UNIVERSITY OF PADUA

DEPARTMENT OF INDUSTRIAL ENGINEERING

MASTER COURSE IN ADVANCED MATERIALS SCIENCE AND ENGINEERING

# Evaluation of manufacturing processes, materials, and energy efficiency in the Italian Eyewear Industry: The potential of electric heating methods towards industry 5.0

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# Summary

With the European Union’s (EU) goal to modernize manufacturing processes and economic activities towards Industry 5.0, the Italian eyewear industry, renowned globally for its excellence and innovation, faces the challenge of adapting to the principles of a regenerative, circular economy. This approach emphasizes minimizing waste, maximizing resource circulation, and increasing the use of renewable energy and sustainable materials. This thesis studies the current manufacturing processes, materials, and energy efficiency within the industry, and explores the potential of electric heating methods (induction, radiofrequency, and microwave) to enhance energy efficiency, product quality and traceability. Particular attention is given to the application of more efficient heating technologies and the recent development of sustainable materials. By referencing the EU Reference Documents on Best Available Techniques (BREFs) and relevant research, this study aims to provide a framework for the Italian eyewear industry to improve productivity and achieve sustainable manufacturing practices.

# Introduction

The Italian eyewear industry, a global leader renowned for its innovation and craftsmanship, faces the challenges and opportunities presented by Industry 5.0. The European Union (EU) has set ambitious goals to transform its industrial sectors into more sustainable, human-centric, and technologically advanced operations. The shift towards a regenerative and circular economy, which emphasizes the minimization of waste, the maximization of resource circulation, and the increased use of renewable energy and materials.

In this context, the Italian eyewear industry, traditionally characterized by its high standards of quality and design, must adapt to these new paradigms to maintain its competitiveness. This thesis investigates the current manufacturing processes, materials, and energy efficiency within the industry with a specific focus on how these elements can evolve to meet the demands of Industry 5.0 and sustainability.

A key area of exploration is the potential of electric heating technologies, particularly induction, radiofrequency, and microwave heating to enhance energy efficiency, product quality, and traceability in eyewear production. These methods offer significant advantages in terms of precision, speed, and energy consumption, making them a suited solution for the complex and diverse demands of modern eyewear manufacturing. The thesis also studies the recent development of more sustainable materials, and practices, which are critical for aligning the industry with the EU's environmental and sustainability goals.

Furthermore, the thesis references the EU's Reference Documents on Best Available Techniques (BREFs) to provide a comprehensive framework for improving productivity and sustainability in the eyewear industry. By integrating these advanced heating technologies and sustainable practices, the thesis aims to present a framework for the industry to achieve more efficient and environment-friendly manufacturing processes, positioning it for long-term resilience and growth in a rapidly evolving global market.

# 1. Italian eyewear industry

The optical products industry originated in Italy, with Venice as its epicenter, where the first eyeglasses were produced in 1285 using materials such as leather, wood, and metal for the use by the aristocracy. The industrial production of eyeglasses also began in Italy at the end of 19th century under the leadership of Angelo Frescura, an optician from Belluno, who developed the plastic frames that expanded the range of styles available. [1]

The eyewear industry is one of the most important industries in the north-east of Italy, with the district located in Belluno being responsible of the 80% of the country's production. This industry is known for the innovation applied in manufacturing processes and materials, such as lightweight and durable components.[2]

The Belluno district has experienced significant transformation since 1970, when the companies Safilo and Luxottica began their partnership with Giorgio Armani, working together to combine external fashion expertise with local manufacturing knowledge, creating products with style and quality. This collaboration led to innovation and revolutionary changes in other districts, such as the Montebelluna district, known for sportswear, which is an example of combining external and internal knowledge with results as the "plastic revolution".[3]

Italian companies lead the eyewear industry, producing almost 25% of the world's eyewear frames, primarily through small and medium-sized enterprises concentrated in the Belluno district. Companies such as Luxottica, Safilo, De Rigo, and Marcolin are among the world's top ten producers, demonstrating Italy's strength in the global eyewear industry.[4]

To summarize the importance of the Italian eyewear industry it can be said that it is the leading manufacturer and exporter of sunglasses and frames in Europe, the second largest exporter of sunglasses and frames in the world, and the leading manufacturer and exporter of sunglasses and frames in the high-end product range. Approximately 90% of its production is destinated for export and over 75% of its turnover is derived from the export of its products.[5]

# 2. Materials and manufacturing processes of eyewear

## 2.1 Historic development of eyeglasses

The evolution of eyeglasses from its scientific basis to their current status as a fashion accessory dates back to the beginning of the 11th century when the Alhazen's "Book of Optics"[6] first described the foundation of today's optics studies. Then in the 13th century, the first recognizable eyeglasses were developed in Italy, producing advances in bifocals and astigmatism lenses with improved functionality.

Finally, in the 1970s, the rise of designer eyewear began, making eyeglasses a way to express personal styling, with innovations in both functionality and design.[7]

## 2.2 Materials used for eyeglasses

The first materials used as eyeglasses were convex quarts lenses surrounded by oakwood frames, invented in Florence Italy in 13th century.[8]

### 2.2.1 Materials used for eyeglasses lenses

Eyeglasses lenses were made exclusively of glass until the introduction of polymeric or plastic materials. The first polymer with good optical properties used was the polymerized methyl methacrylate (PMMA) then an acrylic resin made of allyl diglycol carbonate (now known as CR-39®).[9]

Glass being a highly transparent material, chemical resistant, having the property of not discolor with time, and being relatively scratch-resistant was ideal for optical use, then with the addition of alkaline metal oxides, the creation of thinner lenses of high refractive index and chemical resistance was possible.[10]

Plastic lenses made of polymers with long-chain molecules, interconnecting branches, and crosslinks provide greater flexibility and better impact resistance than glass. Materials like polycarbonate and polyurethane resins are used to produce lower density and lightweight lenses.[9]

Heat treatments like tempering, are used to reduce defects, polish, and preform the lenses, to be later pressed and cooled.[11]

### 2.2.2 Materials used for metal frames

Many materials are used for different parts of the frames of the glasses, for example for the nosepiece arms and end pieces, the nickel is used because of its strength and ability to be pliable, making this material suitable for parts that will be bent and adjusted.

#### 2.2.2.1 Monel (Ni-Cu alloy)

Monel is an alloy of nickel and copper. It is the most common material used to create metal designs. Monel is a strong, stable material that can also be used to make nose pads arms, bridges, and end pieces. It is resistant to corrosion and is economical to use in the frame manufacturing process.

Figure 9 shows Monel eyeglasses.

*Figure 9 Monel eyeglasses.*[1]

#### 2.2.2.2 Nickel

Nickel is a strong element that generally bends without breaking, making it suitable for end pieces and nose pad arms. Nickel is also used with other metals to form alloys that are used to make eyeglass frames, such as stainless steel.

Figure 10 shows Nickel frames eyeglasses.

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[1] Image source: https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcRaCsys7-D-sDHAPaBjb0275Ebl3Fi3IsobQQ&s

*Figure 10 Nickel eyeglasses.*[2]

### 2.2.2.3 Nickel silver

Also known as alpaca or German silver, nickel silver is an alloy of copper, zinc, silver, and nickel. It is a strong, rigid material suitable for hinges, end pieces, bridges, and decorative trim. This material is brittle, making it a poor choice for frame fronts or thin parts. However, when used as an inner core for plastic temples, it improves the durability of the product and allows for longer lasting adjustments.

Figure 11 shows Nickel-Silver eyeglasses.

*Figure 11 Nickel-Silver eyeglasses.*[3]

### 2.2.2.4 Stainless steel

Stainless steel frames are popular for their strength, even in thin, streamlined designs. This alloy of manganese, nickel, iron, and chromium is rigid and tough, making some adjustments difficult. As a result, these frames should fit well initially. Stainless steel's

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[2] Image source: https://lunettes-shop.de/en/Vintage-Glasses/Style-Era/1900-1940/nickel-spectacles-black.html

[3] Image source: https://www.opticianonline.net/cpd-archive/4377/

high resistance to corrosion makes it an excellent choice for people who work outdoors or who experience frame corrosion from perspiration.

Figure 12 shows Stainless steel eyeglasses.

*Figure 12 Stainless steel eyeglasses.*[4]

#### 2.2.2.5 Titanium

Titanium is a naturally occurring element known for its high corrosion resistance and incredible lightness (specific gravity of 4.54). Its comfort and durability have made it highly valued in the eyewear industry, resulting in a wide range of titanium frames. However, the exact percentage of titanium in these frames can vary and is often not specified, which is critical for wearers with metal allergies who seek titanium frames to avoid allergic reactions. The industry is working to establish guidelines for titanium content. Due to the difficulty of extracting titanium and its rigidity, which requires special manufacturing tools, titanium frames are generally expensive.

Figure 13 shows Titanium eyeglasses.

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[4] Image source: https://www.opticianonline.net/cpd-archive/4377/

*Figure 13 Titanium eyeglasses.*[5]

### 2.2.2.6 Aluminum

Years ago, aluminum frames were popular because aluminum is abundant and lightweight (specific gravity of 2.69), even lighter than titanium. However, aluminum is rigid and difficult to adjust, so its use declined as more advanced materials became available.

Figure 14 shows aluminum eyeglasses.

*Figure 14 Aluminum eyeglasses.*[6]

### 2.2.2.7 Beryllium and Cobalt

Beryllium and cobalt are elements used in alloy form to create strong and durable frame materials. Beryllium combined with copper creates a resilient material ideal for temple construction. However, beryllium alone is strong but expensive. Similarly,

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[5] Image source: https://blog.favrspecs.com/the-best-titanium-frames/

[6] Image source: https://www.gessato.com/wp-content/uploads/2013/12/exovault-aluminum-eyeglasses-5.jpg

cobalt is used in alloys to create very strong, non-corrosive frames. Because of its higher cost, cobalt is typically used as a stabilizing inner metal in high-end frames, providing a highly polished finish and often incorporated into thin frame designs.

Figure 15 shows beryllium eyeglasses.

*Figure 15 Beryllium eyeglasses.*[7]

### 2.2.3 Materials used for plastic frames

The polymeric materials, by having long-chain molecules, and many interconnecting branches or crosslinks, provide better impact resistance than glass and more flexibility.[12]

The information in the description of the next materials and process is taken from the same source(unless otherwise noted).[13]

#### 2.2.3.1 Cellulose acetate

Cellulose acetate is a modified natural polymer obtained from renewable sources such as trees and cotton linters. The cellulose is then treated with acetic anhydride to transform it into cellulose acetate powder.

During the manufacturing process of the frames, the polymer powder is intimately mixed with substances designed to promote the desired workability, flexibility, and toughness, called plasticizers. Other additives, such as light and heat stabilizers (dyes and pigments), may be added in small quantities as needed.

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[7] Image source: https://m.media-amazon.com/images/I/61rHyr12SsL._AC_SX679_.jpg

Figure 5 shows eyeglasses made of cellulose acetate.

*Figure 5 Cellulose acetate eyeglasses.*[8]

### 2.2.3.2 Cellulose propionate

Cellulose propionate is a plastic material used in injection-molded frames and is known for being lightweight and strong, making it ideal for ultra-thin and oversized styles. The coloring process for propionate is applied in the final stages, sealing in the plasticizers, but the material is very heat sensitive and can be damaged at temperatures above 105°C. Proper heating with an air blower or low heat in a bead pan is recommended to avoid damage. Since propionate does not stretch or shrink significantly, lenses should be sized to be mounted without heating.

Figure 6 shows eyeglasses made of cellulose propionate.

*Figure 6 Cellulose propionate eyeglasses.*[9]

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[8] Image source: https://www.opticianonline.net/cpd-archive/4377/

[9] Image source: https://image.made-in-china.com/2f0j00ZtQkFNnfArzO/Cellulose-Propionate-Full-Frame-Reading-Glasses.jpg

### 2.2.3.3 Polycarbonate

Polycarbonate is the most impact-resistant material used in frame or lens production and is manufactured mainly through injection molding technology for safety and sports styles. Due to its rigidity, polycarbonate frames are difficult to adjust and should fit well initially, as heating does not increase flexibility. Lenses should be trimmed for a "cold mount," as the material does not stretch when heated.

Figure 7 shows a comparison between polycarbonate eyeglasses and plastic or glass eyeglasses.

*Figure 7 Polycarbonate eyeglasses.*[10]

### 2.2.3.4 Polyamide

Polyamide, a type of nylon, is a transparent, strong, and lightweight material suitable for injection molding frame technology, making it ideal for thin and durable frames. It is easily tinted and available in a variety of colors. However, polyamide is very heat-sensitive and shrinks at temperatures above 230°C, so fitting lenses in these frames, lenses should be cut and size for being cold-mounted into the frame. However, this heat sensitivity can be an advantage if the lenses are slightly undersized; heating the frame with the lenses in place can shrink the frame to fit the lenses properly.

Figure 8 shows 3d printed polyamide eyeglasses.

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[10] Image source: https://mieye.com/wp-content/uploads/2018/02/6.jpg

*Figure 8 Nylon (polyamide) eyeglasses.*[11]

## 2.3 Manufacturing processes of eyeglasses

The manufacturing of eyeglasses involves several steps; one of them is the design, which is crafted by master artisans with the assistance of Computer Aided Design (CAD) software, another is the prototyping of the design and manufacturing by hand to then be analyzed and confirm its suitability, once the model is suitable master tools are used to manufacture the different components of the eyeglasses via automation, however some components need between 60 to 90 steps in the manufacturing process that are still handmade.[13]

Figure 16 shows the components and their configuration to assemble eyeglasses.

*Figure 16 Eyeglasses components configuration.*[12]

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[11] Image source: https://www.opticianonline.net/cpd-archive/4377/

[12] Image source: https://www.linkedin.com/pulse/how-manufacture-metal-eyewear-step-sean-yang/

### 2.3.1 Metal eyeglasses manufacturing

The making of the components process consists of four steps: shaping, grinding, cutting, and bending each individual metal parts such as rings, temples, bridges, etc.

The shaping can be done either by manual methods or using oil press machines with molds, this process is called stamping and temperatures ranging from 400°C to 700°C are needed depending on the metal alloy. The shaped components are trimmed to remove sharp edges and burrs, then are bent into their final shape.

Figure 17 shows a stamping machine used for metallic eyeglasses components shaping

*Figure 17 Stamping machine for eyeglasses components shaping.*[13]

The final components are assembled and joined by soldering, being laser soldering mostly preferred due to its high precision and the minimal impact done on the metal, although traditional soldering can be used when joining different metals. The temperature needed for soldering depends on the solder material, soldering at 180°C-300°C for soft solders such as Tin (Sn), Lead (Pb), Bismuth (Bi), etc., and up to 600°C for Silver (Ag) solder, the last is often used for components under high mechanical stresses.[14]

Figure 18 shows an example of soldering of eyeglasses components

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[13] Image source: https://www.linkedin.com/pulse/how-manufacture-metal-eyewear-step-sean-yang/

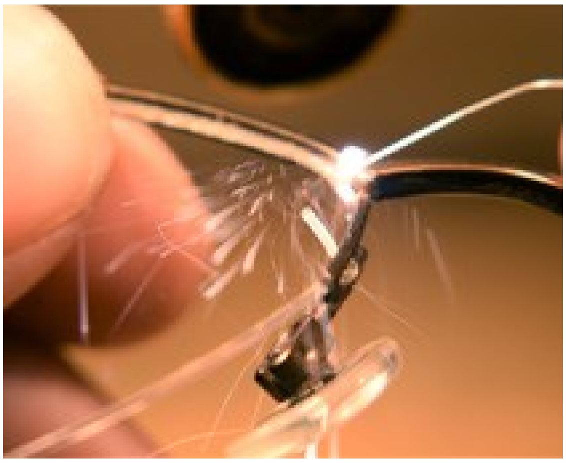

*Figure 18 Laser soldering of eyeglasses components.*[14]

The manufacturing processes for metal and plastic frames are described as follows, and the information (unless otherwise noted) is taken from the same source.[13]

### 2.3.1.1 Metallic temples

One manufacturing method used for these components is to stamp the temples from the metal sheet, in other cases a metal cylinder is used and is stretched into the desired length for being molded into its final form.

### 2.3.1.2 Eye wires

These parts are made of titanium or alloys such as stainless steel or nickel-copper (Ni-Cu) alloys. These components are bent into the desired shape by using curling machines.

### 2.3.1.3 Finishing

In the final stage of eyewear manufacturing, soldering or spot welding is used to attach parts such as nose pad arms and bridges. This process is done by hand but can be replaced with automated ultrasonic and laser soldering to improve adhesion and durability.

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[14] Image source: https://www.zenttech.com/images/welding-laser-sml.jpg

One of the final stages of production is the galvanizing of the metal parts by immersing them in a series of hot baths to protect the metal parts from environmental risks and make them more aesthetically attractive and durable.

### 2.3.2 Plastic eyeglasses manufacturing

The overall process consists of three main steps: shaping (which can be done by t or thermoforming or by injection molding), polishing and coloring. In the thermoforming process the initial part is cut from the material sheet and is heated to soften the material at temperatures from 150°C to 250°C depending on the polymer used, then are shaped under pressure using molds.

In the injection molding process, plastic pellets are melted into a liquid state to be then injected under high pressure trough a nozzle into a mold, at temperatures from 160°C to 320°C depending on the polymer used.

Figure 19 shows injection molding molds used for manufacturing eyeglasses frames.

*Figure 19 Molds used in injection molding.*[15]

The polishing step involves removing manufacturing marks, connection points, and tumbling in wood pellets, also hand polishing is done for more precise areas, this step is also a preparation for the coloring step, which can be done by using colored plastic materials or painting.[15]

Figure 20 shows eyeglasses after polishing process with wood pellets.

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[15] Image source: https://www.linkedin.com/pulse/how-produce-plastic-eyewear-from-scratch-sean-yang/?trackingId=Qh%2BlEsFeS2aZ%2BN1luIXZCw%3D%3D

*Figure 20 Polished eyeglasses with wood pellets.*[16]

### 2.3.3 Cellulose acetate eyeglasses manufacturing

Cellulose acetate (CA) is the most commonly used material for the production of polymeric frames because it is stable, light and offers unlimited coloring possibilities. This material is mixed with additives (which will be explained later) to form a composite that is later compressed by heated rollers to form sheets or blocks or made into granular forms that are then melted and used to make injection molded frames.

The CA sheets are cut into smaller blocks that are heat treated to prevent shrinkage, this heat treatment is called roasting and is done at 60°C for one week, these treated sheets are cut into the different components using CNC machines and then are bended or shaped using the same thermoforming process described before.

Both plastic and CA eyeglasses require the insertion of a metal core inside the temples to give more stability and avoid deformation of the polymeric components, this is done by heating the temples at temperatures of 100°C to 150°C to soften the polymer making it easier to insert the metal core, using a stamping machine the metal core is placed in the correct position.[16]

Figure 21 shows the process of metal core insertion in the temples.

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[16] Image source: https://www.linkedin.com/pulse/how-produce-plastic-eyewear-from-scratch-sean-yang/?trackingId=Qh%2BlEsFeS2aZ%2BN1luIXZCw%3D%3D

*Figure 21 Metal core insertion in CA temples.*[17]

### 2.3.3.1 CA Frame fronts and temples

The fronts of the frames are milled from small sheets of cellulose acetate using pantograph machines, which mill the temples first on the inside and then on the outside.

The manufacturing processes are described as it follows, and the information is taken from a manufacturer of eyeglasses in Italy.[17]

- **Block process:** is a handcraft process used to obtain three-dimensional designs ranging from natural effects, through the reproduction of fabrics, to geometric effects of great complexity. The raw materials used in this process are cellulose acetate powder, plasticizers, and solvents; these raw materials are combined until a malleable mixture is obtained, then the impurities are eliminated by heavy filtration. The color in the mixture is applied through a calendering process that homogenizes the colors and smooths the mixture. The resulting sheets are superimposed in presses and melted by means of heat and pressure. After the last pressing, the final sheets are cut and straightened to the desired thickness, and the solvent is removed from them by evaporation.
- **Extrusion process:** is an industrial process used to obtain sheets from colored granules. This process involves the use of a co-extrusion line where granules of different colors are melted and passed through a dye. Once outside the dye, the sheet is cooled and cut to the appropriate size.
- **Compression process:** is a process that uses semi-finished products coming from the first two processes, which are eventually cut into predetermined

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[17] Image source: https://www.linkedin.com/pulse/acetate-eyewear-bulk-production-break-down-sean-yang/?trackingId=Qh%2BlEsFeS2aZ%2BN1luIXZCw%3D%3D

shapes, melted again in a mold that allows to obtain the final sheet without using solvents as in block process.

- **Lamination process:** allows to multiply some desired visual effects in a new sheet by combining different components, obtained from the previous three processes, through lamination. For example, by combining different color extruded sheets and laminating them.
- **Die cutting:** is performed after preheating the material uniformly at a temperature around 50°C, this is mostly done by high-frequency heating devices. If the process is done at a too low temperature, chipping on the surface can be produced.
- **Core insert:** is done keeping the temperature of the electrodes used for heating the temples to heat the core, inserting, and positioning it without causing distortions, changes, or deformation of the material due to excessive heating.
- **Thermoforming or bending:** is used to deform the sheets into curves or rounded endings keeping their form stable over time, to ensure this, it is necessary to perform the bending at a temperature that is sufficient to delete the elastic memory of the polymer. This is done by using a temperature 10-15°C higher than the glass transition temperature (Tg) of the polymer, commonly used temperatures are 90, 100, 110, 120, and 130°C.

The heating systems that are most frequently used are:

- Heating by infrared rays (IR).
- Heating by hot plates (resistors).
- High frequency (Radiofrequency RF or Microwaves MW).
- Liquid baths (glycerin).

## 3. Electric heating theoretical background

Electric heating, also called “electroheat” consists of various technologies that transform electrical energy into heat for different industrial applications. The electric heating processes are characterized by the ability to deliver high temperatures, high power densities, all in short times and high frequency, and with high energy efficiency[18].

This work will introduce and describe the electric heating technologies of induction, radiofrequency, and microwave heating.

### 3.1 Induction heating

Induction heating is based on the heat produced on electrically conducting materials under the influence of currents induced by alternating magnetic fields. The transmission of the electromagnetic energy is done without direct contact from the inductor to the workpiece. The main advantages of the process rely on the generation of heat sources inside the workpiece to be heated in a very short time, the possibility to concentrate the heat in specific areas[19], and its high efficiency of electrical energy use compared to fuel heating. From a technological point of view, this process has a wide acceptance because of its capability of repeatability, the heating characteristics, and its high production rates due to high power densities possible with this process.

Nowadays the full theoretical understanding of the physical phenomena involved, combined with numerical simulation software, gives the ability to design new and more efficient inductors. The use of new solid-state components like generators allow the development of high power and efficiency frequency converters to deliver a whole frequency range for different applications.[20]

#### 3.1.1 Mathematical equations

The induction heating is based on the mechanism of heat generation in the substrate from induced electric currents. The induction of currents is a consequence of Faraday's law, which implies that an alternating magnetic field $\bar{B}$ generates an electric field $\bar{E}$[21], as described in equation (EQ1).

$$rot\,\bar{E} = -\frac{\partial \bar{B}}{\partial t} \tag{EQ1}$$

If an electrically conductive material is exposed to an electric field, electric currents are induced according to Ohm's law[22], describing the electric current density $\bar{J}$ as shown in equation (EQ2).

$$\bar{J} = \sigma \bar{E} \tag{EQ2}$$

The induced electric field creates Eddy currents within the material, which has three-dimensional electrical conductivity $\sigma$.

The volumetric heat generation rate or power density $P$ can be calculated with Joule's law described in equation (EQ3).

$$P = \bar{J}\bar{E} = \sigma \bar{E}^2 \tag{EQ3}$$

Based on the volumetric heat generation rate, the temperature distribution is obtained by solving Fourier's equation for heat conduction in solids as described in equation (EQ4).[23]

$$\rho C_p \frac{\partial T}{\partial t} = -rot(k\, rot\, T) + P \tag{EQ4}$$

Where:

| | |
|---|---|
| $\rho$ | Density of the material (Kg/m$^3$) |
| $C_p$ | Specific heat capacity (J/Kg·K) |
| $T$ | Temperature (K) |
| $k$ | Thermal conductivity (W/m·K) |
| $P$ | Power density (W/m$^2$) |

Induction heating is influenced by the skin effect, which causes the current to concentrate near the surface of the conductor, this can be represented by the penetration depth $\delta$ that determines how deeply the current penetrates the material and affect the efficiency and the distribution of the heating. Equation (EQ5) describes the penetration depth.

$$\delta = \sqrt{\frac{2\rho}{\pi \mu_0 \mu_r f}} \tag{EQ5}$$

Where:

| | |
|---|---|
| $\rho$ | material resistivity (Ωm) |

| | |
|---|---|
| $\mu_0 = 4\pi \cdot 10^{-7}$ | magnetic permeability of vacuum (H/m) |
| $\mu_r$ | relative magnetic permeability of material |
| $f$ | frequency (Hz) |

### 3.2 Dielectric heating

Dielectric heating is based on the thermal effect that a high frequency alternating electrical field produces in a dielectric material. These dielectric materials are characterized by both low electrical and thermal conductivity. The thermal effect is due to the polarization process which consists in moving , orienting, and rotating the ions (if any) or dipole molecules inside the materials by applying an external electric field, creating current and heat.

Dielectric heating can be done both by radiofrequency and microwaves. Conventionally the heating processes using a frequency range between 1 and 100 MHz are considered as radio frequency heating, while processes using higher frequencies are considered as microwave heating.[20]

#### 3.2.1 Radiofrequency heating

In an RF heater, a high-frequency field is created between the electrodes of a working capacitor, the shape of the electrodes determines the shape of the field. Although various electrode shapes are possible, rod and plate electrodes are the most common. A lossy dielectric is placed between or over the electrodes to induce heating. The electric field strength is determined by frequency, applied voltage, and electrode spacing. The practical electrode spacing is limited by the applied voltage, as increasing spacing requires higher voltages to maintain field strength. The maximum electrode spacing, and product thickness are limited to prevent arcing between the electrodes.[24]

##### 3.2.1.1 Mathematical equations

The specific electrostatic energy per unit volume $w_E$ of a dielectric material in which an electric field $\bar{E}$ and an electric flux density $\bar{D}$ are present, can be expressed by the equation (EQ6).

$$w_E = \frac{\bar{E} \cdot \bar{D}}{2} \tag{EQ6}$$

With:

$$\bar{D} = \varepsilon_0 \bar{E} + \bar{P} = \left(1 + \frac{\bar{P}}{\varepsilon_0 \bar{E}}\right) \varepsilon_0 \bar{E} = (1 + \chi_e) \varepsilon_0 \bar{E} = \varepsilon_0 \varepsilon \bar{E}$$

Where:

| | |
|---|---|
| $\bar{P}$=$\chi_e \varepsilon_0 \bar{E}$ | dielectric polarization vector |
| $\varepsilon_0$=8.86$\times$ $10^{-12}$ | dielectric constant of vacuum (F/m) |
| $\chi_e$ | dimensionless quantity known as electric susceptibility of material. |

The first Maxwell equation in a domain where $\bar{E}$ and $\bar{D}$ are present can be noted by the equation (EQ7).

$$rot\ \bar{H} = \sigma \bar{E} + \frac{\partial \bar{D}}{\partial t} \tag{EQ7}$$

Where:

| | |
|---|---|
| $\bar{H}$ | magnetic field intensity (A/m) |
| $\sigma$ | electrical conductivity (S/m) |
| $\bar{H}$= $\sigma \bar{E}$ | conduction current density (A/m$^2$) |
| $\frac{\partial \bar{D}}{\partial t}$ | Displacement current density (A/m$^2$) |

Under the influence of an alternating electric field, the polarization is not instantaneous, the vector $\bar{P}$ lags to the applied electric field. This is why the coefficient $\chi_e$ is a complex number and therefore the vector $\bar{D}$ lags to the electric field $\bar{E}$ at an angle $\delta_p$ which describes the active power delivered in the dielectric material during the polarization process.

Figure 22 [20] shows a phasor diagram where $\sigma_e \bar{E}$ represents the component of the total current density in phase with $\bar{E}$, which is the sum of the term $\sigma \bar{E}$ due to the non-zero electrical conductivity of the material, and the component $\omega \varepsilon_0 \varepsilon'' \bar{E}$, in phase with $\bar{E}$, due to the displacement current density $j\omega \bar{D}$.

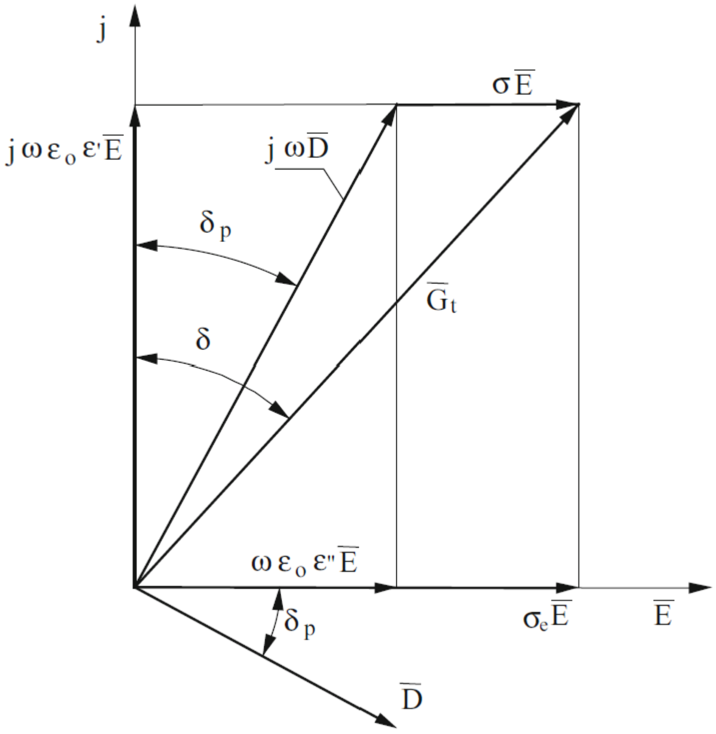

*Figure 22 Phase diagram of quantities characterizing a dielectric material under an applied alternating electric field.*

From the diagram shown in Figure 22 the equations (EQ8) and (EQ9) can be written as follows:

$$\sigma_t = j\omega\varepsilon_0\varepsilon'(1 - jtg\delta) \tag{EQ8}$$

Where:

| | |
|---|---|
| $\sigma_t$ | the complex equivalent electrical conductivity of dielectric |
| $\omega = 2\pi f$ | the frequency |
| $\varepsilon'$ | the real part of the dielectric permittivity |

$tg\delta$ tangent of the dielectric loss angle.

$$tg\delta = \frac{\varepsilon''}{\varepsilon'} \tag{EQ9}$$

Where:

$\varepsilon''$ the imaginary part of the dielectric permittivity

The dielectric loss angle of a material determines the ability of a material to be heated in the presence of electromagnetic fields. $\varepsilon'$ determines the fraction of incident energy that is reflected and absorbed, while $\varepsilon''$ measures the dissipation of electric energy in the form of heat within the material.[25]

The parameters $\varepsilon'$ and $tg\delta$ define completely the behavior of a dielectric material submitted to a sinusoidal electric field. The diagram shown in Figure 1 represents the physical phenomena from electromagnetic point of view and can be associated with an equivalent circuit shown in Figure 23.[20]

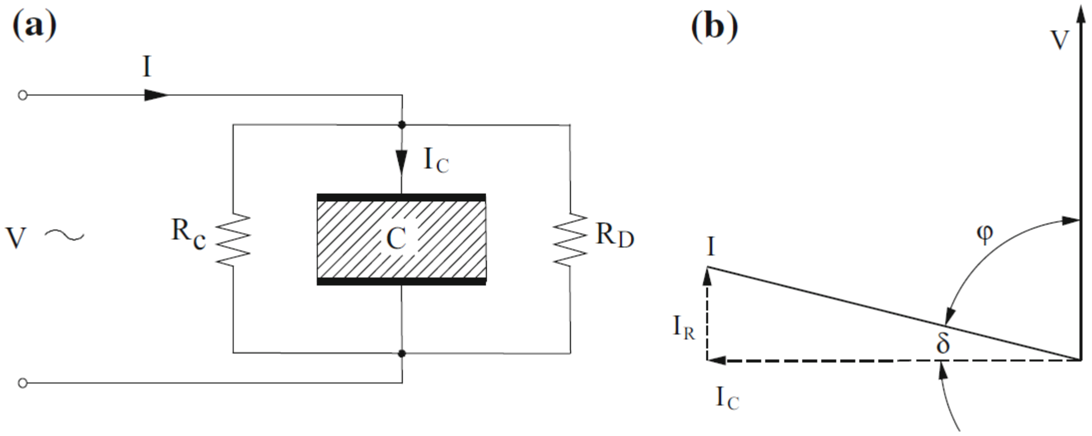

*Figure 23 (a) Equivalent circuit of a dielectric material submitted under an AC electric field; (b) Phasor diagram of the circuit.*

The equivalent circuit shown before is also equivalent to a working capacitor and the total power transformed into heat in the material, which is dependent on the frequency ($\omega = 2\pi f$), the square of the electric field intensity ($E$) and the "loss factor" that is described as the quantity ($\varepsilon_e'' = \varepsilon' tg\delta$) can be represented by the equation (EQ10).

$$w_a = \omega E^2 \varepsilon_0 \varepsilon' tg\delta \tag{EQ10}$$

Furthermore, to consider the real dimensions of the heated workpiece, is necessary to make reference to the geometry of an ideal plane capacitor where the vectors $\bar{E}$ and $\bar{D}$ are distributed uniformly in the dielectric material denoting *Sd* as the volume of the capacitor and *P* as the delivered power, the equation (EQ10) can be redefined as the equation (EQ11) that will be the basic equation of dielectric heating.

$$w_a = \frac{P}{Sd} = \omega E^2 \varepsilon_0 \varepsilon_e'' = \omega E^2 \varepsilon_0 \varepsilon' tg\delta \qquad \text{(EQ11)}$$

Equation (1.6) shows the proportionality between specific power per unit volume and the frequency, while the electric field intensity cannot exceed the limit of the dielectric strength and the loss factor remains as a characteristic of the material.

The electromagnetic waves of the electric field interact with the dielectric material surface, one part of these waves is reflected, and another is absorbed by the material, through this process the workpiece is heated.

Equation (EQ12) describes the “thermal penetration depth”, that is the distance from the surface at which the power density is reduced to 37% from the value measured at the surface.

$$x_T = \frac{1}{2\alpha} \approx \frac{\lambda_0}{2\pi\sqrt{\varepsilon' tg\delta}} = \frac{4.77 \times 10^7}{f\sqrt{\varepsilon' tg\delta}}\ [m] \qquad \text{(EQ12)}$$

Where:

$\lambda_0$ the velocity of propagation in vacuum, equal to $3 \times 10^8$m/s.

Knowing and computing the characteristic values of materials, the thickness of the heat penetration depth can be calculated and verified, the distribution of the heat can be considered as uniform in the volume of the load material, if the field applied in the surface is uniform.

If the load has variable thickness, adopting a suitable profile of the upper electrode is suggested to achieve a more uniform distribution of the electric field, in this case the airgaps are shaped conveniently between the electrode and the material to be heated.[20]

### 3.2.2 Microwaves heating

Heating with microwaves is also based on the principle of the power per unit volume produced in a dielectric material by an alternative field, described in the equation (EQ10). In this case the frequencies used are higher (in a range of 300 MHz to 300 GHz)[26], so the power is higher, therefore the use of high frequencies allows to shorten the heating time or to reduce the value of electric field intensity. This is the main reason that makes microwaves heating very attractive for industrial heating application. The most used frequencies in practical applications are 915 and 2450 MHz

The fundamental differences between RF heating and MW heating, besides the use of higher frequencies for MW heating, are that in RF heating, the material to be heated is placed between electrodes, thus the workpiece becomes part of the circuit capacitance. As a result, any change in the dielectric properties of the material and the geometry of the load will directly affect the working conditions of the generator.

In contrast, MW heating uses electromagnetic energy produced by the generator, which is extracted through a coupled loop and delivered via waveguide to a resonant cavity where the material is placed. This method allows variations in the shape and dielectric properties of the material without significantly affecting the performance of the generator.[20]

The magnetron is a cylindrical cathode with a magnetic field along its axis and a block anode and is frequently used as a MW generator for continuous industrial applications. When a high DC voltage is applied, the electric field interacts with the magnetic field, converting DC energy into high frequency electromagnetic energy. The magnetron maintains high output power in a linear relationship with the anode current, typically achieving efficiencies greater than 50%.[27]

Figure 24 shows a schematic of a magnetron.

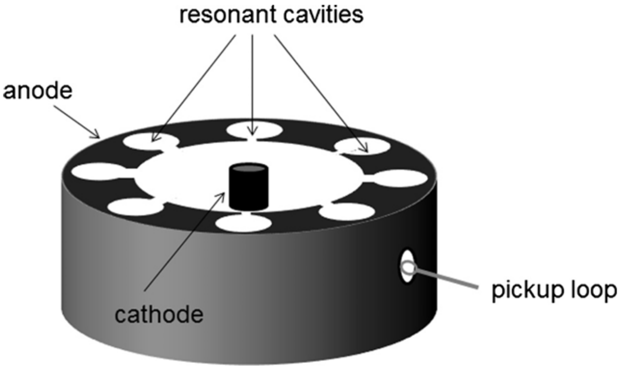

*Figure 24 Schematic of a magnetron used for producing high energy microwave radiation.*[28]

On the other hand, solid-state generators are preferred for their reliability and accuracy in controlling frequency and power output. These generators use semiconductor technology, are more compact, and have fewer mechanical parts, which increases durability and reduces maintenance. Solid-state generators achieve higher efficiency over a wider range of conditions with precision in frequency generation.[27]

Figure 25 shows an example of a solid-state generator.

*Figure 25 Solid State Microwave Generator of 500 W.*[18]

RF and MW heating technologies are widely used in industrial processes because of their advantages, such as the ability to generate heat directly within workpieces with uniform distribution in a short time, preventing surface overheating and undesired drying. High power densities up to 100W/cm$^3$ and heating rates up to 20°C/s are possible with these technologies, making them very useful in applications such as

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[18] Image source: https://www.microwaveheating.net/en/solid-state-tech/solid-state

welding thermoplastics, gluing wood, preheating thermosetting resins and rubber, moisture reduction of textiles, paper, and food.[20]

## 3.3 Properties of dielectric materials

The polarization phenomena and the conduction current are the factors influencing the heating effects in dielectric materials. These phenomena can be explained in terms of the following mechanisms:

### 3.3.1 Electronic Polarization

When an electric field is applied in an atom, the electrons are shifted against the direction of the field, while the nucleus is moved in the direction of the field. Therefore, the gravity center of the charges (positive and negative) is displaced from the center of the atom, producing an “induced dipole moment”. This polarization mechanism is independent of the temperature and is directly proportional to the electric field strength.[29]

### 3.3.2 Ionic Polarization

The ions inside of a dielectric material are moved under the influence of an electric field, the positive ions leave their equilibrium positions and are moved into the direction of the field, while the negative ions are shifted into the opposite direction of the field. This kind of polarization is also independent of the temperature but is dependent of the binding energy of particles in the molecule.[30]

### 3.3.3 Dipolar Polarization

When an extern electric field is applied in a polar material, or even without the field the molecules act like dipoles, these dipoles are permanent and are in asymmetric distribution, under the action of an electric field these permanent dipoles rotate into the direction of the field contributing to a net polarization. This mechanism of polarization depends on the temperature, with increasing temperature, the thermal energy tends to randomize the alignment of the permanent dipoles inside the material.[29]

### 3.3.4 Volume Polarization

It is a polarization phenomenon observed in multi-component materials where one component consists of large volumes of conductive material. Examples include wet materials containing water, or substances such as food and wood, which are characterized by a cellular structure. Inside these cells is a conductive fluid, while the cell boundaries are made of dielectric material. When an electric field is applied, ions and free electrons move within the conductive parts, causing the conductive inclusions to function as large-polarized molecules with dipole momentum. Due to the non-uniform structure of the material, charge movement is confined to the macro-inclusions, which behave like bound charges.[20]

The material polarization behavior depends on the frequency, temperature, and moist. Depending on the frequency the dipoles will move or not, in steady state ($\omega=0$), the dipoles do not move , also when frequency is maximum ($\omega=\infty$), the dipoles will not have time to move, so in both cases the losses are equal to zero ($tg\delta=0$). This behavior is represented in Figure 26.

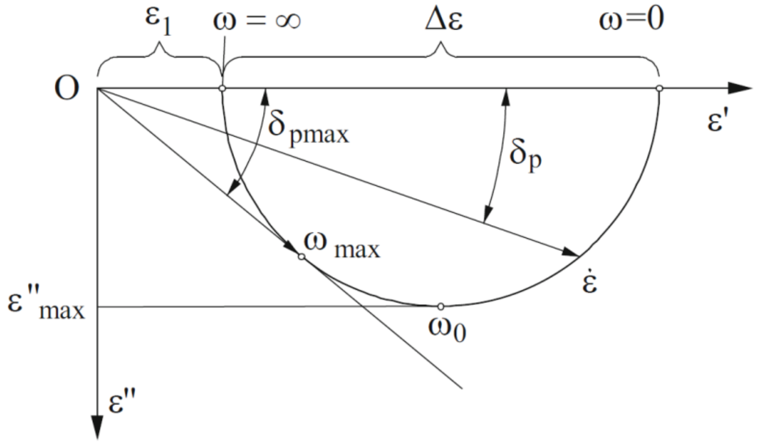

*Figure 26 Circular diagram of complex dielectric permittivity as a function of frequency.* [20]

There are other factors that affect the dielectric properties of materials; for example, for water, the dissipation factor is highly dependent on temperature and chemical state (free, ionized, crystallized, confined).

The loss factor of any material depends on conditions such as temperature, internal humidity, frequency, chemical and physical state of the material, and the direction of the applied electric field.

Understanding the theoretical background of dielectric heating is critical for the application of these technologies to specific materials, particularly polymers, which play a key role in the eyewear industry. The dielectric properties of these polymers are fundamental to optimize the heating processes described before.

## 4. Polymeric dielectric materials

Both low and high permittivity dielectrics play critical roles in the electronics industry. Low dielectric constant materials serve primarily as insulators, often referred to as passivation materials. They are used to isolate signal-carrying conductors, facilitate fast signal propagation, serve as interlayer dielectrics to mitigate resistance-capacitance (RC) time delays, minimize crosstalk, and reduce power dissipation in high-density, high-speed integration scenarios.[31]

Active components aim for high ε values, ideal for capacitors, electromagnetic wave devices, rectifiers, semiconductor devices, piezoelectric transducers, dielectric amplifiers, and memory elements. While inherently non-polar, materials can be polarized with trace impurities, enabling significant charge storage even under minimal electric fields. One example is polyvinylidene fluoride with impurities as chlorotrifluoroethylene demonstrates this effect.[32]

### 4.1 Dielectric properties of polymers

The dielectric response of polymers is mainly associated with dipolar, atomic, and electronic polarization. Dipolar polarization depends on the relaxation of electric dipoles responding to the alternating electric field in a frequency range up to 108 Hz and lead materials to exhibit high dielectric constants. In the case of atomic polarization, the phenomenon is caused by nucleus displacement, which occurs at infrared frequency (1013 Hz). Electronic polarization is due to electrons movement, which can be produced in the ultraviolet frequency domain (1015 Hz), is also related to the bandgap of the dielectrics.[33]

Figure 27 shows a graphical demonstration of the polarization mechanisms mentioned before.

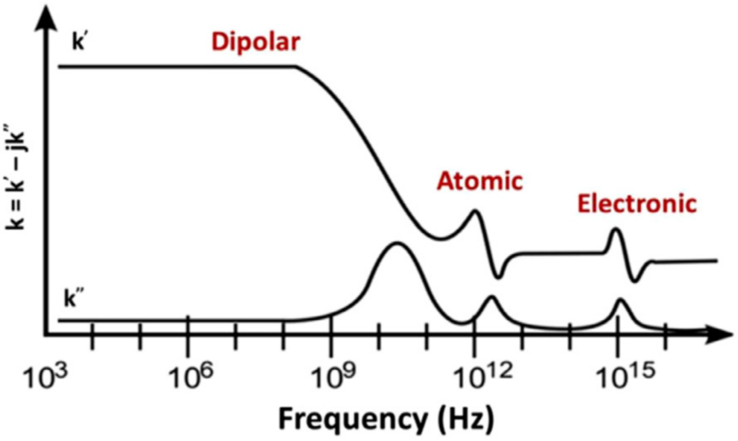

*Figure 27 Polarization mechanisms of polymeric-dielectric materials as a function of frequency.* [34]

Polymers exhibit lower dipole moment and dipolar correlation compared with ferroelectric ceramics; these factors joined with higher barriers for the dipole's rotation present in polymers are the major causes for lower dielectric constant found in dielectric polymers.[35]

Certain structures and elements, such as aromatic rings, sulfur, iodine, and bromine, exhibit high polarizability, leading to an increase in dielectric constant. Free volume, defined as unoccupied space within a polymer, also influences dielectric constant; the presence of pores decreases it because air occupies this space with a relative permittivity of about one.

Temperature affects dielectric properties by affecting intermolecular forces, increasing thermal agitation, and allowing polar groups to orient more freely, thus affecting the dielectric constant. At lower temperatures, chain segmental motion decreases, reducing the dielectric constant, while at higher temperatures, strong thermal motion disrupts dipole orientation, again decreasing the dielectric constant.[6]

### 4.2 Cellulose acetate (CA) as dielectric polymer.

Polymer dielectrics are generally amorphous or semi-crystalline structures, and those subjected to high temperatures must have a high glass transition temperature (Tg) and a high melting temperature (Tm).[36]

Cellulose acetate is a semi-crystalline biopolymer and has a reported Tg of 83.40°C, it is insoluble in water, its chemical properties are unique as it contains the carboxyl groups (C=O) in its structure. In addition, it has good film forming properties due to its intermolecular hydrogen bonds, therefore cellulose acetate films have high mechanical strength.[37]

Analysis of dielectric parameters of cellulose acetate such as ε' and ε'' shows that at low frequencies there is an increase due to the formation of a space charge region at the electrode interface, known as non-Debye type behavior. This behavior is attributed to ion diffusion[38]. At low frequencies, ε' and ε'' are high due to interfacial polarization and free charge motion[39]. At high frequencies, however, mobile ions have difficulty orienting due to rapid electric field reversals, leading to saturation, or decreased dielectric constant[40].

## 5. Energy efficiency in Europe's industries

The European Union (EU) has set ambitious energy efficiency goals, looking for at least 32.5% improvement by 2030 compared to the previous goal of 20% by 2020. These targets drive innovation and investment in industry, promoting the development of energy-efficient technologies and practices. Adopting improved energy efficiency practices, can result in reductions in energy bills, greenhouse gas emissions, health issues, and in improvement in quality of life, all of this helping the EU to achieve the commitments of the Paris Agreement on climate change.[41]

The Energy Efficiency Directive requires EU countries to reduce their annual energy consumption by an average of 4.4% by 2030. This directive aims to reduce energy consumption, and Europe's dependance on energy imports, by stimulating investment in new technologies, and providing better information on energy bills so that consumers know how to contribute to a more sustainable, innovative, and prosperous EU.[42]

The industries in Europe account for 25% of the total final energy consumption, from which 73% is needed for heating and cooling, the other 27% is used for mechanical application driven by electricity. The industry is diverse, and some processes require different temperatures ranging from 160°C and up to 2000°C, for example, the production of plastics requires temperatures from 180°C to 290°C, while drying technologies require a temperature range from 160°C to 180°C.

In 2020 the use of renewable energy for heating and cooling was 21.5% and is expected to be 27-31% in 2030 and 47-54% in 2050. [43]

Some approaches suggest savings potentials in the industry by applying more than 230 energy saving measures, from which 100 are related to heat process. These measures include integrated control systems, exhaust gas and low temperature heat recovery, the use of higher efficiency burners (or heat sources), and materials substitution. The application of these measures would be translated into a 20% reduction of energy consumption and 4-5% energy savings by 2030 and 8-10% by 2050. [44]

The improvement areas for industry with higher energy efficiency rely on innovative and efficient technologies, process intensification, and the integration of renewable sources. The processes improvement can be achieved through the use of efficient equipment such as efficient boilers, steam systems, and the use of state-of-the-art kilns.[43]

State-of-the-art kilns are advanced industrial heating systems designed to maximize energy efficiency, precision, and performance in various manufacturing processes.[45] These systems include modern and efficient heat sources, advanced insulation materials to minimize heat loss, heat recovery systems to capture and reuse waste heat and automated control systems, that can include solid-state power electronics such as generators to control the power delivery precisely and more efficiently.

As industries in Europe try to become more energy efficient, the emergence of Industry 5.0 provides an opportunity to integrate these efforts with broader technological advancements. Industry 5.0 not only aims to enhance energy efficiency, but also to revolutionize the way industries operate by incorporating human-centric, sustainable, and technologically advance practices.

## 6. Industry 5.0 in Europe's industries

According to the European Commission[46], Industry 5.0 is defined by technologies that include human-centric solutions and human-machine-interaction, bio-inspired technologies and smart materials, real-time-based digital twins and simulation, cyber safe data transmission, storage, and analysis technologies, Artificial Intelligence (AI) and technologies for energy efficiency and trustworthy autonomy.

Industry 5.0 offers a transformative approach to European industry that not only focus on efficiency and productivity, but also on the development of modern, resource-efficient, and sustainable industries. This means the creation of new technologies that promote circular production models, respecting the limits of the planet while increasing prosperity. The sustainability approach of Industry 5.0 aims to reduce energy consumption and minimize waste. Research and innovation are central to this vision, promoting industry resilience and better equipping them for future challenges.

Industry 5.0 also promotes the use of smart sensors and equipment, connected devices, and advanced data analytics, enabling real-time monitoring and control of energy consumption, minimizing waste, and improving energy efficiency. The reduction in resource consumption contributes to environmental sustainability.[47]

The eyewear industry was undergoing significant transformation driven by Industry 4.0 which was defined by the integration of advanced innovative technologies like AI, additive manufacturing, and robotics into manufacturing processes. These technologies have allowed greater customization and enhancement of product design, and more optimized supply chains. Companies like Kering and Luxottica have implemented automated systems to make operations more efficient. With these technologies the industry has improved both product quality and processes innovation.[48]

However, as the industry advances technologically, there is the need of sustainable business models to mitigate the environmental impact of the increased energy and resource consumption. While Industry 4.0 focuses on business optimization and economic growth, it misses key elements for the true systemic transformation. Such as regenerative industrial practices, social inclusion, and mandatory environmental safeguards.[46]

That is why Industry 5.0 appears like a solution to achieve climate neutrality by 2050, promoting the EU to shift towards green and socially inclusive industrial strategies, integrating sustainable and circular economic models, prioritizing the wellness of the workers, and driving decarbonization across the industries. Eyewear industry is also encouraged to integrate circular economy principles to reduce waste, enhance sustainability, and meet customer expectations, all including long-term profitability.

In the next chapter, this thesis explores how the Italian eyewear industry can apply the electric heating technologies previously discussed, along with other best practices identified in the literature, to align with principles of Industry 5.0. By integrating these advanced technologies and practices, the industry can achieve more sustainable and efficient manufacturing processes, supporting a more resilient and innovative sector.

# 7. Electric heating, and other good practices to be applied in the Italian eyewear industry towards Industry 5.0 and sustainability.

## 7.1 Electric heating for eyewear industry

As seen before, industries like the Italian eyewear industry need the adoption and application of technologies that allow the reduction of energy consumption, and to make the processes more sustainable. One of the ways to do it is the application of electric heating methods such as induction, radio frequency and microwaves heating described before.

These methods are well known for their higher efficiency in delivering and distributing heat into the workpieces in short time. The combination of these methods with automated machines and solid-state generators makes them an advantageous technology in energy consumption reduction, cost savings, and quality assurance of the products in the manufacturing processes.

Induction heating can be used in the welding and heating processes of thermoplastics[22][23], which are the primary polymers used in eyewear manufacturing. Thermoplastic containing polar groups can be welded using both RF and MW heating, the dielectric loss in the polymer dissipates energy, generating heat internally, and with the application of pressure the welding is completed in typically a few seconds[49]. The welding process is generally performed at 27.12 MHz, applying RF through shaped electrodes. Other frequencies like 13.56 MHz can be used for elements with large area of welding, and 70 MHz is used fir welding nylon.[20]

RF heating is used also to dry and heat a diversity of materials in an efficient way, and by using electronic matching networks it is possible to increase the energy efficiency of heating to more than 90%[50]. Also, RF heating can be used for heat-treatments and surface heating of metals[51], this can be applied as a heat source for heating before stamping and shaping the components of metallic eyeglasses.

Other research has shown that MW heating can be used for different applications depending on the required processing temperature, ranging from low temperatures below 500°C for heating polymers, to moderate temperatures from 500°C to 1000°C for processing ceramics and low melting point metallic materials, to high processing temperatures above 1000°C for heating high density ceramics, high melting point metals, and metallic-matrix composites, all with energy efficiencies as high as 86%.[52]

## 7.2 Best Available Techniques for different sectors related to eyewear industry

This chapter describes strategies to enhance energy efficiency in industrial sectors related to the manufacturing processes of eyeglasses, which are the production of metallic and polymeric materials that are the mostly used group of materials in the eyewear industry.

The European Commission through the European Bureau for Research on Industrial Transformation and Emissions (EU-BRITE) has developed the Reference Documents on Best Available Techniques (BREFs) for specific agro-industrial activities regarding the best technologies and measures to be applied to different industries in order to enhance sustainability, energy efficiency, and reduce emissions and energy consumption in the European industrial sectors.

The Best Available Techniques (BAT) for energy management for metallic materials production focus on enhancing energy efficiency through strategies such as the implementation of Energy Efficiency Management Systems (ENEMS) like ISO 50001, the use of regenerative or recuperative burners, the application of methods for heat recovery from waste processes, the use of high efficiency electric motors, and automated control systems to optimize energy consumption.[53]

The goal of these strategies is to improve energy performance across various industrial applications, especially in high-temperature processes, by capturing and reusing waste heat and optimizing energy consumption.

The BAT in the production of polymers focus on the improvement of energy efficiency, the reduction of emissions, and the optimization of resources consumption across the manufacturing processes. The strategies include the implementation of Environmental Management Systems (EMS), the use of advanced-design equipment to minimize air pollutants, the use of systems that recover heat, solvent vapors, and other emissions for reuse.

BAT also promotes the reduction of energy and water consumption through cogeneration of heat and power plants, water recirculation systems and advanced treatment methods for waste and emissions. The adoption of sustainable practices such as the use of recycled materials, the reduction of hazardous waste, and the application of technologies to minimize energy and water consumption are part of the focus of these techniques.[54]

Other relevant BAT are the ones for improve energy efficiency in industrial facilities, their goal is to balance environmental protection and economic viability, and to reduce energy consumption, to enhance environmental management, and to minimize pollution. The strategies start with the identification of the issues related to energy efficiency, the evaluation of effective solutions, and the determination of the optimal efficiency levels, considering costs, policy drivers, and environmental impact. Other strategies are the implementation of ENEMS and energy audits.

The application of measures such as the optimization of combustion and steam systems, with the use of heat recovery technologies like heat exchangers and cogeneration, and the improvement of electrical systems with high efficiency transformers are key to enhance energy efficiency and to sustain energy performance.[55]

### 7.3 Other good practices found in literature

In the literature research works have conducted studies, analysis, and diagnosis of issues related to energy efficiency in processes such as glass production, polymer injection molding and other industrial plants, which will be described below with some suggestions to solve these issues.

The research has been applied on examples in the eyewear industry, and more specifically the production of eyeglass frames, comparing the conventional manufacturing systems, with distributed manufacturing systems (DMS) and 3D printing technology. The study shows that improving the efficiency of 3D printing and using cleaner energy sources can reduce the environmental impact, while material selection, such as the use of polylactic acid (PLA), can also reduce the toxicity-related impact, as other polymers produce toxic gases. While DMS offers potential benefits, the increased consumption of 3D printed products due to their ease and low cost of production could reverse the environmental benefits.[56]

All these production processes have high energy consumption, mostly because of the energy performance of their equipment and its distribution, for instance, research has shown that glass industry is highly energy-intensive, with an approximate consumption of energy of 700 million GJ per year. The replacement of inefficient equipment with equipment of better performance is a good strategy to reduce that energy consumption. The proposed measures consist in the installation of electric fusion furnaces, electric boosting ovens, recuperative furnaces, and burners to use the heat of the flue gases to preheat the steam or the glass scraps entering the production process. Also, the use of the patented "E-Power System", which is a passive filter that adjusts the inductance to match the power absorption required by the system, using electricity transformers.[57]

Other research proposes the application of Additive Digital Molding (ADM), which is an Industry 5.0-driven approach that integrates digital reverse engineering, additive manufacturing, and plastic injection molding to modernize the product development. This technology gives a framework of actions that focus on enhancing energy efficiency and sustainability in manufacturing processes. By utilizing Industry 5.0 technologies such as the Internet of Things (IoT), Big Data Analytics (BDA), and Digital Twins to optimize the manufacturing processes, reduce waste, and improve supply chain transparency. These technologies allow real-time decision-making, on-demand production, and resource optimization, all contributing to sustainability.[58]

### 7.4 Sustainable Eyewear

It is worth mentioning that Italy is the country in the EU that has invested the most in in renewable energies, reaching a 37% of the total investments done in Europe in renewable energies production[59]. And so far, the importance of the Italian Eyewear Industry has been described and noted in this thesis, some proposals of technologies and good practices have been made in order to create a framework for the industry to align with the EU’s goals to make industries more energy efficient and sustainable in order to reverse climate change and reduce the environmental impact due to industrial activities.

Following the sustainability goals, the Italian Association of Optical Goods Manufacturers (Associazione Nazionale Fabbricanti Articoli Ottici ANFAO in Italian) has developed a sustainability certification for eyewear products to valorize the efforts made by the eyewear manufacturers to improve the environmental performance of their supply chain. This promotes the enhancement of sustainability in the eyewear industry.

The certification is named Certified Sustainable Eyewear (CSE) and its goal is to promote the demand and the supply of those products and services that cause the least harm to the environment, thus helping to stimulate a market-driven process of continuous environmental improvement, also the certification aims to contribute to the reduction of environmental impact associated with eyewear products by identifying products that meet specific criteria of an overall better environmental performance.[60]

The criteria for the certification are developed based on principles from the UNE EN ISO 14020 and 14024 standards, focusing on significant life cycle stages such as resource extraction, production, distribution, usage, and disposal. [61][62][63]

The criteria for the resource extraction stage focus on sustainable sources, and to promote the use of certified, renewable biogenic (material derived from biomass), and recycled materials. Certain materials, such as wood and cork, must come from sustainable sources.

The production stage criteria aim to minimize waste, optimize water and energy use, and prioritize renewable energy sources, including recycling of excess material. They also emphasize the handling of defective products and promote the use of renewable energy in production. At the distribution stage, the criteria highlight the importance of responsible supply chains, the reduction of transportation distances, and the use of sustainable, recycled, and certified packaging materials. In the usage and disposal stages, the criteria focus on the importance of ensuring that materials and products are safe to use, that are repairable, and recyclable at the end of their life, with an emphasis on material recovery. Together, these criteria ensure that materials, lenses, and eyewear meet high sustainability and environmental standards throughout the value chain.

As explored in this chapter, through the application of electric heating technologies and the adoption of the best practices in the Italian eyewear industry, it is clear that these innovations can significantly contribute to the industry’s alignment with Industry 5.0 principles. The discussed strategies not only provide immediate improvements in energy efficiency and sustainability, but also place the foundation for long-term resilience and innovation. These advances are critical to maintain the industries competitive in a globalized marketplace. The following conclusions summarize the implications of these findings and give suggestions for future research and industry practices.

# 8. Conclusions

1. The Italian eyewear industry, with its great history and global leadership in innovation has faced challenges to align its activities towards sustainability and energy efficiency. This thesis explored the evolution of the industry and provided suggestions for the industry to adopt transformations in its manufacturing processes through the application of technologies and best practices related to materials and manufacturing techniques, with emphasis on energy efficiency and sustainability.
2. Electric heating technologies, such as induction, radiofrequency, and microwave heating, were identified as important solutions to reduce energy consumption and the enhancement of production efficiency in the eyewear sector. These technologies align with the goals of Industry 5.0 and provide practical benefits, including reduced environmental impact and improved product quality.
3. The principles of Industry 5.0 provide a framework for the Italian eyewear industry to integrate sustainable practices into its operations. By embracing circular economy principles, applying smart technologies, and investing in sustainable materials and efficient equipment, the Italian eyewear industry can maintain its competitiveness, its innovation, all while making contributions to EU’s environmental goals.
4. The Future of the Italian eyewear industry lies in its ability to innovate sustainability. By adopting the technologies and practices discussed in this thesis, the industry can lead the way towards a more sustainable and prosperous future, setting a standard for other sectors to follow.

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