Energy 281 (2023) 128242

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Integrated design and operational optimization of energy systems in dairies

Sverre Stefanussen Foslie [a,b,*], Brage Rugstad Knudsen [a], Magnus Korpås [b]

[a] SINTEF Energy Research, Kolbjørn Hejes vei 1A, Trondheim, 7034, Norway
[b] Norwegian University of Science and Technology, O.S. Bragstads plass 2E, Trondheim, 7491, Norway

ARTICLE INFO

Keywords:
Optimization
Integrated energy systems
Process heating
Industry decarbonization
Food sector

ABSTRACT

Around 70% of worldwide industrial energy use is today based on fossil energy. Electrification of low temperature heat in this sector is pointed out as a key measure to reduce emissions. A large amount of the low temperature heat demand can be served by mature technologies, providing a possible fast way to decarbonize parts of the industry sector. Still, to reduce costs and accelerate broad, sector-wide implementation, integrating thermal and electrical energy systems will be important. Here a model is presented to analyse cost-optimal industrial energy system investments, applied to a dairy. The model uses heating, cooling and electric demands at an hourly resolution, including hourly power prices and yearly increases in energy and emission costs. The model minimizes investment, grid, energy and emission costs over a given planning period. Real data from a Norwegian dairy is used to investigate the effect on an industrial energy system subject to different future cost scenarios. The results show that an energy integrated dairy can reduce costs by 24% and emissions by 96% compared with a traditional dairy, and is cheaper to decarbonize. It is also shown that thermal energy storages provide flexibility at a low cost, eliminating the need for batteries.

1. Introduction

To meet the goals defined in the Paris agreement and reduce global warming, decarbonization of energy use is critical. Transition to zero-emission energy requires both significant investments in new renewable energy generation, such as wind and solar, as well as a change in energy demanding technologies. Both the EU [1] and Norway [2] have set goals to reduce greenhouse gas emissions by 55% until 2030. In the industry sector, around 70% of the total energy use is based on fossil fuels, and emissions from light industries are required to decline drastically to achieve the climate goals [3]. Heat production in the industry sector accounts for about 21% of global CO_2 emissions, mainly related to burning of oil, gas or coal [4]. The characteristics of industrial heat range from room heating temperatures to several thousand degrees Celsius. Therefore, a variety of solutions are required to decarbonize this heat demand. To cover high temperature demands, significant technology developments are required, while low-to-medium temperature demands up to around 200 °C, accounting for around 37% of industrial process heat, can be electrified in the near future through heat pumps (HP) or direct electrification [5]. In combination with a low-carbon electricity system, electrification of low temperature heat is a prioritized path to decarbonization [6]. As low-temperature heat (below 100 °C) primarily rely on mature technologies, electrification of these heat demands is a first step towards full decarbonization. Heat in these temperature ranges are primarily used in the food industry [7], where the electrification rate is currently around 25% [8].

Rapid electrification of industrial processes, as well as the rest of the society is estimated to quadruple the need for electric flexibility by 2050 delivered by batteries, demand response and low carbon flexible power plants [3]. To alleviate the strain on the electric power infrastructure from this massive increase in electric power demand, improved energy efficiency and waste heat utilization in the industry sector will be crucial. As the strain on the power grid is expected to become higher and higher, power prices will be subject to higher fluctuations, and future grid tariff designs are investigated to accommodate for evening out the power demand over days and seasons [9].

Energy prices are subject to significant disruptions due to decarbonization and political instability. The combination of these effects increases the uncertainty of the energy costs of future industrial systems. This will encourage more variation within end-user energy technologies to hedge large energy price variations, and challenge the investment decisions in decarbonized energy technologies for industrial actors. In this work, an techno-economic model with high detailing grade in both electrical and thermal energy systems is used to investigate how different energy and carbon tax scenarios will affect cost optimal industrial energy systems. The focus of this work is a dairy with electric, cooling and heating demands below 100 °C, and how an integrated

* Corresponding author at: SINTEF Energy Research, Kolbjørn Hejes vei 1A, Trondheim, 7034, Norway.
E-mail address: sverre.foslie@sintef.no (S.S. Foslie).

https://doi.org/10.1016/j.energy.2023.128242
Received 28 June 2022; Received in revised form 15 June 2023; Accepted 22 June 2023
Available online 28 June 2023

energy system taking into account several energy technologies, price variations and future cost developments will affect the cost optimal system. As seen in the literature review below, there is a gap in the research literature on such integrated energy systems in industrial applications.

Process heating demands below 100 °C account for around 11% of the industrial heating demands, in total 222 TWh/year [5] in Europe. The food and beverages sector is one of the main consumers of heating in this temperature range, typically used in the form of hot water. In dairies, around 90% of the heating demand is below 100 °C, while in other subsectors of food and beverages, the heating demand below 100 °C accounts for 10% to 55% of the demand. At the same time, process cooling or refrigeration is widely used in the food and beverages industry, but is generally less quantified [10].

Process heating in the food and beverages industry is mainly based on indirect heating from burning of fossil fuels [11]. In low to medium temperature demands, decarbonization of heat is most likely to be met by a combination of HPs, biomass heaters, electric heaters and hydrogen heating, with HPs seeing the largest increase towards 2030 [6]. HPs are today available as high-performance equipment up to around 100 °C, with different research projects testing technologies up towards 180 °C [12]. The relatively low electrification grade in the sector, combined with low-temperature demands and mature technology make the food and beverages sector highly relevant for a rapid transition to full electrification. Several studies have investigated the decarbonization of heat and energy savings in the food sector [11], with dairies gaining a lot of attention [13].

With electrification of heat, energy storage is also recognized as a relevant technology which may enable industry actors to lower their energy costs. Energy storage can be segmented into several subcategories, with electricity storage and thermal energy storage being two important categories relevant for the industry. Energy storage may also be an important enabler in overcoming a temporal mismatch between availability of cheap energy and the demand for energy [14]. Electrical energy storage is typically studied on a grid-scale, while thermal energy storage is of high interest in industrial energy systems in the literature. This also reflects the industrial electrification studies, which are typically either focusing on energy efficiency and fuels for individual industrial systems, or on electrification of a whole sector or a region [15]. Few studies have investigated the cross-section between power grid characteristics and electrification and energy storage on an industrial level, taking into account the internal industry system and the energy types in the final energy demand.

Due to profitability and the requirement for short payback times, cost-optimal investments are of high importance in industrial systems, and has been the topic of several research studies. In [16], a methodology for a cost optimal thermal storage for industrial systems is developed, based on a Mixed-Integer Linear Programming (MILP) optimization model in Pyomo. In Philipp et al. [17], energy demand and pinch analysis is used to find optimal energy supply structures for a food processing plant in different regions. They find HPs to be of major importance in decarbonizing heat supply, especially in regions with low electricity prices. In [18], a MILP-optimization model in MATLAB is developed to obtain the cost-optimal design of a cooling system under a time-varying electricity tariff. It is found that an ice storage system in combination with the chiller can reduce overall costs, and the optimal size of the storage increases with higher variations in electricity prices.

The energy hub concept was developed by Favre-Perrod [19] as a multi energy carrier system able to interconnect different types of energy producers and consumers, utilizing conversion technologies and storage to enable more strategic planning of energy supply. The concept was further developed by Geidl [20], establishing modelling and optimization methods, and investigating the potential of connecting multiple energy hubs in a network. The concept has been further developed and investigated in several research activities, as presented by Mohammadi et al. [21], describing typical components of energy hubs as resources, conversion and transmission components, storage units and consumption and demand. The energy hub concept is typically used to find the cost-optimal way to serve multiple demands, and is mostly used in power and gas network systems, or for producing multiple energy carriers from various energy inputs, such as presented by Mahmoudan et al. [22]. In Mohammadi et al. [23], a review of the applications of the energy hub concept is presented, dividing into micro- and macro energy hubs, where the former focuses on small scale individual units, such as houses or industries, while the latter focuses on system or grid levels. The application of the energy hub concept is found to be scarcely used in industrial applications, however with a significant potential in integrating variable renewables in industrial energy systems, and incentivizing demand response. This also aligns with the findings of Halmschlager and Hofmann [24], where a gap in industrial applications of the energy hub concept is found, and they develop the concept for taking account of product streams in addition to energy streams. They find significant cost savings potential in utilizing both product and energy streams in the energy hub optimization. Also in the work by Taqvi et al. [25], the energy hub concept is used to find a cost optimal approach to integrating renewables into the process industry, and specifically a refinery. They find the optimal capacities of various conversion and storage technologies to reduce emissions from the refinery process. To the authors knowledge, there exist no previous research applying the energy hub concept to the food sector, and how thermal demands may be met by different conventional technologies under variations in energy prices and emission taxes.

In addition to energy costs, such as power prices and fuel prices, grid tariffs may affect the optimal energy system of an industrial actor. The grid tariff impact on optimal energy systems have been investigated mainly on a residential building level, and on an overall energy system level. In Kirkerud et al. [9] and Sandberg et al. [26], the effect of different grid tariffs in the Nordics are used to investigate the impact on power-to-heat in district heating systems. They find that the different tariff schemes significantly affect the use of power-to-heat technologies, and the distribution between them. In Johannsen et al. [27], grid tariff schemes for the Danish district heating sector were investigated . Also in this study, they found significant impact on the use of electric boilers (EB) and HPs depending on the grid tariff scheme. Grid tariffs typically consist of a fixed subscription charge, a volumetric charge based on the volume of energy consumed and a capacity charge based on the maximum capacity of the connection or the used power [28]. Most European countries today have a mainly volumetric-based grid tariff, which to little degree reflects the cost drivers of the grid companies [29]. A transition to other tariff schemes is therefore subject to a lot of ongoing research, but the impact on industrial energy hub design has to little extent been investigated.

How the emission tax levels affect industrial energy systems has to the author's knowledge been little explored. Several top-down studies have been performed, typically using computable general equilibrium models, on how carbon taxes affect the overall economy or prices in an area, especially for the Chinese economy. Lin and Jia [30] find that the carbon tax is a very efficient way to reduce emissions, especially from energy industries, and that the level of the carbon tax is of high importance. In the study by Wang et al. [31], they investigate how varying carbon tax levels affect different industry segments, and suggest measures to reduce competitiveness issues rising from variation in taxation burdens. Few, if any, studies have investigated how different carbon tax levels will affect the optimal infrastructure selection of a single industrial actor.

The investigated literature shows that the impact of future price changes in energy, emission taxes and grid tariffs to industrial energy systems has been little investigated. Specific heating and cooling technologies have gained significant attention, but the combination of these, including energy storage and electric utilities into an integrated industrial energy system, is a field yet to be explored.

This paper adds to the extant literature on decarbonized industrial energy systems by presenting a methodology to investigate the sensitivity of future changes in cost parameters on optimal investments in an industrial energy infrastructure for a dairy. To this end, the main contributions of this article are as follows: (1) adopting the concept of energy hubs and applying it for economic analysis of integrated energy systems in a dairy; (2) investigating how different grid tariffs and future changes in energy prices and carbon taxes will affect the optimal energy system design. The developed model includes both fixed costs from investments and operational costs over a multi-year period towards the climate targets set for 2030. The model operates on an hourly resolution, and is adapted for analysis of dependencies and interactions between different energy carriers, heating, cooling, and energy storage. The work also evaluates to which degree energy storage systems are able to even out loads and reduce overall costs. The cost of decarbonization of the different energy system designs are evaluated. A real case study is performed on a Norwegian dairy, to present the value of the approach.

2. Method

This section describes the proposed model to obtain the cost-optimal capacity and operation of the industrial energy system of a dairy with heating, cooling and electric demands. The general model structure is described first, followed by a detailed description of the variables, parameters objective function, and constraints of the model. The model includes both capacity investments and operation of the energy system, and is designed for hourly resolutions over a horizon of several years.

2.1. General model structure

The model consists of nodes connecting demands, import/export possibilities, components, storages and decentralized energy resources (DER) such as rooftop photovoltaics (PV). Several components can be connected to a node, such as different energy conversion components, which are connected to further nodes.

For each time step, the optimization model finds the least-cost solution to handle the demand, considering the restrictions of each of the included components. The demands are defined as hourly energy demands, and are connected to nodes with components able to deliver the specific demand, depending on characteristics such as electricity or thermal, and temperatures. The costs are related to discounted capacity investment costs, energy import or export, grid peak demands and emissions from local combustion of fossil fuels.

The model is developed and used for a case study of a dairy, which is described in detail in Section 3. The energy technologies included in the model are the ones identified as the most relevant for the specific dairy and include a natural gas boiler (NGB), electric boiler (EB), high temperature heat pump (HP), vapour compression chiller, hot water thermal energy storage (TES), ice storage for cold thermal storage purposes (CTES), a battery and photovoltaic modules (PV). Fig. 1 presents the technologies and the energy flows present in the model. The nodes are shown as black dots, connecting the energy flows of the different components, resources and demands.

2.2. Model description

This section describes the details of the model formulation, and how it is implemented. The sets, indices, parameters and variables of the model are presented in Tables 1–4.

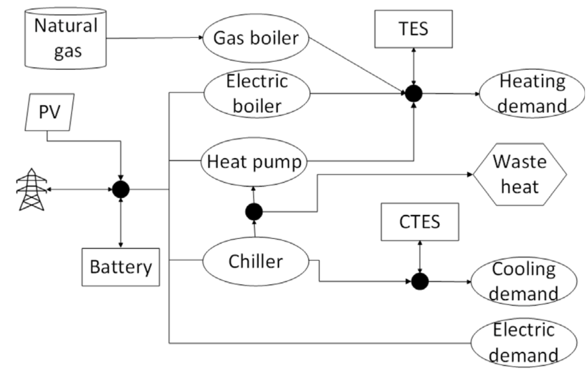


Fig. 1. Graphical presentation of the energy balances in this work.

Table 1
Model sets.

Set	Description
I	All energy technologies, I = {NGB, EB, HP, CH, TES, CTES, BATT, PV}
I^b	Boiler technologies, subset of I, I^b = {NGB, EB}
I^s	Storage technologies, subset of I, I^s4 = {TES, CTES, BATT}
I^h	Heat pumping technologies, subset of I, I^h = {HP, CH}
F	Energy carriers, F = {el, ng, Qh, Qc}

Table 2
Model indices.

Index	Description
y	Year within analysis period, $y = 1, \dots, Y$
m	Month within year, $m = 1, \dots, 12$
t	Timestep within year , $t = 1, \dots, T$
i	Technology in set I
f	Energy carrier in set F

Table 3
Model parameters.

Parameter	Description
COP_i	Coefficient of performance of technology i [-]
$D_{f,t,y}$	Energy demand of type f at time t in year y [MWh/h]
I_i	Investment cost per capacity of technology i [€/MWh or €/MW]
L_i	Expected lifetime of technology i [years]
$P^{el}_{t,y}$	Price of electricity from grid at time t in year y [€/MWh]
P^{em}_y	Price of carbon emissions in year y [€/ton$_{CO_2}$]
P^{ng}_y	Price of natural gas in year y [€/MWh]
$P^{grid,en}$	Electricity grid price of energy component [€/MWh]
$P^{grid,peak}$	Monthly electricity grid price of power component [€/MWp/m]
$P^{grid,fix}$	Yearly electricity grid price [€/y]
r	Discount rate [-]
S_i	Discount factor for investment i, accounting for salvage value after the investigation period [-]
$X^{ch,max}_i$	Maximum charging capacity of technology i [MWh/h]
$X^{disch,max}_i$	Maximum discharging capacity of technology i [MWh/h]
X^{min}_i	Minimum operation of technology i [MWh/h]
η_i	Efficiency of technology i [-]
η^{ch}_i	Charging efficiency of technology i [-]
η^{disch}_i	Discharging efficiency of technology i [-]
η^{sd}_i	Hourly self-discharging of technology i [-]
ϵ_y	Discount factor of year y [-]
λ_t	Capacity factor of PV in hour t [-]
ϕ_f	CO_2 intensity of energy carrier f [ton/MWh$_{LHV}$]

2.2.1. Objective function

The objective function of the model minimizes the total cost over the investigated period, consisting of energy costs, emission costs, grid costs and discounted costs from investments, including salvage value,

Table 4
Model variables.

Variable	Description
C^{energy}	Total cost of energy [€]
$C^{emission}$	Total cost emissions [€]
C^{grid}	Total grid costs [€]
C^{inv}	Total discounted investment costs [€]
C^{total}	Total costs [€]
$p^{c}_{f,i,t,y}$	Energy of type f consumed by technology i at time t in year y [MWh/h]
$p^{d}_{f,i,t,y}$	Energy of type f delivered by technology i at time t in year y [MWh/h]
$p^{ch}_{f,i,t,y}$	Energy of type f charged to technology i at time t in year y [MWh/h]
$p^{disch}_{f,i,t,y}$	Energy of type f discharged from technology i at time t in year y [MWh/h]
$p^{imp}_{f,t,y}$	Energy of type f imported at time t in year y [MWh/h]
$p^{exp}_{f,t,y}$	Energy of type f exported at time t in year y [MWh/h]
$p^{wh}_{t,y}$	Waste heat at time t in year y [MWh/h]
$p^{el,max}_{m,y}$	Maximum hourly electricity import or export in month m in year y [MWh/h]
$s_{f,i,t,y}$	Storage fill level of energy carrier f in technology i in time t in year y [MWh]
x_i	Installed capacity of technology i [MWh/h]
$\delta_{i,t,y}$	Binary variable determining on or off operation of technology i at time t in year y [MW or MWh]
$\psi_{i,t,y}$	CO_2 emissions from technology i at time t in year y [ton/h]

calculated as presented by Korpås [32].

$$\min C^{total} = C^{energy} + C^{emission} + C^{grid} + C^{inv} \tag{1}$$

The separate cost functions are modelled as presented in Eqs. (2)–(5).

$$C^{energy} = \sum_y \left(\sum_t \left(P^{el}_{t,y} * (p^{imp}_{el,t,y} - p^{exp}_{el,t,y}) + P^{ng}_y * p^{imp}_{ng,t,y} \right) * \epsilon_y \right) \tag{2}$$

$$C^{emission} = \sum_y \left(\sum_t (\psi_{NGB,t,y} * P^{em}_y) * \epsilon_y \right) \tag{3}$$

$$C^{grid} = \sum_y \left(\left(P^{grid,fix} + \sum_t (P^{grid,en} * p^{imp}_{t,y}) + \sum_m (P^{grid,peak} * p^{el,max}_{m,y}) \right) * \epsilon_y \right) \tag{4}$$

$$C^{inv} = \sum_i x_i * S_i \tag{5}$$

where (6)

$$S_i = I_i * \frac{1-(1+r)^{-Y}}{1-(1+r)^{-L_i}} \tag{7}$$

The cost functions of energy and emissions are calculated using hourly prices for electricity ($P^{el}_{t,y}$) and yearly prices of natural gas (P^{ng}_y) and emission prices (P^{em}_y). The grid costs include the yearly price ($P^{grid,fix}$), the energy term ($P^{grid,en}$) and the monthly power term ($P^{grid,peak}$). Annual investment costs are based on investment costs (I_i), lifetime (L_i) and the optimization period (Y).

2.2.2. Energy balances

Four nodes with energy balances are taken into account in the modelling, which are specific to the investigated component setup. In this work, there is one electric energy balance including grid import and export, PV electricity production, battery charging and discharging, EB, HP and chiller electric consumption, as well as the final electric hourly demand ($D_{el,t,y}$).

$$p^{d}_{el,PV,t,y} + p^{imp}_{el,t,y} - p^{exp}_{el,t,y} + p^{disch}_{el,BATT,t,y} - p^{ch}_{el,BATT,t,y} = p^{c}_{el,EB,t,y} + p^{c}_{el,CH,t,y} + p^{c}_{el,HP,t,y} + D_{el,t,y}, \quad \forall\, t,y \tag{8}$$

The thermal energy balances include one on the hot thermal side, one on the cooling side, as well as one waste heat balance to limit the HP to using the chiller waste heat as its heat supply. The input parameters are the hourly process heating demand ($D_{Qh,t,y}$) and process cooling demand ($D_{Qc,t,y}$).

$$p^{d}_{Qh,EB,t,y} + p^{d}_{Qh,NGB,t,y} + p^{d}_{Qh,HP,t,y} + p^{disch}_{Qh,TES,t,y} = p^{ch}_{Qh,TES,t,y} + D_{Qh,t,y}, \quad \forall\, t,y \tag{9}$$

$$p^{d}_{Qc,CH,t,y} + p^{disch}_{Qh,CTES,t,y} = p^{ch}_{Qc,CTES,t,y} + D_{Qc,t,y}, \quad \forall\, t,y \tag{10}$$

$$p^{d}_{Qh,CH,t,y} = p^{c}_{Qc,HP,t,y} + p^{wh}_{t,y}, \quad \forall\, t,y \tag{11}$$

2.3. Modelling of energy technologies

In the following section, a description of the included energy technologies are given, as well as the formulation for modelling of the technologies.

2.3.1. Boilers

Both electric boilers and natural gas boilers are commonly used for providing hot water or steam in industrial processes. They are able to operate at low part loads (typically 5% to 15%), and with fast start-up times [33]. Hence, linear operation is assumed over the time step of one hour applied in this work. The boiler energy demands rely on the efficiency of the boiler (η_i) [16], while emissions from the NGB is calculated using the natural gas consumption and the CO_2 intensity of natural gas (ϕ_{ng}).

$$p^{d}_{Qh,EB,t,y} = p^{c}_{el,EB,t,y} * \eta_{EB}, \quad \forall\, t,y \tag{12}$$

$$p^{d}_{Qh,NGB,t,y} = p^{c}_{ng,NGB,t,y} * \eta_{NGB}, \quad \forall\, t,y \tag{13}$$

$$p^{d}_{Qh,i,t,y} \le x_i * \eta_i, \quad \forall\, t,y,i \in I^{b} \tag{14}$$

$$\psi_{NGB,t,y} = p^{c}_{ng,NGB,t,y} * \phi_{ng}, \quad \forall\, t,y \tag{15}$$

2.3.2. Heat pump and chiller

Heat pumps are available as state-of-the-art equipment up to around 100 °C, however at higher investment cost than boilers [12]. The part load performance of heat pumps and chillers depend on the number of compressors, their capacities, and to what degree they can be frequency controlled. In this work, a minimum part load limit (X^{min}_i) of approx. 25% of the installed capacity is assumed for both chillers [34] and heat pumps [33]. The binary variable $\delta_{i,t,y} \in \{0,1\}$ determines the on/off operation of the chiller and the heat pump. The chiller COP (COP_{CH})is specified as a cooling COP, and the HP by a heating COP (COP_{HP}), and they are limited by the cooling demand and the chiller waste heat, respectively [16].

$$p^{d}_{Qh,i,t,y} = p^{c}_{el,i,t,y} + p^{c}_{Qc,i,t,y}, \quad \forall\, t,y,i \in I^{h} \tag{16}$$

$$p^{c}_{Qc,CH,t,y} = COP_{CH} * p^{c}_{el,CH,t,y}, \quad \forall\, t,y \tag{17}$$

$$p^{d}_{Qh,HP,t,y} = COP_{HP} * p^{c}_{el,HP,t,y}, \quad \forall\, t,y \tag{18}$$

$$X^{min}_{CH} * \delta_{CH,t,y} \le p^{c}_{Qc,CH,t,y} \le x_{CH} * \delta_{CH,t,y} \quad \forall\, t,y \tag{19}$$

$$X^{min}_{HP} * \delta_{HP,t,y} \le p^{d}_{Qh,HP,t,y} \le x_{HP} * \delta_{HP,t,y} \quad \forall\, t,y \tag{20}$$

2.3.3. Energy storages

The energy storages consist of a battery, a hot water tank and an ice tank. The thermal storage tanks are considered as ideally stratified, providing stable temperatures to the processes. Energy storage efficiencies are related to self discharge (η^{sd}_i), charging (η^{ch}_i) and discharging (η^{disch}_i) [35]. The hot water tank is considered full when the entire volume is at the maximum allowed temperature, and the tank is considered empty at the lowest allowed temperature. The energy storage levels in the end of the period are limited to be equal or greater than the starting level, and the maximum charge and discharge per hour are defined by the input parameters $X_i^{disch,max}$ and $X_i^{ch,max}$.

$$s_{f,i,t,y} = s_{f,i,t-1,y} * (1 - \eta_i^{sd}) + p^{ch}_{f,i,t,y} * \eta_i^{ch} - \frac{p^{disch}_{f,i,t,y}}{\eta_i^{disch}}, \quad \forall\, t, y, f \in \{\text{el}, \text{Qc}, \text{Qh}\}, i \in \text{I}^s \tag{21}$$

$$s_{f,i,1,1} \le s_{f,i,\text{T},\text{Y}}, \quad \forall\, f, i \in \text{I}^s \tag{22}$$

$$s_{f,i,1,y} = s_{f,i,\text{T},y-1}, \quad \forall\, f, i \in \text{I}^s, y \in \{2..\text{Y}\} \tag{23}$$

$$s_{f,i,t,y} \le x_i, \quad \forall\, t, y, f \in \{\text{el}, \text{Qc}, \text{Qh}\}, i \in \text{I}^s \tag{24}$$

$$p^{ch}_{f,i,t,y} \le \text{X}_i^{\text{ch,max}}, \ \forall\, t, y, f \in \{\text{el}, \text{Qc}, \text{Qh}\}, i \in \text{I}^s \tag{25}$$

$$p^{disch}_{f,i,t,y} \le \text{X}_i^{\text{disch,max}}, \ \forall\, t, y, f \in \{\text{el}, \text{Qc}, \text{Qh}\}, i \in \text{I}^s \tag{26}$$

2.3.4. Photo-voltaic panels

Photovoltaic (PV) panels are modelled as a DER source of electric energy, limited by a maximum production capacity. The maximum production capacity is a product of the installed PV capacity and the estimated maximum hourly power output in the specific location (λ_t) [35], based on data from Pfenninger and Staffell [36].

$$p^{d}_{\text{el,PV},t,y} \le x_{\text{PV}} * \lambda_t, \quad \forall\, t, y \tag{27}$$

3. Case study

The methodology described in Section 2 has been applied to analyse cost sensitivity of technology choices for decarbonization of a dairy located in Bergen, Norway, set into operation in 2019. In the following section, the setup of the case study is outlined, and the energy price scenarios used to assess the technology investments are described.

3.1. Description

The considered dairy was investigated by Ahrens et al. [37], and it was concluded to be highly energy efficient. In our study, the final energy demands of the dairy are used, and are classified as heating, cooling and electricity demands. The heating and cooling demands are monitored data, while the electrical demands have been estimated using the PROFet load modelling tool [38]. PROFet uses monitored data to generate load profiles for heating and electricity at an hourly resolution. The availability of hourly thermal demand data from a real case allow for a detailed and precise bottom up economic modelling for investigation of the cost sensitivity of technology choices. The hourly heating, cooling and electrical demands over the first week in the time-period considered are shown in Fig. 2. An annual increase in energy demand of 1% over the analysis period is assumed.

In this case study, a traditional dairy utilizing an EB, NGB and a chiller is used as a base case and compared with a state of the art energy integrated dairy including energy storage and PV. The traditional dairy can switch between NGB and EB for the heating demands, but other than that has no possibilities for load shifting or flexible demand. In the integrated dairy a high temperature HP, TES, CTES, PV and electric battery storage can be included to optimize investments and operation. To investigate the sensitivity of the integrated dairy to changes in energy prices, emission taxes and grid tariffs, different scenarios are established. Schematic layouts of the traditional and the integrated dairy are shown in Fig. 3(a) and Fig. 3(b), respectively.

3.2. Scenarios

The energy costs are divided into spot prices for electricity, grid tariffs for the electricity grid and costs for natural gas. In this work, the electricity spot price is based on the 2021 price in the Norwegian price area NO5, as obtained from the power market Nord Pool, with a mean power price of 74.6 EUR/MWh and a standard deviation of 47.5 EUR/MWh. However, as the period of analysis are the seven years from 2024 to 2030, the power prices are scaled to average at 94 EUR/MWh in 2024, as prognosed by Statnett [39]. The model uses a linear change in power prices over the years of the analysis period, and a high, medium (baseline) and low scenario are used. The medium scenario is based on the prognosed power price in 2030 by Birkelund et al. [40], while the low and high scenarios use a 50% decrease and increase from that expectation. In Fig. 4 the spot prices over the year in 2024 and 2030 for the baseline scenario are presented.

Table 5
Scenarios.

	Avg. spot price	Gas price	Grid tariff	
	2030 EUR/MWh	2030 EUR/MWh	Energy EUR/MWh	Power EUR/MWp/m
Baseline	54	26.9	19.0	5450
Low el cost	27	26.9	19.0	5450
High el cost	81	26.9	19.0	5450
Low peak cost	54	26.9	23.2	0
High peak cost	54	26.9	0	9778
Low gas cost	54	13.5	19.0	5450
High gas cost	54	40.4	19.0	5450

The grid tariff scenarios used in the study include a fixed term of 1050 EUR/year, as well as an energy term and a monthly power term. The grid tariffs and the corresponding scenarios are presented in Table 5. The baseline scenario is based on the local grid company tariff scheme [41]. The high and low peak tariff scenarios are created to give approx. equal income for the grid company for a non-flexible customer of this size.

The natural gas prices used in the model also change linearly from the prognosed 2024 level of 110 EUR/MWh [39], to the Announced Pledges Scenario of the International Energy Agency [6] in 2030 of 26.9 EUR/MWh, used as a baseline. Also the natural gas cost scenarios include a low and high, with a respective 50% decrease and increase in the 2030 prognosis.

In Norway, the carbon tax rate of 2024 is estimated to be approx. 100 EUR/tonne CO_2, and is announced to increase to 200 EUR/tonne CO_2 in 2030 [42], which is used in all scenarios.

The variations between scenarios are summarized in Table 5.

3.3. Technology parameters

The optimization model uses investment costs and lifetime as the main cost parameters for the different components, in addition to efficiencies and maximum capacities. Discounted costs are calculated from (7). All investment costs are assumed to have a linear correlation to the capacity in the relevant capacity range. The parameters used in this study are presented in Table 6.

4. Results

The results section first presents the results for the baseline scenario, comparing the traditional and the integrated dairy, and how an integrated dairy would take advantage of batteries and PV for decarbonization, while the following section focuses on the integrated dairy, and how the different scenarios for 2030 affect optimal operation and investments.

The model is formulated as a deterministic mixed integer linear program (MILP), and is implemented in Julia/JuMP [44] for the optimization analysis, using Gurobi [45] as optimization solver. In the current application, the model consists of nearly 1 472 000 continuous and 123 000 binary variables.

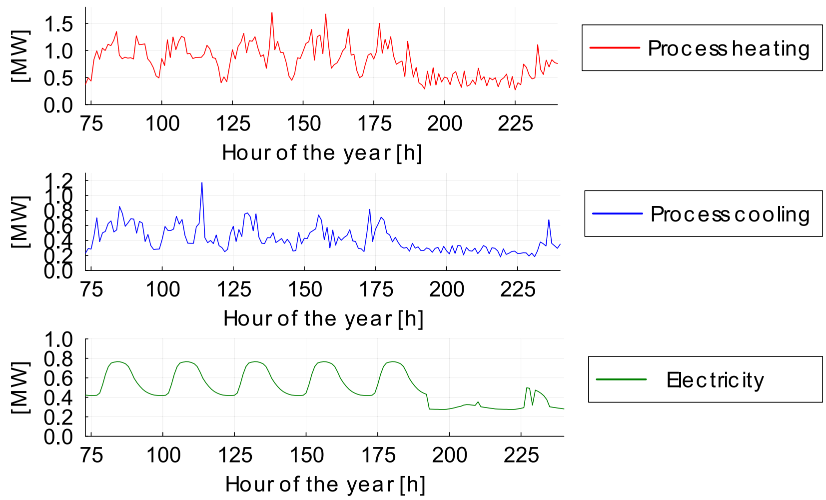
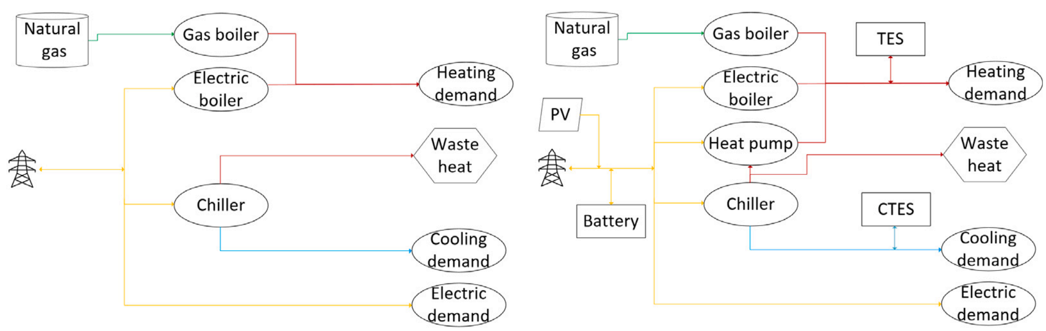


Fig. 2. Energy demand of the case dairy over the first full week.



(a) Traditional dairy (b) Integrated dairy

Fig. 3. Schematic layout of energy utilities in the case dairy.

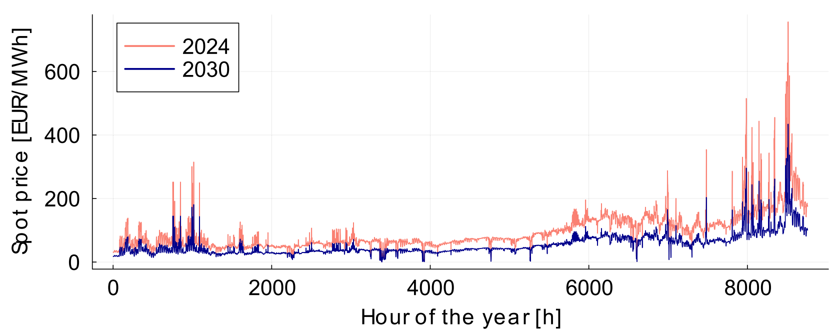


Fig. 4. Spot prices in 2024 and 2030.

4.1. Comparison of a traditional dairy with an energy integrated dairy with energy storage and PV

In Table 7, the emissions and costs when comparing the cost-optimal investment and operation of the traditional dairy including only the NGB, an EB and a chiller to an integrated dairy with heat pump, energy storage and PV. A "business as usual"-case is compared to a decarbonized case, in which no local emissions are allowed. The results show that in the business as usual case, the total costs of an integrated dairy are reduced by 24%, while total emissions are reduced by 96% compared to the traditional dairy. While energy costs are significantly reduced, the investment costs are increased due to additional investment in new energy technologies. Fig. 5 presents the change in cost-optimal capacities of the cases, and in the business as usual case, the optimization presents HP, PV, TES, and CTES as part of the energy system of the integrated dairy, reducing the capacities of NGB and CH. The capacity of the chiller is reduced by 55% due to the CTES handling the peak demands.

The most significant advantages of the integrated design appear when the cost of decarbonization is compared between the different dairy designs. When there is a constraint limiting the emissions to zero, the traditional dairy has increased cost of 12% compared to the business as usual case. The integrated dairy presents increased costs of only 0.3%, increasing the gap in total cost between the two dairy designs further. The possibility of flexible operation thus enables the integrated dairy to take advantage of the energy storages to lower energy and grid costs by shifting power demand to periods of lower prices. In addition, significant amounts of PV reduce the overall energy costs, supplying nearly 16% of the consumed electricity.

Table 6
Technology parameters.

	I_i	L_i	Other	Ref.
Electric boiler	80 000	25	η_{EB} = 99%	Danish Energy Agency [33]
Natural gas boiler	40 000	25	η_{NGB} = 93%	Danish Energy Agency [33]
Heat pump	870 000	20	COP_{HP} = 2.45 X_{HP}^{min} = 0.25	Danish Energy Agency [33], Ahrens et al. [37][a]
Chiller	240 000	20	COP_{CH} = 6.31 X_{CH}^{min} = 0.15	Vetterli and Benz [18], Ahrens et al. [37][a]
Battery	1 042 000	20	η_{BATT}^{ch} = 95.4% η_{BATT}^{disch} = 95.4% $X_{BATT}^{ch,max}$ = 2.0 $X_{BATT}^{disch,max}$ = 2.0	Danish Energy Agency [33]
TES	100 000	40	η_{TES}^{ch} = 99.0% η_{TES}^{disch} = 99.0% η_{TES}^{sd} = 0.2% $X_{TES}^{ch,max}$ = 1.7 $X_{TES}^{disch,max}$ = 1.7	Danish Energy Agency [33], Steen et al. [43]
CTES	25 000	20	η_{CTES}^{ch} = 99.0% η_{CTES}^{disch} = 99.0% η_{CTES}^{sd} = 0.1% $X_{CTES}^{ch,max}$ = 1.2 $X_{CTES}^{disch,max}$ = 1.2	Vetterli and Benz [18]
PV	870 000	35		Danish Energy Agency [33]

[a]Heat pump and chiller COP is based on a Carnot efficiency of 50%, using the chiller as waste heat source. For further details, the reader is referred to Ahrens et al. [37].

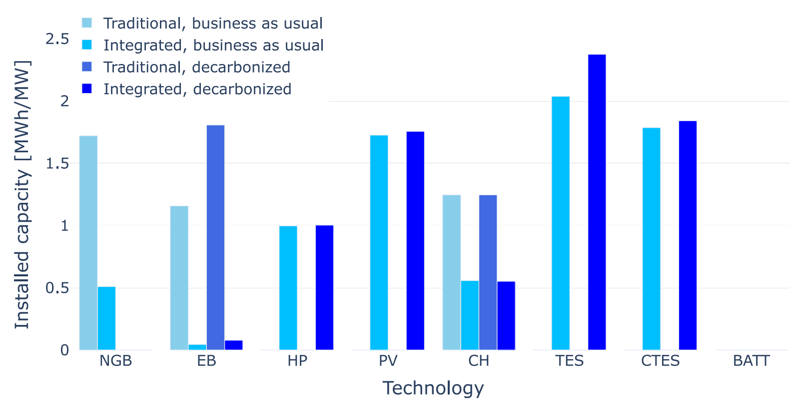


Fig. 5. Comparison of cost-optimal capacities of technologies in the traditional and integrated dairy in the business as usual and decarbonized cases.

Table 7
Emissions and total costs in cost optimal investment and operation of a traditional and an integrated dairy in a business as usual and a decarbonized case.

	Business as usual		Decarbonized	
	Traditional	Integrated	Traditional	Integrated
Total costs [MEUR]	6.94	5.29	7.81 (+12%)	5.31 (+0.3%)
Investment costs [MEUR]	0.22	1.17	0.21 (−3.4%)	1.19 (+1.5%)
Energy costs [MEUR]	4.64	2.96	5.31 (+14%)	2.96 (+0.0%)
Grid costs [MEUR]	1.55	1.14	2.29 (+48%)	1.15 (+1.4%)
Emission costs [MEUR]	0.54	0.02	0 (−100%)	0 (−100%)
Total emissions [kTon]	4.52	0.16	0 (−100%)	0 (−100%)

As seen in Fig. 5, batteries are not included in the cost optimal energy system in any of the investigated cases. This demonstrates the importance and relevance of investigating integrated thermal and electric demands when considering industrial energy systems. Towards 2050, the battery investment costs are expected to decrease from the 2020 level of 1 042 000 EUR/MWh to 255 000 EUR/MWh [33], however the estimates for battery cost development are highly uncertain. Fig. 6 presents how decreasing investment costs of batteries affect the cost-optimal capacities of energy storages and PV. Hence, batteries are at the current cost level not competitive to thermal energy storages in the investigated dairy. PV panels are presented as a part of the cost-optimal solution both in the business as usual case and the decarbonized case in Fig. 5. With high electricity prices, the possibility of reducing electricity through self-consumption of DER is economically viable. Fig. 7 presents the optimal capacities of energy storages and PV with decreasing PV costs. The optimal capacity of PV increases more or less linearly with decreasing costs, however, without affecting the optimal capacities of the energy storages. Thus, with higher installations of PV, the export to grid increases, but the ability to store the produced energy to become self-supplied by electricity does not prove cost optimality.

In Fig. 8, the operation of the energy storages and the power import, export, demand and PV generation is presented for one week. A battery could here theoretically provided the possibility of demand response to avoid peak hours, but this is here provided by the CTES and TES. However, the State of Charge (SoC) of the energy storages do not present a clear correlation to the spot prices. To a large degree the SoC is closely linked to the heating and cooling demands, and thus reduce

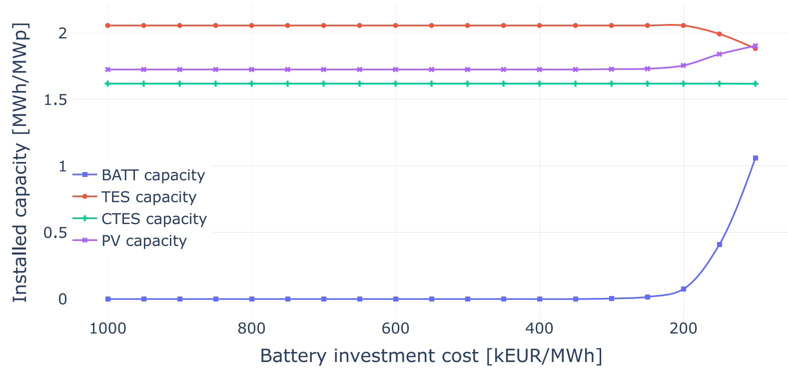


Fig. 6. Optimal capacities of energy storage and PV with decreasing battery investment costs.

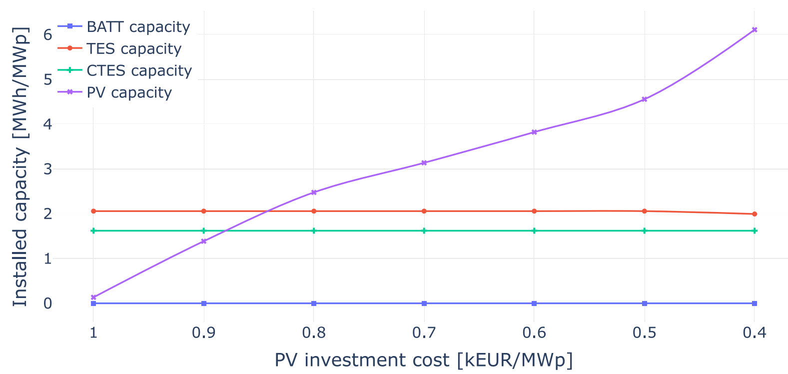


Fig. 7. Optimal capacities of energy storage and PV with decreasing PV investment costs.

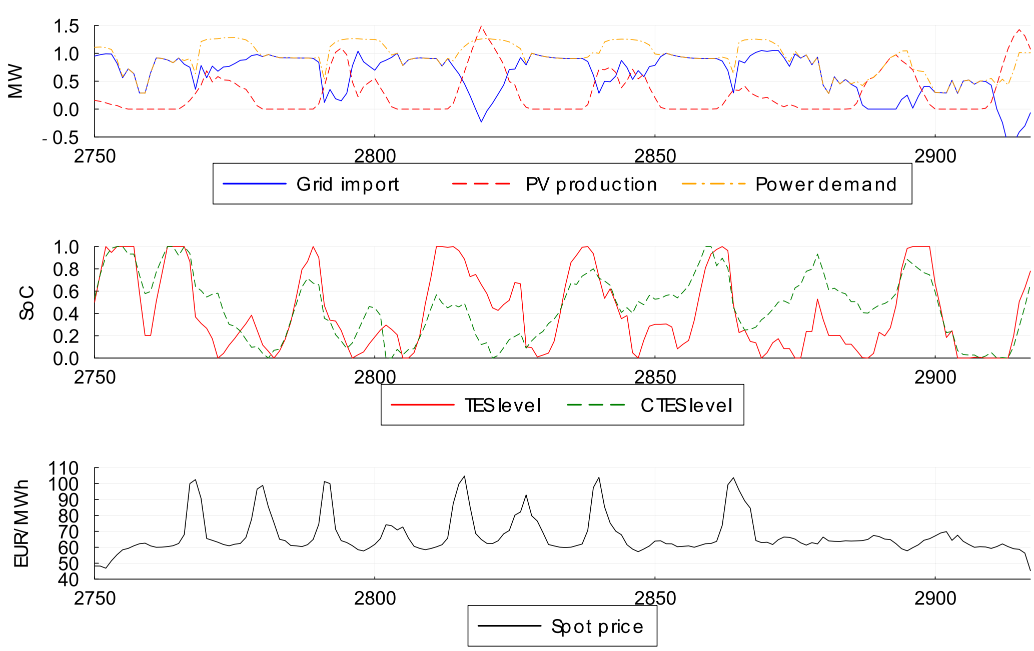


Fig. 8. Operation of energy storages.

the required installation capacity of the chiller and the heat generation technologies.

4.2. Effect of future price scenarios on optimal capacities in the integrated dairy

The scenarios presented in Section 2 are investigated for the integrated dairy to see how different developments in energy related costs would affect the results. The total cost and the cost distribution between energy, grid, emissions and investments are presented in Fig. 9. The scenarios with the highest impact on the total costs are the high and low electricity costs scenarios, where the high electricity price scenario yields over 27% higher total costs than the low electricity price scenario.

The total costs are given that the energy system is optimized for the specific scenario, which may give a significantly different system

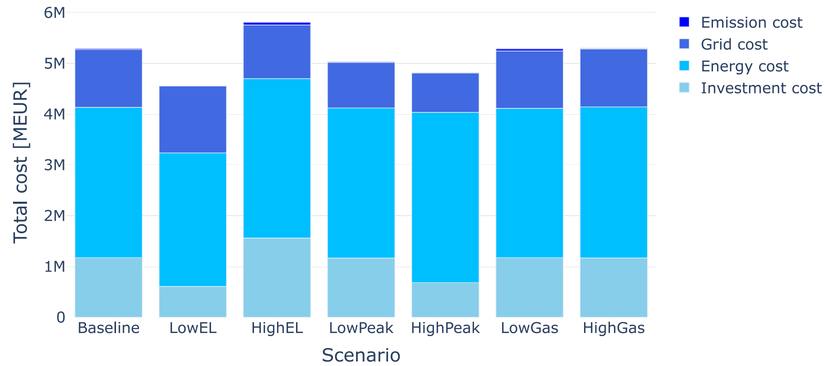


Fig. 9. Cost distribution of total cost in all scenarios.

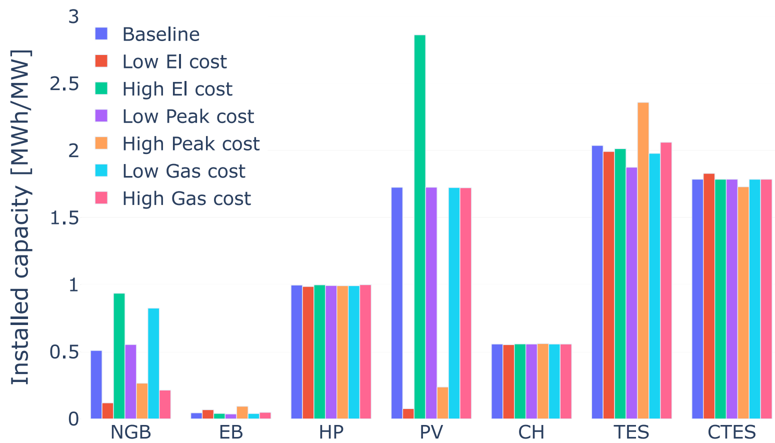


Fig. 10. Installed capacity of components in different scenarios.

design for the scenarios, as seen in Fig. 10. The optimal capacities are in general not very sensitive to the 2030 price development scenarios, with the exception of the NGB and, in particular, PV. Both are, as expected, highly sensitive to the electricity price, with a capacity increase of nearly 800% and 4000%, respectively, from the low to the high electricity price scenario. The results also show how high grid peak tariffs disfavours PV, as the highest grid import *or* export dimensions the grid tariff total cost.

It can also be seen that the investment cost is quite similar for all cases, except the low emission tax scenario, where the investment costs are halved compared to the other cases. The reason for this is the increased invested capacity in the NGB, as seen in Fig. 10, where this replaces alternative investments in EB, HP and TES. Another interesting observation is the high emission costs in the low emission tax scenario, which is 70% higher than the nearest alternative scenario. This is also reflected in the total emissions, being 643% of the baseline scenario.

In Fig. 10, the cost-optimal capacity of the energy system components are shown for the different scenarios. The figure presents NGB, EB, HP, PV and chillers in MW_{peak}, and the TES and CTES in MWh capacity. The battery is not included, as it is not part of the cost-optimal solution in any of the scenarios. Also PV and the EB are installed at quite marginal capacities in a few scenarios.

It is also interesting to see the chiller capacity, which is nearly constant for all scenarios. For the other components, the variations in optimal capacities are significant. The low emission tax scenario gives an optimal NGB capacity more than 3.5 times higher than the baseline scenario, with the optimal TES going to zero. The HP capacity is also significantly reduced in the same scenario. The HP capacity is, however, quite homogeneous in the rest of the scenarios.

The energy storages vary significantly depending on energy costs. High peak costs in the grid tariffs make larger energy storages valuable, as expected. However, the electricity prices have the opposite effect on the TES and the CTES. A low electricity price increases optimal capacity of a TES, and reduces the capacity of the CTES. On the hot side, this is due to increased use of the EB and the HP, increasing the value of utilizing low-cost hours. On the cold side, however, the capacity of the chiller is nearly constant in both scenarios.

Table 8 present the emissions and key energy numbers for all scenarios. The highest and lowest value in each column is marked in red and green, respectively. All the extremes are related to the electricity cost scenarios. The natural gas fraction of the total energy mix of the dairy is in all cases small, which explains the relatively low sensitivity of all key indicators to the gas prices, except the NGB capacity and consumption.

As seen in Table 8 and Fig. 9, gas prices affect the total emissions and natural gas consumption without affecting the total cost significantly. However, the gas price is difficult to control, and the emission tax level towards 2030 is one of the most effective ways to incentivize decreased emissions. In Fig. 11, the total emissions, costs and the optimal capacity of NGB is presented for increasing 2030 emission tax levels. The emission tax level is assumed to increase linearly from 2024 levels of 100 EUR/ton to the 2030-level. The total emissions decline rapidly with increasing levels of emission taxes, until a decrease of approx 84% for 300 EUR/ton compared to 100 EUR/ton. The total costs have an increase of approx. 0.3% in the same emission tax range. These results show that given a predictable tax increase level, it is possible to design an optimal integrated energy system in a dairy for providing process energy demands without increasing total costs significantly.

5. Discussion

This case study has investigated the effect of different input parameters such as energy cost, emission taxes, grid costs and investment

Table 8
Emissions and energy results for all scenarios.

	Total emissions [ton]	Natural gas import [MWh]	Electricity import [MWh]	Electricity generation [MWh]
Baseline	164	814	48274	9011
Low el	42	206	56948	397
High el	422	2090	43856	14857
Low peak	130	646	48331	9012
High peak	115	568	56046	1239
Low gas	325	1610	47970	9001
High gas	85	423	48447	8994

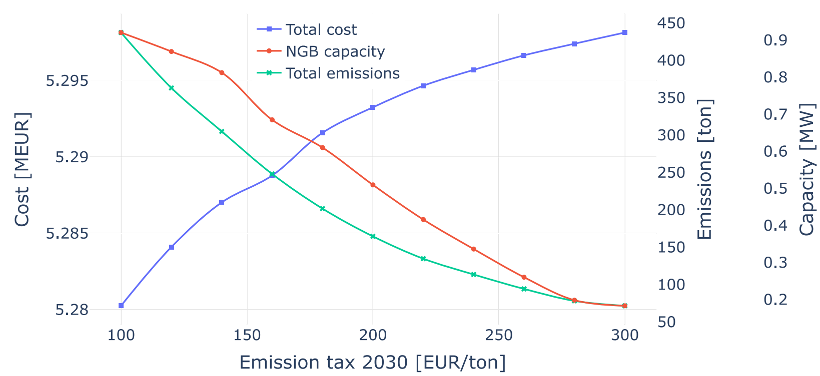


Fig. 11. Total emissions, costs and NGB capacity over increasing emission taxes.

costs to find the effect on the energy system of a dairy. The case study used a 7-year horizon towards 2030 with deterministic costs for both energy, taxes and investments as well as historic demand profiles for a dairy. The main findings indicate that there are large cost and emission savings potentials in developing an energy integrated solution, rather than a traditional dairy energy system. A holistic, energy integrated system will also be more resilient to cost increases under variations in energy prices and increasing emission caps.

5.1. Energy prices and policies

As discussed in the introduction, the effect of different policies on individual industrial energy systems have been little investigated. The results show that in order to achieve sufficient replacement of energy systems to reach climate goals, the most important measure is to incentivize integrated design of industrial energy systems. This is in practice possible through measures such as utilizing waste heat with novel heat pump technology to supply heating demands. Besides incentivizing energy system design, the energy prices and emission costs also affect the rate of decarbonization, with a particular sensitivity to the gas price and the mean electricity price. The recent disruption in energy markets in Europe have increased the pace of renewable electricity generation, which in the long term is expected to lower electricity prices. Emission taxes also prove an efficient way to decarbonize industrial energy supply, indirectly affecting the cost of utilizing fossil fuels in the energy mix.

5.2. Grid tariffs

Grid tariff design does not have a significant impact on the optimal capacity and operation of the process equipment of the study. Compared to the overall energy costs, the grid tariff is a minor contributor to total costs. However, the grid tariff design has a very significant impact on the optimal capacity of PV, which has also been identified as an issue in residential PV. As the grid needs to have capacity to handle both import and export from an area, increased DER production may lead to increased cost for the grid operator, which in the next turn must be paid by the customers. In order to enable high DER penetration in the future energy mix, the grid tariff design and grid development requirements must be handled with care, as they in certain areas may be a limitation for increased variable renewables in the electricity grid. However, the high peak scenario also shows that TES and CTES are installed at a much larger capacity than in the low peak scenario, enabling increased flexibility in the electricity demand, which is considered an important step on the way to decarbonization.

5.3. Energy system design

Heat pumps are in the results emphasized as the most important measure for decarbonization and lowering overall costs in the energy system. In all scenarios the heat pump is installed at a significant capacity, delivering most of the high temperature heating demands. These results are in line with De Boer et al. [5], pointing at heat pumps as the most important measure for delivering process heat below 200 °C. Heat pumps enable integrated heating and cooling in an industrial energy system. However, as the heating and cooling demands are not necessarily all at the same time, thermal energy storages are required to take full advantage of the waste heat potential. This is also seen in the results, where thermal energy storages on the hot and cold side are cost-effective in all scenarios. The energy storages are first and foremost used to lower the peak demand of the heating and cooling equipment, decreasing the required capacities installed. Participation in the energy markets through demand response at low and high power price periods has not been found significant, even in periods of high fluctuations in prices. The optimization model shows that the energy storages are only used on an hourly basis, and do not store significant amounts of energy between days, weeks or seasons.

5.4. Limitations and further work

The current study examines the energy system of a dairy located in western Norway using a MILP optimization model. The study is deterministic, ensuring optimal operation over the whole period, while in reality, the electricity prices are only known for a maximum of 36 h up front. In a future study, investigating how a rolling horizon would affect the results could be valuable in industrial applications. In this study, all investment costs have been considered linear. In reality, specific cost per capacity are subject to economy of scale, which is especially relevant for industry specific process equipment. Future work could investigate the impact of non-linear investment costs, and how this would affect the optimal capacity for different sizes and types of industrial plants. As an extension to the work, additional technologies could also be added to the model, which are relevant to other industrial plants and temperature levels. The study does neither take into account uncertainty of solar irradiance, which could affect the results of optimal PV capacities, and variations between years.

6. Conclusion

Integration of thermal and electric energy systems in industrial applications is expected to become increasingly important in the years to come. This study shows that it is possible to increase profitability for industries by doing so, especially when considering future emission caps which may come. Integrated design of the energy system of the dairy only shows a cost increase of 0.3% when a decarbonization is forced, in contrast to a 12% increase in cost for the traditional dairy. In particular, the energy storages of the integrated dairy are able to reduce the peak costs of the dairy by nearly 50%.

Although the total cost varies little between the investigated cost-scenarios, the specific design varies depending primarily on electric energy costs. This opens for a robust system design of the industrial energy system, able to cope with increasing emission taxes, without challenging the competitiveness of the industrial actor. Some technologies show high capacity variations under variations in scenarios. Especially when it comes to local production of electricity, the scenarios show high importance, with optimal PV capacities ranging from 0.1 MW_{peak} in the scenario with low electricity prices to 2.9 MW_{peak} in the scenario with high electricity prices.

This study also shows that integration of thermal and electric energy systems may eliminate the need for electric energy storage in industrial energy systems in these temperature ranges. Thermal energy storage shows a much larger potential in providing the required flexibility at a low cost. Battery costs must decrease below 200 000 EUR/MWh before they become relevant in replacing parts of the thermal energy storages. Thermal energy storage becomes increasingly important with the grid tariffs turning to higher peak pricing, driven by electrification of high power applications.

Electrification of industrial energy systems is expected to increase in the near future. This study has lifted the importance of investigating the *integration* of thermal and electrical technologies in industrial energy system to obtain the cost-optimal solution, however, the uncertainty of future electricity prices make precise design of cost-optimal energy systems challenging.

CRediT authorship contribution statement

Sverre Stefanussen Foslie: Conceptualization, Methodology, Software, Investigation, Writing – original draft, Visualization. **Brage Rugstad Knudsen:** Conceptualization, Investigation, Writing – review & editing. **Magnus Korpås:** Supervision, Conceptualization, 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.

Data availability

The authors do not have permission to share data.

Acknowledgements

This work has been funded by the Norwegian Research Council under grant number 323330, and partly by HighEFF - Centre for an Energy Efficient and Competitive Industry for the Future under the FME-scheme (Centre for Environment-friendly Energy Research, 257632). The authors would like to thank TINE for sharing data from the dairy.

References

[1] European Commission. 2030 Climate Target Plan. 2021, URL https://ec.europa.eu/clima/eu-action/european-green-deal/2030-climate-target-plan_en.
[2] Norwegian Ministry of Climate and Environment. Klimaendringer og norsk klimapolitikk. 2021, URL https://www.regjeringen.no/no/tema/klima-og-miljo/innsiktsartikler-klima-miljo/klimaendringer-og-norsk-klimapolitikk/id2636812/.
[3] International Energy Agency. Net Zero by 2050: A Roadmap for the global energy sector. Technical Report, International Energy Agency; 2021.
[4] Thiel GP, Stark AK. To decarbonize industry, we must decarbonize heat. Joule 2021;5(3):531–50. http://dx.doi.org/10.1016/j.joule.2020.12.007.
[5] De Boer R, Marina A, Zühlsdorf B, Arpagaus C, Bantle M, Wilk V, Elmegaard B, Corberan J, Benson J. Strengthening Industrial Heat Pump Innovation: Decarbonizing Industrial Heat. 2020.
[6] International Energy Agency. World energy outlook 2021. Technical Report, International Energy Agency; 2021.
[7] Bühler FM, Holm F, Elmegaard B, Bühler F, Holm FM. Potentials for the electrification of industrial processes in Denmark. In: Proceedings of ECOS 2019: 32nd International conference on efficiency, cost, optimization, simulation and environmental impact of energy systems. POLAND; 2019, p. 2137–52.
[8] Wei M, McMillan CA, de la Rue du Can S. Electrification of Industry: Potential, Challenges and Outlook. Curr Sustain Renew Energy Rep 2019;6(4):140–8. http://dx.doi.org/10.1007/s40518-019-00136-1.
[9] Kirkerud JG, Trømborg E, Bolkesjø TF. Impacts of electricity grid tariffs on flexible use of electricity to heat generation. Energy 2016;115:1679–87. http://dx.doi.org/10.1016/j.energy.2016.06.147.
[10] Rehfeldt M, Fleiter T, Toro F. A bottom-up estimation of the heating and cooling demand in European industry. Energy Efficiency 2018;11(5):1057–82. http://dx.doi.org/10.1007/s12053-017-9571-y.
[11] Atuonwu J, Tassou S. Decarbonisation of food manufacturing by the electrification of heat: A review of developments, technology options and future directions. Trends Food Sci Technol 2021;107:168–82. http://dx.doi.org/10.1016/j.tifs.2020.10.011.
[12] Zühlsdorf B, Bühler F, Bantle M, Elmegaard B. Analysis of technologies and potentials for heat pump-based process heat supply above 150 °C. Energy Convers Manag: X 2019;2(May):100011. http://dx.doi.org/10.1016/j.ecmx.2019.100011.
[13] Bühler F, Nguyen TV, Jensen JK, Holm FM, Elmegaard B. Energy, exergy and advanced exergy analysis of a milk processing factory. Energy 2018;162:576–92. http://dx.doi.org/10.1016/j.energy.2018.08.029.
[14] Miró L, Gasia J, Cabeza LF. Thermal energy storage (TES) for industrial waste heat (IWH) recovery: A review. Appl Energy 2016;179:284–301. http://dx.doi.org/10.1016/j.apenergy.2016.06.147.
[15] Bühler F, Zühlsdorf B, Nguyen T-V, Elmegaard B. A comparative assessment of electrification strategies for industrial sites: Case of milk powder production. Appl Energy 2019;250:1383–401. http://dx.doi.org/10.1016/j.apenergy.2019.05.071.
[16] Beck A, Sevault A, Drexler-Schmid G, Schöny M, Kauko H. Optimal selection of thermal energy storage technology for fossil-free steam production in the processing industry. Appl Sci (Switzerland) 2021;11(3):1–23. http://dx.doi.org/10.3390/app11031063.
[17] Philipp M, Schumm G, Peesel RH, Walmsley TG, Atkins MJ, Schlosser F, Hesselbach J. Optimal energy supply structures for industrial food processing sites in different countries considering energy transitions. Energy 2018;146:112–23. http://dx.doi.org/10.1016/J.ENERGY.2017.05.062.
[18] Vetterli J, Benz M. Cost-optimal design of an ice-storage cooling system using mixed-integer linear programming techniques under various electricity tariff schemes. Energy Build 2012;49:226–34. http://dx.doi.org/10.1016/j.enbuild.2012.02.012.
[19] Favre-Perrod P. A vision of future energy networks. In: Proceedings of the inaugural IEEE PES 2005 Conference and exposition in Africa, vol. 2005. IEEE; 2005, p. 13–7. http://dx.doi.org/10.1109/PESAFR.2005.1611778, URL http://ieeexplore.ieee.org/document/1611778/.
[20] Geidl M. Integrated modeling and optimization of multi-carrier energy systems (Ph.D. thesis), ETH Zürich; 2007, http://dx.doi.org/10.3929/ethz-a-005377890.
[21] Mohammadi M, Noorollahi Y, Mohammadi-ivatloo B, Yousefi H. Energy hub: From a model to a concept – A review. Renew Sustain Energy Rev 2017;80:1512–27. http://dx.doi.org/10.1016/j.rser.2017.07.030, URL https://linkinghub.elsevier.com/retrieve/pii/S1364032117310985.

[22] Mahmoudan A, Esmaeilion F, Hoseinzadeh S, Soltani M, Ahmadi P, Rosen M. A geothermal and solar-based multigeneration system integrated with a TEG unit: Development, 3E analyses, and multi-objective optimization. Appl Energy 2022;308:118399. http://dx.doi.org/10.1016/J.APENERGY.2021.118399.

[23] Mohammadi M, Noorollahi Y, Mohammadi-ivatloo B, Hosseinzadeh M, Yousefi H, Khorasani ST. Optimal management of energy hubs and smart energy hubs – A review. Renew Sustain Energy Rev 2018;89:33–50. http://dx.doi.org/10.1016/j.rser.2018.02.035.

[24] Halmschlager V, Hofmann R. Assessing the potential of combined production and energy management in Industrial Energy Hubs – Analysis of a chipboard production plant. Energy 2021;226:120415. http://dx.doi.org/10.1016/J.ENERGY.2021.120415.

[25] Taqvi S, Almansoori A, Elkamel A. Optimal renewable energy integration into the process industry using multi-energy hub approach with economic and environmental considerations: Refinery-wide case study. Comput Chem Eng 2021;151:107345. http://dx.doi.org/10.1016/J.COMPCHEMENG.2021.107345.

[26] Sandberg E, Kirkerud JG, Trømborg E, Bolkesjø TF. Energy system impacts of grid tariff structures for flexible power-to-district heat. Energy 2019;168:772–81. http://dx.doi.org/10.1016/j.energy.2018.11.035.

[27] Johannsen RM, Arberg E, Sorknæs P. Incentivising flexible power-to-heat operation in district heating by redesigning electricity grid tariffs. Smart Energy 2021;2:100013. http://dx.doi.org/10.1016/J.SEGY.2021.100013.

[28] Backe S, Kara G, Tomasgard A. Comparing individual and coordinated demand response with dynamic and static power grid tariffs. Energy 2020;201:117619. http://dx.doi.org/10.1016/J.ENERGY.2020.117619.

[29] Skytte K, Bergaentzle C, Soysal ER, Olsen OJ. Design of grid tariffs in electricity systems with variable renewable energy and power to heat. Int Conf Eur Energy Market, EEM 2017. http://dx.doi.org/10.1109/EEM.2017.7981940.

[30] Lin B, Jia Z. The energy, environmental and economic impacts of carbon tax rate and taxation industry: A CGE based study in China. Energy 2018;159:558–68. http://dx.doi.org/10.1016/J.ENERGY.2018.06.167.

[31] Wang X, Li JF, Zhang YX. An analysis on the short-term sectoral competitiveness impact of carbon tax in China. Energy Policy 2011;39(7):4144–52. http://dx.doi.org/10.1016/J.ENPOL.2011.04.020.

[32] Korpås M. Distributed energy systems with wind power and energy storage (Ph.D. thesis), Norwegian University of Science and Technology; 2004.

[33] Danish Energy Agency. Technology Data. 2022, URL https://ens.dk/en/our-services/projections-and-models/technology-data.

[34] Yu FW, Chan KT. Part load performance of air-cooled centrifugal chillers with variable speed condenser fan control. Build Environ 2007;42(11):3816–29. http://dx.doi.org/10.1016/J.BUILDENV.2006.11.029.

[35] Askeland M, Backe S, Bjarghov S, Korpås M. Helping end-users help each other: Coordinating development and operation of distributed resources through local power markets and grid tariffs. Energy Econ 2021;94:105065. http://dx.doi.org/10.1016/j.eneco.2020.105065, URL https://linkinghub.elsevier.com/retrieve/pii/S0140988320304059.

[36] Pfenninger S, Staffell I. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. Energy 2016;114:1251–65. http://dx.doi.org/10.1016/J.ENERGY.2016.08.060.

[37] Ahrens MU, Foslie SS, Moen OM, Bantle M, Eikevik TM. Integrated high temperature heat pumps and thermal storage tanks for combined heating and cooling in the industry. Appl Therm Eng 2021;189:116731. http://dx.doi.org/10.1016/j.applthermaleng.2021.116731.

[38] Lindberg KB, Bakker SJ, Sartori I. Modelling electric and heat load profiles of non-residential buildings for use in long-term aggregate load forecasts. Utilities Policy 2019;58:63–88. http://dx.doi.org/10.1016/J.JUP.2019.03.004.

[39] Statnett. Short-term market analysis 2022–2027. 2022, URL https://www.statnett.no/for-aktorer-i-kraftbransjen/planer-og-analyser/kortsiktig-markedsanalyse/.

[40] Birkelund H, Arnesen F, Hole J, Spilde D, Jelsness S, Aulie FH, Haukeli IE. Langsiktig kraftmarkedsanalyse 2021–2040. Technical Report, NVE; 2021, URL www.nve.no.

[41] Nett B. Nettleie for bedriftskunder. 2022, URL https://nett.bkk.no/produktdetaljer?productId=9af3a3e7-9813-489f-9eb4-4fbcb29dd768&divisionName=Nett&productTab=1.

[42] Norwegian Ministry of Climate and Environment. Norway's comprehensive climate action plan. 2021, URL https://www.regjeringen.no/en/historical-archive/solbergs-government/Ministries/kld/news/2021/heilskapeleg-plan-for-a-na-klimamalet/id2827600/.

[43] Steen D, Stadler M, Cardoso G, Groissböck M, DeForest N, Marnay C. Modeling of thermal storage systems in MILP distributed energy resource models. Appl Energy 2015;137:782–92. http://dx.doi.org/10.1016/J.APENERGY.2014.07.036.

[44] Dunning I, Huchette J, Lubin M. JuMP: A Modeling Language for Mathematical Optimization. SIAM Rev 2017;59(2):295–320. http://dx.doi.org/10.1137/15M1020575.

[45] Gurobi Optimization. Gurobi Optimizer Reference Manual. 2023, URL www.gurobi.com.