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Short communication

Surfing the microwave oven learning curve

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ABSTRACT

The microwave oven has penetrated into many kitchens throughout the world and has substituted old polluting forms of cooking with new cleaner ways. Its exponential market uptake in the residential sector has been realized thanks to substantial cost reductions during its deployment phase, which started more than 70 years ago. Today, the annual production capacity reaches almost 100 million units per year. The cumulative number of microwave ovens produced since their commercial launch in 1947 surpasses 1.7 billion units to date. We express the observed price reduction during the expansion of the microwave oven market by a learning curve, which reveals a learning rate of 20 ± 2%. We project that at least two doublings in cumulative capacity are probably still to come over the next few decades, thanks to both replacements and further market uptake. This additional scale-up could imply close to another 40% reduction in the price of microwave ovens. Despite today's total installed capacity of around 1.1 TW, the aggregate energy consumption of all microwave ovens in use is low as a result of their limited usage time. This may change in the future if novel applications of microwave technology are implemented, for instance for heating or conversion purposes. A significant increase in energy consumption is likely to be expected if, for example, the technology diffuses in industry or finds its way in the energy sector, for instance as pyrolysis or plasma-generating device. We recommend that innovative microwave technology options are explored in more detail, and that their potential role in the energy transition is further investigated.

1. Introduction

The microwave oven is currently a common piece of equipment in many kitchens worldwide. The core of this technology is a cavity magnetron, which was invented a century ago. The first reports about these magnetically controlled vacuum tubes reach back to the beginning of the 20th century (Wathen, 1953; Redhead, 2001). Significant development of magnetrons for microwave radar applications emerged during World War II, notably as a result of the multicavity magnetron designed by Harry Boot and John Randall (Boot and Randall, 1976). It was only after World War II that some companies expressed interest in magnetron application for microwave heating (Osepchuk, 1984). After the first patents by Percy Spencer from the Raytheon company, in which the term microwave oven was mentioned for the first time (Spencer, 1945, 1947), it took only a couple of years before the "Radarange" – the first commercial microwave oven – was introduced in 1947. Since then, the growth of the market has been exponential and today the microwave oven has become a basic, clean, and affordable electric appliance for many households worldwide. Its uptake is often accompanied by the replacement of old, polluting forms of cooking with new, cleaner ways of heating food. Despite the large installed capacity today, the energy consumption of microwave ovens is low as a result of their limited usage time. In this paper we raise three main questions. First, can additional growth and further cost reductions for microwave ovens be expected? Second, could the idle time of today's capacity somehow be usefully employed? Third, could their contribution to the implementation of cleaner processes be expanded beyond the residential sector?

The purpose of this paper is not so much the creation of yet another theory as done by many others in this field (Kuhn, 1970; Poincare, 1903), but the application of an existing theory – that of learning curves (Wene, 2000) – to the deployment of microwave ovens. We present historical data for the cumulative production and price of

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microwave ovens and construct a learning curve for microwave oven manufacturing. Learning curves have been reported in the literature for many energy demand technologies (e.g. Weiss et al., 2010), but this contribution represents the first example of a learning curve for microwave ovens. We formulate the implications of this learning curve for future price developments and discuss opportunities for possible microwave heating applications.

2. Analysis

The first Radarange appeared on the market for a price of more than 50,000 US$ (Davis, 2016; SMECC, 2019; see Fig. 1). In our analysis we express all price data in US$(2016). In 1955, Tappan entered the consumer market with a 900 W microwave oven for a price of slightly over 10,000 US$ using Raytheon technology. Mass production, initiated in Japan in the middle of the 1960s, led to a steep increase in market uptake of the oven as household appliance. This surge resulted mainly from rapid price reductions, down from around 3500 US$ in 1967 to approximately 1200 US$ in the late 1970s (Osepchuk, 1984). Starting in the late 1970s, large-scale production in South Korea further decreased the unit price in the 1980s down to around 600 US$ (Gutis, 1985). Although already millions of microwave oven units were produced annually in the 1990s, another boost in the microwave oven market appeared around the turn of the century, when Chinese companies increased their production capacity to supply both the domestic and global market (Daxue Consulting, 2013; EP&I, 2019). This resulted in a market largely dominated by Chinese production. Consequently, during the 2010s, unit prices dropped down to 100–300 US$ (UN, 2019). Market diffusion today varies significantly between countries, from almost full saturation since the 1990s in, for instance, the USA and Japan, to less than 20% (in 2008) of households possessing a microwave oven in advanced developing countries, like Colombia and Morocco (USDA, 2009).

The development of novel microwave heating technology, e.g. for use in the energy sector, might be significantly stimulated if one can use existing experience from the residential microwave oven industry. Rapid and economically attractive deployment of a technology often involves a steep learning curve. A learning curve expresses the level of learning-by-doing, in terms of relative cost reductions, as function of cumulative deployment or use of a technology (Ferioli et al., 2009; McDonald and Schrattenholzer, 2001). It is empirically observed that with each doubling of cumulative production (X_t), starting from the initial cumulative production (X_0), the price (P_t) (or cost) of a technology typically decreases by a fixed percentage (called the learning rate, LR), in comparison to the initial price (P_0). The higher the learning rate, the faster price reductions are realized. The LR can be derived using equations (1) and (2), in which b is a constant known as the learning parameter (Wene, 2007).

$$P_t = P_0 (X_t / X_0)^{-H} \tag{1}$$

$$LR = 1 - 2^{-b} \tag{2}$$

To construct a learning curve for microwave ovens, we estimate the total annual global microwave oven production capacity starting from the first unit in 1947 up to 2016. Data are taken from, respectively, publications (Osepchuk, 1984; Magaziner and Patinkin, 1989), websites (Daxue Consulting, 2013; EP&I, 2019; Toshiba, 2019), and the United Nations industrial commodity statistics database (UN, 2019). Supplementary data behind our analysis can be found in the supporting information (available online). The microwave oven market has reached a mature scale, for which we find that the global annual production capacity today amounts to almost 100 million units per year (Fig. 2, left). The cumulative amount of microwave ovens produced over the period from 1947 to 2016 surpasses 1.7 billion units (Fig. 2, right). We confirm these values by cross-checking them against the numbers obtained by multiplying the worldwide number of households with the average market uptake over time (see Appendix A). Today, more than 50% of households worldwide possess a microwave oven.

Plotting unit price data versus cumulative global production on a double logarithmic scale results in a learning curve for microwave ovens (see Fig. 3). The linear downward relationship covers a period of 70 years and an extraordinary nine orders of magnitude (more than 30 doublings) of cumulative production. A power law fit ($y = 119 \cdot 10^3 x^{-0.32}$, with $R^2 = 0.74$) reveals that b is equal to −0.32, which corresponds to an LR of 20 ± 2%. The uncertainty range indicates the dependence of the central value of LR on the first (least reliable) datapoints of the learning curve. If we fix the 2016 value of the fitted curve and assume that the real price in 1947 is 30% lower, we obtain a more conservative LR value of 18%. In contrast, for a 30% higher initial price, the LR value would be 22%.

3. Discussion

The LR we determined for microwave ovens of 20 ± 2% corresponds well with the average LR of around 19 ± 8% for technologies in general (Dutton and Thomas, 1984; Ferioli et al., 2009) and 18 ± 9% for energy demand technologies more specifically (Weiss et al., 2010). Our results confirm the learning curve methodology, and notably the work by McDonald and Schrattenholzer (2001). If we assume that each microwave oven represents a power capacity of 1 kW, the total installed capacity today is approximately 1.1 TW, or

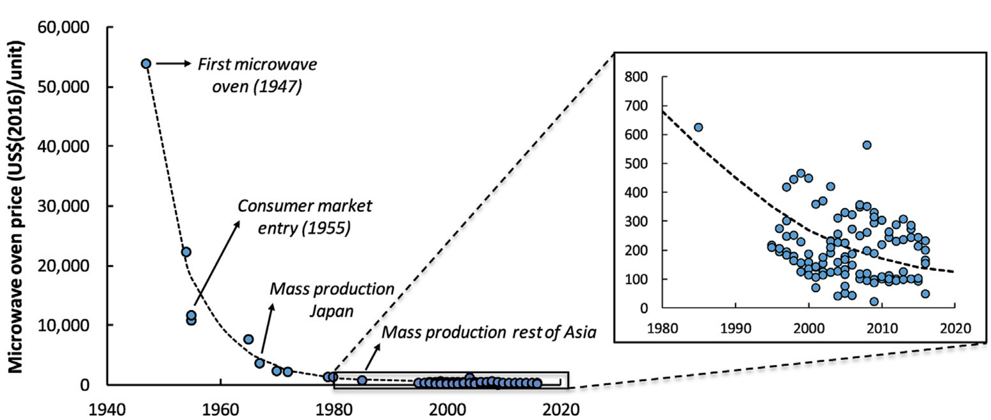

Fig. 1. Microwave oven price evolution since 1947.

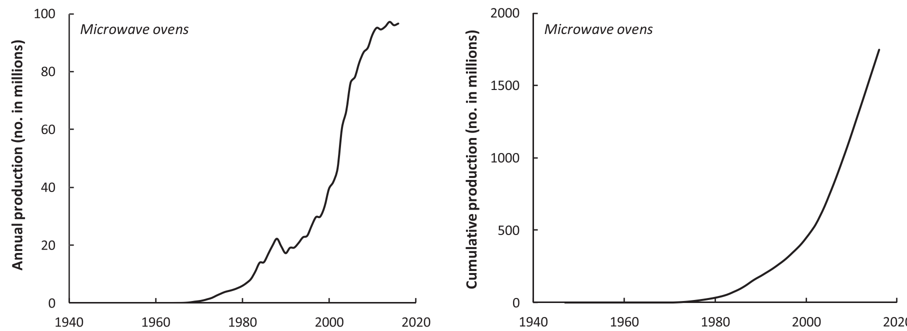

Fig. 2. Annual production capacity (left) and cumulative production (right) of microwave ovens worldwide.

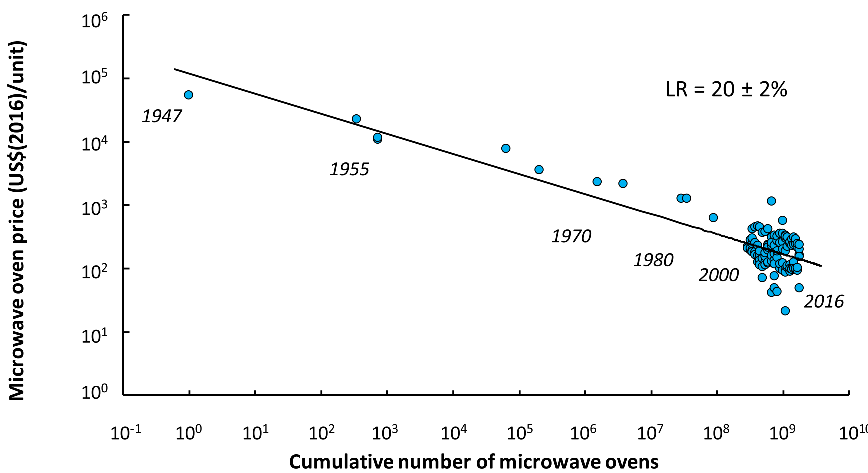

Fig. 3. Worldwide microwave oven learning curve covering 70 years of market diffusion.

around half that for coal-based power. More than 80% of all microwave ovens have been installed during the last decade. This number may still grow substantially when market uptake in, for instance, Africa and India increases. In these regions, the microwave oven introduces a new cleaner form of cooking and is likely to continue to contribute to sustainable development. Consumers often replace or discard their microwave oven because of outdated product design, and much less due to poor product quality or costs of spare electrical parts (Dindarian et al., 2012). Minor changes in the design of used microwave ovens may improve their re-usability and lifespan. Currently, the average product lifetime is 12 years and replacement rates impact considerably future cumulative production figures. These expectations allow us to project at least two additional doublings in cumulative capacity during the coming decades and, thus, a price reduction of close to 40%. Such a price reduction estimate seems justified in view of likely novel microwave developments, such as semiconductor generators and fifth generation (5G) mobile telecommunication technology (Capmany et al., 2016).

Although enormous microwave oven capacity is available worldwide, the overall energy consumption of residential microwave ovens is fairly limited, since the average usage time amounts to typically only a few minutes per day. The average electricity use of a microwave oven is around 72 kWh per year (Gallego-Schmid et al., 2018). Total electricity use of today's installed capacity adds up to some 77 TWh per year or 0.3% of global electricity generation (which was 24,919 TWh in 2016; see IEA, 2018). If other or new types of use of these electric appliances are developed in the future, their energy demand may substantially increase. Might it be possible to use kitchen microwave ovens to heat tap water for storage in tanks? Such an (ideally plug-in) application could thus store excess electricity, produced for example by residential solar panels, and thereby promote sustainable development.

Besides residential use, application of microwave heating technology in industry may gradually become attractive as CO_2 emission reduction option, for example as alternative for heating that thus far occurred predominantly by combusting oil or natural gas. Microwave heating for industrial processes has a long track record, mainly as drying method (Osepchuk, 1984). Industrial microwave technology for pyrolysis processes has been developed to efficiently heat and convert specific materials, such as biomass, plastic waste, and tires, into various hydrocarbons like gases, naphtha, oil, and char (Kostas et al., 2017; Lam and Chase, 2012; Undri et al., 2013; Zhang et al., 2017). Microwave reactors have also been applied in the chemical synthesis of e.g. pharmaceuticals, ceramics, and nanomaterials (Dąbrowska et al., 2018). Microwave irradiation of gases can create non-thermal plasmas. Such microwave plasmas can be utilized to e.g. gasify coal and generate synthesis gas (Uhm et al., 2014) or to convert CO_2 and produce renewable fuels or chemicals (Qin et al., 2018; van Rooij et al., 2018). The usage time of microwave heating technology in industry is higher than that in the residential sector. Scale-up of novel industrial microwave technology, possibly to produce synthetic (solar) fuels, would substantially increase electricity demand. The rapid on-and-off response time of microwave heating could perhaps help to stabilize the electricity system, which likely requires flexible demand options to cope with an increased share of intermittent renewable energy. If an LR of around 20% sustains during the deployment of novel microwave technology options, prices may reduce further than the 40% indicated above, thanks to perpetuated learning-by-doing processes. Microwave technology could maybe play a meaningful role in the energy transition. We therefore recommend that energy-related microwave technology applications are studied in more detail, for possible use beyond the residential sector.

4. Concluding remarks

Microwave ovens have played a large role in the substitution of old polluting forms of cooking with new cleaner ones. We expect this substitution process to continue into the foreseeable future, for example in Africa and Asia, so that the spread of microwave ovens can continue to contribute to sustainable development. Microwave ovens could expand their contribution to the implementation of cleaner processes beyond the residential sector, if microwave technology can be applied in other sectors such as energy supply and industry. Our work provides insight into the possible cost reductions of microwave ovens if these developments materialize.

CRediT authorship contribution statement

Remko J. Detz: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Bob van der Zwaan:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.122278.

List of abbreviations

kW	kilowatt
kWh	kilowatt-hour
LR	learning rate
no.	number
TW	terawatt
TWh	terawatt-hour
UN	United Nations
US$	United States dollar

Appendix A

We validate the numbers for annual and cumulative production of microwave ovens, as reported in the main part of this article by multiplying the number of households in a region with the average market uptake, i.e. the percentage of households possessing a microwave oven in that region. We assess the number of households over time in 156 countries for a few selected years and categorize the countries into 11 regions. We intra- and extrapolate the resulting concise dataset so as to cover the entire period from 1947 to 2016. All countries combined in our analysis encompass 91% of the world population. We correct for the missing 9% by multiplying the region “Other” with a factor 1.7, which adds around 8% to all households worldwide. The total number of households hereby increases from around 0.5 billion in 1947 to over 2.0 billion in 2016 (see Figure A1).

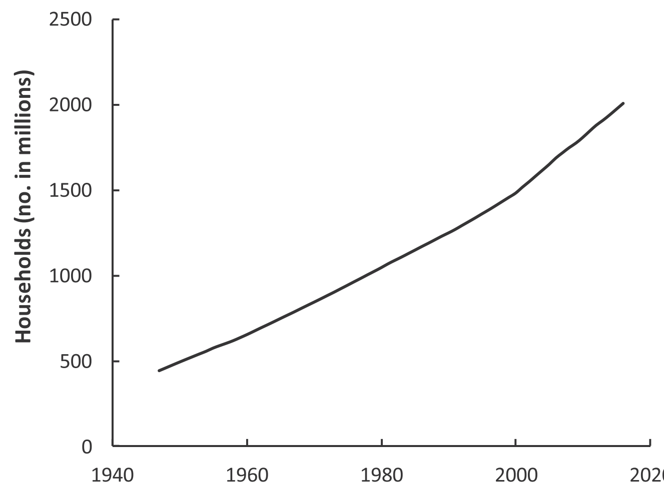

Fig. A1. Number of households worldwide.

We estimate the total market uptake for our regions, based on market uptake data of specific countries in those regions. We observe substantial differences in regional market uptake, ranging from e.g. 23% in India to almost 100% in the USA in 2016. Multiplying the total number of households per region with its market uptake yields the total number of microwave ovens possessed by the households in each region. Our calculations indicate that currently approximately 1.1 billion microwave ovens are in use worldwide (see Figure A2). This corresponds to a global average market uptake of 53% in slightly over 2 billion households worldwide in 2016.

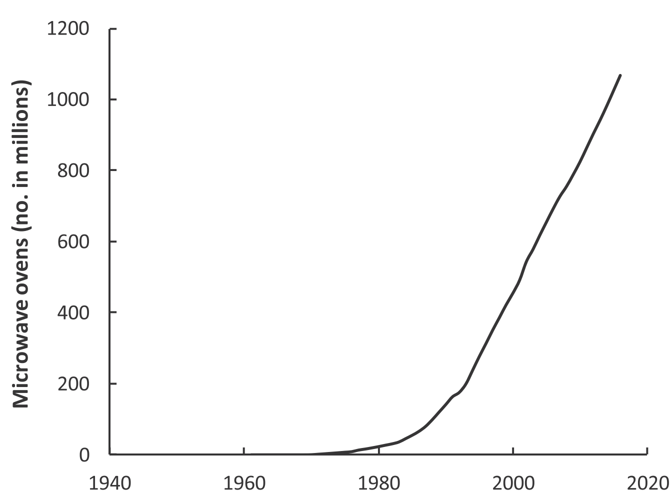

Fig. A2. Number of microwave ovens worldwide.

A comparison of the approximately 1.1 billion microwave ovens in use and their cumulative production of over 1.7 billion in 2016 implies that more than 0.6 billion units have already been replaced or discarded. This number matches with an average product lifetime of 12 years, which is realistic, and is comparable to the 8 years lifetime expectancy used in a life cycle assessment of microwave ovens by Gallego-Schmid et al. (2018). More supplementary data behind the analysis presented in this article can be found online.

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