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Review of Energy Efficiency Technologies in the Food Industry: Trends, Barriers, and Opportunities

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ABSTRACT The industry sector has a significant responsibility for the depletion of fossil fuels and emission of carbon dioxide. Thus, several initiatives have been implemented by the industry sector to mitigate those issues. One initiative corresponds to the implementation of energy efficiency strategies. In particular, the food industry is heavily dependent on fossil fuels, and the food demand is expected to grow significantly in the coming years. Therefore, developing energy efficiency strategies for this particular industrial sector is crucial. This paper investigates the different opportunities for energy efficiency in the food industry. It first provides a brief overview of the various food industries and related energy consumption. Then, the different options for energy efficiency in the thermal and electric sector are discussed. New trends and opportunities, arising from industry 4.0 and demand response, are also presented.

INDEX TERMS Energy efficiency, food industry, industry 4.0, renewable energy, waste-to-energy.

I. INTRODUCTION

Environmental concerns and fossil fuel depletion are forcing the development of policies to reduce greenhouse gas (GHG) emissions. Renewable Energies (REs), such as solar and wind, are among the most frequently adopted options. However, fossil fuels correspond to 80% of the total worldwide energy usage, and half of all electricity generated comes from fossil fuelled plants [1], [2].

Another policy includes industrial energy efficiency [3], which is a major concern particularly in developing countries, and it is defined as the ratio of service output of a process to the energy input into that process [2]. The goal of industries could be to maximize the useful outputs or minimize the energy inputs. Energy efficiency can be used, particularly at the macrolevel, to analyze industrial activity and its performance. Energy efficiency indicators could be divided into thermodynamic, thermophysic, thermoeconomic, and economic [2].

In particular, industrial factories are high energy consumers and thus represent an opportunity for electricity utilities to properly manage electricity consumption [4]–[6]. Energy efficiency initiatives enable large industries to reduce their consumption and improve their operational output, thereby improving their benefits [7]. However, industrial processes are mostly rigid due to production constraints of the plants, which discourage some industries from adopting these initiatives [8]–[10].

Among the others, growing attention has been devoted to the food industry. The food industry also includes energy-intensive activities, and the energy-related costs among the total productions costs are between 20% and 50% [11]. Moreover, the food industry represents a high percentage (approximately 12%) of the total electricity consumed in the industrial sector [12]. However, the energy in the food sector is not always appropriately used due to many inefficiencies are observed in the food processing technologies [9], [13], [14]. Food industries are also responsible for greenhouse (GHG) emissions like carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Once fossil fuels are burned for energy generation, carbon dioxide is released. Methane is produced from paddy fields, from the fermentation of livestock and from the decomposition of food waste in land-fills, while nitrous oxide emanates from the application

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of fertilizers to grow crops [15]. The emissions are divided in direct and indirect emissions. Direct use of energy is for on-farm operations at the processing of raw materials and during various stages of manufacturing processes, while indirect use of energy is during storage, transport and use of electricity to run the food industry [16]. Moreover, industrial sector customers usually participate less in energy efficiency activities, mainly because of their smaller individual contributions to grid management as well as the technical barriers of integrating these customers due to the rigidity of their activities [17]. Significant efforts are needed towards more sustainable agriculture to face the growing population, especially for developing countries, where the population growth rates are higher. In particular, a gap will likely occur between energy and food production growth, with the FAO (Food and Agriculture Organization) estimating that food production will need to increase by 70% by 2050 but forecasting that energy production will only increase by one third [11]. The main energy types are electrical, thermal, and mechanical. All these types can be supplied by REs, such as solar, wind, and geothermal energy. Moreover, in developing countries, many farms and food industries are located in isolated places, which increases the expenses required for a distribution system; thus, distribution in RES-based microgrids becomes more economically beneficial.

Opportunities are available to reduce energy consumption in the food industry in all stages; however, the success of energy efficiency measures depends mostly on behavioral change [18].

In the food industry, the energy consumption is spread all over the various food treatment processes, although energy consumption is observed in the global agri-food chain, such as in the input agriculture products (e.g., water pumping, livestock housing, greenhouse climate control, storage, etc.) and the delivery process, such as transportation and refrigeration.

The aim of energy efficiency in the food industry is to produce more or similar amounts of food using a lower amount of energy [18].

With new advances in Information and Communication Technology (ICT), new techniques are available to improve the use of energy in various industries, such as the food industry, especially through the application of the Internet of things (IoT) [19], [20].

The aim of this paper is to identify the main technologies of energy efficiency in food industry. It explains the typical strategies, highlighting the new trends, barriers, and opportunities.

The rest of this paper is organized as follows: Section II presents an overview of the classification of food processing technologies, and related energy consumption patterns. Section III discusses the thermal energy efficiency options. Section IV studies the Waste to Energy technology in food processing. Section V presents the new trends in Smart food processing. Section VI presents the RE in food processing. Section VII explains the challenges and barriers to energy efficiency in food industry. Finally, Section VIII highlights the main conclusions and challenges.

II. BACKGROUND: CLASSIFICATION OF FOOD PROCESSING TECHNOLOGIES AND RELATED ENERGY CONSUMPTION PATTERNS

In the food industry, to convert edible raw materials into more high-value food products, food processes use considerable amounts of labor, technology, and energy. The amount of energy used is different in each country, although in developing countries, the energy consumed by the food industry is generally very high. For example, in certain African countries, the share of the national energy consumed by the agri-food chain may contribute to as high as 55%, while in USA is around 15.7% [18]. Note that of the energy consumed for agri-food in African countries, around 65-75 % corresponds for cooking and preparation, which is typically inefficient.

Moreover, the energy consumption and energy type used for the processing of a certain quantity of goods depends heavily on their nature. For example, in fruit and vegetable processing in the UK, 13.68 MJ/kg product of fuel and only 1.48 MJ/kg product of electricity are required for French fries; 9 MJ/kg product of electricity and 8.3 MJ/kg product of fuel are required for crisps production; while only 0.43 MJ/kg product of electricity and 1.50 MJ/kg product of fuel are required for jam production [21]. The energy consumption by the end users mostly includes process heat, refrigeration, motor drives, heat, ventilation and air conditioning (HVAC) systems [22].

A. SIZE OF THE FOOD INDUSTRY

Food processing systems can be categorized based on their size and range from small family consumption to large commercial consumption, which could supply huge amounts of food across the world [18]. Although energy efficiency can be improved across all food processing systems, the dependence on fossil fuels varies significantly based on the size of the food processing system; thus, greater attention must be devoted to high energy-consuming systems to reduce their consumption [23].

- Subsistence: Subsistence producers are families engaged in the most basic forms of small-scale farming and fishing, and they produce food for their own use solely. Subsistence producers use very low inputs of energy, usually from human and animal power. These inputs of energy are generally not included in world energy statistics.
- Small farms: Small family farming units can engage in different activities depending on modernization, including the development of small gardens or rice fields, organic vegetables, orchards, cattle rearing, private fishing boats and dairy herds (from a few to dozens of cattle). Depending on the type of modernization, these farms can engage in different activities.
- Small business: These farms can be managed by a family but are often private. They work slightly more and hire more people than small farms. These companies can reduce their fossil fuel dependence by improving energy

TABLE 1. Energy dependency based on the scale of the food industry [23].

Food industry scale	Fossil fuel dependence	Capital availability	Major food markets	Energy intensity
Subsistence level	Zero	Micro-finance	Own use	Low
Small family unit	Low/medium	Limited	Local own use	Low to high
Small business	High	Medium	Local/regional/export	Low to high
Large corporate	High	Good	Regional process/export	Low to high

efficiency and generating RE on-farm, which may offer the local community additional benefits.

- Large farms: Corporate food systems depend on high direct external supply chain energy inputs, and they include fish trawler fleets, feed farms, sugar companies and palm oil farms. A processing mill company may own and manage large farm estates. Some benefits are more likely to flow to local communities that belong to a growing cooperative. In general, large corporate companies have access to investment financing for clean energy and energy efficient equipment. For additional sales, energy can be used on-farm or off-farm.

Table 1 summarizes the energy consumption based on the food industry scale. It should be noted that the capital availability depends considerably on the willingness to invest in energy efficiency strategies.

B. TYPE OF FOOD INDUSTRY

There are various food industries, although we can identify some of the main industries that are the focus of this work:

- Dairy farms
- Meat farms
- Grain and oilseed milling
- Sugar and confectionary processing
- Fruit and vegetable processing
- Bakery industry

C. ENERGY-CONSUMING TECHNOLOGIES

The main energy-consuming technologies are present in various steps, and they are detailed as follows, as depicted in Fig. 1.

- Drying: This process consists of artificially drying cereals after harvesting and before storage and transport. The energy used is approximately 0.5-0.75 MJ/kg, which could be electricity, natural gas, or liquefied petroleum gas (LPG), to dry wet grain to an appropriate storage moisture content [23]. This step could be one of the more energy-intensive operations, especially for developing countries.
- Storage: This process consists of maintaining food at the proper temperature conditions to avoid degrading the quality of the product and provide both safe and high-quality foods. The typical machines used for storage in the food industry are energy consuming and include refrigerators and freezers. Storage involves approximately 1-3 MJ/kg product of retail food product.

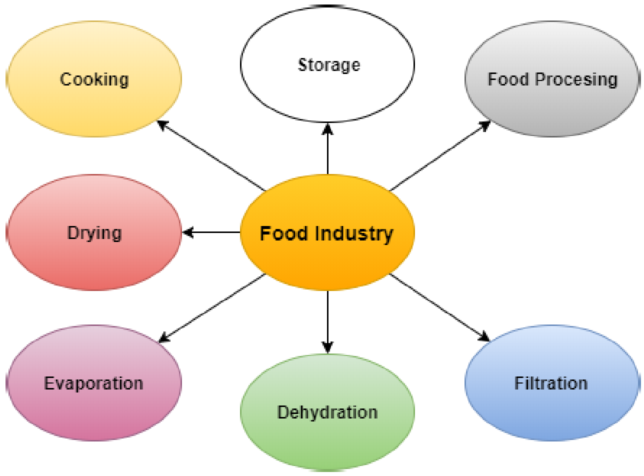

FIGURE 1. Processes or end-uses technologies in food industry.

- Food and beverage processing: this process represents the transformation of agricultural products into food and requires energy for heating, cooling, and electricity. The amount of energy needed is approximately 50-100 MJ/kg.
- Food cooking: this process involves applying heat to food. It consumes approximately 5-7 MJ/kg of energy.
- Evaporation: this process involves partially removing water from liquid food via boiling. It consumes approximately 2.5-2.7 MJ/kg.
- Dehydration: this process involves reducing moisture in food to low levels for improved shelf life by adding one or more forms of energy to the food.
- Filtration: this process involves separating solids from a suspension in a liquid via a porous medium, screen or filter cloth, which retains the solids and allows the liquid to pass through.

The techniques to save energy on these processes are presented in the next sections.

III. THERMAL ENERGY EFFICIENCY OPTIONS IN FOOD PROCESSING

A. WASTE HEAT RECOVERY

Food industry processes have a high demand for energy, and the main one is heating. Due to some inherent constraints in processes, a portion of heat is wasted. Heat recovery consists of using this waste heat by power generation technologies [24].

Chowdhury *et al.* [25] analyzes techniques to recover a portion of heat in the same processes. One strategy is recovering heat in processes with heat exchangers, and it was also validated in [26], where a milk process was analyzed and demonstrated an increase of 10% in energy efficiency by rescheduling the process and using heat exchangers. Another technique used in this industry is recovering heat for other processes or storing heat. This strategy was implemented in [27], where photovoltaic energy is used to run the refrigeration cycle of a cold chamber when the grid electricity cost is high and cold temperatures are stored in a phase change material for use when conditions are suitable. Finally, a strategy of using heat from a low-temperature process in a high-temperature process is discussed. All of these processes show a clear benefit for energy efficiency. However, the barriers to implementing these strategies depend on the policies, social-technical framework, or even fuels used. This work stated that the key factor to overcoming the barriers are business models. White et al. [28] simulated different thermodynamic fluids to improve the performance of the Organic Rankine Cycle, which is one of the most used thermodynamic cycles in heat recovery. They analyzed three fluids and three different heat source temperatures to analyze different-sized processes. Finally, the results of the fluids performance were compared in terms of the lowest specific-investment cost and power output.

B. NOVEL THERMODYNAMICS CYCLES

Some novel thermodynamic cycles are presented that use low grade heat or RE for heating or cooling processes in the food industry.

1) HEAT PUMPS

A heat pump is a thermodynamic equipment that consists of two heat exchangers, a condenser and an evaporator, a compressor and a valve. This device uses a heat source that could come from waste heat or a RE that is transferred in the evaporator, and with the help of the compressor, it improves heat conditions, which are transferred with the condenser [29]. Heat pumps are classified by the temperature of the heat source in three main categories as described in Table 2 adapted from [30].

Depending of the food industry, heat pumps could be used directly in certain processes, such as the pasteurization process. However, other systems require high temperatures, and in these cases, they are used to upgrade low-quality waste heat up to 150°C, which is required in many food industries. However, adequate working fluids must be selected to overcome various problems, such as flammability, toxicity, and required compressor technology [31]. Wang et al. [32] analyzed heat recovery from a spray-drying process in a milk powder plant by a combined system with a heat pump and a conventional air-to-air heat exchanger. The results show that heat pumps can recover up to 40% of waste heat and lead to 20% lower energy costs in the operation. Furthermore, heat pumps represent other benefits as stated in [26], where heat pump technology was analyzed in the dairy and meat industries in Germany and showed reduced global gas heating emissions at up to 52%.

2) NOVEL REFRIGERATION CYCLES

Novel refrigeration cycles were analyzed in small plants like smallholder dairy farms or simulated with software.

- Absorption-desorption cycle: it consists of an absorber, a heat exchanger, a generator or desorber, a condenser, an evaporator, expansion valves and a pump. This process uses an absorption solution and a refrigerant solution, and low-grade waste heat is used in the heat exchanger in an absorption-desorption process. This cooling cycle has a low COP because the cycle uses low-grade heat. Yildirim and Genc [33] analyzed the absorption-desorption cycle in the pasteurization process of the milk industry and showed that is possible to use low heat from geothermal for cooling. However, the source of the heat could be any low-grade waste heat coming from other processes.
- Adsorption system: it is another mechanical refrigeration machine that consists of a condenser, an evaporator, a valve and an adsorber, which replaces the compressor. During adsorption, refrigerant vapor from the evaporator produces a cooling effect, and in the desorption period, heat is transported to the absorber to discharge the refrigerant, which is transferred to the condenser. Finally, the liquid refrigerant is transferred to the evaporator in a closed loop [34]. Ndyabawe *et al.* [35] analyzed zeolite as an adsorber and biogas and found that it performed well for a small-size-batch cooler for milk.
- Ejector refrigeration system: it consists of an ejector, a condenser, an evaporator, a boiler and a valve. The cycle starts when the fluid refrigerant is boiled to form vapor that is transferred to the ejector to join with the vapor coming from the evaporator. Then, the vapor is pressurized with the ejector and transferred to the condenser, where the fluid loses heat to the environment. Then, the fluid is pumped back to the boiler to start over the cycle. The remaining fluid is transferred to a throttling valve to reduce the pressure, and in the evaporator, the fluid is evaporated, and then the cooling

TABLE 2. Heat pump classification by temperature.

Heat pump classification		
Type	Heat source temperature	Heat sink temperature
Heat pump	0 - 40°C	0 - 80°C
High temperature heat pump	40 - 60°C	80 - 100°C
Very high temperature heat pump	60 - 120°C	100 - 160°C

cycle takes place. Finally, the refrigerant vapor joins with the vapor coming from the boiler and the cycle starts again [34]. Zhang *et al.* [36] analyzed a new freeze drying system, and ejectors are used in the equipment. The results show that heat consumption can be reduced by up to 46.1% compared with conventional freeze dryers.

3) HEAT PIPES

This method consists of using a pipe with two ends as heat exchangers and a working fluid. One side of the pipe that has fins works as a condenser, and the other side works as an evaporator. This method has some advantages, such as almost no maintenance and less operational costs compared to conventional heat transfer methods. However, this method requires analyzing the fluid used, wick type and pipe material. The heat pipe method works with latent heat, which makes it efficient for heat transfer with no changes in temperature. This method could improve cooking and cooling processes by reducing processing time [29], [34]. Brahim and Jemni [37] simulated the performance of a heat pipe, and the results showed a better performance compared with a conventional tubular heat exchanger.

4) HYBRID HEATING SYSTEMS

In general, food processes are too rigid, which increases the difficulty of implementing the demand respond strategy. However, when a process relies on different sources of energy, this issue can be overcome. For example, [6] studied an option of implementing a low-temperature hybrid heating system in the dairy industry. The study analyzes additional sources of energy, such as RE, heat pumps and grid electricity, to generate heat as a supplement to the high-temperature source of energy. The study demonstrates that it is possible to implement hybrid-heating systems without affecting the process. However, this technique requires an analysis of the constraints, such as RE availability, inherent processes constraints, and grid prices, which are also analyzed for the DR method.

C. APPLICATION OF NON-THERMAL FOOD PROCESSES

Some processes in the food industry were developed with heat, such as pasteurization; however, these processes could be developed with other technologies to accomplish the same goal. For instance, pasteurization processes are generally developed with heat to destroy harmful microorganisms. However, other techniques will be presented that can accomplish the same goal.

1) FOOD IRRADIATION

This process consists of applying very high energy electrons to food for a short time period. These rays are in a wavelength range from $\lambda = 10^{-7} - 10^{-12} m$, which correspond to ultraviolet rays, X-rays, beam rays and gamma rays. The emitted irradiation damages the DNA of living cells, thereby inactivating bacterial and viral microorganisms. Some advantages of this process are that it is a cold process and has lower costs compared to the conventional pasteurization process [34]. Bhattacharjee *et al.* [38] and Bouzarjomehri *et al.* [39] analyzed this technology by applying ultraviolet rays to juice and an electron beam in sausages, respectively, and the results indicated that they were good sterilization processes that did not affect the sensory characteristics.

2) PULSED ELECTRIC FIELDS

The process consists of applying an electric field to biological cells to damage the cell membrane, thereby causing cell death. This technology presents some benefits; for example, the temperature of the treated food or beverage is not increased. Nevertheless, the amount of energy required is 100 kJ/kg at 30°C, which is higher than that of thermal processes with recovery [34]. Pulsed electric fields could be used to pasteurize beverages to minimize physical and nutritional changes [40]. When operating at high temperatures and assuming a 95% of heat recovery, the pulsed electric fields energy input might be reduced to the amount of 20 kJ/kg like conventional thermal pasteurization [41].

3) HIGH-PRESSURE PROCESSING

This technique applies high pressure to liquids, which causes the alternation of proteins or lipids, thereby damaging the membranes of biological cells. However, this process demands 52 kJ/kg to reach a pressure of 600 MPa, which also increases the temperature of beverages by 3°C for every 100 MPa of pressure applied. This process was analyzed in [34] and [38], and the results showed a reduction in microbial activity. Huang et al. [42] described several health benefits of this technique compared to conventional pasteurization; however, the investment cost is still a constraint compared to conventional pasteurization.

4) MEMBRANE PROCESSING

The separation process is quite common in the food industry, and it changes the concentration or clarity of liquid food, which is generally performed by evaporation of water. Nevertheless, this activity generally has a high demand of energy, although separation could be perform by membrane filtration, which saves up to 50% energy compared with conventional processes [34]. This process is the most widely applied nonthermal process in juice processing since it is performed at low temperatures, thereby conserving the nutrients and quality of the fruit, and it also leads to increased production yields [38]. Nazir *et al.* [43] analyzed the ability of this technique to recover nutrients from waste food or byproducts and found that it has wide applicability in the food industry.

D. NOVEL HEATING METHODS

1) INFRARED, MICROWAVE AND RADIO FREQUENCY HEATING

These techniques use electromagnetic waves to sterilize food. Infrared radiation exhibits low penetration in food, which is

TABLE 3. Technologies used in agroindustry for Waste to Energy.

Waste to Energy technologies		
Technology	Type of Residue	Reference
Bio-diesel	palm oil, waste cooking oil	[49], [50], [51]
Bio-ethanol	fruit lignocellulose	[52]
Biogas	grease trap waste, livestock manure, brewery residues, household organic waste	[53] [54] [55]
Biomass	residue crops, olive mills solid waste, digestate	[56] [57] [58]
Pyrolysis	swine manure, sugar cane bagasse, rice straw	[59] [60] [61]

why it is used for sterilizing the surfaces of food. However, its heat transfer coefficient is higher than that of convective heated air or water. In microwave technology, food needs to be exposed for a short period of time for sterilization, although the process leads to the loss of energy in moisture. Radio frequency heating is a more controlled technique since the penetration of the wave is greater than that of microwaves [34]. Guo *et al.* [44] analyzed the radio frequency heating process in the food industry, and the results showed a high potential due to the low cost and other previously mentioned advantages.

2) OHMIC HEATING

This method consists of applying an electric current directly to a beverage to generate heat; therefore, no losses will be generated due to the conductivity of the material, which is an advantage compared to other methods. The heat generated depends on the voltage difference in the field and conductivity of the beverage, which should be in a range between 0.01 S/m and above 10 S/m. This process has some advantages, such as ensuring uniform heating, which prevents thermal damage or nutritional losses [38].

IV. WASTE MANAGEMENT IN FOOD PROCESSING (WASTE-TO-ENERGY)

Waste management has become crucial due to the growing problem of natural resource depletion and contaminant generation. In particular, the concept of waste-to-energy has gained attention in recent years, as a waste management strategy. Waste-to-energy is the process of transforming waste into a useful form of energy, such as electricity, heat, or other type [26]. In agroindustry, waste has become also a huge problem because it requires especial treatment due to environmental regulations before disposal. This waste treatment could increase the cost of processes and the energy demand of this industry. An effective solution to overcoming these problems is to apply the waste to the energy concept, which can reduce waste disposal, generate energy for the agroindustry or provide an energy surplus that can be sold to other industries. This concept of waste-to-energy is also widely used in other industries like in waste treatment, where the main goal of the process is to reduce waste, which is mainly organic. For instance, some municipal solid waste plants use plasma gasification technology, where waste undergoes a thermochemical process to generate synthetic gas used as source of energy [45]. Therefore, plasma gasification technology could be used with agriculture residues to generate heat or electricity [46]. Moreover, the waste from food industries could offer the possibility to produce, apart from electricity, byproducts such as single-cell protein, photosynthesis plant fertilizer, and waste heat [47]. Table 3 describes the main waste-to-energy technologies used in the agroindustry. Fig.2 depicts the Waste-to-Energy technologies for food industry.

A. BIODIESEL

This technology consists of transforming vegetable oil into biodiesel based on several steps. First, oil is subjected to hydrolysis, where two components are obtained: free fatty acids (FFAs) and glycerol. Then, the FFAs are subjected to an esterification process under critical conditions, and finally, this liquid is filtered to obtain biodiesel [49]. This technology has been analyzed in several studies because of the importance of biodiesels in the biofuel production market as well in the consumption market, especially for transportation. Hossain *et al.* [49] and Prussi *et al.* [50] used edible oil coming from the food industry and final consumers as the feedstock and applied a re-esterification process to generate biodiesel. The results showed that biodiesel from waste has a similar performance to conventional diesel, which was analyzed in different types of generators. In addition, in the study, biodiesel was found to generate fewer emissions than conventional diesel in certain cases. Hossain *et al.* [49] used a different catalyst material in the re-esterification process and showed an improvement in the process relative to conventional processes.

B. BIOGAS

Another important technology is biogas, which is generated via an anaerobic process under a temperature generally between 20 and 60°C. In this process, organic feedstock is digested by microorganisms, and several days later, biogas and sludge is generated. The authors of [52], [53], and [54] analyzed biogas with different sources of feedstock. The studies demonstrate the importance of the type of feedstock and feeding ratio in the process. The analysis in [53] demonstrates that a plant that uses residues sourced from the vicinity as feedstock has less impact on the environment and less cost in biogas generation. Additionally, the location of the biogas plant is a key factor for achieving positive impacts. In fact, an adequate location presents less sources for the transportation of feedstock and possible usage of heat from factories or residences near the biogas plant.

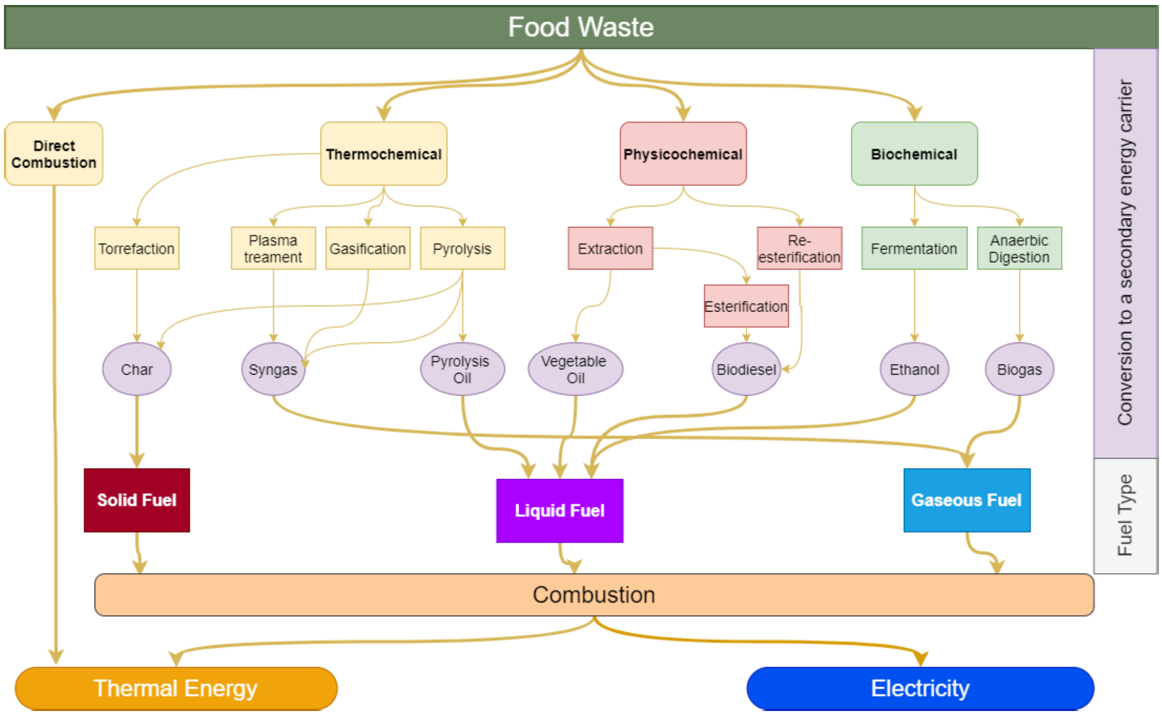

FIGURE 2. Waste to energy technologies for food industry.

Pantaleo et al. [61] analyzed different-sized anaerobic digestion plants that used cattle manure and energy crops in Italy, and the results showed that the key factors for profitability in such projects are the manure recovery rate, slurry reuse and cogeneration system. The importance of this technology was determined in [54], who analyzed the use of brewery residues and household organic waste and determined that such technology had the potential to meet 72% of the energy demand in the brewery industry or 1% of the energy demand in 27 EU countries.

C. BIOMASS

Biomass is used as fuel for combustion, and is generally subjected to a mechanical pretreatment that removes moisture to enhance the calorific value of the substrate. Biomass has a high demand, especially for heating. In [62] was estimated that in British Columbia in Canada, biomass potential coming from residue crops could reduce up to 2% of GHG. Technical and economic evaluations of waste management have been previously performed. For example, the authors of [56] performed a multidisciplinary technical and cost analysis for the production of olive mill solid waste pellets for the case of Cyprus. The results indicated that the solid waste of a three-phase process has less moisture content than that of a two-phase process. The mean calorific value was 21,645 MJ/kg, which was between the values observed in other studies. Cyprus generates 13000 tons of olive solid waste generated via two processes technologies. The annual estimated energy potential is 38 GWh in Cyprus. Pellets from olive waste have been estimated to provide 0.9% of the total energy consumed in households for heating at 2784 toe, and this sector has a higher energy demand than industry and agriculture in Cyprus. Key factors for project viability are the working days and capacity of the plant. The plant could generate pellets with a cost of 142 Euro/ton, which is competitive with wood pellets. Chen *et al.* [57] analyzed the digestate produced via anaerobic digestion. This waste went through a granulation process to obtain a type of pellet. The results showed that this material has a similar energy potential as wood fuels, although this material could have higher nitrogen monoxide emissions. Some examples of waste-to-energy approaches have also been presented by [61], [63], [64].

D. PYROLYSIS

Pyrolysis is a thermochemical process that consists of applying heat in the absence of oxygen to organic substrates to generate energy fuels, such as liquid pyrolytic oil, solid charcoal and light gases (e.g., hydrogen, carbon monoxide, carbon dioxide, and methane) [65]. Kanwal et al. [59] subjected sugarcane bagasse to a pyrolysis process at temperature between 200 and 300°C at different residence times. The results showed an improvement in the substrate, such as a higher carbon content and a higher heating value of 24.01 MJ/kg. [60] found an improvement of the thermochemical process using CO_2, which shows an increase of CO formation and suppression of H_2. However, the process requires temperatures above 520°. Amer *et al.* [58] analyzed a microwave pretreatment to reduce the moisture content in substrate in four agriculture wastes: rice straw, rice husk, sugarcane bagasse and cotton stalk. The study shows that this pretreatment helps to reach higher heating values similar to bituminous coal. Dai *et al.* [66] estimated that biochar could reduce up to 1.41×10^6 t CO_{2e} coming for residue crops in China.

V. SMART FOOD PROCESSING: POTENTIAL FOR ELECTRICITY REDUCTION, ACTIVE DEMAND RESPONSE, AND INDUSTRY 4.0

Several industries are currently trying to reduce their energy consumption to save costs. In the food industry, several processes are used to obtain the end product and the processes differ depending on the end product. Therefore, several energy efficiency techniques focus on one or various processes to reduce energy consumption. In many cases, energy efficiency could even improve the quality of the end-products when considering the monitoring of external conditions. For example, in cold rooms, the temperature could be constant and too low, which limits the quality of the product. Therefore, reducing the refrigeration consumption will reduce energy consumption and improve the quality of the product [67].

A. ENERGY SAVINGS TECHNIQUES

The potential for electricity savings by the type of food industry is detailed below.

Water heating is responsible for nearly 40% of the total electricity consumption of dairy farms. Thus, efficient systems should be implemented to avoid electricity losses [68]–[70]. Through data envelopment analysis, it is possible to reduce 12% the energy consumption and around 12% the CO_2 emissions of dairy farms [69]. According to Xu *et al.* [70], it is possible to reduce 50-80% of specific energy consumption and 9-14 million metric tons of carbon in dairy industries, with USA having the biggest potential. Other areas with the potential for reduction include refrigeration, pumping, air compressors, and other electric machines [18], [71]. Moreover, the process of milking requires significant power over short times, which can lead to power peaks in the distribution systems. Thus, the authors of [72] propose that the milking starting time should be varied by participating in different electricity tariffs. The results indicate that cost savings in electricity could achieve between 33% to 39% depending on the size of the dairy farm; however, whether the milking process time could change is difficult to determine because of the cows and other processes.

For meat production, specific efficiency techniques have not be found. However, various energy audits demonstrate that several inefficiencies exist, and fuels are overused; therefore, the energy inputs could be limited with the proper control of energy meters [73]–[76]. For example, electricity savings could reach up to 24% [77].

Several approaches have been developed to reduce electricity consumption in the different steps of food processing. In the case of wines, the technique of cold prefermentation is a process that gained popularity in recent years, and it consists of reducing the temperature of the product to an established temperature for the process. Then, the temperature has to be maintained within the considered limits by compensating for fluctuations of temperature that could occur during the maceration process [78].

Other technology has been considered to optimize the food defrosting system. In [79], the benefits of two energy optimization strategies to improve the overall process efficiency of a food defrosting system are studied. Simulation results show the benefits of the on-line energy optimization strategies, which significantly increase the overall process efficiency.

Climate control is another significant source of electricity. The authors of [80] focus on the optimal operation of energy systems in greenhouses within the context of smart grids. The developed models incorporated weather forecasts, electricity price information, and end-user preferences to minimize the total energy costs and peak demand charges while considering important parameters of greenhouse climate control.

Ventilation could also be optimized with new techniques, such as sequential ventilation. For cheese processing, using this energy efficiency technique is more convenient not only for electricity savings but also because the end-product could have better quality [81], [82].

In food production, machining processes consume a large amount of energy. Therefore, various techniques have been proposed to improve this consumption. In [83], an on-line approach for monitoring machine tools was presented, and various power reduction experiments were performed to obtain the management measure that consumed the lowest power.

B. DEMAND RESPONSE

Demand response (DR) is a technique that motivates changes in electricity usage of end-use customers depending on the electricity price, grid reliability or incentivized revenue when system reliability is jeopardized via the reduction in energy consumption, transferal of energy consumption to other periods, or use of distributed energy resources instead of the main grid [84]. Additionally, DR may facilitate the integration of Renewable Energy Sources (RESs) and energy storage, which are unpredictable and inflexible generators, thereby increasing the flexibility of the overall power system, as shown in Fig 3. This technique was first considered a solution for the residential and commercial sector; however, due to the significant load in the industrial sector, the application of DR in the industry sector has attracted attention [4], [85]. However, implementing DR in industries is more difficult because the traditional processes have been considered rigid [86]; however, previous studies have demonstrated that there are processes with certain flexibility that may be explored. Moreover, DR has been evaluated in the food industry.

For example, [87] presented an evaluation and assessment of DR in the meat industry. The most energy-consuming process in this industry is the cooling production and distribution

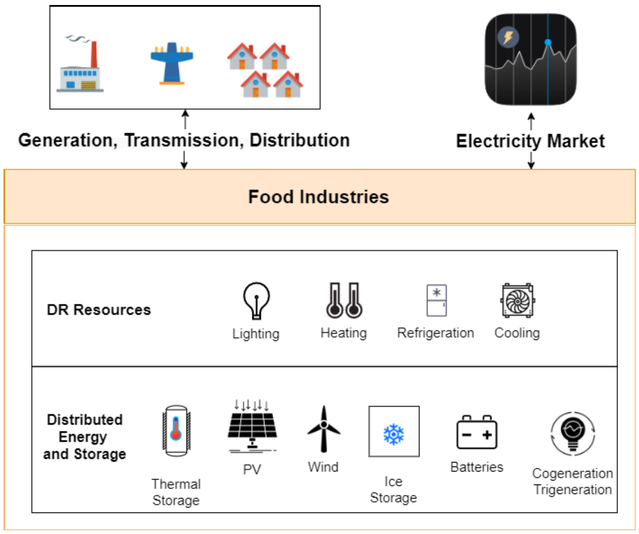

FIGURE 3. Overview of DR in food industries.

process, which account for between 45% and 55% of the total final electricity consumption in the analyzed industry. DR actions cannot be applied in sensitive production areas and in sensitive processes directly related to the quality of the final product. The main production processes in the meat industry are working rooms, preserving chambers, freezing chambers and drying lines. In DR, actions that reduce the power and response time are important. The DR action proposed in this paper is based on the interruption of the electricity supply used in cooling production so that the thermal inertia of the system can maintain both the temperature and humidity within acceptable limits. In the process, two hour interruptions of 450 kW in the peak period were performed. The results showed that with DR, savings of 5% of the total annual cost and power reductions in the range of 50% of the total peak demand could be achieved in the analyzed facilities.

Furthermore, Alcazar-Ortega et al. [88] demonstrated the considerable potential of meat industry customers to provide DR flexibility. Effective competition in electricity markets needs to be enhanced, including demand response programs that allow customers to participate in such markets. Flexibility actions include not consuming energy or shifting energy use to cheaper periods, and the costs that the customer incurs when a flexibility action is performed have been analyzed. In the meat industry, DR actions, such as the interruption of cooling production and control of cooling distribution in drying rooms, have been implemented using the inertia of the systems. The study proves that approximately 6% of the cost of balancing markets and secondary regulation could have been avoided using the DR potential of the meat-producing segment. In [89], the participation of a meat factory in the Spanish tertiary was also studied by using a parallel particle swarm optimization, resulting in an improvement of 40 % of the maximum profit per unit of reduced energy, significantly improving the economic performance.

According to previous studies, the implementation of DR actions must be completely automated (communication, monitoring and control) to avoid human errors and reduce the required advance notification time. The notification time must consider the ramping up and down periods of the involved processes as well as the preparation and recovery periods.

Other interesting options for DR in the food industry correspond to the use of ice storage. An ice storage system makes ice during off-peak periods to partly or entirely serve the requirements of on-peak periods [90]. Isolated systems could consider the integration of DR, PV and ice storage, in which ice is made during PV generation and used for storage where PV or other generation is not available [91], [92]. Since most types of the food industry use refrigeration machines, producing enough ice during valley periods for storage and use in peak periods while shutting down the refrigeration and maintaining the temperature at proper levels through the produced ice could be advantageous.

C. POTENTIAL OF INDUSTRY 4.0 IN SUSTAINABLE FOOD PROCESSING

The term Industry 4.0 refers to the fourth big current trend of industrialization concepts, and it implies the industrial use of recent trends in electrical, communications, and computer systems. The main topics of Industry 4.0 include smart factories, cyber-physical systems, self-organization, new systems in distribution and procurement, new systems in product and service development, adaptation of human needs, and corporate social responsibility, as illustrated in Fig. 4 [93]. In Industry 4.0, two main focuses of research have emerged: smart factories, which are based on intelligent manufacturing systems and processes and networked distributed production facilities; and intelligent production, which focuses on human-computer interaction, logistics management, 3D printing and other advanced technologies that can be applied to the entire industrial process to create a highly flexible, personalized and networked industrial chain [94]. Thus, Industry 4.0 enables more sustainable and efficient processes

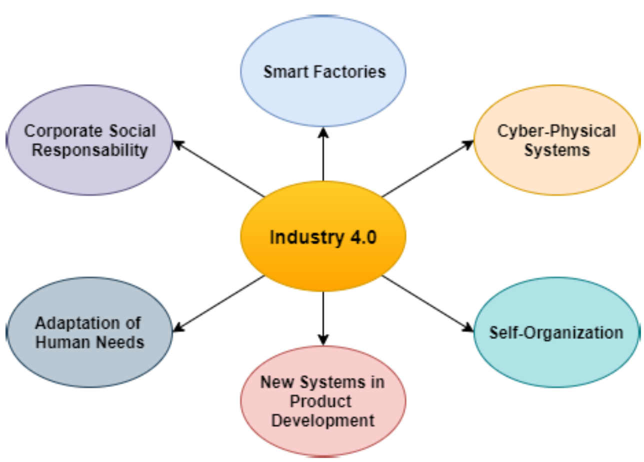

FIGURE 4. Industry 4.0 topics.

during food processing to cover the growing demands in food markets and ensure the quality and the quantity of the products [95], [96].

With intelligent manufacturing, it is expected that advanced robotics and artificial intelligence will be implemented to allow for the precise control of all production lines [97]. Therefore, possible energy losses could be monitored to implement solutions immediately and avoid such losses [98]. For example, the logistics management of Industry 4.0 allows for the safe, secure, and reliable transportation of raw foods, and the energy of transportation in the factory could be minimized. The temperature of the equipment, especially refrigeration equipment, could be controlled and adjusted to a specific range to avoid temperature losses, thereby reducing energy bills. Finally, during food processing, some machines could be working improperly, and Industry 4.0 could enable fault diagnostics and management to allow for the immediate repair of machines and avoid long-term losses [99].

VI. RENEWABLE ENERGY IN FOOD PROCESSING

In the new grid, RE is expected to have a larger share in the total electricity production. Therefore, RE was also proposed for the supply of energy loads to the food industry. Photovoltaic (PV) and wind generators are considered suitable alternatives to conventional diesel generators or electric distribution lines. For example, in [100], the RE planning (PV and wind) of a dairy farm was studied, and it demonstrated that the introduction of RE could provide a sizeable backup of 136 GWh/year to the Algerian grid while mitigating 80 million tons of CO_2. This work was complemented by [101], [102], who validated the technical and economic feasibility of introducing PVs in dairy farms in Algeria. Solar energy integrated with energy storage could avoid peaks for milking [103].

Solar energy could also be useful for thermal processes, such a drying. In rural areas, drying of agricultural products is performed directly via solar energy. However, it presents some disadvantages, such as longer drying times, difficulty controlling the drying process, or contamination. Solar dryers have emerged as a solution to tackle these issues. These dryers present proper energy and exergy results, such as the one analyzed by [104], who successfully dried ghost chili pepper and sliced ginger. Solar energy could also be useful for heating water for processes that need it. These solar systems are already implemented and could be very appropriate for developing countries and isolated food industries [105]. In particular, the performance of the solar dryers depends on the solar radiation, and most of the developing countries are located close to or within the equatorial belt, where the solar radiation is high, and they can take advantage of this property [106].

In [107], an existing conventional system in an ice cream factory in Isparta, Turkey was changed to a RE system. The processes analyzed in the factory were those that require heating and cooling, and the study proposed changing the energy source from grid electricity to heat from a parabolic to solar collector (PTSC) system. The PTSC system shows up to 98.56% energy savings compared with the current system. However, the proposed system has some limitations, such as the high cost of investment, 8.5-year payback time, and variations of solar radiation. The PTSC system works in a low/medium temperature range.

To increase the performance of solar PV in food industries, it is possible to integrate it in a trigeneration system. These systems are designated as PV and combined cooling, heating, and power (PV-CCHP) systems or PV-trigeneartion (PV-T) systems [108], [109]. Since most of the food industries require heating and cooling, these systems could improve the energy efficiency, but they could require up to 25 years to generate Net profit [110]. Furthermore, the PV-T systems could include electric storage such as batteries, and pumped hydro [111]; and thermal storage such as molten salts, phase change materials, concrete storage tanks [27], [63], [112].

VII. CHALLENGES AND BARRIERS TO ENERGY EFFICIENCY IN FOOD INDUSTRY

The issues of energy efficiency, environmental protection, food processing waste management, improvement of production quality and safety have attracted increasing attention in the food industry. Effective energy utilization and energy sources management in food processing facilities are desirable for reducing processing costs, saving fossil energy resources and minimizing environmental impact. The food processing industry, however, faces several challenges to develop advanced energy conservation and conversion technologies. The barriers can be classified as technical and not technical ones. The technical barriers are mostly related to the complexities of some food processing sectors, where cascade, intermittent and inter-connected processes are implemented, and some energy saving measures should be integrated with particular attention to the implications in terms of quality of final product, safety issues, effectiveness of processes. This is valid, as examples, when it comes to the optimal setting of processing temperature levels or waste heat recovery options to mimimize energy consumption and at the same time to secure the end products quality standards. Other barriers regard the difficulties and/or profitability to recover low temperature and/or intermittent/seasonal discharged heat, which is often available in such processes. In addition, environmental/amenity issues are often major drawbacks, and these aspects can be related for instance to the use of waste by products for on site energy production, to space/logistic constraints arising from the location and operation of renewable energy and energy saving technologies (i.e. solar panels, biomass storage and biomass logistics of supply). The non technical barriers mostly regard the limited specific know how, knowledge and skills of food sector operators in energy saving technologies, which are out of the core business of the industrial operators. In the following, a description of the typical challenges to energy efficiency in food industry is provided, with comments on the most viable options to overcome these issues. The challenges and barriers to energy efficiency in food industry could be divided into the following aspects: economic, technological, environmental, and regulatory.

A. ECONOMIC

The industrial entrepreneur perception towards innovative integrated and sustainable energy saving solutions, which are not well known and understood, may be a major barrier, if the options are considered too risky. Energy efficiency enables long-term profits for food processing companies, however, in the short term they have to invest in additional equipment to implement the presented strategies. Due to important market competition between food processing companies, it is not possible to assume that energy efficiency strategies will be implemented alone, and therefore there is a need of economic incentives from governments [18]. Observe also that many incentives fail to persuade industrial customers to participate since the costs of modifying the processes could be higher than the incentives for adopting energy efficiency strategies.

The benefits of energy efficiency in the food industry could differ significantly, depending of the size and kind of processes of the industry. Thus, a first evaluation needs to be performed to evaluate the possible benefits. In this evaluation, some uncertainties appear, which could lead to wrong evaluations and the benefits could results lower, which could discourage other customers to partipate in these strategies.

B. TECHNOLOGICAL

Food industry is a sector with high possibilities for improvement since reduced percentages of energy savings involve large amounts of energy. Due to the technologies commonly used in this type of industry, thermal energy, electrical energy and water use are the main technologies on which to focus efficiency actions. In all processes in which thermal energy is used, there are important savings opportunities: improvement in the processes, in the equipment and the specific treatment of the products that is made; improvement in the process as a whole. Global solutions must be proposed that provide reductions in consumption. For example, in many cases, there is a gas boiler to generate heat and an air-water chiller to obtain cold. The use of a water-water thermal machine that generates cold and heat simultaneously has higher energy efficiency. In processes in which electric power is used directly, they are also susceptible to significant savings: improving equipment performance, the use of drives in all processes that feed motors, making a record of consumption, that enables subsequent analysis of opportunities to shut down unnecessary equipment, among others. The reuse of all materials and waste energy is essential (waste-to-energy). Finally, the change to industry 4.0 will enable the measurement of many variables of the processes, energy consumption. It is crucial to make a historical data base of the variables that enables a later analysis of the information. The search for synergy between several actions to be taken is crucial and is what will cause the improvement in energy efficiency to be greater.

Although various opportunities exist, organizational and managing issues related to the installation of energy consumption measurement systems, or planned stop of production processes to install energy saving technologies, are often remarkable not technical barriers, in particular considering that the entrepreneurial focus is mostly on the food production business. The perception of potential influence of energy saving intervention on the effectiveness of the food processing and quality of final products constitute further drawbacks. Most of the processes are complex and difficult to be changed. Moreover, even in some cases the product quality was improved such as the cheese [81], [82], setting parameters modulation to save energy consumption can negatively influence end product quality. Finally, as previously stated, some food production processes are very rigid due to end quality, and hence it is difficult to accommodate renewable energy and energy saving options.

C. ENVIRONMENTAL

There is a clear relation between agriculture and environmental problems like greenhouse gas emissions. Where this industry represents the second largest GHG emitter as is mentioned in [113]. On the other hand, renewable energy and energy efficiency contribute to reduce GHG emissions. However, a challenge to assess environmental improvements by energy efficiency is the method used, which has some uncertainties to quantify their impacts. For instance, greenhouse gases are quantified based on carbon foot print,and some guidelines are used like IPCC. However, these guidelines are subjective and non universal as is mentioned in [16]. Slorach *et al.* [114] analyzed how to reduce environmental impacts from food waste in UK using different scenarios. Although some technologies where analyzed, the best way to reduce environmental impacts was to reduce 2% food waste generation, showing that new technologies has less contribution to overcome environmental impacts.

D. LEGISLATIVE AND REGULATORY

Permitting issues and legislative aspects are also relevant barriers in the case of integration of complex technologies, including biomass waste to energy technologies, consuming both endogenous and external bio-fuel resources. The financial aspects, and the relatively high investment costs of some technological options are other typical non technical barriers, considering that the investment horizon of energy saving measures can be longer than what expected/interesting for the industrial operators. These legislative and regulatory issues limit the growth of energy efficiency initiatives in the industries, especially in the developing countries. The installation of RE or cogeneration plants, the tools for industry 4.0, or implementation of DR programs are limited by the local or national electric companies regulations. For example, in countries where there is no electricity markets, these strategies could not be implemented. Moreover, the benefits of the governments for food industries for GHG reduction must be clear to encourage to implement energy efficiency strategies.

Some particular standards for communications need to be adopted in the energy market to facilitate the communication between the different agents participating in energy efficiency strategies. Finally, since many food industries are small, an administrative burden could exist. Hence, it is crucial to include in the energy market new entities such as aggregators for DR [4].

VIII. CONCLUSION

The food industry is a large energy consumer and GhG emitter. Assessing the challenges for the future is important since the expected growth in food demand will not be proportional to the growth in energy capacity. Therefore, significant initiatives for energy efficiency need to be developed.

Thus, in this paper, different energy efficiency strategies in the food industry have been presented. A background on the classification of food processing technologies was first presented, with a focus on energy-consuming technologies. Then, typical energy efficiency opportunities were introduced. Novel trends for the food industry were also discussed, such as waste-to-energy, demand response, and Industry 4.0. The use of RE and energy storage is becoming crucial for providing electricity or thermal energy in peak periods.

Although typical and new trends in energy efficiency for food processing appear to represent promising pathways to decarbonize the food processing sector, the actual implementation is still limited. Proper policies must be developed to better encourage users to adopt energy efficiency strategies. First, many industries do not feel comfortable changing their processes; therefore, incentives for demand flexibilities must be provided. Moreover, incentives must be provided to purchase technologies associated with smart food processing that are profitable over the long-term.

In the future, a gap will exist between the food production (that will increase by 70%) and the energy sector, so it is crucial that important investments must be performed in the energy sector. To mitigate GHG emissions, investments in RE for generation may be achieved. Furthermore, proper standards for various strategies of energy efficiency may be developed to obtain significant energy savings.

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