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Energy conservation in the dairy industry: A critical review

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Abstract
The dairy industry is an energy-intensive food-processing sector in which thermal and electrical energy are required throughout milk reception, pasteurization, sterilization, evaporation, drying, refrigeration, cleaning and packaging. This review critically examines energy-use patterns in dairy processing and evaluates major strategies for energy conservation, including heat regeneration, waste-heat recovery, boiler optimization, refrigeration efficiency, insulation, variable-speed drives, efficient pumping, optimized clean-in-place systems, process integration, renewable-energy utilization and digital energy management. Among the major operations, heating, evaporation and drying are particularly important thermal-energy consumers, while refrigeration, compressed air, pumping and agitation contribute substantially to electrical demand. Regenerative heat exchange in pasteurization is one of the most established opportunities because it can recover a large proportion of heat from the outgoing product stream. Additional opportunities exist through condensate recovery, economizers, heat pumps, mechanical and thermal vapour recompression, membrane concentration, multi-effect evaporation, improved dryer operation and refrigeration-system optimization. However, energy-saving measures must be evaluated against food-safety requirements, product quality, capital cost, maintenance, process reliability and water consumption. Renewable-energy systems such as solar thermal, photovoltaic power, biogas from dairy effluent and anaerobic digestion of organic residues can reduce dependence on fossil fuels, particularly when integrated with energy-efficiency measures. The review identifies major research gaps in plant-level benchmarking, integrated energy-water optimization, digital monitoring, low-carbon heat, thermal storage and techno-economic assessment. Future dairy plants should move from isolated equipment-level interventions toward integrated energy management based on process heat cascading, electrification, renewable energy and data-driven optimization. Such approaches can simultaneously reduce operating costs, greenhouse-gas emissions and resource consumption while maintaining food safety and product quality.

Keywords: Dairy industry, energy conservation, energy efficiency, refrigeration, pasteurization, renewable energy

1. Introduction
The dairy industry converts a highly perishable biological raw material such as milk into a wide range of products, including pasteurized milk, fat rich dairy products such as milk cream, butter & ghee, fermented products, butter, cheese, milk powders, condensed milk, ice cream and value-added dairy foods. These processes require substantial amounts of thermal and electrical energy. Energy is consumed for heating and cooling, refrigeration, evaporation, drying, pumping, agitation, compressed air, lighting, cleaning and packaging. The relative importance of each demand depends on plant size, product portfolio, process technology, production schedule, climate and utility system. Energy efficiency is increasingly important because energy costs affect product competitiveness while fossil-fuel use contributes to greenhouse-gas emissions. At the same time, dairy plants must maintain strict temperature, hygiene and food-safety requirements. Consequently, energy conservation cannot be pursued by simply reducing energy input; it must reduce avoidable energy losses while maintaining required process conditions. The purpose of this review is to critically evaluate energy consumption in dairy processing, identify the opportunities for energy conservation and examine the technological, economical and environmental considerations that determine whether an intervention is practically successful [1, 2, 3].

2. Energy Consumption Profile of Dairy Plants

Dairy plants typically use both thermal and electrical energy. Thermal energy is required mainly for pasteurization, sterilization, evaporation, drying, hot-water generation, boiler operation and cleaning. It is commonly supplied through steam, hot water, direct combustion or electrical heating. Electrical energy is consumed by refrigeration compressors, pumps, fans, agitators, homogenizers, packaging machinery, air compressors, control systems and lighting. The energy profile differs substantially among dairy products. A fluid-milk plant has a relatively high refrigeration and hot-water demand, whereas a milk-powder plant can have a much greater thermal demand because evaporation and spray drying remove large quantities of water. Therefore, benchmarking energy use on a single basis for all dairy plants can be misleading. Energy performance should be normalized according to product type, throughput, solids concentration, climate and processing configuration [1, 2, 17].

3. Major Energy-Intensive Operations in the Dairy Industry and strategies for energy conservation

The principal energy-intensive operations include heating, evaporation, spray drying, refrigeration, cleaning and utilities. Heating is required to reach pasteurization or sterilization temperatures and to generate hot water. Evaporation removes water from milk and can consume significant quantities of thermal energy. Spray drying is among the most energy-intensive dairy operations because a large quantity of water must be evaporated from concentrated milk to make it powder. Refrigeration is essential for raw milk storage, product cooling, cold rooms, frozen products and distribution. Cleaning-in-place requires heating of cleaning solutions and pumping of water and chemicals. Utilities such as boilers, compressed air, chilled-water systems and cooling towers can account for substantial indirect energy consumption [1-3, 17].

3.1 Pasteurization

Pasteurization provides one of the clearest examples of energy conservation through process integration. In a plate heat exchanger, hot pasteurized milk leaving the heating section transfers heat to incoming cold milk. This regenerative section reduces the amount of external energy required to heat the incoming milk and reduces the cooling load for the pasteurized outgoing milk. Regeneration efficiency depends on heat-exchanger design, temperature approach, fouling, flow arrangement and product characteristics. Routine cleaning is therefore not only a hygiene requirement but also an energy-efficiency measure because fouling increases thermal resistance and reduces heat-transfer performance in the plate heat exchanger. Heat regeneration should be regarded as a standard design principle for continuous dairy heating processes [1, 2, 10, 17].

3.2 Evaporation and Concentration

Evaporation is important in the manufacture of condensed and dried milks, Single-effect evaporation can have relatively high steam demand because steam is used to evaporate water directly. Multi-effect evaporators reuse vapour generated in one effect as the heating medium for another effect, thereby reducing fresh steam demand. Thermal vapour recompression and mechanical vapour recompression can further reduce external thermal energy requirements by recycling vapour energy. Membrane technologies such as reverse osmosis and ultrafiltration can remove part of the water or concentrate milk solids before thermal evaporation. Because membrane separation does not require phase change for the separated water, it can reduce the thermal load imposed on subsequent evaporation. The optimum configuration depends on product composition, membrane fouling, capital cost, cleaning requirements and desired concentration [4, 9].

3.3 Spray Drying

Spray drying is typically among the most energy-intensive operations in a powder plant. Energy conservation opportunities include increasing feed solids before drying, optimizing inlet and outlet air temperatures, improving atomization, controlling air flow, recovering heat from exhaust air, reducing pressure losses and maintaining efficient air-handling systems. Upstream concentration by efficient evaporation or membrane processing can reduce the quantity of water that must be removed in the spray dryer. However, excessive reduction of drying energy may increase residual moisture or affect powder properties. Therefore, energy optimization must be integrated with the final product quality [4-8].

3.4 Boilers

Boilers are major sources of thermal energy and can become significant sources of avoidable losses [2, 3, 4].

Important conservation measures include correct boiler sizing, combustion optimization, regular burner maintenance, insulation of steam lines, use of economizers, blowdown control, condensate recovery, steam-trap maintenance and prevention of steam leakage. Condensate contains both sensible heat and treated water value. Returning hot condensate to the boiler feed system can reduce fuel and water requirements. Steam distribution systems should be routinely inspected for leaks, failed steam traps and damaged insulation. A critical point is that improving boiler efficiency alone may have limited benefit if downstream processes waste steam. Boiler optimization should therefore be combined with plant-level integration for steam usage [2, 3, 4].

3.5 Refrigeration

Refrigeration can be one of the largest electrical energy consumers in dairy plants. Energy-saving opportunities include high-efficiency compressors, appropriate refrigerant selection, floating head-pressure control, variable-speed drives, optimized suction pressure, efficient condensers, clean heat-transfer surfaces, proper insulation and minimizing cold-air leakage. Cold-storage doors should remain closed as far as operationally possible, and evaporator coils should be kept clean and free of excessive frost. Refrigeration systems should also be correctly sized. Oversized equipment can operate inefficiently at partial load, whereas undersized systems may operate continuously under stressful conditions. Heat recovered from refrigeration compressors can potentially be used for hot-water generation, creating a useful connection between electrical and thermal energy systems [2, 3, 17].

3.6 Clean-in-Place (CIP) Systems

CIP is necessary for dairy hygiene but can consume substantial amounts of hot water, electricity and chemicals.

Energy conservation can be achieved through optimized cleaning sequences, appropriate chemical concentration, conductivity based control, recovery and reuse of final rinse water, heat recovery from spent cleaning solutions and improved flow velocities. The objective should not be to minimize cleaning energy at the expense of hygiene. Instead, the process should deliver the required microbiological and hygienic performance with the minimum validated resource input. Automated CIP systems can improve repeatability and prevent unnecessary cleaning duration or excessive use of hot water [2, 3, 11].

3.7 Pumping, Motors

Pumps and motors are widespread throughout dairy plants and can represent a significant electrical load. Energy-efficient motors, correct pump selection, reduced throttling losses, efficient piping layouts and variable-speed drives can reduce energy consumption. A common inefficiency occurs when pumps are selected for maximum theoretical demand and then throttled during normal operation. Matching pump capacity to actual process requirements is more efficient. Variable-speed drives are especially useful where flow demand changes during production, cleaning or product changeover [2, 3].

3.8 Compressed-Air Systems

Compressed air is often an overlooked energy consumer. Leaks, excessive pressure, inappropriate use of compressed air for cleaning and poorly maintained compressors can cause significant losses. Conservation measures include leak detection, reducing system pressure where possible, eliminating inappropriate end uses, sequencing compressors and using variable-speed compressors for variable demand. Compressed air should be treated as a high-cost utility and not as a free source of cleaning or cooling energy [2, 3].

4. Strategies for energy conservation in dairy industry

4.1 Waste-Heat Recovery

Dairy plants generate recoverable heat from pasteurized product, hot wastewater, boiler flue gas, compressor discharge, condensate, refrigeration systems and drying exhaust streams. Heat recovery systems can transfer this energy to incoming milk, boiler feedwater, cleaning water or other low-temperature demands. The feasibility of heat recovery depends on temperature level, heat availability, operating schedule, fouling potential, hygienic requirements and the distance between heat source and heat sink. The concept of heat cascading is particularly important. High-temperature heat should first serve processes requiring high temperature, while lower-grade heat can be used for hot-water production, preheating or cleaning [2, 4, 10, 17].

4.2 Insulation and Thermal Loss Reduction

Insulation of steam lines, hot-water tanks, pasteurization equipment, evaporators, refrigeration lines and cold rooms can reduce unnecessary heat losses to the environment. Damaged or wet insulation can substantially reduce performance. Thermal imaging and routine plant inspections can identify hot spots and cold losses. Insulation is often a comparatively low-capital intervention and can provide rapid payback when applied to high-temperature surfaces, low temperature lines and frequently operated systems [2, 3].

4.3 Heat Pumps and Electrification

Industrial heat pumps can upgrade low-temperature waste heat into useful process heat. Potential sources include refrigeration condenser heat, wastewater, dryer exhaust and other low-grade streams. Heat pumps become particularly attractive when electricity has a lower carbon intensity than the displaced fossil fuel and when suitable waste heat is continuously available. Electrification of low- and medium-temperature heat demand can also support decarbonization when combined with renewable electricity. However, high-temperature applications may still require steam, electric boilers or other technologies, so plant-specific temperature mapping is essential [12, 17].

4.4 Renewable Energy Integration

Renewable energy can complement energy-efficiency measures. Solar photovoltaic systems can supply electricity for pumps, refrigeration, lighting and other electrical loads. Solar thermal systems can provide hot water or preheating where solar availability matches plant demand. Anaerobic digestion of dairy effluent and organic residues can produce biogas for boiler fuel or combined heat and power. Renewable energy should not be viewed as a substitute for efficiency. Reducing energy demand first generally decreases the size and cost of renewable-energy systems required to supply the plant [4, 17].

4.5 Biogas and Dairy Waste-to-Energy

Dairy wastewater contains biodegradable organic matter and can be treated using anaerobic digestion. Biogas generated through digestion can contain methane suitable for thermal energy generation after appropriate gas cleaning and conditioning. Integration of wastewater treatment and energy recovery can provide multiple benefits: reduction in organic pollution, production of renewable fuel and reduction in fossil-fuel consumption. The economics depend on plant size, wastewater characteristics, biogas yield, digester performance, gas utilization and local energy prices [13-16, 18].

4.6 Energy Auditing and Benchmarking

A systematic energy audit is a foundation for conservation. The audit should establish energy balances for steam, electricity, refrigeration, compressed air, hot water and major process equipment. Measurements should include fuel consumption, electricity demand, steam flow, condensate return, temperatures, pressures and production quantities. Energy intensity can then be calculated using an appropriate functional unit, such as energy per litre of milk processed or energy per kilogram of milk powder produced. Benchmarking should account for product mix because energy requirements vary considerably between fluid milk, cheese, butter, fermented products and powders [1, 2, 10, 17].

4.7 Digital Energy Management

Digital monitoring can significantly improve energy management. Smart meters, temperature and pressure sensors, flow meters and industrial control systems can provide real-time information about utility performance. Data analytics can identify abnormal consumption, equipment degradation, simultaneous heating and cooling, refrigeration inefficiencies and excessive standby loads. Artificial intelligence and machine-learning methods may eventually support predictive energy optimization, although model quality depends on reliable plant data and appropriate process understanding. Digitalization should therefore support, rather than replace, sound engineering analysis [2, 17].

4.8 Energy and Water

Energy and water conservation are closely linked in dairy processing. Water is heated, pumped, cooled and treated, so reductions in water use can also reduce energy demand. However, water-saving measures can sometimes increase cleaning time or chemical requirements. Therefore, optimization should consider both energy and water rather than treating them as independent objectives. Heat recovery from wastewater can provide a simultaneous energy and water-efficiency opportunity [10, 11, 13].

5. Economic Evaluation of Energy-Conservation Measures

Technical potential does not necessarily imply economic feasibility. Energy-saving projects should be assessed using capital cost, annual energy savings, maintenance cost, equipment lifetime, production impact and payback period. Simple payback is useful for screening but does not account fully for time value of money or project lifetime. Net present value, internal rate of return and life-cycle cost analysis can provide more robust investment decisions. Projects with short payback periods, such as steam-leak repair, insulation, refrigeration controls and lighting improvements, may be implemented first, followed by larger investments such as heat pumps, major heat-recovery systems and process redesign [2, 4, 10, 17].

6. Environmental Benefits

Energy conservation reduces greenhouse-gas emissions when energy savings displace fossil fuels or carbon-intensive electricity. The environmental benefit depends on the energy source being displaced. Electricity savings can be particularly valuable in regions where grid electricity has a high carbon intensity. Energy efficiency can therefore contribute directly to climate targets while also reducing operating costs. Life-cycle assessment is recommended for comparing alternative technologies because equipment manufacturing, refrigerant choice, chemical use and end-of-life impacts may influence the overall environmental outcome [2, 4, 13, 17].

7. Barriers to Energy Conservation

Common barriers include limited capital, lack of energy data, competing production priorities, inadequate technical expertise, uncertainty about payback, maintenance limitations and concern about affecting product quality. In smaller dairy plants, sophisticated energy-management systems may not be economically feasible. Low-cost measures and operator training can nevertheless produce meaningful improvements. A successful energy program requires management commitment, defined performance indicators and regular review rather than one-time equipment replacement [2, 3, 17].

8. Integrated Energy Conservation Strategy

The most effective approach is as follows:

1. Measure energy use and establish a baseline [2, 4, 10, 17].
2. Eliminate avoidable losses such as leaks, poor insulation and unnecessary operation [2, 4, 10, 17].
3. Improve process efficiency through heat regeneration, optimized refrigeration and efficient equipment [2, 4, 10, 17].
4. Recover waste heat and cascade heat between processes [2, 4, 10, 17].
5. Electrify suitable low-temperature heat demand [2, 4, 10, 17].
6. Integrate renewable electricity, solar thermal energy and biogas [2, 4, 10, 17].
7. Monitor performance continuously using digital systems [2, 4, 10, 17].

These steps avoids the common mistake of investing in renewable energy while continuing to operate inefficient processes [2, 4, 10, 17].

9. Future Perspectives

Future research should address integrated plant-level energy models rather than isolated equipment studies. More work is needed on low-carbon high-temperature heat, industrial heat pumps, thermal energy storage, advanced heat exchangers, membrane-assisted concentration, hybrid drying, intelligent refrigeration control and low-global-warming-potential refrigerants. The development of standardized energy benchmarks for different dairy products and plant configurations is also important. Research should increasingly evaluate energy, water, carbon, product quality and economics simultaneously. Digital twins and real-time optimization may provide new opportunities for large dairy plants, while simplified energy-management tools could make conservation accessible to small and medium processors [4, 5, 12, 17, 18].

10. Conclusion

Energy conservation in the dairy industry requires a systems approach. The largest opportunities are associated with thermal processes, refrigeration, evaporation, drying, boilers, CIP and utility systems. Heat regeneration in pasteurization, condensate recovery, steam-system maintenance, refrigeration optimization, improved insulation, efficient motors and pumps and optimized CIP are among the practical measures that can provide substantial benefits. For milk-powder manufacture, upstream concentration, multi-effect evaporation, vapour recompression and optimized spray drying are particularly important. Waste-heat recovery and industrial heat pumps offer opportunities to convert low-grade energy into useful process heat. Renewable energy can further reduce fossil-fuel dependence through photovoltaic electricity, solar thermal systems and biogas from anaerobic digestion. However, renewable energy should follow energy-efficiency improvements rather than substitute for them. The future dairy plant should therefore be designed as an integrated energy system in which heat is recovered and cascaded, electricity is used efficiently, waste streams are converted into resources and renewable energy supplies an increasing share of the remaining demand. A combination of energy auditing, process integration, digital monitoring, efficient equipment, renewable energy and continuous improvement can reduce production costs and environmental impact while maintaining food safety and product quality [1-18].

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