TRL 1	Basic principles observed and reported	This is the lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples might include paper studies of a technology's basic properties or experimental work that consists mainly of observations of the physical world. Supporting Information includes published research or other references that identify the principles that underlie the technology.

[1] Simulants should match relevant chemical and physical properties.

[2] Testing with as wide a range of actual waste as practicable and consistent with waste availability, safety, ALARA, cost and project risk is highly desirable.

Source: US Department of Energy, 2015

Appendix B: Industrial Microwave Questionnaire

The following questions were used to gather information from manufacturers and industry experts.

- What are the newest developments with technology and where do you see the technology heading in the future?
- Do you experiment on the technology's energy savings capabilities? If so, have you learned any recent statistical breakthroughs in terms of energy efficiency and decarbonization goals?
- What applications are you mainly targeting with industrial microwave technologies?
- How feasible are retrofits/installations for the technology?
- What are the requirements for product installation? Are there any necessary technology safety standards (e.g. UL Standards, energy efficiency ratings, Electrical Testing Laboratories (ETL) Certification for Life Safety & Security Industry)?
- What opportunities for growth do you see?
- What are the barriers for industrial microwave technologies?
- What are the estimated costs and payback for industrial microwave technologies (capital expenditure + installation)?
- Do you have any recommendations for streamlining adoption and program pathways?
- Who are your main competitors?