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A systematic review of electrification technologies for Danish food and beverage industry

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Abstract:

A significant reduction of primary energy consumption and CO_2 emissions can be obtained in a future fossil fuel free power system by converting the energy supply of industries to a fully electric one. The key to this transformation is electro-technology, which provides the possibility of efficient using of electric power for process energy supply. In recent years, the technological revolution, nutritional awareness, and continuous demand of the new generation provided advanced technologies to ensure optimal efficiency as well as green and sustainable manufacturing of food products.

The present study extensively reviewed the appropriate technological options for the electrification of industrial processes in the Danish food and beverage industry. A number of non-conventional technologies have been investigated to improve, replace, or complement conventional processing technologies in the highest energy-demanding processes such as drying, evaporation, cooking and backing, pasteurization and sterilization.

The study shows that a wide range of electrification technologies exist for the mentioned processes. The alternative technologies offer many advantages such as significant reduction of CO_2 emissions, reducing process time, and improving product quality, process controllability and flexibility. Technologies such as heat pumps can significantly increase the energy efficiency of the corresponding processes, which may lead to lower operational cost and shorter payback period. However, they also introduce some challenges such as high capital costs, requirement for electrical capacity upgrades, as well as variability and uncertainty in the electricity supply.

Keywords:

Electrification technologies, Decarbonisation, Food and beverage industry.

1. Introduction

In the recent years, the electrification of industrial processes, referring to the switch of the primary energy source from fossil fuels to electricity, has gained great interest as a way to decarbonize the industry, together with the use of renewable fuels and carbon capture technologies. Reasons for this interest are that, in many cases, electric systems can be significantly more efficient than those using fossil fuels [1], but most importantly, that the electricity can have a renewable origin.

The industrial sector is highly dependent on fossil fuels. As an example, in 2015, 55% of the final energy use of the industry in the EU was covered by fossil fuels [2]. Moreover, industry has been pointed out as one of the most challenging sectors to be decarbonized, due to lack of cost-effective substitution technologies [1]. For instance, as of today, there is no significant efficiency gain from a shift to electricity for high-temperature industrial processes. In addition, high-temperature electric furnaces or heat pumps for commercial applications are not yet commercially available.

Nevertheless, the potential benefits of electrification of industry should not be disregarded. It is estimated that industry has one of the highest potential for electrification, which is estimated to be about (34 % to- 52 %) [1]. Only in Denmark, it is estimated that 88% of the natural gas use in industry could be replaced by electricity [3]. It should also be noticed that many electric heating technologies (e.g. heat pumps, electric heaters) are more efficient than fuel fired systems, which in the long run will significantly reduce the energy required for given processes. Additionally, if the consumed electricity is primarily of renewable origin, the annual carbon emissions will be cut proportionally, contributing to reducing the environmental impact of industry locally and globally.

IRENA has estimated that deep electrification of the end-use sectors could reduce the emissions from industry by 16% [1]. While the cut of CO_2 emissions is a main driver towards decarbonisation after the Paris agreement in 2015, the electrification of industrial processes may bring additional benefits, such as a reduction of local air pollution, and lower water demands, better usage of energy and better control of the final quality of the product. It is therefore important to point out that the benefits of electrification go beyond the reduction of greenhouse gas emissions, which its effect may not be noticed in the short term, but also, has an immediate positive impact in the environment of areas surrounding industries.

Luckily, the Danish electricity mix has a significant share of renewable resources, being one of the most decarbonized electricity systems in the world, and plans are to have at least 100% of renewable energy share in the electricity market by 2030 [4]. These numbers place a more than favourable situation for the implementation of electrification in the Danish industry, which has the potential to become one of the main drivers for the decarbonisation of the industry.

1.1. Estimation of power-to-heat potential for food industry in Denmark

An analysis of the energy use of the Danish industry reveals that about 70% corresponds to the manufacturing industry, which is largely dominated by food and beverage industries [5]. Given the fact that industrial processes in these sectors mainly require heat at low temperatures (< 100 °C) [2], the possibilities for electrification are greater both in terms of feasibility and availability.

Fig. 1 shows the temperature levels of the heat demand by different processes in the food and beverage industries in Denmark [6].

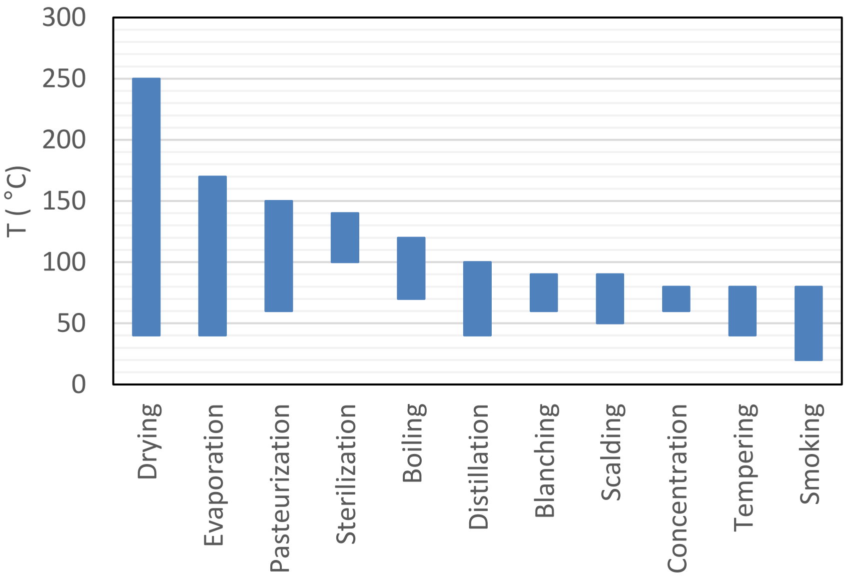

Fig. 1 – Temperature level of heat demand in different food processes in Denmark

As it can be from Fig.1, drying and evaporation processes may require higher temperatures, and thus greatest potential for CO_2 reduction and energy savings. Pasteurization and sterilization processes, of vital importance for food safety, also require high temperatures. The rest of the processes may be easier to electrify, and bring CO_2 emissions reductions.

Fig. 2 shows the distribution of energy used for the most energy-demanding food processes in Denmark [7].

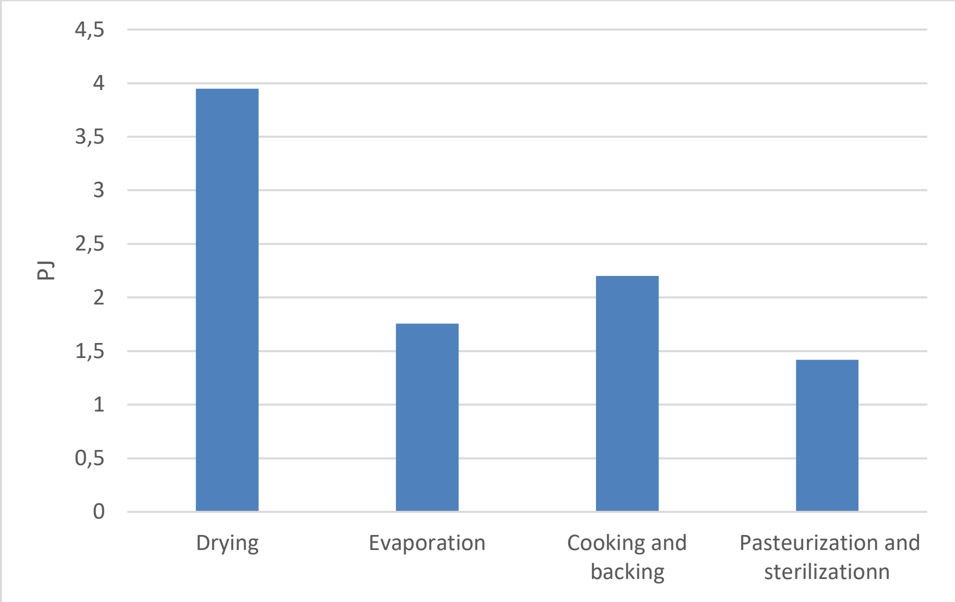

Fig. 2 - The distribution of energy used for the most energy-demanding food processes in Denmark

As it can be seen from Fig. 2, the drying is a significant process in terms of energy need, and cooking and backing processes are the second greatest need. Other processes such as evaporation and pasteurization and sterilization are in third and fourth places but still require a considerable amount of energy.

This study presents a review of the electrification technologies that can be used to replace highly energy intensive or fossil-fuel based technologies in different processes in Danish food and beverage industry. The industrial processes with the highest energy demand such as drying, evaporation, cooking and backing, pasteurization and sterilization serve as a base to discuss the different technological options that can transform the energy supply of the existing processes towards electricity. Such approach will not only limit to evaluating the electrification technology for specific food processes, but could also complement the planning and design of technology demonstrations, as well as supporting the technology development and risk mitigation in industry.

1.2. State of the art technology in the high energy demand food processes

1.2.1. Drying process

Drying is a key process in the food and beverage industry, and its main objective is to remove moisture from the product to extend its life, preserve it, or facilitate posterior processes [8]. The national share of energy used by the drying process in the industry is estimated to be around 25% for Denmark [9], which brings out the relevance of improving the efficiency and increasing the renewable energy as energy source of these processes.

Traditionally, drying in the food industry is in more than 85% of the cases carried out by convection, using superheated steam dryers or hot air, which are obtained by using the combustion of gas or coal as the heat source [9]. Depending on the starting product features and final product requirements, different drying methods have been used so far within the food and dairy industry, mostly comprising spray drying, vibrating fluid bed drying, integrated fluid bed drying and integrated belt drying [10].

1.2.2. Evaporation process

Evaporation process consists in the removal of a solvent (most of the times water) from a solution or slurry by vaporizing it, with the objective of concentrating the fluid solution. Evaporation occurs also in other operations such as distillation or drying. However, contrary to distillation, evaporation does not attempt to separate the components in the vapour, and, contrary to drying, in evaporation, the final product is always a liquid or slurry [10].

During evaporation, the product undergoes changes of physical structure and appearance, and the final product could be in the form of a liquid-like product or a slurry, depending on the humidity content. The most optimal technology used for evaporation process depends on the starting product and final product requirements.

Evaporation in the food industry can be carried out by boiling off water using immersed electric heaters, but the most common used equipment are multistage shell and tube evaporators, or plate evaporators [11], using process heat ,which is normally generated by fossil fuels. The suggested electrification alternatives for evaporation process, in this study, are specific for this process, but beyond them, electricity can be used to generate the process heat necessary for the evaporator.

1.2.3. Backing and cooking an process

Baking and cooking are thermal processes, which are carried out under high temperatures (60 °C to 250 °C), through which the food product develops the desired characteristics including several physical, chemical, biochemical and rheological changes. Although baking could be, in principle, included as a cooking process, we refer here to the cooking process in which specific surface of final properties are expected (e.g. roasting, grilling). While cooking, in general, refers to an overall bulk treatment of the product.

Currently, baking and cooking processes rely mostly on the use of fossil fuels for direct heating in the ovens, or for the production of process heat.

1.2.4. Pasteurization and sterilization

Pasteurization is the process that uses a relatively mild heat treatment to kill key pathogens, and inactivate vegetative bacteria and enzymes to make food safe for consumption. Sterilization is a more severe thermal treatment, traditionally designed to achieve commercial sterility of the products, giving it long-term shelf stability. However, it has to be noticed that the required degree of thermal treatment depends on the product pH, as it accounts for the effects of pH on the resistance of the microbial spores.

Pasteurization and Sterilization processes in the food industry are carried out mostly by using steam or dry heat, which are commonly generated by using fossil fuels.

2. Method

In this section, a series of alternative electrification technologies are briefly introduced and comprehensively screened to find the most relevant technologies to be replaced of the conventional ones in the four processes of the Danish food and beverage industry with the highest energy demand.

2.1. Alternative technologies

The alternative technologies suitable for food and beverage products are presented in table 1, divided into three categories: (i) Electro heating technologies, (ii) Non-thermal processing technologies and (iii) Electricity-driven waste heat upgrade technologies, which have been introduced previously by [12].

Table 1- Alternative technologies

Technology		
Electro-heating technologies	**Electrified non-thermal processing technologies**	**Electricity-driven waste heat upgrade technologies**
- Radiofrequency (RF) heating - Microwave heating - Ohmic heating (Direct resistance heating) - Indirect resistance - Infrared - Induction heating techniques	- Pulsed electric field processing - Pulsed light processing - High voltage electric field, cold plasma and ozone processing - Ultraviolet radiation (UV) - Ultrasonic and megasonic - High pressure processing (HPP) - Membrane process	*- Heat pumps* *- Mechanical Vapour recompression (MVR)* *- Freeze Concentrates*

A description and working principle of each of the above-mentioned technologies can be found in [12–14].

2.1.1. Hybrid solutions – Possible future operational schemes

Hybrid solution will provide the possibility of exploiting synergies between different technological options as well as improving output flexibility of the food processes. The hybrid solution can be combination of non-thermal pre-treatment followed by electro heating techniques or different combination of non-thermal and conventional thermal techniques.

In addition, hybrid electrification solutions, consisting of combining an electrification technology within an existing installation without fully removing it, may offer two benefits for the short-term electrification. First, since the electrification system will aim only at carrying out part of the process, the capital investment needed will be lower, while the installation may require less modifications of the existing process, providing some energy savings without the need of a full re-design of the process. Second, hybrid systems in which the share of each technology can be controlled, may offer the client the possibility to use the electrification alternative when periods of lower electricity prices are expected.

2.1.2. Real demonstration projects

Several parameters such as policies, technology development actions and activities, and technological limitations play a major role in the evaluation and eventual adoption of efficient technologies. However, in the real world applications, the demonstrated success of the new technologies is among the most critical activities. Demonstrations of advanced technologies will provide the possibility of assessing new technologies as well as improvement or enhancement of these technologies. In addition, it involves addressing issues related to optimized integration of these technologies into real world settings.

2.2. Screening process

The alternative electro-technologies were comprehensively reviewed in terms of: Applications in the four selected food processes with the highest energy demand such as drying, evaporation, cooking and backing, and pasteurization and sterilization; Technological benefits and challenges; Energy efficiency; and finally Maturity level assessment from the early stages of the development to the full implementation in the industrial cases. Below briefly explained the four criteria considered in the screening process.

2.2.1. Applications

A comprehensive review has been done to assess the applicability and performance of each of the electro-technologies mentioned in section 2.1 in the most energy-demanding processes of the food and beverage industry identified above. Majority of the studies reviewed in this study [12,13,15,16] are lab-scale, however few successful demonstration cases are also reported.

2.2.2. Technological benefits and challenges

Technological benefits and challenges of each of the technologies are briefly listed in the study. Identifying and analysing the challenges, limitations and barriers that inhibit the wide application of the technologies in the current industry would lead to right selection of the appropriate technology for a specific applications, as well as finding smart solutions and strategies to overcome such issues.

2.2.3. Energy Efficiency

For each technology a wide range of overall process, efficiency has been reported. However, for more extensive quantification, a specification of the process and the product is required.

2.2.4. Technology readiness level (TRL)

The level of development and readiness of each of the described technologies was graded as a function of their technology readiness level (TRL) and their commercial availability. The technologies with TRL equals to 8-9 are commercially available and have been installed at least once, technologies with TRL equals to 6-7 are commercialized by companies but still needed a full scale first installation, and finally technologies with TRL 4-5 have been proven in pilot scale / lab conditions. It is important to mention that although a technology may be fully developed for a specific application (e.g. induction for heating) it may still be not completely available for another specific application (e.g. induction for drying).

3. Results

3.1.1. Selected technologies for the four processes

Table 2 presents the most realistic alternative technologies for electrification of the four processes identified as the highest energy-demanding processes in the food and beverage industry such as drying, evaporation, cooking and backing, pasteurization and sterilization processes.

Table 2- Selected electro-technologies for the highest energy-demanding processes in the food and beverage industry

Selected Technology					
		Drying	**Evaporation**	**Cooking and backing**	**Pasteurization and sterilization**
Electro-heating technologies	**Radiofrequency (RF)**	x		x	x
	Microwave	x		x	x
	Ohmic heating	x		x	x
	Indirect resistance			x	
	Infrared			x	
	Induction	x		x	x
Electrified non-thermal processing technologies	**Pulsed electric field processing**	x		x	x
	Pulsed light processing				
	High voltage electric field	x			x
	Cold plasma				x
	Ozone processing				x
	Ultraviolet radiation (UV)				x
	Ultrasonic and megasonic	x			x
	High pressure processing (HPP)				x
	Membrane process	x	x		x
Electricity-driven waste heat	**Heat pumps**	x	x	x	x
	MVR	x	x	x	
	Freeze Concentrates		x		

It can be seen from table 2 that for the processes such as drying, cooking and backing, and pasteurization and sterilization, a wide number of technologies is available. However, when it comes to evaporation process, only a couple of options exist.

3.1.2. Technological benefits and challenges, Energy efficiency and TRL

Apart from CO_2 emissions reduction as one of the main benefits of electrification, mentioned above, electrification of industry would bring additional social and economic benefits. For instance, some electrification technologies present a better energy efficiency (e.g. more thermal power per unit of electrical power), therefore requiring less energy input for the same production results. In addition, electro-technologies may offer more flexibility and controllability of the process, and even increased productivity .Furthermore, as more electro-technologies become available and mature thanks to new technological advancements, they will also become economically feasible, as this will also bring adjustments in energy prices.

Table 3 presents the technological challenges, energy efficiency and TRL of the electro-technologies selected in section 3.1.1.

Table 3- Technological benefits and challenges, Energy efficiency and TRL for the selected electro-technologies

	Challenges [13,15]	**Energy Efficiency** [13]	**TRL** [15]
Radiofrequency (RF)	- High capital costs (about half as much as MW) - Materials must be compatible - Requires electrical capacity upgrades - Applications are more cost-effective when combined with less expensive processes (e.g. infrared, hot air) - More appropriate for large and flat material	50-70%	Commercial TRL 4-8 depending on application
Microwave	- High capital cost - Materials must be compatible (dielectric, i.e. non- conductors of electricity) - Changes in dielectric properties may have some effects on the heating pattern quality - Requires electrical capacity upgrades - Low unit power; may require multiple power sources; may restrict size of installation - Undesirable heating effects for some materials (run- away temperature rise, burning) - Actual temperature profiles might not be available - Difficult to treat large areas uniformly	50-70%	Commercial TRL 4-8 depending on application
Ohmic heating	- Effectiveness depends on the resistance of target material - Scalability challenges - Situation specific design -Clean contact surface is required - Scale free for good electrical connection - Mainly relies on continues-flow systems - Non-homogenous foods may require stirring, intermittent heating or combining with other energy source, in order to improve the heating uniformity	75-95%	Commercial TRL 8
Indirect resistance	- Inefficient in large spaces - Requires electrical capacity upgrades -Service life of heating element - Heat transfer rate between the heating elements and load	~70%	
Infrared	- Requires electrical capacity upgrades - Less appropriate for bulk heating (more will be absorbed by the surface of a martial, and depending on the thermal properties, heat will transfer through the material) - IR emitters in dirty environments require higher maintenance	>80%	Commercial
Induction	- Capital and energy costs - Requires electrical capacity upgrades - Maintenance - Not well suited to irregularity-shaped parts during forging	70-90%	Commercial

	- Inductor should be changed and sometimes compensation for parts that are non-repetitive in shape		
Pulsed electric field processing	- High capital costs - Requires electrical capacity upgrades - Electrode reliability - Not suitable for pasteurization of certain vegetable juices , which need to be acidified [17]	---	Commercial TRL 8
High voltage electric field **Cold plasma** **Ozone processing**	---	---	---
Ultraviolet radiation (UV)	- High capital costs - Requires electrical capacity upgrades - Non-penetrating, effects of shadows may limit the application - Line-of sight limitation - Limited capacity - Not effective on dry products - Flow viscosity might be a constraint	---	Commercial TRL 8
Ultrasonic and megasonic	---	---	Commercial, TRL 7
High pressure processing (HPP)	- High capital costs - For commercial application of high pressure sterilized low-acid food products - Usually on pre-packed products - Not effective on dry products - Possible changes in texture or color	---	Commercial TRL 8
Membrane process	- Microfiltration: Depending on degree of filtration, the product taste might be affected	---	Commercial
Heat pumps	- High initial investment- More complex to use than the conventional technologies - Limited upper temperature (max 90°C) for supply temperature	COP (coefficient of performance) 3-5	Commercial
MVR	- High initial investment - More complex to use that conventional technologies	COP (coefficient of performance) 10-30	Commercial
Freeze Concentrates	---	---	---

As, it can be seen from table 3, for the drying process, a wide number of technologies have been developed and are available commercially, and ongoing research is in progress to introduce other novel technologies. However, for the evaporation process only a couple of options exist including heat pump and MVR. Both of these technologies share the benefits of substantially improving the energy efficiency of the process, but at the expense of complex and expensive equipment installations.

Pasteurization and sterilization processes are vital importance for food safety and may require higher temperatures above 100 °C. However, a wider range of alternative electro-technologies with sufficient level of maturity can be considered for such processes.

In addition, it can be observed from table 3 that there are however, various challenges and barriers for electrification, both for private companies and on a national level. Among all the challenges listed above, high capital cost, and the requirement for electrical capacity upgrades can be considered as the major barriers. Generally, electrification will increase the electricity demand, which may require significant utilization of renewable recourses. This may lead to variability and uncertainty in electricity supply [18].The previous study [19] has shown that 2 to 4 times expansion of the electricity grid and a significant increase in electricity storage capacity is required for full electrification of heat in Denmark, unless heat storages and the use of heat networks be included [20].

Moreover, other barriers and challenges have been reported by [21], including heterogeneity of industrial sectors, process integration difficulties and lack of engineering knowledge to redesign the manufacturing process line, fuel and other operating costs, electric delivery infrastructure costs and constraints, exiting regulations and policies that may favour one fuel or technology over another, and finally, lack of adequate policy and regularity supports.

Furthermore, the U.S. department of energy (DEO) has reported historically slow adoption of new technologies in U.S. food processing for several reasons. The first reason was the industry conservatism and closed monitoring of food processes to insure compliance with safety and sanitation standards. Consequently, every new technology should be thoroughly tested to fulfil the standards. The second reason was the high cost of R&D technology, which has limited a lot of in-house research, due to industries low profit margin. The third reason was industry competitiveness and secret recipes, which has limited the wide collaboration and interaction options between different subsectors of the food industry, and final reason was low technology awareness, which has limited the full benefit of specific technology, until it is fully mature [22].

However, to reach the highest level of electrification possible, the above mentioned barriers can be addressed by supporting the efforts in the R&D related activities of the industrial electro-technologies to improve the performance and lowering the costs, more pilot and demonstration projects to evaluate the electrification impacts on process performance, cost and output, as well as more policies that support low carbon or renewable heating in industry [21].

3.1.3. Successful demonstration cases and hybrid solutions

Two successful demonstration cases of emerging and newly commercialized technologies such as radio frequency for drying purposes, and pulse electric field for pasteurization purposes targeting cookies and crackers manufacturing and orange juice manufacturing respectively in U.S. food industry, has been reported previously by U.S. department of energy (DEO) [22]. As a conclusion, the sector-wide energy savings in the range of 134 million kWh to 2.22 million kWh was obtained, depending on the available market portions. This can lead to CO_2 emission reduction range from 123 million kg to 249 million kg per year [22].

In addition, several successful demonstration cases of integration of heat pumps (up to 90 °C) in the food and beverage industry to utilize the available low temperature excess heat from different processes can be found in [23].

An example of hybrid systems, combining electromagnetic energy (such as microwave or radio frequency) and convective hot air can accelerated the drying processes by selectively targeting moisture [16,24]. In addition, combining the microfiltration technology (as a cold pasteurization technique) with conventional heating method for pasteurization may reduce the required energy demand of such processes.

4. Discussions

Considering the novelty in the industry of many of the electro-technologies, estimated implementation costs still are not easily available. Even for the more mature technologies, cost may vary depending on the capacity or the specific case study. However, a few reports have investigated the economics of alternative electrification technologies. The National Renewable Energy Laboratory in USA, made an extensive analysis of the electrification options for industry [25] estimating their payback time based on predicted capital costs, and fuel costs (i.e. operational costs). It should be mentioned that the electrification options covered only immersion heaters, heat pumps (i.e. for space heating), and electric heaters. The analysis revealed three main conclusions. First, the payback times may differ for the same technology, if it applied in different industries. Second, even for the same technology and application, the variability of payback period can be very high. Third, the lowest payback period for the considered options has changed from 1 year for electric heaters, to 5 years for space heating heat pumps. A similar report for the Dutch process industry [16] provided estimation on the energy efficiency of different electrification technologies, as well as an overview of the potential savings in the operational costs. In this range, mechanical vapour recompression and high temperature heat pumps account for the highest gain, as on average they are expected to provide 10 and 4 units heat per unit electricity, respectively. Moreover, Electric boilers of different types have efficiencies close to 100 %.

Generally, when it comes to the more mature technologies, the easiest technology to be implemented (e.g. electric heaters) may provide a good option for electrification in the short term, with minimal process changes and lower capital investment, but in the long term, operational costs might be more than the required amount by the traditional technologies. On the contrary, some technologies, for which a major redesign and installation of complex equipment is needed, such as mechanical vapour recompression and heat pumps will require a higher capital investment, but will bring significant savings in the operational costs. With respect to technologies with more novelty, it is more difficult to estimate their capital or even operational costs. However, many of them provide considerable advantages such as better control, improved final quality of the product, etc., that may not be easy to evaluate in terms of capital or operational costs, but should be definitely taken into account in the final decision.

5. Conclusions

This study presents a systematic review of the electrification technologies that can be used to replace the conventional technologies in the highest energy-demanding processes of the Danish food and beverage industry such as drying, evaporation, cooking and backing, and pasteurization and sterilization processes. The criteria such as application ranges, technological benefits and challenges, energy efficiency and technology reediness level are considered for the screening purposes. The main outcomes of the study are:

- A wide range of electrification options for food processes exist, and many of them are available in the market. Overall, all of them require a significant initial investment cost, which may be the first main barrier for their implementation. However, compared to traditional technologies, some of these electrification technologies such as heat pump can significantly increase the energy efficiency of the corresponding processes. Depending on the process, this may lead to lower operational cost and shorter payback period.

- Switching from fossil-fuel based process heating to electrified heat can offer many advantages such as significant reduction of CO_2 emissions, reducing process time, and improving product quality, process controllability and flexibility. However, it also introduces some challenges such as high capital costs, electrical capacity upgrades, as well as variability and uncertainty in the electricity supply.

- A number of technologies are at the early stages of the development. However, results at the laboratory or pilot scale yield promising. It is expected that the maturity of these technologies will increase in a few years, and potentially contribute to the market of electrification technologies for industry.

- Hybrid solutions can help in introducing the novel electrification options in the industrial processes while still operating in combination with the existing technologies. Solutions based on electromagnetic heating such as microwave for cooking and backing processes and membrane for pasteurization and sterilization processes may provide an easy implementation of electrification at lower costs, as hybrid solutions. Moreover, it is expected that many of these solutions will bring significant time and energy savings.

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