

Flexibility exploitation in Net-Zero Energy Factories. A technical and economic study case for dairy systems located in Central and South Europe

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ABSTRACT

The decarbonization of energy systems (electric, thermal, gas, and transportation) requires flexibility to integrate power generated by volatile and renewable energy sources (vRES). Industrial systems can contribute to exploiting the flexibility needed to integrate the electricity generated by vRES into energy systems. Designing industrial systems as Net-Zero Energy Factories (NZEF) offers the possibility of exploiting the flexibility that could be used internally to integrate the power generated by renewable energy sources. This study addresses, on one hand, the presentation of a methodology to identify and quantify the flexibility potential of continuous processes typical in dairy systems. On the other hand, it aims to demonstrate a methodology for designing additional flexibility options to operate dairy systems as NZEF. A model has been developed in which the energetic and material flows of conventional dairy systems are simulated. The model allows for the design of conventional dairy systems as NZEF and the evaluation of their potential to exploit flexibility. Two different European climate zones have been investigated: Bari (Italy) and Magdeburg (Germany). This study is relevant for designers and facility managers who are following their decarbonization plans, aiming to operate their industrial facility as Net-Zero Energy Factories and located in southern Europe (Bari, Italy), the operational costs are much lower than those operating in central Europe (Magdeburg, Germany). Specifically, integrating an 800 kW PV system reduced operational costs by 16.3 % in Bari, compared to 3.8 % in Magdeburg. Additionally, achieving 97 % vRES integration in Bari requires a 1000 kWh thermal storage capacity, whereas in Magdeburg, a 500 kWh capacity is sufficient. These findings suggest that NZEF designs can be optimized based on regional climatic conditions to maximize cost efficiency and vRES integration. The analysis indicates that sensible heat storage systems should be preferred over electrochemical batteries when designing additional flexibility options, considering both technical and economic criteria.

1. Introduction

According to Ref. [1], the EU dairy sector is the second biggest agricultural sector in the European Union. More than 64 % of dairy cows are located in central and northern Europe. Germany has the largest production of cow's milk in Europe. In contrast, Italy accounts for approximately 7.8 % of European milk production [2]. Dairy facilities require a significant amount of energy mostly for heating and cooling processes. Generally, electricity is used for milk pumps, refrigeration, automation and separation, whilst for the thermal and cleaning processes, fossil fuels (diesel or natural gas) are mostly used.

In recent years, the sustainability of the dairy industry has become

increasingly relevant. In Ref. [3], a circular economy model within the dairy industry has been evaluated, highlighting that technological improvements (primarily in the cleaning processes) and the electrification of thermal processes could make the most significant contributions to energy sustainability. Reference [4] presents a strategic action plan for operating dairy systems as net-zero carbon emission facilities. The entire supply chain, spanning from the animal farm to the end-consumers and passing through the dairy plant and cold chain, has been considered. The study indicates that the highest electricity consumption occurs in the dairy facility in which the final products are manufactured, while the greatest fossil fuel consumption is observed in the cold chain.

Conventional dairies in which the thermal processes (for the pasteurization and the cleaning) are supplied using fossil fuels are

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Nomenclature:			
AEO	Annual Energy Output	LCOE	Levelized Costs of Energy
C_d	Actual energy consumption	LCOH	Levelized costs of heat
C_s	Scheduled (or benchmarked) energy consumption	LCOSh	Levelized Costs of Stored heat
CIP	Cleaning in Place	LCOSe	Levelized Costs of Stored electric energy
COP	Coefficient of Performance	n	Life time
CRF	Capital Recovery Factor	NZEF	Net-Zero Energy Factory
DSO	Distributed System Operators	OC	operation costs
E_{e_dis}	Electrical energy discharged from electrical storage system	P_d	electric Power demanded
E_{e_grid}	Electric energy drawn from grid	P_g	electric Power generated
E_{PV_RES}	Total annual electricity generated by photovoltaic system	P_o	operative electric Power demanded
E_{th}	Total annual heat generated by heap pups	PV	Photovoltaic
E_{th_dis}	Thermal energy discharged from thermal storage system	T_{sink}	initial temperature in front of the condenser
φ_p	Flexibility of power	T_{source}	temperature of the heat source for the evaporator
φ_T	Temporal flexibility	TSO	Transmission System Operator
i	Discount rate	vRES	volatile Renewable Energy Sources
IC	investment costs	α	azimuth angle
k_{e_grid}	electric grid energy price	β	tilt angle
		Φ	latitude

struggling with higher operating costs due to rising natural gas prices. Different studies have focused on efficiency measures to reduce gas consumption and, thus, operating costs. The feed-in regulation of combustible fuels in a burner to supply hot water for the pasteurization process of raw milk offers only a small saving potential. It has already been investigated using a mathematical model in MATLAB software [5] that an optimized feed-in of liquefied petroleum gas reduces the cost of the latter and electricity by 3 %. Furthermore, the support of existing conventional heat supply methods with renewable measures was investigated. A dairy factory in Spain was analyzed in Ref. [6], and thermal solar panels were considered to support the gas boiler. Such a solution reduced the gas consumption by 71 % with the same target temperature of 95 C. A solar collector field of 1694 m² was proposed for this approach and studied using a pinch methodology based on a mathematical model that considered the thermal energy demand of milk for drinking, yogurt and cheese production processes. Another approach was the exchange of the conventional pasteurization methods using industrial high-temperature heat pumps. A heat pump was considered in Ref. [7], instead of a gas boiler system within a food and beverage sector in the UK. An energy saving of 57–75 % could be determined by assuming a coefficient of performance (COP) varying between 2 and 6. Similar results were also obtained for a carbon dioxide (CO₂) heat pump with a primary energy saving of about 51.5 % [8]. The use of a liquid-to-liquid vapor compression heat pump is compared to a plate pasteurization system and a double-jacketed boiler system for milk pasteurization for cheese production could save the primary energy demand by 66 % [9]. Current studies are researching the integration potential of locally generated renewable energy, for example, photovoltaic (PV), solar collectors, or wind energy. A solar-assisted dairy factory combining a PV, heat recovery, and heat pump system allowed a CO₂ emission reduction of about 65–75 % in an investigation using mixed-integer linear programming [10]. A study of solar milk pasteurization with an n-type PV and parabolic concentrator in Ref. [11] proposed a system that is self-sufficient for a 6-h operation for a product quantity of 216 kg.

In addition to cheese dairies, a great deal of research is also concerned with optimizing thermal treatment methods on dairy farms. The combination of a spectra-splitting parabolic trough hybrid PV-thermal system could supply 52 % of hot steam and 40 % of hot water demand for a dairy farm in Bari (Italy). This system also produced a net electrical output of 14 % of the electrical dairy demand [12]. An energy audit methodology investigated the implementation of a 25 kW wind turbine, which allowed the supply of the majority of the operation energy

demand in the study [13] of a dairy farm in Oyster Bed Bridge.

This study aims to propose a methodology for designing a dairy system as a NZEF. The study focuses only on the dairy facility in which the final products (milk, cheese, yogurt etc) are produced. The cornerstone of the study is the identification and quantification of flexibility that can be harnessed from industrial processes involved in the production processes. Additionally, the study contributes by presenting a design methodology for determining the optimal sizing of additional flexibility options, such as thermal and electric energy storage systems. These options might be necessary to be integrated into the dairy facilities to operate them as NZEFs. The methodologies presented in this study enhance the comprehension of how to harness and design flexibility within industrial facilities characterized by continuous processes, a common trait of dairy facilities. Furthermore, these methodologies provide valuable support to designers and facility managers who aspire to decarbonize their industrial systems by shaping them into NZEFs. Importantly, the developed methodology is not limited to the Southern and Central Europe climate zones but can be applied to other climatic conditions and industrial processes, demonstrating its broader applicability and potentiality.

This study is structured as follows: In Section Two, the benefits of designing Net-Zero Energy Factories, as well as the methodology for identifying and quantifying the potential for exploiting flexibility within the dairy system, are described. The implemented mathematical model depicting the energy and material flows of a referenced dairy system is explained in Section Three. Section Four deals with the design of Net-Zero Energy Factories for the Magdeburg and Bari sites, while Section Five presents the results of exploiting flexibility using energy storage systems. The conclusions are summarized in Section Six.

2. Net-zero energy factories: benefits and methodology to design flexibility options

The scientific literature offers many definitions of Net-Zero Energy Factories. Generally speaking, a Net-Zero Energy System, whether residential, tertiary, or industrial, is understood as a system that aims to balance its energy consumption with energy generation over a defined period, typically on an annual basis [14–18]. However, in this study, a Net-Zero Energy System is defined as a system that enables the generation of electricity using vRES and the integration of all the generated electricity into the considered system, thus avoiding the need to feed the external grid. This definition highlights the critical importance of flexibility in NZES. Specifically, the minimal degree of flexibility required,

which corresponds to the optimal degree of flexibility, is fundamentally tied to the system’s ability to fully utilize the generated vRES power internally. This optimization process ensures that the system’s operations are adjusted in real-time to match the variable power generation, thereby maximizing efficiency and sustainability without the need for external grid support. There are various benefits to designing systems in this manner. From a holistic perspective, systems designed as defined by Net-Zero Energy indirectly assist grid operators (DSO and TSO) in the decarbonization efforts. Such system design results in lower power volatility that needs to be balanced, which, in turn, positively affects balancing service costs. Additionally, all consumers stand to benefit since the costs of grid balancing are generally distributed among the smaller consumers [19,20]. However, designing of a Net-Zero Energy System requires exploiting flexibility options within the considered system [21]. The inherent adaptability of a NZEF lies in its capacity to modify its energy consumption in response to renewable energy generation. Within the design of flexibility, the modification of the energy consumption has two main meanings:

1. Increasing or decreasing the power consumption compared to a benchmarked value (generally the day-ahead scheduled one),
2. Anticipating or postponing industrial processes, which could have the same, less or more energy consumption compared to a benchmarked value (generally the day-ahead scheduled one).

By considering these aspects, two flexibility indicators need to be determined. Let T denote the time span of electricity generation by vRES, expressed as $T = \{t_i, t_j, \dots, t_f\}$, where t_j represents equally divided intervals. Within this temporal framework, the flexibility of power (φ_p) across the entirety of T can be formulated as per equation (1). This equation incorporates ΔP_{dj} , signifying demand variation within time interval t_j due to alterations in power generation ΔP_{gj} over the same interval t_j .

$$\varphi_p = \frac{\Delta P_{dj}}{\Delta P_{gj}} \tag{1}$$

In addition to the power flexibility (φ_p), the temporal flexibility (φ_T) defines the system’s capacity to shift its energy consumption either earlier (anticipate) or later (postpone) relative to a predefined scheduled consumption profile. These adjustments alter the timing of consumption to better align with energy availability from vRES without necessarily changing the total energy consumed. The temporal flexibility is mathematically expressed as in equation (2).

$$\varphi_T = \frac{\sum_{t_j \in T} |C_{dj} - C_{sj}|}{\sum_{t_j \in T} C_{sj}} \tag{2}$$

Where:

- C_{dj} indicates the actual energy consumption in interval t_j , adjusted for flexibility.
- C_{sj} denotes the scheduled (or benchmarked) energy consumption in interval t_j , reflecting the initial consumption plan absent flexibility adjustments.
- The numerator, calculates the total absolute deviation of the actual consumption from the scheduled consumption across all intervals, quantifying the extent of consumption shifts.
- The denominator, represents the total scheduled energy consumption over the analysis period, providing a baseline for assessing flexibility.

Industrial systems hide a high potential of flexibility. Such a potential is generally related to industrial processes, which can be classified according to two criteria: the variety and the volume of manufactured products (see Fig. 1). For example, industrial facilities manufacturing according to customer-oriented products present the highest potential to exploit flexibility. On the other side, continuous and repetitive processes, which are typical of dairy facilities, have the lowest potential.

However, within dairy facilities, the potential of flexibility can increase if the thermal processes are supplied using heat pumps and if the logistic sector, dealing with the distribution (at low temperatures) of the products manufactured in the dairy facility, is electrified. In this case, the dairy facility could be considered as a multi-energy system in which electricity is converted into other energy forms and fed into other energetic infrastructures. Multi-energy systems present a very high degree of flexibility and it is one of the solutions to better integrate high amounts of vRES [22,23]. The operation of a dairy system as a NZEF should be geared towards maximizing the energy efficiency of the entire system. Logistic factors and the supply chain also play roles in enhancing the operational efficiency of the dairy systems. In Fig. 2, it is illustrated how material storage (e.g., for yogurt, cheese, etc.) and the supply chain of raw milk impact the balance between vRES generation and energy consumption within the dairy system. The black point on the graph represents the equilibrium where vRES generation matches consumption. Should vRES generation increase or decrease, and provided the supply of raw milk along with storage capacity for final products (e.g., yogurt, cheese, etc.) proves sufficient, the new operational point will align with the same energy balance line at a 45° angle. However, the degree of flexibility of such an operational strategy is limited and

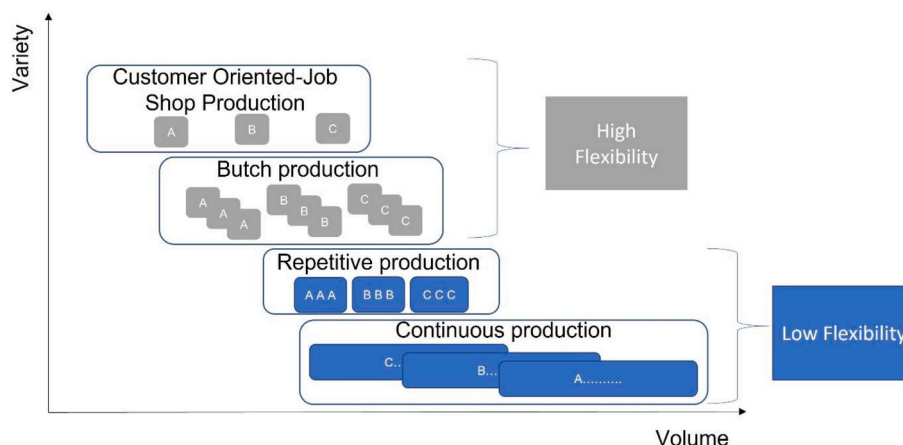


Fig. 1. Flexibility potential within industrial processes.

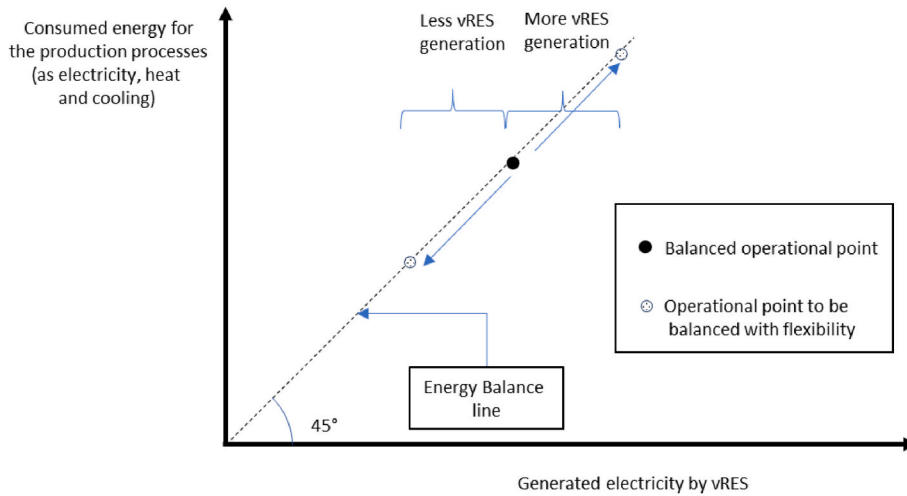


Fig. 2. NZEF operation. Option a): more efficient and a lesser degree of flexibility.

constrained by all the components (i.e., milk pumps, mixer machines, etc.) used to operate the processes. Conversely, balancing vRES generation via energy storage systems (such as electric or thermal storage) without altering the production rate of the dairy system will lead to an increase in system inefficiency (refer to Fig. 3). The energy balance line will exhibit a steeper incline (in cases of reduced vRES generation) or a gentler slope (in cases of heightened vRES generation). However, such a solution offers a higher degree of flexibility when compared to the operation shown in Fig. 2.

The effectiveness of flexibility options in NZEFs is significantly influenced by the response speed and duration of these adjustments under varying load conditions. Flexibility adjustments need to be prompt and sustained to match the dynamic nature of vRES. The response speed of flexibility adjustments is defined as the time taken to activate flexibility measures after a signal is received. Energy storage systems (electrochemical and thermal) offer flexibility at different response speeds. Thermal storage systems, such as sensible heat storage, typically exhibit slower response times compared to batteries. However, they provide sustained flexibility over longer periods, which is beneficial for balancing daily variations in vRES generation. Batteries can respond almost instantaneously (within milliseconds) to load adjustment signals, making them suitable for handling rapid fluctuations in power generation and demand. Heat pumps also play a critical role in the system's flexibility. Their ability to modulate load can significantly

impact the system's overall responsiveness. Modern industrial heat pumps can adjust their load relatively quickly typically within minutes, allowing for efficient thermal energy management [24]. This rapid modulation capability enhances the system's ability to respond to dynamic changes in energy demand.

The design of industrial systems as NZEFs can represent an interesting alternative for the facility operators aiming to greening the manufactured goods. It can also be an economic alternative if digital solutions like Blockchain are used for certifying the energetic sustainability of the manufactured goods [25,26]. Furthermore, the designed flexibility within NZEFs could not only be used for fully integrating the vRES locally generated, but also for supporting flexibility services to system operators in the time in which the factories are not operated for example during weekends [24,27,28].

The developed methodology comprises four key steps. The first step for designing industrial systems as NZEFs consists to identify and quantify the potential that the industrial processes offer to exploit flexibility. The developed methodology is based on four steps (see Fig. 4):

1. Data collection;
2. Modelling;
3. Validation;
4. Action plans and Evaluation.

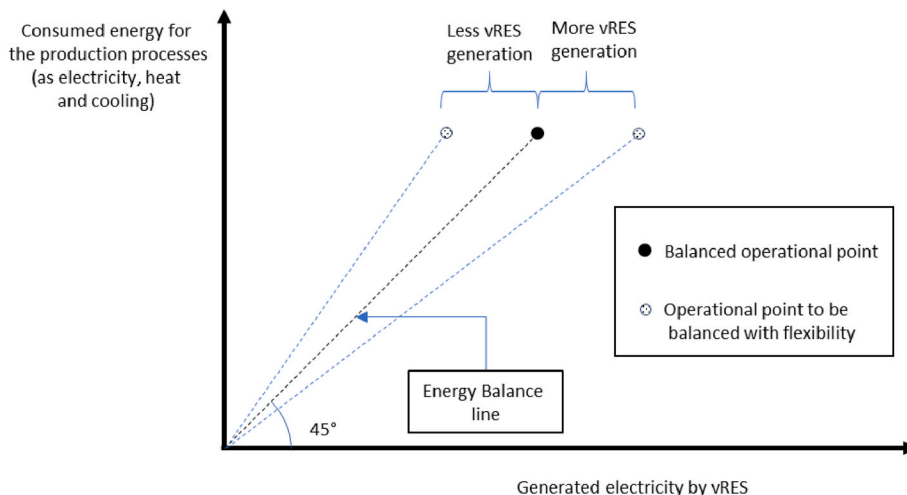


Fig. 3. NZEF operation. Option b) less efficient and a higher degree of flexibility.

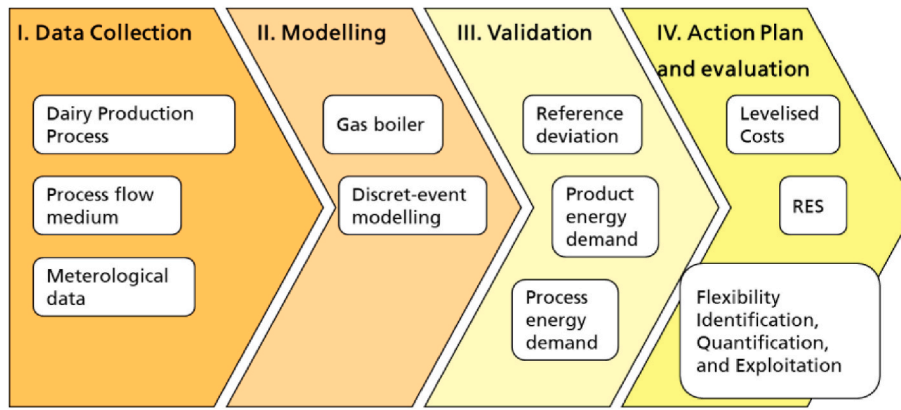


Fig. 4. Schematic of the methodology for the design of a net-zero energy dairy.

The first phase of the methodology for an NZE dairy is “data collection.” The creation of a dairy facility model requires knowledge of the energy and materials flows as well as the production processes. As a starting model, conventional dairy systems have been considered. In this study, conventional dairy systems are referred to as those in which the thermal processes are supplied using fossil sources. Data and descriptions of a dairy under conventional conditions are used from the studies [6,29]. Besides to the technical data of the industrial processes, meteorological data, mostly solar irradiation and ambient temperature have been collected. After the data collection, the second step involves building of a mathematical model enabling the simulation of the materials and the energy flows. First, all the processes that allow for the depiction of the energy (electric and thermal) and material flows for the conventional dairy system have been modeled. For a conventional and renewable-based dairy system, a discrete-event modelling approach was chosen to represent the dependencies of the production chains in the continuous production mode of a cheese factory. Depending on the trigger conditions, such as process time, flow rate, milk tank capacity, and schedule, the energy demand flows (electric and thermal) and product outputs (milk, yogurt, cheese) can be simulated, replicated, and controlled. The third step involves the validation of the developed model. The validation of the dairy model was accomplished by comparing the energy and material flows of the conventional dairy system at each station in the process chain with the reference values from Refs. [6,29]. The deviations in energy and material flows between the developed model and the referenced one have been calculated. In the last phase, action plans for designing the conventional dairy system as a Net-Zero Energy Factory have been drafted. They consider power generation using photovoltaic panels and heat generation using heat pump technologies. The considered flexibility options include measures to match the power generated with the load. By running the model, the required flexibility, expressed in terms of both power and time, has been estimated. These flexibility options allow the facility to be operated as a Net-Zero Energy Factory. They have been evaluated considering economic and technical criteria, which were performed analyzing the levelised energy costs and evaluating the system vRES integration.

3. Mathematical modelling and validation of traditional dairy systems

reference [6] gave the details for the daily product volume of milk products and product losses, scheduling time of the production process, thermal energy demand and material flow (raw milk, pasteurized milk, milk for drinking, yogurt, cheese, hot water, cold water). The electrical energy demand of the auxiliary consumers, such as “ventilation,” “lighting” and “storage,” are derived from the production quantity and energy demand of the reference plant from Ref. [29] in relation to the production quantities used by Ref. [6]. The electric and thermal demand

and process time of each process station of each process chain, displayed in Fig. 5, was taken from the data sheets of suitable industrial plants according to production volume, flow volume and temperature requirements.

During the pasteurization, the milk is heated to a temperature of 75 C. In order to be able to draw an economic and technical comparison, the model is equipped with a gas boiler for pasteurization in the benchmark first scenario, which depicts the traditional dairy system (see Fig. 6). The raw milk supplied is already preheated to 35 C by the 75 C hot pasteurized milk in the economizer (heat exchanger) when it is introduced into the production process. To provide the hot water for pasteurizing the raw milk, 12.2 C cold feed water is heated to 95 C by the boiler. The raw milk, with a flow rate of 1.1444 kg/s, and the hot water, with 2.539 kg/s, flow through a heat exchanger for the pasteurization process to heat the milk up to 75 C and hold the temperature for 15–20 s as high-temperature short-time thermal treatment to reach the thermal death time and ensure the destruction of pathogenic microorganisms. Raw milk flow with dairy product flow, and water flow were created as two linked flow models in Anylogic (see Fig. 7).

After pasteurization, the pasteurized milk is cooled with a heat exchanger using 12 C cold tap water to decrease the milk temperature to 42 C for milk for drinking, 34 °C for fermentation in yogurt production and 30 C for curdling for cheese production. The production steps from pasteurized milk to sliced cheese includes the preparation of milk for 20 min at 30–32 C, curdling for 40 min at 30–34 C, curd processing, salting

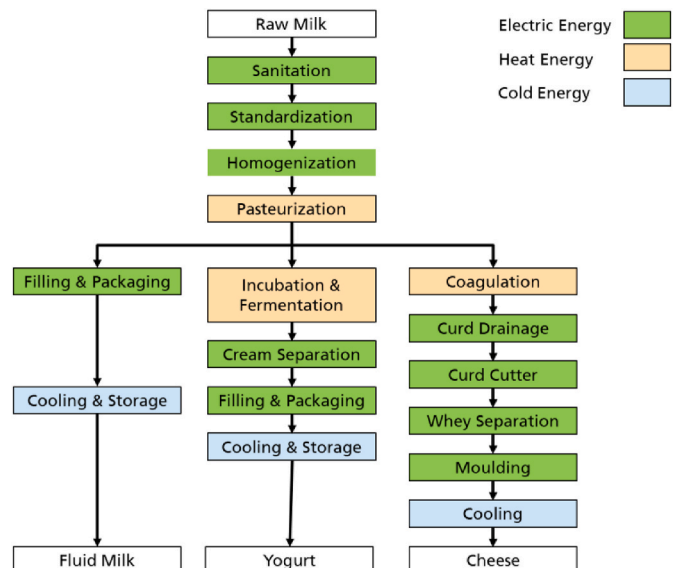


Fig. 5. Dairy production process [8,29–32].

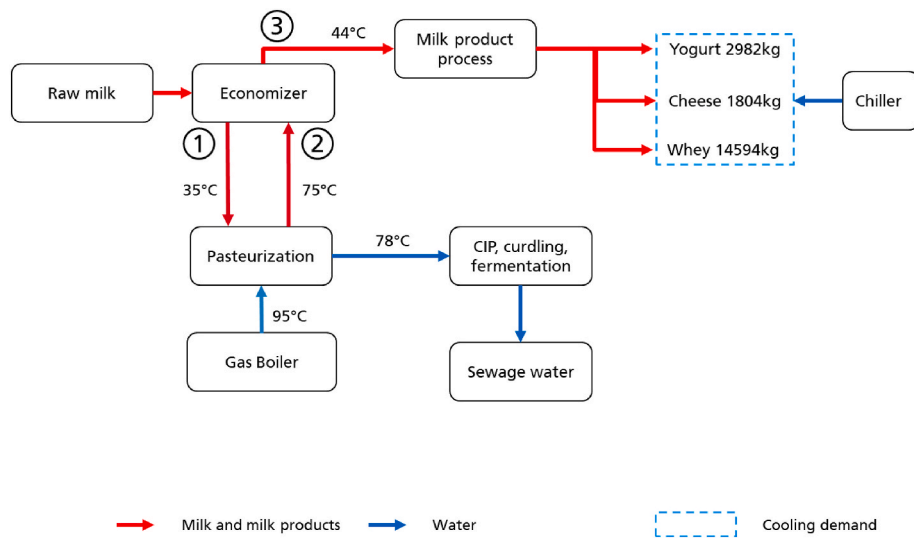


Fig. 6. Process flowsheet of water, milk and milk products in the traditional dairy systems.

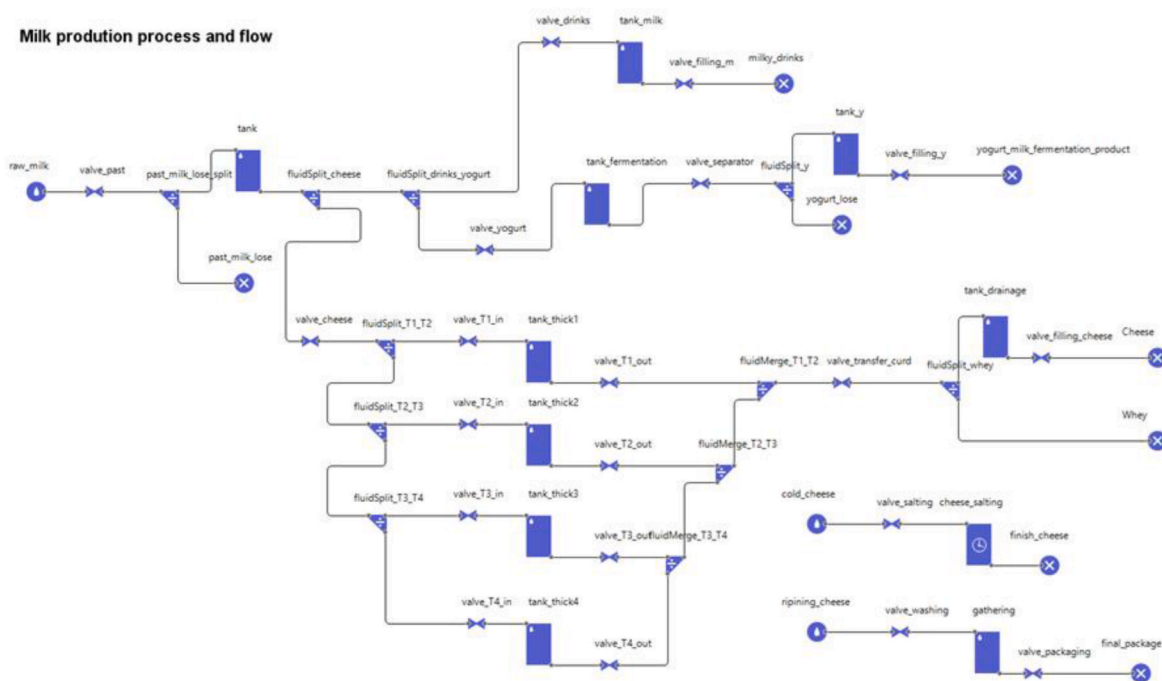


Fig. 7. Dairy model in Anylogic® with milk product and water flow and parameter overview.

for 15 h, airing for 13 days and completed with maturation for 90 days. The refinement of the cheese takes place subsequently. The cheese is washed and cut, packed and stored until delivery. The treatment steps and conditions, such as treatment time and treatment temperature of cheese production, are referred to Ref. [8,29–31]. The amount of milk processed daily and dairy products produced is depicted in Fig. 6.

The comparison of the total energy demand per kilogram of dairy products of the cheese dairy model from the simulation model in Anylogic® and reference [29] is presented in Table 1. Two scenarios have been analyzed respectively for a dairy facility operating in the city of Magdeburg (Germany) and in the city of Bari (Italy). The differences in energy consumption are primarily due to variations in weather conditions, as the same production processes were considered. The energy consumed in the milk production process shows a deviation of 4.5–4.7 %. The lowest deviation is observed in yogurt production, with an error

Table 1

Energy demand of dairy products and deviation from reference values.

Product	Referenced energy consumption [29] in kWh/kg	Energy demand in kWh/kg in Magdeburg	Energy demand in kWh/kg in Bari
Milk	0.425	0.405 (−4.7 %)	0.406 (−4.47 %)
Yogurt	0.475	0.488 (+2.7 %)	0.489 (+2.95 %)
Cheese	3.67	4.146 (+12.97 %)	4.162 (+13.4 %)

of 2.7–2.95 %, while the highest deviation is found in cheese production, with an error of approximately 13 %. The deviation of individual process stages is displayed in Fig. 8. Notable differences are observed in the standardization process, with a −9% deviation in milk and yogurt production, a 6.5 % deviation in the separation process of the yogurt

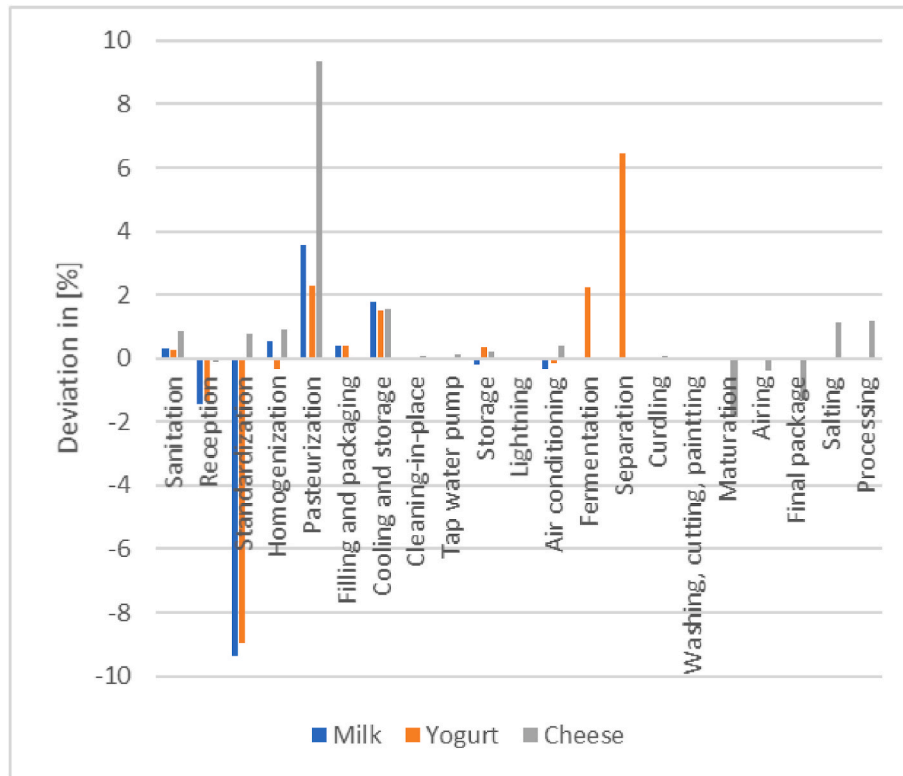


Fig. 8. Deviation of the total energy demand from a simulation with gas boiler to reference values for the dairy system located in Magdeburg.

production chain, and a 9 % deviation in pasteurization in the cheese production process. These differences in consumption are attributed to the use of different separator machines, standardization measures, and various types of cheeses.

4. Designing a Net-zero energy dairy facility: thermal and electric energy generation in the study cases Bari and Magdeburg

The NZEF approach includes measures to reduce CO₂ emissions, while increasing the share of renewable energy integrated into the production process. The NZEF concept aims to fully integrate electric power, locally generated by volatile renewable sources, into the facility. This principle ensures that if the power generated by vRES falls short of fully covering the demand, the facility does not rely solely on generating surplus energy. Instead, it emphasizes efficient energy utilization and management through adaptive strategies, aligning consumption with

renewable generation to achieve NZEF status. If the power from vRES falls short of the demand, the external grid supplies the remaining load. This operation underlines a nuanced approach to achieving NZEF status, focusing on the integration and flexible management of energy within the facility’s operations rather than exceeding consumption with production. The NZEF schematic is displayed in Fig. 9. Remuneration for the PV system is not considered because its electric power generation is never fed into the external grid. This strategy highlights the facility’s commitment to utilizing every kilowatt-hour of generated renewable energy within its operations, minimizing external grid dependence to be used as an expensive buffer for the community and fostering a self-sufficient energy ecosystem.

Designing a Net-Zero Energy dairy facility requires electrifying all processes. In comparison with the conventional dairy system, the gas boiler has been substituted with two heat pumps operating in cascade. The first heat pump extracts heat from the environment to heat water,

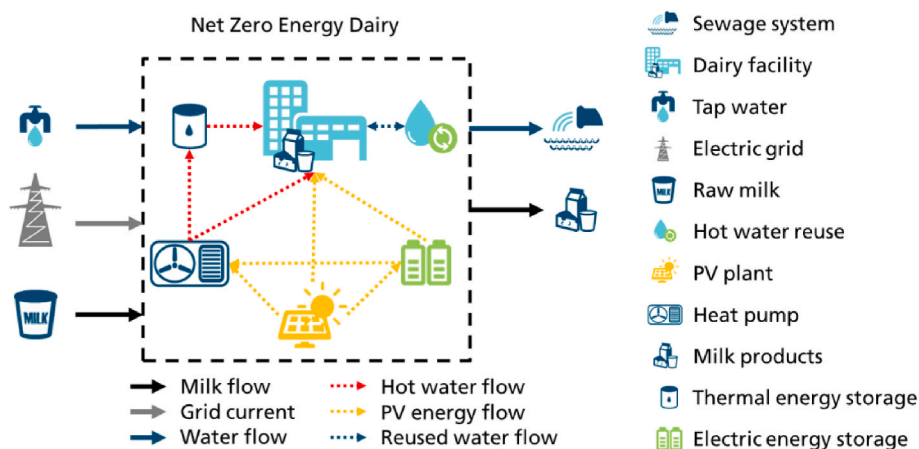


Fig. 9. Net-zero energy dairy concept.

which is used as heat source for the second heat pump. It must always provide 40 °C hot water as the target temperature. The second heat pump is supplied with a source temperature of 40–60 °C under nominal conditions. It can raise a sink temperature of 50 °C to 80–100 °C and provide a COP of 5–8. Accordingly, it can provide the hot water at 95 °C for pasteurization with its operating temperature. The hot water storage tank allows the reuse of the remaining hot water (60 °C), which is no longer needed for cleaning-in-place (CIP), curdling or fermentation after pasteurization. Fig. 10 depicts the energetic and material flows. A thermal power of about 511 kW is needed to be provided by the two heat pumps in order to pasteurize at flow rate of 152.34 kg/min of milk.

In order to evaluate the electric demand of the heat pumps, functions depicting the coefficient of performance (COP) has been evaluated. It takes into account the source temperature (T_{source}) and the sink temperature (T_{sink}). Table 2 shows the technical characteristics for air-to-water and water-to-water heat pumps respectively. The ambient temperature values for calculating the COP of the heat pump, using the formula from Table 2, are available in hourly resolution for the year 2015 from the European database “CM-SAF SARAH” using the “renewable.ninja-tool [33–35].” The outdoor temperature in Magdeburg (Germany) varied from –7.59 to 40.6 °C in 2015. The temperature band was somewhat narrower in Bari (Italy), with temperatures ranging from 4.16 to 38.38.

Fig. 11 show the daily electric power demanded by the main industrial processes (left) and the cumulative electric load profile (right).

Related to the power generation side, a PV plant has been designed with the tilt angle (β) and the azimuth (α) angle for the highest annual yield. The optimal tilt angle for the northern hemisphere of both cities was calculated with equation (3) [38], in which Φ depicts the latitude.

$$\beta = 1.3793 + \Phi(1.2011 + \Phi(-0.01444 + \Phi(0.000080509))) \quad (3)$$

The solar module orientation, performance ratio and annual final yield for Magdeburg and Bari are listed in Table 3. The annual final yield for the PV system is calculated from the generation profile created for the year 2015 with the data values of “CM-SAF SARAH” using the “renewable.ninja-tool” and the performance ratio from Refs. [39,40].

Table 4 summarizes the main energy indicators of the dairy systems considered in Bari and Magdeburg. When considering the same production quantity, the differences in weather conditions between the two analyzed sites affect the total annual electricity demand, which is slightly higher for the dairy system located in Magdeburg. Weather conditions also have a similar impact on electricity generation by the photovoltaic plant. As a consequence, since the same system design has been considered (same dairy system and same size of the photovoltaic plant), the ratio between energy generation and energy consumption is

Table 2

Measuring points of “Oxford” air-to-water heat pump, based on the data referenced in [36,37].

Heat pump with condenser temperature 40 °C	T_{source} in °C	T_{sink} in °C	COP equation	Electric Power in kW
Swegon Oxford HP/LE 33.4	Ambient temperature	40 °C	$f(x) = 0.068x + 3.22$	162
GreenPAC-R Hybrid	40–60	95	5	103

different. It is higher in Bari than in Magdeburg. In addition, Table 4 reveals a gap between photovoltaic generation and total electricity consumption. This discrepancy initiates a reevaluation of what constitutes a NZEF in the study’s context. The findings suggest that the essence of a net-zero energy factories lies in its adeptness at managing and integrating generated renewable energy, leveraging flexibility and demand-side strategies to fully integrate the generated electricity by RES, rather than producing an energy surplus.

5. Identification, quantification and sizing flexibility options: technical and economic analysis for the site Bari and Magdeburg

The integration of the power generated by PV into the dairy processes requires the utilization of flexibility options. The identification and quantification of the flexibility options look to estimate how much power can be flexibilized and how long it could be flexibilized. With reference to Fig. 12, considering P_{max} and P_{min} the maximum and minimum operative power demanded by a single machine respectively, the quantification of the flexibility of power φ_p looks to estimate the difference between P_{max} and P_{min} . In addition to it, if processes could be anticipated at time T_{ante} or postponed to the time T_{post} , then the quantification also looks to estimate the temporal flexibility φ_T . Anticipating processes is strongly related to the capability to increase the production rate at the time T_i and store the produced goods into the material storage. Similarly, postponing processes are correlated to the capability to decrease the production rate at the time T_i and take part of the to be delivered goods from the material storage. It is important to point out that, in continuous processes, P_{min} is generally not equal to zero since these processes can not be switched off and switched on. On the other side, P_{max} corresponds to the nominal power of the machine.

The flexibility of power (φ_p) and the temporal flexibility (φ_T) serve as a foundational basis for distinguishing between high flexibility and low flexibility processes within the dairy facility. High flexibility pro-

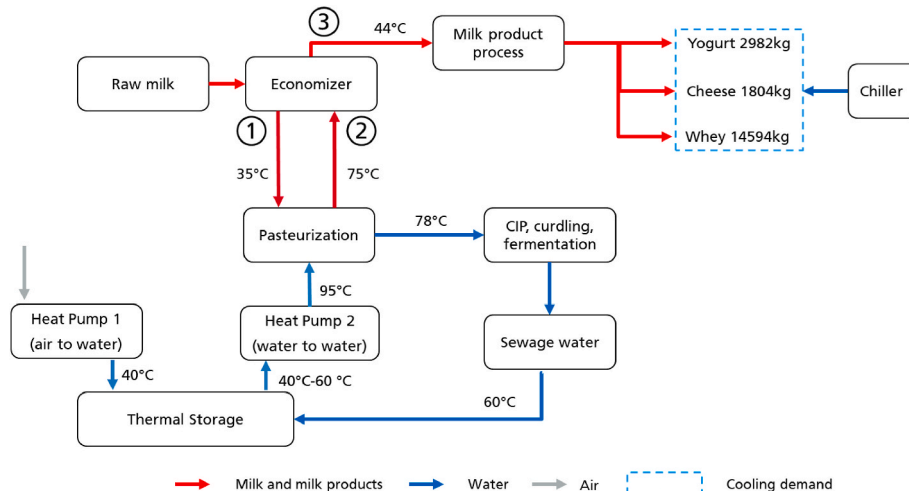


Fig. 10. Process flowsheet of water, milk and milk products in the Net-Zero Energy dairy system.

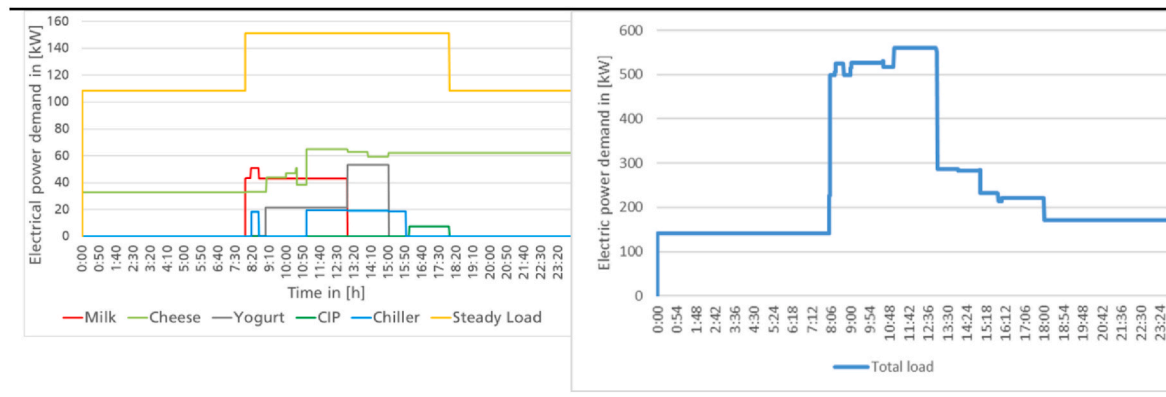


Fig. 11. Daily electric load profiles of the main industrial processes (left). Cumulative electric load profile (right).

Table 3

Environmental conditions in Magdeburg and Bari.

City	Optimal tilt angle β in [°]	Optimal azimuth angle α in [°]	PV Performance ratio	Annual final yield for PV Systems [kWh/kWp a]
Magdeburg	36.3	180	0.80 [39]	1037.50
Bari	32	180	0.77 [40]	1390.54

cesses are characterized by their ability to adjust energy demand in real-time, adhering to the dynamics of vRES energy generation. These systems optimize the use of renewable energy by modifying operational parameters (within the range P_{max} and P_{min}) and adjusting timings (T_{ante} to T_{post}) to ensure that all generated energy is utilized within the facility, thus adhering to the net-zero concept that precludes feeding energy back into the external grid. On the other hand, low flexibility processes require a stable and uninterrupted energy supply/energy consumption to maintain continuous operation, making them less adaptable to the variable nature of renewable energy generation. While these processes are based on the “old” paradigm that the supply follows the

Table 4

Summary of the main energetic indicators for the considered dairy systems.

City	HPs power demanded in kW	Other electric loads in kW	Annual total electricity demanded in MWh/year	Installed PV power in kW	Annual total electricity generation in MWh]	Ratio Energy generation to energy consumption
Magdeburg	511.00	50	2246.53	800	830.50	0,37
Bari	511.00	50	2232.36	800	1112.42	0,49

consumption, the NZEF ‘s goal remains to maximize on-site energy usage without exporting supply to the grid.

By running the developed mathematical model for operating the dairy as NEZF, for all the processes of the dairy facility the potential flexibility metered in the time and in the power has been identified and quantified. The demanded power is considered as a deterministic process. This exercise has been performed through the running of simulations looking to match the generated energy with the demanded one considering 1-min time step and taking in consideration the total daily amount of the milk to be processed. In each time-step the difference between the total power demanded (P_d) and the power generated by the PV plant (P_g) as well as the total energy demanded and the total energy generation are calculated. If the generated energy does not match the demanded one, the options to anticipate or postponing the processes are evaluated. By anticipating the processes, the operative power demanded (P_{op}) by each machine (i) is set to their maximal value ($P_{max,i}$). By postponing the processes, the operative power demanded by each machine is set to their minimal operative power ($P_{min,i}$). If by setting the new operative power the generated energy matches the demanded one and if the daily processed milk matches the scheduled daily processed milch than it is not necessary to identify other flexibility options. In the

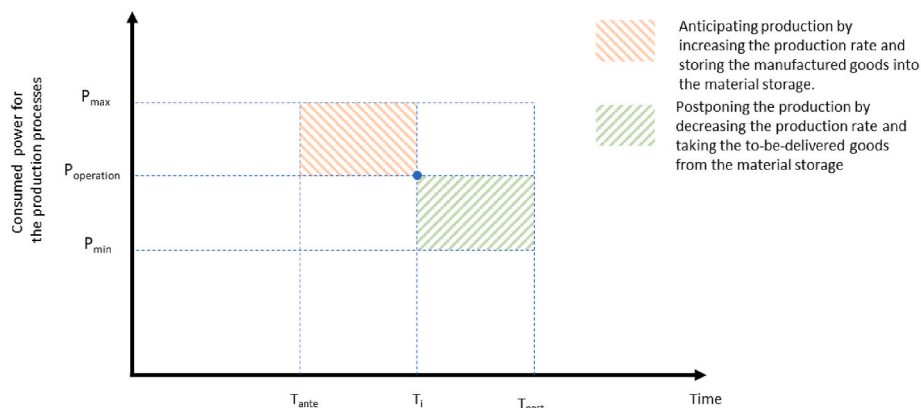


Fig. 12. Quantification of the needed flexibility for a particular process or machine.

opposite case, if the generated energy does not match the demanded one and if the daily processed milk does not match the scheduled one then it is necessary to design new flexibility options. A 1-h time step has been considered for the simulation resolution, and one year has been considered as the duration of the simulation. Fig. 13 shows how the flexibility of the processes are identified and quantified.

When evaluating the flexibility potential that the dairy processes can supply, it became evident that there is limited flexibility which can be exploited by some processes like that of the milk pumps and milk mixers. This is primarily because dairy processes are continuous, and the milk pumps and milk mixers consistently operate at their nominal power (P_{max}). Therefore, more flexibility options need to be designed. Greater flexibility can be achieved by operating heat pumps in combination with heat storage and by designing electrochemical storage systems (Li-ion battery) which can store the generated electricity by PV. In order to size the needed flexibility, sensitivity analyses have been performed. These analyses consider both the integration into the dairy system of the power generated by vRES as well as the operative costs. As operative costs, the costs for generating electricity by vRES, the costs to generate heat by heat pumps, the costs to store heat and the costs to store electricity have been considered. Such costs have been calculated according the Levelized Cost of Energy (LCOE) method (see equation (3)). It considers investment costs (IC), operating costs (OC) and the annual energy output (AEO) and the capital recovery factor (CRF), which considers the present value over the discount rate (i) and the lifetime (n) of the flexibility measure (see equation (4)).

$$LCOE = \left\{ \frac{CRF * IC + OC}{AEO} \right\} \quad (4)$$

$$CRF = \frac{\{i * (1 + i)^n\}}{\{(1 + i)^n - 1\}} \quad (5)$$

The total annual operative costs (aOC) have been evaluated as in equation (5), in which

- $LCOH$ depicts the levelized costs to generate heat by heat pumps;
- $LCOSH$ depicts the levelized costs to store heat in the sensible storage systems;
- $LCOSE$ depicts the levelized costs to store electricity in electro-chemical storage systems;
- $LCOE$ depicts the levelized cost to generated electricity by PV plant;
- E_{th} depicts the total annual generated thermal energy by the heat pumps;
- E_{thdis} depicts the total annual heat discharged by the thermal storage system;
- E_{edis} depicts the total annual electricity discharged by the electro-chemical storage system;
- E_{PVRES} depicts the total annual electricity generated by the photovoltaic system;
- $k_{e_{grid}}$ depicts the electricity price during the time in which the external grid supplies the dairy and
- $E_{e_{grid}}$ depicts the total annual electricity supplied by the external grid.

$$aOC = LCOH * E_{th} + LCOSH * E_{thdis} + LCOSe * E_{edis} + LCOE_{-pv} * E_{PVRES} + k_{e_{grid}} * E_{e_{grid}} \quad (6)$$

Table 5 summarizes the main assumptions for the evaluation of the generation and storage costs. In all the cases a discount rate of 6 % has been assumed.

Fig. 14 shows the load and power generation on a summer day for the dairy facility located in Magdeburg. On this particular day, the thermal storage was already fully charged the previous day and therefore the battery served as the first flexibility option to balance the surplus generated by the photovoltaic plant (from 07:00 to 08:00). During the second part of the day (11:00–15:00), the electricity surplus was first balanced by the thermal storage (until around 13:30) and subsequently by the electric storage. Due to the higher charging-discharging efficiency and the lower aging effect (that has been not metered in the simulation), the control of thermal storage is prioritized over the control of the electric storage system. However, the most significant contribution to

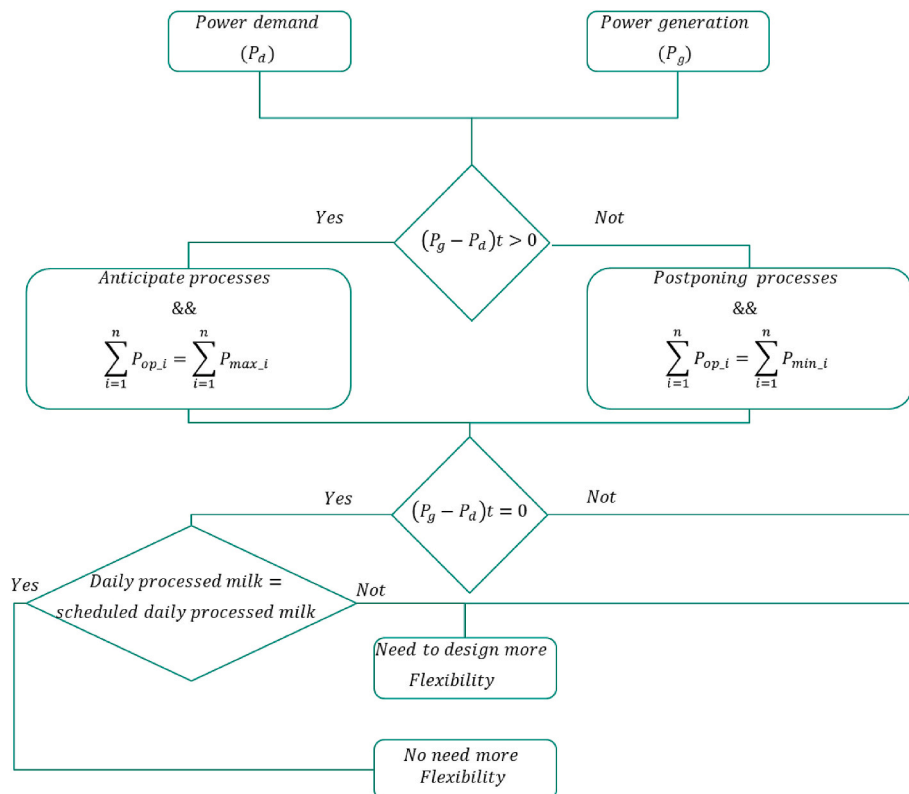


Fig. 13. Scheme for identify and quantify the flexibility of the processes.

Table 5
Costs and characteristics of the electrical and thermal storage systems.

Technology	Investment costs	Operating costs	Self-discharging rate	Efficiency	Life time
Lithium-ion battery	407.857 €/kWh [41]	2 % of Investment costs [42]	0.5 % per month [43]	90 % [44]	8000 cycles
Sensible heat storage	1630.287 €/kW [41] 0.4–10 €/kWh [47]	2 % Investment costs [48]	0.5 % per day [49]	90 % [49]	120 years [45, 46] [50, 51]
Photovoltaic	900 €/kW	Not considered	–	20 %	30 years [52, 53]
Heat Pump	1147 €/kW	Depending on the electricity costs and on electricity price	–	COP ranging 2.88–5	15 years [54]

flexibility was made by the coupled heat pump and thermal storage. Due to the limited energy capacity of both storage technologies, there were a few hours in the afternoon when the generated surplus could not be stored, requiring the power generated by vRES to be cut. This occurs only for a few hours each year. A cost-benefit analysis is needed to decide whether the energy capacity of both energy storage technologies should be increased. Similarly, Fig. 15 shows the load and power generation on a winter day. The thermal storage has been used at beginning of the day to decrease the electric load. In this case the thermal storage has been charged the day before. During the winter season, due to the lower power generation by sun, the flexibility offered by the thermal and electric storages is less required to operate the dairy as a NZEF. Fig. 16 shows the utilization of the flexibility options during a day. Also in this case, the flexibility offered by the battery and by the couple heat pump-thermal storage allows to match the load and the power generated by the photovoltaic plant.

Table 6 displays the energy balance and operation costs of the

simulation scenario A (dairy with conventional pasteurization method with gas boiler), scenario B (dairy with a heat pump system as the electrification measure) and scenario C (similar to scenario B with an additional PV system). In order to better understand the potential to design dairy as NZEF, the scenario A is used as benchmark.

The electrification of the thermal processes allows to save about 34 % of energy both in Magdeburg as well as in Bari. By considering the gas price of 194 €/MWh from Ref. [55] for September 20, 2022, and an electricity grid price of 401 €/MWh [55] for 2022, the implementation of the heat pump system as a sole measure results in an increase of operation costs of 23.0 % in Magdeburg and 22.1 % in Bari. This results from the higher electric energy demand and high electricity grid price. By considering the same economic assumptions as in scenario B and by integrating an 800 kW PV plant, the operational costs decrease by 16.3 % in Bari and 3.8 % in Magdeburg, respectively, when compared to the benchmark scenario (scenario A). Without implementing any additional flexibility options, 89.6 % of the electric energy generated by vRES is integrated in Magdeburg, and 88.5 % is integrated in Bari.

Figs. 17 and 18 display the sensitivity analysis for annual total operational costs and vRES integration as thermal storage capacity increases in the study cases of Magdeburg and Bari, respectively. In Magdeburg, a thermal storage capacity of 500 kWh minimizes the total annual operational costs while increasing vRES integration to 97 %. In Bari, the same vRES integration is achieved with a thermal storage capacity of 1000 kWh, contributing to further reducing the total annual operational costs if compared with the study case of Magdeburg.

The impact of electric storage on increasing RES and on the total annual operative costs is depicted in Figs. 19 and 20 for Magdeburg and Bari respectively. The analysis assumes that the electric storage system offers additional flexibility beyond that provided by the thermal storage system, which was sized to 2000 kWh. The control algorithms prioritize charging and discharging the thermal storage system, using the electric storage system only when no further flexibility can be harnessed from the thermal storage system. Three different power storage capacities (50 kW, 75 kW, and 100 kW) have been considered in combination with an energy storage capacity ranging from 50 kWh to 200 kWh. The utilization of electric energy storage systems does not significantly contribute to RES integration. However, its utilization increases the total operational costs for the dairy system located in Magdeburg, while offering

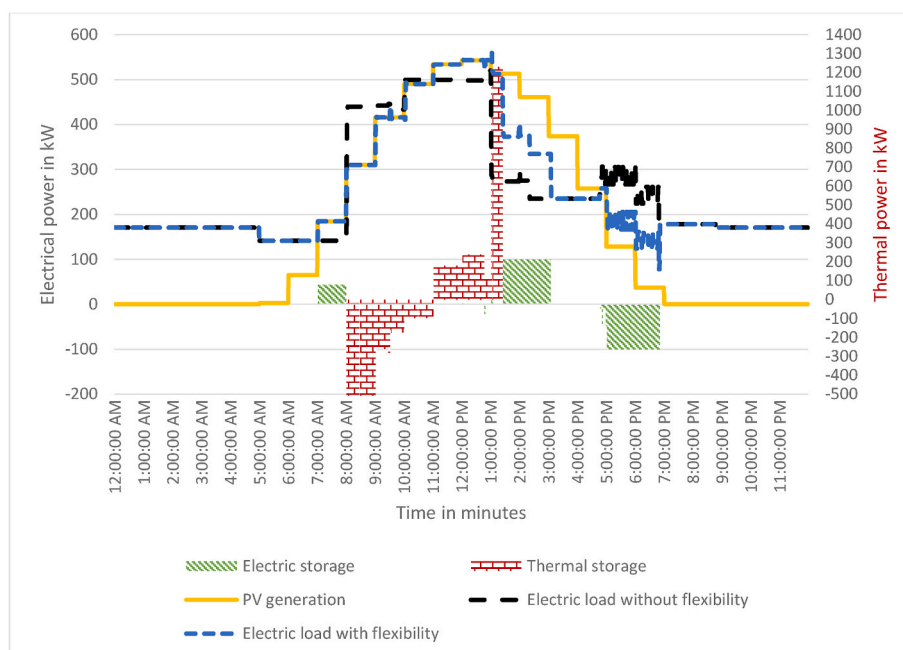


Fig. 14. Load and generation profiles, electric and thermal charging and discharging profiles (summer day).

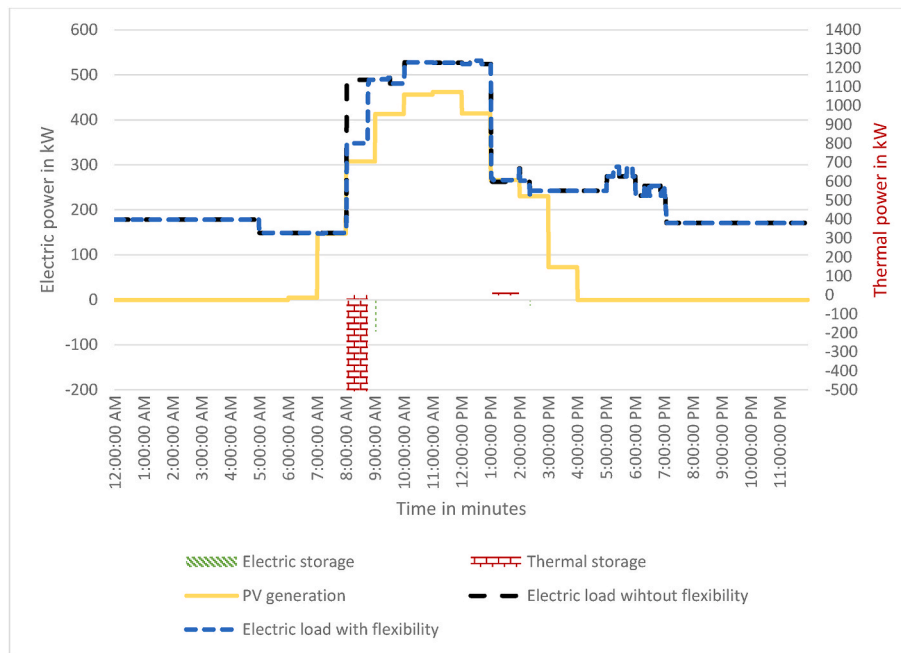


Fig. 15. Load and generation profiles, electric and thermal charging and discharging profiles (winter day).

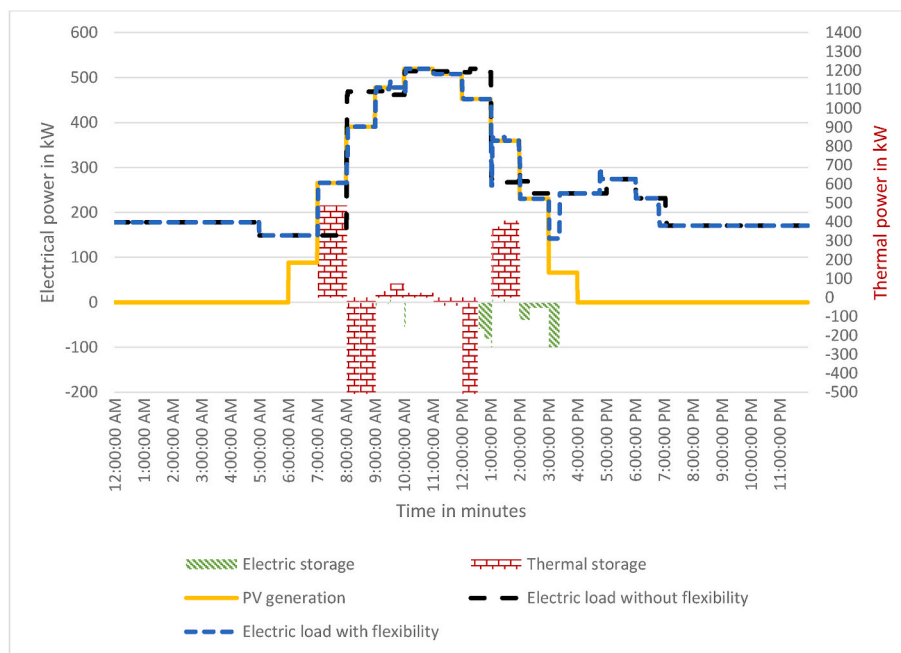


Fig. 16. Load and generation profiles, electric and thermal charging and discharging profiles (spring day).

Table 6

Annual operation costs of Scenario A (gas boiler), Scenario B (heat pump system) and Scenario C (heat pump system and 800 kWp PV system).

Scenarios	Magdeburg (A)	Magdeburg (B)	Magdeburg (C)	Bari (A)	Bari (B)	Bari (C)
Total consumption in [MWh]	3416.80	2246.53	2246.53	3424.40	2232.36	2232.36
Electric consumption in [MWh]	1810.40	2246.53	2246.53	1818.20	2232.36	2232.36
PV production in [MWh]	0.00	0.00	830.00	0.00	0.00	1112.44
Drawn from grid in [MWh]	1810.40	2246.53	1502.75	1818.20	2232.36	1247.47
PV Energy cut in [MWh]	0.00	0.00	86.22	0.00	0.00	127.55
LCOE of PV in [€/kWh]			0.08			0.06
Total annual operation costs in [Mio.€]	1.04	1.28	1.00	1.04	1.27	0.87

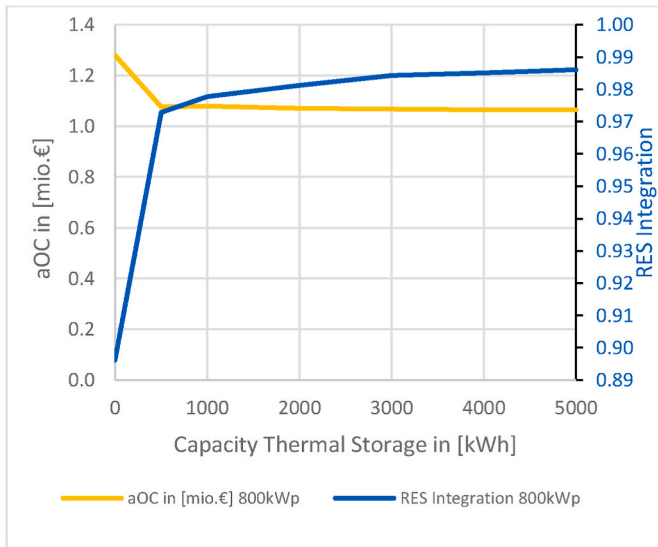


Fig. 17. Sensitivity analysis of the total annual operative costs and of the RES integration with different thermal storage capacity in Magdeburg (Germany).

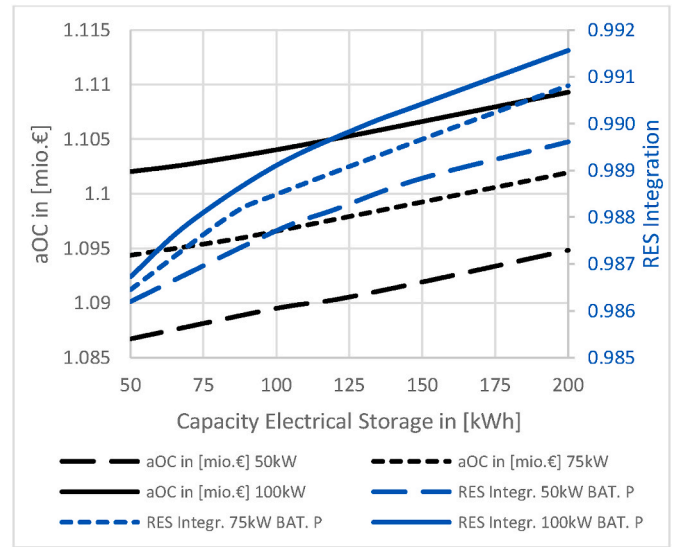


Fig. 19. Sensitivity analysis of the total annual operative costs and of the RES integration with different electric storage capacities in Magdeburg (Germany).

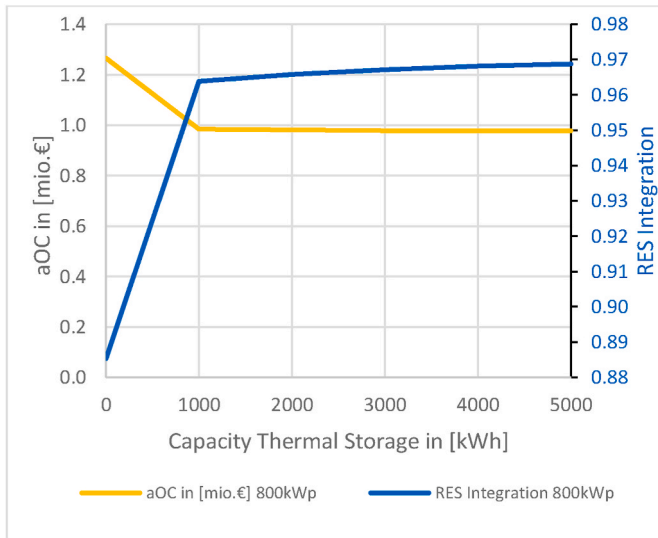


Fig. 18. Sensitivity analysis of the total annual operative costs and of the RES integration with different thermal storage capacity in Bari (Italy).

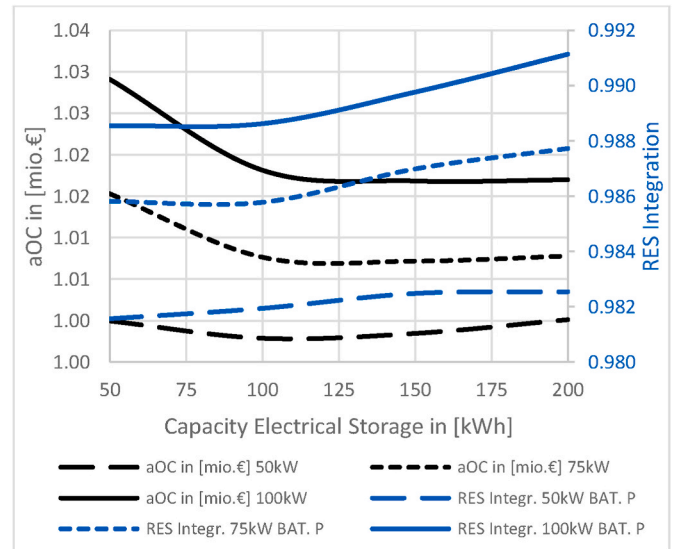


Fig. 20. Sensitivity analysis of the total annual operative costs and of the RES integration with different electric storage capacity in Bari (Italy).

the possibility to decrease the operational costs for the dairy system in Bari. This difference is primarily due to the higher vRES generation at the Bari site. In both the cases, the operation time of the electric storage system ranges between 50 and 75 h per year.

6. Conclusion

This study focuses on the decarbonization of energy systems by incorporating flexibility to integrate a significant amount of power from volatile and renewable energy sources (vRES). The research highlights the potential role of industrial systems in harnessing this flexibility for the effective integration of vRES-generated electricity. Specifically, it explores the concept of designing industrial systems as Net-Zero Energy Factories (NZE) to leverage internal flexibility for renewable energy integration. A simulation model is developed to analyze the energetic and material flows within traditional dairy systems, aiding in their transformation into NZEF and the assessment of their flexibility potential. The study concentrates on two different European climate zones,

Bari, Italy, and Magdeburg, Germany.

The results indicate that the electrification of thermal processes (scenario B) results in approximately 34 % energy savings in both Magdeburg and Bari, however this measure contributes to increase the operational costs by 23.0 % in Magdeburg and 22.1 % in Bari due to higher electric energy demand and electricity grid prices. Adding an 800 kW PV system (scenario C) decreases operational costs by 16.3 % in Bari and 3.8 % in Magdeburg compared to the benchmark scenario (scenario A). Related to the vRES integration, without implementing additional flexibility options, 89.6 % of power generated by volatile and renewable energy sources could be integrated in Magdeburg, and 88.5 % is integrated in Bari. A thermal storage capacity of 500 kWh minimizes total annual operational costs while achieving 97 % vRES integration in Magdeburg. In Bari, the same vRES integration is achieved with a thermal storage capacity of 1000 kWh. Electric storage systems do not significantly contribute to RES integration. In Magdeburg, they increase total operational costs, while in Bari, they offer the possibility to decrease operational costs. The operation time of the electric storage

system ranges between 50 and 75 h per year in both cases.

CRediT authorship contribution statement

Pio Alessandro Lombardi: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Hannes Peter Wasser:** Writing – original draft, Visualization, Validation, Software, Resources. **Antonio Marco Pantaleo:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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