

Renewable Energy in Food Processing: Innovations for Sustainable Practices in the Food Industry

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Abstract

The world food system has sustainability weaknesses. Agricultural production has an environmental impact, accounting for about a quarter of human greenhouse gas emissions. Food processing accounts for around one-fourth of global water consumption and of discharges of organic water pollutants. Among the various edible items produced, about half are wasted, including fruits, vegetables, and cereals. The industry generates waste that affects the environment through water, air, and solid waste. Improvements in sustainability focus on energy consumption, waste reduction (upcycling), water use, and wastewater reduction for legislative or consumer purposes. Thermal processing comprises operations such as pasteurisation, heating, drying, and sterilisation used in food. Food safety still relies on energy-intensive treatments. It is therefore essential to develop technologies to produce high-quality food in line with rising expectations of sustainability. Sustainable, low-energy (and low-water) processes for waste and biomass valorisation are being developed (Picart-Palmade et al., 2019). Complementary green approaches aim to safeguard the energy of foods or the quality of nutrients by preventing nutrient loss during prolonged storage or transport.

Food production is also responsible for around a quarter of global greenhouse gas and energy emissions, while carbon and energy intensities are forecast to remain high. The incorporation of efficient processing technologies can improve resource use and reduce waste and GHGs. The relevant food engineering applications, such as the Vaction™ Pump and Steam Infusion cooking, support sustainability reporting by reducing demand for steam, carbon, and energy simultaneously during sterilisation, pasteurisation, and cooking (Brooks et al., 2021). By

harmonising these technologies, we aim to build manufacturing resilience and facilitate the much-needed re-engineering of processes, enabling safer, more efficient operations. The food supply chain's resource use could be improved by investing in processing R&D, which can be assessed by evaluating the return on investment in production capacity, revenue, and brand equity. The COVID-19 crisis has highlighted the weaknesses of the food supply system and the need for speedy, flexible production, with non-thermal processing offering potential resilience.

Keywords: Renewable energy, food processing, sustainability, energy efficiency, biomass utilisation, solar energy, carbon footprint reduction, process innovation.

1. Introduction

Whether in the industry or other sectors, everyone wants to go sustainable today. The reason is to save the environment, and because the Resource Peak will definitely arrive. The food processing sector is no different. The incorporation of renewable energy and the electrification of processes enable process innovation to increase sustainability. According to Brooks et al. (2021), these energy innovations will enable a rethinking of conventional practices to make them more resource-efficient while helping to deliver stronger sustainability and climate goals.

Food production is vital for human survival; it must never stop. Immediate processing is required for fresh milk, meat, fish, fruits and vegetables. Food processing cannot be fully electrified due to intrinsic limitations. There is no particular relationship between the electrical and thermal systems, and, thanks to the principle of Energy Conservation, the processing versatility

driven by electricity is strongly limited (Picart-Palmade et al., 2019). The food processing industry is best suited to utilising readily available renewable energy.

2. Overview of Renewable Energy Technologies in Food Processing

Food production is mostly done using sophisticated, energy-intensive machines. Food processing accounts for about 30% of global industrial energy use and 3% of total use. The processing technology for food and agricultural produce relies on conventional electricity and thermal energy, resulting in significant GHG emissions. Many studies have been done on technologies utilising renewable energy in food processing.

Four renewable energy sources, solar, wind, biomass, and geothermal, relevant to food processing, are distinguished. Photovoltaic (PV) and solar thermal technologies are examples of solar technologies. Although widely used for grid-connected applications, wind energy is used directly in food-

processing processes only in very large installations. Biomass usually comes from food-processing waste and residues, which can be reused, converted into fuel or energy (through biogas digestion or similar routes), or combusted. Geothermal energy is stable and is currently mainly used in warmer regions for direct heating.

Shifting from conventional to renewable-energy processing influences design and operational choices. In the business-as-usual case, thermal energy is produced primarily by burning fossil fuels. At the same time, renewable-energy options affect grid electricity use or the carbon cycle - and hence the pursuit of complementary circular design strategies. Most often, the renewables-relevant strategies consist of enhanced process design; heat recovery and cascaded heating/cooling; electrification of suitable process steps, e.g., pasteurisation, drying, sterilisation, pumping; and thermal energy storage coupled with demand-side load shifting.

2.1. Solar Thermal and Photovoltaic Applications

Food processing typically involves transforming fresh produce into various forms for subsequent use. Specifically, food processing aims to preserve or otherwise improve the state of food so that it may be consumed directly or utilised in other food processing. Many

energy-intensive operations transform milk into milk powder or other products. Energy is consumed during the heat treatment, transport, and refrigeration of milk. Another opportunity is to consider regions with ample solar radiation, allowing solar energy to be the primary source of heat or cooling. As a result, various authors have investigated the use of solar energy in food processing, given the dependence on fossil fuels and the lower carbon footprint of solar energy (Omeji et al., 2012). According to Tora's (2010) report, not every establishment in the food processing sector is eligible to use these opportunities, and alternative energy sources, such as waste-to-energy, remain scarce.

2.2. Wind Power Integration

Installing wind turbines in several locations can ease electricity demand for food processing while decreasing the dependency on fossil fuels. In harnessing wind energy, one needs to consider grid connection, backup generation, and the extent of energy storage. Wind energy can exhibit strong diurnal patterns, including considerable overnight generation and lower production in the mid-afternoon (Fikiin et al., 2017). In addition, more energy becomes available seasonally during the winter months.

2.3. Biomass and Biogas Utilisation

Anaerobic digestion of biomass, a green way to handle organic matter, is being researched today. Biogas will convert biomass, such as agricultural residues, livestock manure, and food-processing wastes, into a viable alternative energy resource. Biogas can be used for space and water heating, combined heat and power generation, and upgrading to biomethane.

Every day, the agricultural and food industries generate large quantities of residual biomass. Proper recycling of them will substantially reduce climate impacts and increase economic profitability while generating new job openings across industries (Berruto et al., 2015). The conversion of residual biomass into products for various manufacturing sectors contributes to circular economies (M. (Abdeen) Omer, 2017). However, managing odours and inorganic residues that persist in anaerobically digested raw biomass is challenging.

2.4. Geothermal Solutions

Heating is required for the performance of many food-processing operations, either directly or indirectly. As a result, heating operations account for a substantial share of the world's energy consumption (Picart-Palmade et al., 2019). Energy-use monitoring in food

processing is intended to increase energy efficiency and reconfigure existing treatment steps to the new renewable energy systems to come (Cooper et al., 2019). In this regard, many renewable energy technologies have been proposed and tested for various direct-use applications, such as geothermal energy. Geothermal Applications are classified by depth into direct-use heating, geothermal heat pumps, and deep geothermal systems. Geothermal resource viability depends on the site, with an inverse relationship to the physical scale potential of commercially available global technologies.

3. Process-Level Innovations Driven by Renewable Energy

Strategies and designs for process operations oriented toward renewable energy can significantly reduce process energy use and greenhouse-gas emissions, thereby improving sustainability. Design strategies for process integration, pinch analysis, utility targeting, and heat exchanger network optimisation will form the basis of the food industry's zero-carbon energy and emissions strategy. These will also be applied to renewable energy system design (Picart-Palmade et al., 2019). Heat-recovery and cascaded-energy systems leverage opportunities for cascaded heating and cooling, multistage

thermal recovery, and the integration of evaporative drying and pasteurisation.

Replacing conventional fossil fuel-based thermal energy processes (pasteurisation, sterilisation, pumping, and so on) with electric alternatives can eliminate fossil fuel use and the associated carbon emissions (Brooks et al., 2021). By pursuing electrification, the option to shift to renewable-energy-based electricity is also available. This option also helps avoid the energy loss that occurs when converting biomass or biogas to thermal energy. Sensible and latent thermal storage solutions allow load shifting from high-demand to low-demand periods. It also enables grid-responsive operation. By operating in non-continuous steps in response to grid signals, it is possible to reduce consumption during peak-load hours further and enable the utilisation of renewable sources whenever they are available.

3.1. Energy-Efficient Process Design

The process design of a food manufacturing involves minimising energy usage and greenhouse gas emissions while increasing throughput. Process integration refers to the systematic consideration of raw material and utility streams throughout the system. It seeks opportunities to utilise waste energy or materials from one operation as inputs to another. Pinch

analysis helps process developers identify the temperature at which the minimum energy match occurs. Utility targeting identifies the minimum energy quantities and utility specifications for heating and cooling across a process.

The process of heat-exchange network optimisation arranges energy-efficient heat exchangers of an entire system cost-effectively. Most food manufacturing processes rely on chemical reactions and phase-change phenomena to determine their energy profiles. The electrification of liquid pumping, pasteurising, sterilising, and filtering steps, which have significant energy demand for supply and delivery, can be a viable opportunity to use indirect or direct electric drives and to shift loads to other energy-generation time windows (Brooks et al., 2021).

3.2. Heat Recovery and Cascaded Systems

When processes are designed and operated to reduce or eliminate energy-intensive heat sources, most of their energy requirements can be met by renewable heating capacity. Not only will demand for energy drop immediately, but we can also rethink many of the design specifications and topology. Fossil-fuel-driven processors typically rely on the delivery of uniform, high-temperature heat for many operations, despite the availability of

lower-grade thermal energy, such as pasteurisation, drying, condensation, and evaporation (Ling-Chin et al., 2018). As a result, renewable energy-driven food factories can take advantage of cascading temperature requirements using an interconnected method.

Cascade systems enable heating and cooling to happen at different temperature levels with negligible thermal transmission losses. These can include several pieces of equipment, such as heated mixers, coolers, spray dryers, and pasteurizers, located at varying distances from one another. The energy and material exchange between the two activities occurs at an intermediate temperature. Multistage heat-recovery systems using more than one heat-exchange medium may also use stored thermal energy to offset a power blackout. Recovering heat between drying and preheating is often the most valuable, according to Wipplinger et al. (2006).

3.3. Electrification of Processing Steps

Many steps in food processing (e.g., pasteurisation, sterilisation, pumping) can be electrified, enabling more efficient resource use and reducing greenhouse gas emissions (Brooks et al., 2021). The efficiency of equipment can be greatly improved through this electrification, but renewable electricity must be available. For instance, food

manufacturers that want to reap the benefits of renewable sources will have to invest time in demand profiling even for low-lying locations. In the absence of an adequate electricity supply, increasing electrification will trigger self-service emergency power. This will have life-shortening impacts on the thermal systems of equipment and result in hefty maintenance or replacement costs.

3.4. Thermal Storage and Demand Response

The use of thermal storage technologies enables the provision of heating and cooling at times other than when generation occurs (Saffari Tabalvandani et al., 2018). Low-load, or even zero-load, operation of processes is possible with suitable control strategies, enabling demand-side management in combination with other energy sources and shifting consumption outside peak periods (Naegler & Simon, 2018). The thermal energy storage system sizing should consider hourly variations in energy generation and operating costs, as well as the expected renewable energy fraction across all four seasons (Fikiin et al., 2017). Various stages of food production are long enough to allow synchronisation with time-dependent electricity prices. Thus, several process steps in food manufacturing can be electrified profitably. In dairy processing, two practical switching

points were identified for electrifying pasteurisation and sterilisation without adverse impacts on energy efficiency and emissions. When the temperature of hot water is less than or equal to 85 °C, hot-water-circulation pumps can be driven electrically for meat-processing operations; similarly to dairy, the additional emissions associated with these incremental electrical loads are directly offset by avoided fossil energy consumption.

Studies in these fields show that thermal loading can be implemented in food-processing operations for demand-side management without affecting production volume or timing, thereby enabling the integration of renewable energy sources.

4. Supply Chain and Life-Cycle Considerations

To position emerging renewable-energy-driven innovation in the food sector within a global context, a supply chain perspective is essential. A scope of farm-to-table and farm-to-process finds appropriate applications in value chains for food sectors such as dairy, meat and poultry, beverage, and baked goods. Further developments are on product carbon footprints and more advanced, environmentally friendly systems (Picart-Palmade et al., 2019). More attention is being given to the energy requirements, alternative supply chains,

consultation analysis, carbon footprint considerations, and fit within the capex and opex economic limits of sustainability. We also need to ensure that specific savings and net-zero or close-to-net-zero trials are considered within techno-economic realistic boundaries, so we do not end up with costly trial plants that cannot be replicated at scale. Whether it is that rooftop in-situ manufacturing facility or the space station launched into orbit, product performance always lies in tight coupling. With such thermally demanding equipment, there is a need for assured energy supplies across concurrent production zones, as well as for water/steam and cooling. Collectively, these require continuous quantitative analyses. Moreover, these issues can, by themselves, fill full-length articles. Similarly, these require a holistic approach rather than piecemeal actions to deliver a fully reliable outcome.

4.1. Sustainability Assessment and Life-Cycle Analysis

The application of renewable energy in food processing is currently limited; the most common use is water heating. Additionally, the sustainability of renewable energy technologies used in food processing has been characterised by very few studies. Thermal energy is commonly employed in food processing for heating, cooling, drying, pasteurisation, and other operations. As

a result, even if the food industry transitions from fossil fuels to renewable energy sources, its total energy demand may not decline drastically, since food processing is already among the most energy-efficient industries. The integration of renewable energy is likely to drive the necessary decarbonization of the energy sector to counter climate change. As a result, food processing industries are encouraged to use energy sources such as biomass, geothermal, solar heat, and wind electricity. Despite some research into the application of renewable energy technologies in food processing, there has yet to be any systematic life-cycle assessment of these technologies. Further studies along these lines must be made to establish viable ways to lower the carbon footprint of food processing and depletion of fossil resources through alternative source of energy technologies (Picart-Palmade et al., 2019) ; (Brooks et al., 2021).

4.2. Carbon Footprint Reduction and Net-Zero Pathways

Examples from the food processing industry include almost entirely electrified operations and the management of on-site renewables that help reduce carbon emissions. These are features of sustainable industry practices that help with scaling. Thus, the industry achieves sustainable manufacturing practices through various food-

processing innovations. Using renewable energy supply, cross-sectoral exchange networks, heat recovery, electrification, and flexible demand response can reduce the carbon footprint of a typical food-processing centre by up to 95%. After reviewing these direct sources, several uncertainties regarding total net-zero operations remained, necessitating compensatory measures given the decades-long time scale. Should electrification be fully pursued, the food processor already employing cook-chill will be able to develop steps to reduce energy use immediately and GHG impacts by cascading inter-sectoral renewables and smart-gridding its operations during peak times (Picart-Palmade et al., 2019). Transformations and digital management that are more advanced yet cost-competitive could dramatically reduce supply chain carbon footprints while simultaneously minimising operational risks and total investment. They are currently attracting immense interest from a wide variety of actors (Brooks et al., 2021).

4.3. Economic Viability and Policy Implications

The levelized cost of providing and integrating renewable energy is a major economic consideration. Because processing equipment is, for the most part, installed as fixed assets, potential adopters should also account for capital

expenditures and operating expenses in addition to levelized costs (Umar et al., 2017). The policy context can shape the price and availability of renewable energy technologies, the financial inducements offered to encourage their take-up, and the regulatory requirements on potential adopters. As a result, researchers examining the economic viability in the food sector and beyond need to be aware of national and regional policies that may encourage or inhibit the wide deployment of renewable energy technologies by food processors.

5. Case Studies from the Food Processing Sector

Dairy processing energy use generally accounts for a high proportion of overall operating costs. As a result, there is a global focus on reducing energy consumption and integrating renewable energy sources to achieve energy savings and reduce greenhouse gas emissions (Picart-Palmade et al., 2019). One possible dairy operation that fits well with these objectives is a dairy plant's milk chilling, which accounts for the largest single energy cost as a percentage of the total energy consumed in processing raw milk (Brooks et al., 2021). According to statistics, the additional energy required for cooling in warmer regions of the world ranges from 0.061 to 0.077 kWhr/L of milk, using both air- and water-cooled refrigeration systems. The recent shift towards renewable

energy sources has necessitated an evaluation of the milk chilling process to achieve energy savings while maintaining product quality and safety standards (Jagtap & Rahimifard, 2018).

5.1. Dairy Processing

The processing of dairy products accounts for a significant share of the energy used worldwide. This accounts for about 26% of the total energy used for food processing. Also, 7% of the total energy is used by the industry. Common energy-intensive steps that use heat and/or mechanical energy to reach the temperature levels mentioned include pasteurisation, sterilisation, evaporative concentration, and refrigeration. Grid-connected renewable energy provides a range of solutions that enable precise objectives, such as integrating renewable heat into milk processing, optimising dairy raw material chilling operations, and minimising the integration of electrical energy during peak load.

There are many recognised renewable energy opportunities, and many solutions are often suggested, including the use of thermal storage to decouple heating from evaporation, decouple chilling through a stand-alone evaporative cooler and heat recovery from the residue during process operation, pre-heat of incoming milk and/or concentrate for pasteurisation/sterilisation, and extra

refrigeration. There are already several technologies that track, simulate and optimise energy flows in milk processing. There are clearly defined opportunities to integrate grid-connected renewable energy technologies and devices into the dairy sector to achieve well-defined objectives. (Picart-Palmade et al., 2019)

5.2. Meat and Poultry Processing

Energy-intensive operations occur during the processing of meat and poultry, as most of the energy is used for refrigeration and sterilisation. As heat is a major energy carrier, the heat recovery systems offer the highest potential for savings. Anaerobic digestion of wastewater is a growing field that enables the conversion of waste to energy while meeting discharge limits (Ziara, 2015). Energy flows associated with meat processing can be estimated for sustainability assessment using accurate activity data. In a study of a beef processing facility performing primary and secondary slaughter, slightly more than 80% of the energy was used for boiler feedwater (Li, 2019). Most subsequent steps relied primarily on groundwater and recycled water, whereas energy-intensive processes included chilling, refrigeration, and pasteurisation (Picart-Palmade et al., 2019). The installation and extent of processing largely influence particulars.

5.3. Beverage Manufacturing

Beverage production usually requires the most rigorous heat treatment and control of several critical process parameters, i.e., time, temperature and pH. The beverage industry faces various challenges related to safety, preservation, contamination-free end products, changing consumer tastes, and regulatory pressure. Traditional technologies for food processing include heat treatments such as pasteurisation and sterilisation, as well as microfiltration and ultrafiltration for filtration, and concentrating and drying. Only a few alternative non-thermal procedures (high-pressure processing, thermal infrared, radiative heating, etc.) are industrially applicable.

According to Brooks et al. (2021), solar energy offers tremendous opportunities to overcome these challenges by leveraging the wide range of available solar technologies. Solar energy is used to achieve moderate temperatures, as the temperatures required for operations vary significantly in the beverage sector. Solar energy integration is primarily used for drying, pasteurisation, chilling finished products, and milk renewal. Besides these uses, the cold storage of some products already made on site is often used by inland beverage manufacturers, for which solar cold storage is an interesting option. The ongoing solar application projects in the

sector in recent years have been significant, driven by the availability of solar resources and associated time-temperature patterns. The publication of at least three ongoing or operational solar-assisted beverage brand partnership projects in Mexico, South Africa, and India is available, thereby verifying that grid parity/IAP is achievable with solar energy at the beverage industry level at this moment (Picart-Palmade et al., 2019).

5.4. Baked Goods and Starch-Based Products

The energy-intensive nature and reliance on fossil fuels in processing utilities and sectors that produce baked goods like bread, cake, and biscuits provide extensive opportunities for renewables. Drying and baking are high-energy processes that can benefit from insulation, heat recovery and renewable energy supply.

Starch-based products like pasta and noodles are manufactured daily, a process that requires significant energy, especially in warm weather. The processes after water mixing include drying, steaming, cooling, frying and devolatization. Electricity prices usually account for a larger share of production costs than in the food sector as a whole.

'Baked goods such as bread, cakes, and cookies processing are activities with high energy requirements, fossil fuel use,

and opportunities for integration of renewables.' Baking and drying processes are energy-intensive. Their energy consumption can be reduced by using insulating materials, heat recovery and renewable energy supply.

Countries that produce starch-based goods, such as noodles or pasta, consistently expend significant energy in warm climates. The user dries, steams, cools, fries, and volatilizes after mixing with water. Manufacturing costs, including electricity prices, are higher than those in the food sector.

6. Challenges, Barriers, and Risk Management

When deployed effectively, renewable energy technologies could deliver significant operational and environmental benefits for food processing. However, there are still significant challenges regarding cost, technical matters and stakeholder awareness. Barriers related to the technical aspects of this transaction include system intermittency, the need for offsetting capacity to ensure a reliable supply, and the integration of producers with diverse technologies. The financial barrier stems from the high capital costs of long-payback technologies, while market oversight is insufficient to mitigate risks from bearish energy prices and policy uncertainty. Regulatory constraints include requirements for

electricity specifications, hygiene issues that create traceability problems for distributed materials, and occupational health and safety permits (Sambell et al., 2019).

It is essential to direct research attention to (i) enabling flexible renewables-driven processing through hybrid generation, modular equipment and switching guidance; (ii) solving financing barriers by clarifying incentives and creating consortia for energy-electrification audits standardisation; and (iii) improving cross-sector awareness of food-processing measures for development of targeted solutions.

6.1. Technical and Operational Barriers

Fossil fuels are still heavily utilised in the food sector, including harvesting, preservation, and manufacturing. Most importantly, the cooling chain storage and transport of food prior to food processing still run on fossil fuel energy. Consequently, it is necessary to reduce fossil energy use in the food-cooling chain as a precondition for conducting recyclability assessments and for the upscaling of reusable energy food-processing technology along a long-term sustainability pathway (Picart-Palmade et al., 2019).

Integrating renewable energy resources into the food sector offers many opportunities for process innovation.

The inter-firm collaboration model implements open innovation to accelerate the trend. Many renewable process technologies are in operation in other industries. The tested firm can promptly deliver this knowledge to its food-industry customers and develop new renewable food-processing machinery.

6.2. Financial and Market Barriers

Integrated food processing systems that use renewable energy can be achieved by integrating renewable energy-based processes with traditional processing systems. The proposed approach may require high capital investment, a long payback period, disconnection from the conventional energy supply, and a wide range of technical expertise and design capacity. The integration of renewable energy technologies must therefore be a sustained effort. Moreover, indirect appropriation of renewable energy resources would necessitate the application of conventional methods. Partial modifications to the system are all that is required to implement these methods within a short time frame. Food factory operators seeking energy-efficient designs to lower operational costs or products with longer shelf life could find the methods of this project attractive (Seng To et al., 2017).

6.3. Regulatory and Safety Considerations

In terms of energy intensity, high-level processing is an important target for renewable-enabled design modifications (e.g., removing inedible parts, fermenting, freeze-drying, cooking, shredding, pulverising, mixing, emulsifying, pasteurising, coating, freezing, crystallising) (Picart-Palmade et al., 2019). There are considerable opportunities to integrate renewable energy into several processes, such as pasteurisation, sterilisation, cooking, drying, and cooling. This can be achieved through the conversion of heat and electricity. There is also the possibility of recovering waste.

Food processing refers to the numerous steps considered primary, secondary, and tertiary. Food transformation (decontamination of unwanted parts) of primary and secondary foodstuffs, conventional and non-conventional fermentation, extraction, crushing and mixing, blending, coating and purification accounts for more than 50% of industrial activity worldwide. Food company managers place great importance on thermal treatment and operational selection.

7. Future Prospects and Research Directions

According to trend projections, food processing is expected to contribute

significantly to global energy consumption and greenhouse gas (GHG) emissions. Development contravenes sustainability goals established in international agreements, such as the Paris Agreements (Picart-Palmade et al., 2019). Food manufacturers have access to a range of opportunities in renewable energy sources. A move to renewables requires both supply-side technologies that capture resources and process-level innovations that enable their efficient combination. Food processing consumes a lot of energy and has access to abundant low-carbon resources. Therefore, the sector is a key opportunity in industrial transformation.

Decarbonisation involves a shift away from fossil fuels to renewable energy sources that can be replenished on human timescales. Renewable energy takes many forms in food processing. They are thermal (solar, biomass), mechanical (wind), electrical (solar, wind), and rehabilitative (biogas). Evaluation of Technical, Economic, and Ecological Feasibility is Important. Accordingly, other food-processing applications have historically received little attention. Such treatment is most relevant to supply-side technologies that use renewables and to process-level innovations that optimise use when blended with fossil fuels. Food processing encompasses broad trends across industries that are decarbonising,

with growing importance on global agendas, and must be further researched.

7.1. Innovation Trajectories in Renewable Integration

It is predicted that future renewable integration in food processing will take various innovation pathways. Promising candidates for wider replication are new renewable technologies conceived for the sector; hybrids combining renewables and conventional sources; and modular options allowing for progressive upgrades or decoupling of services. The concepts of photovoltaic and biogas, which emerged almost independently of each other, are now being linked to one another and to drying systems. There is an initial emphasis on food preservation and waste treatment. They are already generating concepts for sterilisation, pasteurisation, and thermal drying. The emergence of AI and digital twins will undoubtedly aid use case selection in food processing. Tools like these can help determine the malfunctioning technologies, configurations and operational parameters that can significantly influence both the renewable fraction and the total costs incurred (Picart-Palmade et al., 2019) (Brooks et al., 2021).

7.2. Digitalisation, Automation, and Smart Grids

Digitalisation, automation, and smart grids are vital processes that can maximise energy efficiency in food processing (Jagtap & Rahimifard, 2018). As Internet of Things smart energy meters can curb consumption dramatically and improve profitability. Standards-based energy management systems (ISO 50001) support continual performance improvement, resulting in cost and greenhouse gas emission reductions. Some cost-effective methods include metering, monitoring, equipment retrofitting, process control, and re-engineering. The technology manager oversees production and streamlines processes. They will be in charge of the company's operational technology development.

There is increasing pressure on the food industry to reduce energy use, cut greenhouse gas emissions, and pledge net zero. The targeted reduction strategy will be implemented through digitalisation, automation, and smart grids. Monitoring processes and equipment remotely enables analysis of how things operate so that opportunities for improvement can be identified and the effects of changes can be tracked.

The world water supply is fast becoming scarce and expensive (Hassoun et al., 2022). Efforts are underway to reduce water consumption across all sectors. The expensive investments in water

abstraction, treatment, and discharge typically do not account for the economic benefits of energy billing. Achieving water savings can thus provide a competitive advantage.

7.3. Collaboration Across Stakeholders

Collaboration among stakeholders across the supply chain is essential for a successful transition to renewable energy in food processing. The priority should be a joint language, endorsed by actors in the food industry, that enables knowledge sharing – inviting stakeholders to co-design the next generation of practices and technologies, enabling each processing step based on circular economy principles. Food producers and packers can work together to improve resource efficiency through new solutions. The development and dissemination of circular economy practices will be supported through industry-university partnerships. A call to industries as well as policymakers to come together and co-design policies that shape and guide our local food economy into a circular one. The literature consistently shows that collaborative research initiatives are important. Collaborative research initiatives can also help sustain these efforts (León-Bravo et al., 2017; Brooks et al., 2021).

8. Conclusion

The fast-growing world population drives improvements in efficiency and a

reduction in environmental impact in the food-processing sector. The energy consumed in food production contributes significantly to greenhouse gas emissions and waste generation. The sector depends on fossil fuels for energy, and this dependence is increasing steadily. As a result, food processors must produce more food while reducing their environmental impact.

The food-processing sector can become more sustainable by using renewable energy sources instead of traditional ones. Food processors are deploying many established renewable energy technologies, while others are approaching global commercial readiness. The integration of renewable-energy systems is also prompting other innovations in process design and operation to further sustainable development. For this reason, the time is right to assess two complementary aspects of renewable energy adoption: the core technologies themselves and the process-level innovations these technologies enable. According to Picart-Palmade et al. (2019), such an assessment provides food processors with valuable ideas and inspiration to initiate renewable-based innovations.

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