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Studies on the conceptual design of energy recovery and utility systems for electrified chemical processes

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ABSTRACT

Industrial energy systems under electrified heating were examined to understand the techno-economic impact of electrification on the supply of heat at the process level and the management of heat and power at the site level. Two case studies for chemical production were conducted to discuss the possible designs of electrified heat supply for processing industries and to compare the characteristics of heat recovery networks and utility systems under electrification with those under conventional fossil-fuel energy systems. The application of the heat-integrated design method is effective in providing design strategies for the transformation to electrified energy systems, as well as in evaluating plant-wide implications of electrification in practice. The design interaction between heat recovery and electrification was also investigated, and the cost-effectiveness of electrified energy systems was found to be highly influenced by heat recovery. The current study demonstrated that industrial electrification can be a practical alternative for industrial energy supply and that electrified heating can be economical with a low-cost and renewable source of electricity.

1. Introduction

Electrification is one of the main pathways by which net-zero CO_2 emissions can be achieved by 2050, as it can contribute to an approximately 20% reduction in total CO_2 emissions [1]. Rapid increase in the use of wind- and solar-based clean or low-emission electricity is predicted to contribute 75–90% of electricity provision by 2050 [2]. In particular, the direct use of low-carbon electricity is very important because the largest increase in electricity demand and provision in industries is expected to occur between 2020 and 2050 [1]. As most electricity demand is related to process heating, considerable attention has been paid to the development and implementation of power-to-heat technologies in process industries.

The use of electricity for industrial heating is regarded as an effective strategy for a significant reduction in CO_2 emissions [3]. Usually, electricity or other heating sources, such as waste heat, integrated with electrified process heating, are employed. Several studies have acknowledged the benefits of electrified heating in process industries or have evaluated industry-wide potentials or impacts through industrial electrification in the future. Thiel and Stark [4] estimated a 20% reduction in global CO_2 emissions from the decarbonization of heat in industry and emphasized on R&D for low-carbon heating and electrification with better energy management. The impact of electrification was investigated for specific industrial sectors, such as boiler-operating industries and [5], the chemical industry [6], refining industry [7], basic-materials industry [8], and food industries [9], or for particular geographic regions, such as Germany [10], Europe [11], and the U.S [12].

Although a wide range of power-to-heat technologies is available, industrial practices still rely on the heat supplied through fossil fuel combustion. The major barrier to the implementation of electrified heating in process industries is the higher capital investment and operating costs associated with electrification technologies compared with conventional combustion-based technologies [13]. However, renewable electricity is emerging as a realistic and cost-effective alternative.

From a recent report by International Energy Agency (IEA) [14], the global capacity of renewable electricity generation in 2026 is expected to be 4800 GW, which is a 60% increase compared to 2020; the generation capacity of wind and solar energies is predicted to be larger than those of coal and gas energies by 2023 and 2024, respectively. This accelerated growth in renewable electricity is expected to continue owing to the strong policies and initiatives stemming from climate actions. The cost of renewable electricity has rapidly declined over the last decade, e.g., 70, 89, 56, and 85% decrease in costs has been observed for onshore wind electricity, solar electricity [15], onshore wind electricity, and solar photovoltaic electricity [16], respectively. Approximately 71%

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Abbreviations

BFW	Boiler feed water
CHP	Combined heat and power
COP	Coefficient of performance
CW	Cooling water
DME	Dimethyl ether
e	Electric or electrified
HP	High pressure or Heat pumping
GCC	Grand composite curve
LP	Low pressure
MER	Maximum energy recovery
MP	Medium pressure
ORC	Organic Rankine cycle
TRL	Technology readiness level
ΔT_{min}	Minimum temperature approach

Nomenclature

A	Heat exchanger area [m^2]
C_{HX}	Heat exchanger cost [$]
P_p	Power [kW]
P_s	Steam flowrate [$kg\bullet hr^{-1}$]
Q	Heat utilized for ORC [kW]
T_{CR}	Critical temperature of the working fluid [^oC]
W	Electricity generation [kW]

of power generation projects based on solar and wind sources have been reported to produce cheaper electricity in terms of operating costs compared with existing coal-fired power generation [16], clearly highlighting the competitiveness of renewable electricity over fossil-fuel-based electricity.

It should be noted that full electrification based on zero-carbon electricity should not be seen as a short-term solution achievable in the foreseeable future, because approximately 40% of CO_2 emissions related to global energy production still originates from fossil fuels [17], and the contribution of renewables to power generation in 2019 was only 23.2% [18]. Although the deployment of renewables has gained policy momentum and the growth of renewable electricity capacity is being accelerated, considerable uncertainties in the energy market, as well as technical barriers, must be addressed [14].

In association with the strong momentum observed in the expansion of renewable capacity and the sharp reduction in renewable electricity costs, research and development of electrification technologies have been conducted in industrial sectors. Technologies in electrified heating, such as electric heaters [19] and electrode boilers [20], operating at low or medium temperatures are commercially available, while, for many applications, electrified heating at high temperatures is not available [13]. As process heating is highly application-specific and process-dependent by nature, efforts for technical improvements in industrial electrification technologies have been conducted using industry-targeted R&D activities, such as electrified steam cracking in a refinery [21] and electrification of the calcination process for a cement kiln system [22].

Despite the efforts exerted in the development of electrification technologies, process integration has not been given due consideration. A high degree of process integration is required for the implementation of electrification technologies because a large number of unit operations are interconnected for production; hence, various types of energy supply with different quantities are considered. This heterogeneity and diversity in process heating make it difficult to determine the optimal placement of electrification technologies. However, most decision-making tools or methods used for applying electrification technologies to industries are related to the very high-level evaluation of industry-wide or region-wide potentials or opportunities for electrification, such as the Europe-wide potential of CO_2 reduction from the electrification of power-to-heat [11] or the industry-wide economic or environmental gains expected from specific electrified equipment or technology, such as the investigation of the electrified incumbent kiln and furnace technologies for cement, glass, lime, and steel plants operations [23].

Process design studies conducted at the process level have attempted to redesign this process using an electrified feed or energy. The use of hydrogen generated from electrolysis and the supply of electricity for process heating are considered for the production of ammonia [24], whereas electricity-assisted heating using heat pumps and CO_2 hydrogenation using hydrogen from electrolysis are designed for methanol production [25]. In both cases, the techno-economic impact of electrification was assessed by comparing it with conventional production. These studies provide meaningful insights for future electricity-driven processes to evolve from current processing under electrified industrial environments, although a case-specific decision for the introduction of electrification technologies was made. Wiertzema et al. [26] proposed an assessment procedure for the evaluation of electrification options and applied it to an oxo synthesis plant, in which a pinch analysis was utilized to compare the heating requirements between the conventional and electrified processes. Although energy recovery through the pinch analysis was discussed, their work did not fully provide systematic strategies for the selection of electrification options and supported the design of site-wide utility management under electrified processing. Overall, little attention has been paid to the development of process design methods that are sufficiently generic for applications in a wide range of industrial manufacturing processes.

To design electrified utility systems at the site level, Kim [27] conducted a case study for a refinery consisting of several processes. The use of an electricity header, with which electricity supply and generation from individual processes interact, is proposed to support site-wide electricity distribution. Only the process design framework for site-wide electrified utility systems was proposed, and an investigation was not fully conducted on how a heat recovery system at the process level was integrated with electrified utility management. On the other hand, the impact of electrification on the process-level heat recovery was assessed, in which the design of the heat recovery network under electrification was evaluated with the network being under conventional-fossil energy supply [28]. This study was based on simple and theoretical working examples, without being linked to the process.

Previous studies related to integrating electrified heating into the process mainly focused on a single-point replacement of conventional units with the electrified ones. When electrified heating is considered, investigations have been rather limited to the equipment level, without fully considering site-wide changes in the generation, distribution, and utilization of heat and power. Therefore, this study aimed to develop a generic process design method that not only enables the implementation of electrified heating at the process level for conventional non-electrified processes but also allowed for the systematic integration of process-level electrification with site-level electrified utility management holistically. In addition, the case study conducted in this work investigated the simultaneous introduction of electrified heating options, which highlights the importance of a plant-wide integrated approach for screening different electrified heating options as well as determining the most appropriate schemes for electrification in process industries.

With two chemical processes involving a series of reactors and separators, we aimed to illustrate how process-dependent characteristics can be considered for transiting to electrified processes, as most previous studies have not fully considered the design interactions between process-level electrification and site-wide energy management. The heat integration methodology was used to systematically capture the process-wide characteristics of energy requirements as well as to provide the most appropriate selection of electrified heating options. Furthermore, the benefit of heat integration was exploited to maximize plant-wide heat recovery under electrification, thereby further supporting the industrial uptake of electrified heating.

Overall, this study aimed to develop a heat integration method under electrification that can be applied to the design of industrial energy systems under electrified heating and its supply. It was also intended to demonstrate the applicability of the design method developed in this study to broader fields of process industries when industrial electrification with the integration of renewable electricity is considered. First, a discussion on the applicability of electrified heating to process industries is provided, together with the methodological background for the integrated process design required for the implementation of electrified equipment. Two case studies representing typical chemical plants are introduced, in which the heat integration method is used to design process-level electrified energy recovery and site-level utility systems. An economic analysis was conducted to evaluate the economic feasibility of renewable electrification for process industries. Through case studies, the techno-economic impact of electrified heating on site-wide heat and power management is discussed to improve conceptual understanding and provide design strategies for the integration of electrification in practice.

2. Electrified heating for process industries

A wide range of electric heating techniques using electromagnetic fields or electric currents is available in process industries, as shown in Table 1, and can be used for process heating over a wide range of temperatures. Electricity-based heating offers ease of process operation and control with high energy efficiency compared with thermal heating, because electricity, being a heating medium, has many degrees of freedom for manipulating process variables and regulating heat transfer and allows very fast start-up and shutdown [29]. The benefit of using electricity for process heating is high resiliency and adaptiveness for non-steady and time-dependent operations, as combustion-based heating is not inherently flexible enough to follow the change in working loads [30]. Very high energy efficiency can be achieved by electrified heating because the supply of electrified heat can be conducted in a more uniformly distributed manner, and its processing times for heat exchange are much shorter than those for thermal heating [9].

In addition to the power-to-heat technologies listed in Table 1, heat pumping is an additional alternative that process industries can generate high-temperature streams using electricity-based vapor recompression. The industrial-scale system implementation of electric heaters and electrode boilers is currently available for process industries, for which the technology readiness level (TRL) is regarded as 9 [19]. However, other electrification technologies, such as infrared heaters (TRL 7–8), electric ceramic kilns (TRL 5–6), and microwave heaters (TRL 4–5) require further research and development for demonstration and commercialization [19].

Table 1
Electrified heating options for process industries.

Type		Working temperature
Direct heating	Inductive heating	100–2500 °C[a];
	Microwave	100–1300 °C[a];
Indirect heating	Resistance heating	200–1800 °C[a]
	Electric arc	1200–3000 °C[a];
	Infrared heating	300–2600 °C[a]
	Plasma heating	1600 °C[b]; 2000 °C[c]
Steam generation	Electrode boiler	100–350 °C

[a] Reference: [21].
[b] Application for waste treatment [31].
[c] Application for metal processing [32].

The most appropriate placement of electrified heating can be systematically determined using the heat integration methodology, as shown in Fig. 1. Conventional process heating based on fossil fuels is typically performed by direct heating from furnaces or by indirect heating using steam. The high-grade steam generated from boilers or hot process streams is utilized to produce power, and low-grade steam is then used for process heating at a lower temperature, as shown in Fig. 1 (a). This Combined Heat and Power (CHP), or cogeneration is, generally fully exploited to provide the power required within a plant. Steam generation is also subject to the available waste heat and its quality. Grand composite curves (GCCs) have been widely used over the last few decades as a practical way to select utilities as well as for cost-effective allocation among available utilities [33]. The use of GCCs provides the overall characteristics of energy requirement at the plant level and can be used to determine the most appropriate strategy for electrified heating, as illustrated in Fig. 1(a).

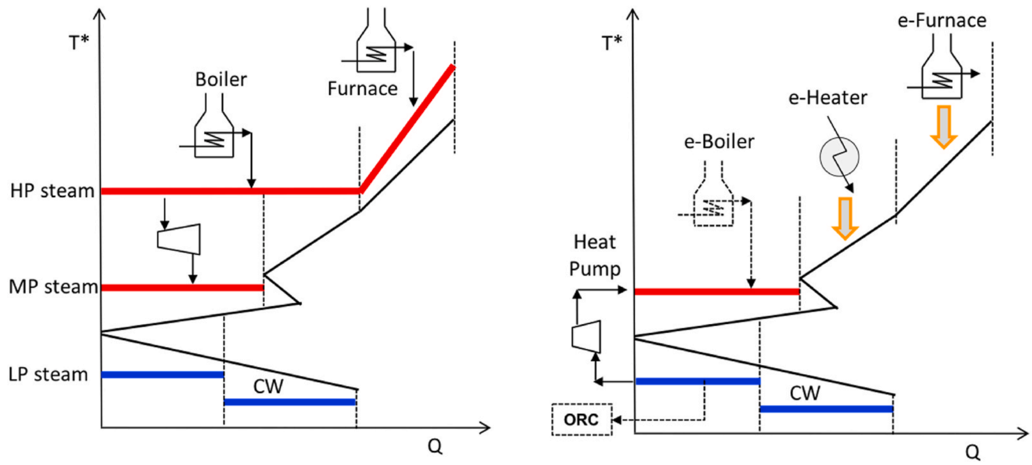
An author's research group studied the impact of power-to-heat technologies on heat recovery systems, in which GCCs were used for the placement of electrified heating for industrial energy systems [28]. Fig. 1(b) shows a possible arrangement for electrified heating. The use of electric furnaces can be considered for providing heat at relatively high temperatures. An electrode boiler or electric heater can be used in the temperature range in which steam is typically provided. The implementation of an electric heater can prevent steam from being used by the plant. However, the use of electrode boilers can be considered when the process requires steam, such as a heating carrier requiring steam for its reactor feed or a stripping agent. When the level of waste heat is much higher than that in the atmosphere, power can be generated through the organic Rankine cycle (ORC). Heat pumping can also be considered when the temperature gap between the heat source and heat sink stream is not considerably large.

Site-wide energy systems can be designed based on the heating duty of utilities and their types used at the process level. When an industrial site or complex consists of multiple units or processes, a centralized utility system in a non-electrified environment is operated to produce steam and distribute steam to individual plants, as shown in Fig. 2(a). The cogeneration illustrated in Fig. 1(a) was performed in a centralized utility system, which often results in complex turbine networks. The site-wide energy infrastructure becomes very different from the conventional infrastructure when all process-level heating is electrified. Electricity is the main energy carrier for electrified site-level energy systems, as electricity interacts with processes and renewable electricity sources, as schematically illustrated in Fig. 2(b). The design procedures for configuring electrified energy systems have been addressed in Kim [27]. As discussed in the previous section, design methodologies between site utility systems and electrified heating at the process level have not been fully coupled. This discussion will be further developed in the two case studies presented in the next two sections. In addition, the dependency of electrified heating on the design of industrial energy systems is addressed in detail in the case studies.

3. Case study 1

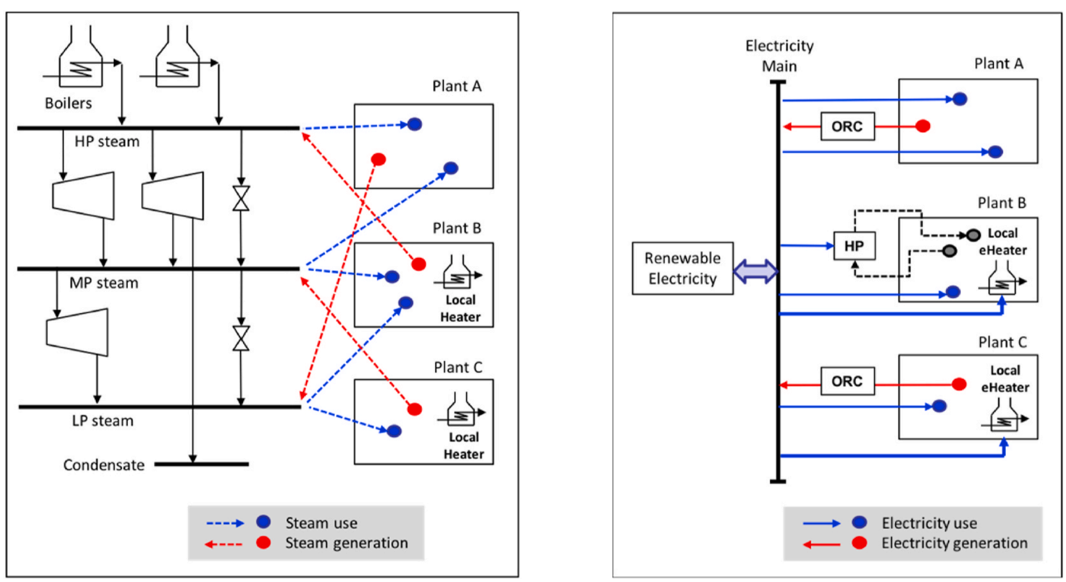
The production of methyl acetate via carbonylation of dimethyl ether was considered, and the process was designed and presented by Lyuben [34]. The process consists of two subsections. The first process involves the production of dimethyl ether through the dehydration of methanol, whereas the second involves the production of methyl acetate by the reaction between carbon monoxide and dimethyl ether. The process diagrams for these two subsections are presented schematically in Fig. 3. Among the three reactor configurations, the dehydration unit based on a cooled reactor was selected for the current study, as this was regarded as the most economical configuration.

This case study is based on the mass and energy balances obtainable from Lyuben [34]. The steam duty of the units associated with process



(a) Conventional systems (b) Electrified systems

Fig. 1. Electrification for process-level energy systems.



(a) Conventional systems (b) Electrified systems

Fig. 2. Electrification for site-level utility systems.

heating and waste heat recovery is shown in Fig. 3. For the design of utility systems, three levels of steam conditions are considered: high-pressure (HP)steam (42 atm, 655 K), medium-pressure (MP) steam (11 atm, 457 K), and low-pressure (LP) steam (6 atm, 433 K). HP and LP steam are generated from reactors, and MP and LP steam are consumed by vaporizers and reboilers.

Two levels of electrification were considered in this scenario. The semi-electrified scenario considers a relatively straightforward option for electrified heating, whereby it replaces the conventional exchanger with an electric heater. The use of electric heaters for the three reboilers and two vaporizers could be readily implemented owing to the high TRL of electric heaters. The semi-electrified dehydration and carbonylation scenarios are schematically illustrated in Fig. 4.

The fully electrified scenario considers a complicated option that requires configurational changes in the unit operations or a flowsheet. The first option for full electrification is to introduce a heat pump that provides the heat required for the process at the expense of the power. The second option is to integrate the ORC with the heat available from the two reactors, in which heat used for steam production in the base scenario is used as the energy source for electricity generation.

The use of heat pumping was only considered between the heating sources and sinks within each subsection; a heat pump across the subsection was not considered. For the dehydration subsection, there are three heating source candidates, namely, the two reboilers of Columns 1 and 2 and Reactor 1, and two cooling sink candidates, namely, the two condensers of Columns 1 and 2. The temperatures of the stream considered for heat pumping are shown in Fig. 5. Because a large temperature difference between the source and sink is not energy-efficient for heat pumping, only temperature differences up to 70 °C from heat pumping were considered. With this method, heat pumping from the condensing stream of Column 1 to the reboiling stream of Column 1 was selected, as the temperature difference between the top and bottom product streams was 62 °C. For the carbonylation process, a heat pump was not introduced because of the large temperature difference between the sources and sinks. The power required to operate the heat pump is characterized by the coefficient of performance (COP), and a COP of 2.8

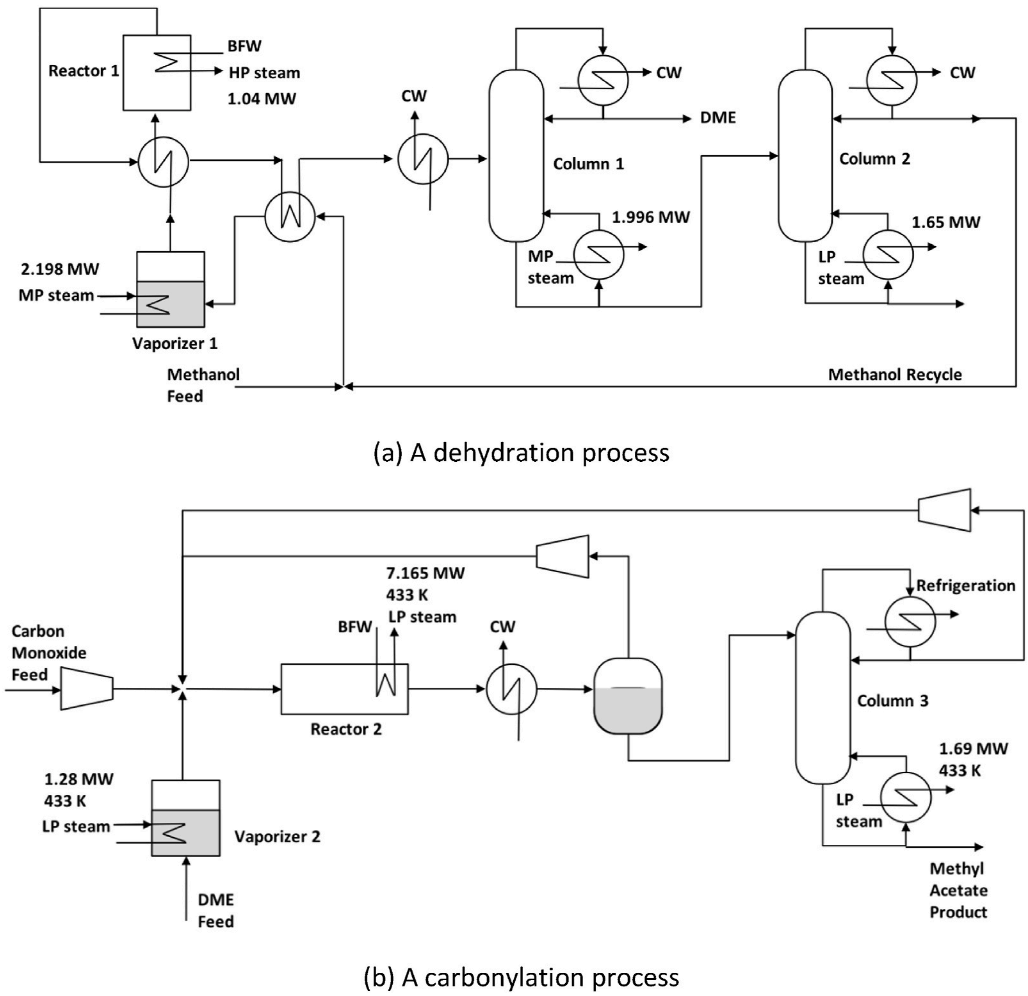


Fig. 3. Flow diagrams for a methyl acetate process.

at a heat pumping temperature of 62 °C was derived from performance data on heat pump systems obtained from Ref. [35].

A plant-wide utility system was designed for a methyl acetate process in which different levels of steam are consumed or generated. A utility system was constructed to generate, distribute, and utilize steam, and was serviced for the three cases considered in this section, as shown in Fig. 6. An industrial site, such as a refining plant or a petrochemical complex, typically consists of several plants, and the utility system is designed and operated for site-wide supply of heat and power to several plants. As the case study includes only two sub-processes, the configurations presented in Fig. 6 cover some aspects of the utility systems utilized in process industries. Although utility systems designed for the methyl acetate process are relatively small in capacity and less complex, the impact of electrification on site-wide heat and energy management can be clearly illustrated, and the differences in the configuration and operating characteristics of utility systems can be distinctively acknowledged.

The utility systems in this case study were designed using a boiler for steam generation, steam turbines for power generation, and three steam mains for steam distribution. Multiple units are not considered for the boiler, and only one steam turbine is used for the expansion of steam between steam mains. Steam balances were calculated using a commercial simulator UNISIM®, subject to the design basis and assumptions given in Table 2. Energy losses related to steam and electricity distribution were not considered, and no pressure drop assumptions were made for the steam flows. Auxiliary systems related to deaeration, boiler feedwater (BFW) treatment, and condensate recovery were not considered, and, for the sake of simplicity, their mass and energy balances were not regarded during the design of utility systems. It was assumed that a power of 2 MW is required for the process, although this is another degree of freedom to be further exploited in the context of combined heat and power (CHP).

For the conventional utility system of a non-electrified process, the minimum steam flow rate of 14.7 t/h to be produced from the boiler was chosen, which satisfied the amount of power required and allows feasible steam balances, as shown in Fig. 6(a). The steam generated from the boiler and the process heat recovery were sequentially expanded through steam turbines from the upper steam main to the lower steam main. The steam flow rates through the turbine were 16.4 t/h of HP, 3.5 t/h of MP, and 6.2 t/h of LP steam, which generated 1.1 MW, 93 kW, and 0.79 MW, respectively.

For the semi-electrified and full-electrified scenarios, the amount of steam generated from the boiler and the flow rates of steam to be passed through turbines are adjusted to accommodate the updated steam balances, as shown in Fig. 6 (b and c). As 1.4 t/h of HP steam and 10.7 t/h of LP steam were self-generated from the process and no steam processing is required, steam generation from the boiler was not required for the semi-electrified scenario. Increases in the electricity required for electrified heating and heat pumping resulted in 12.2 MW and 11.24 MW of power import required for the semi- and full-electrified scenario, respectively, and the amount of power imported was balanced between demand and on-site generation. The use of steam and its utilization cannot be avoided in the semi-electrified scenario, whereas electricity can be used as a single energy carrier under full electrification. A step-

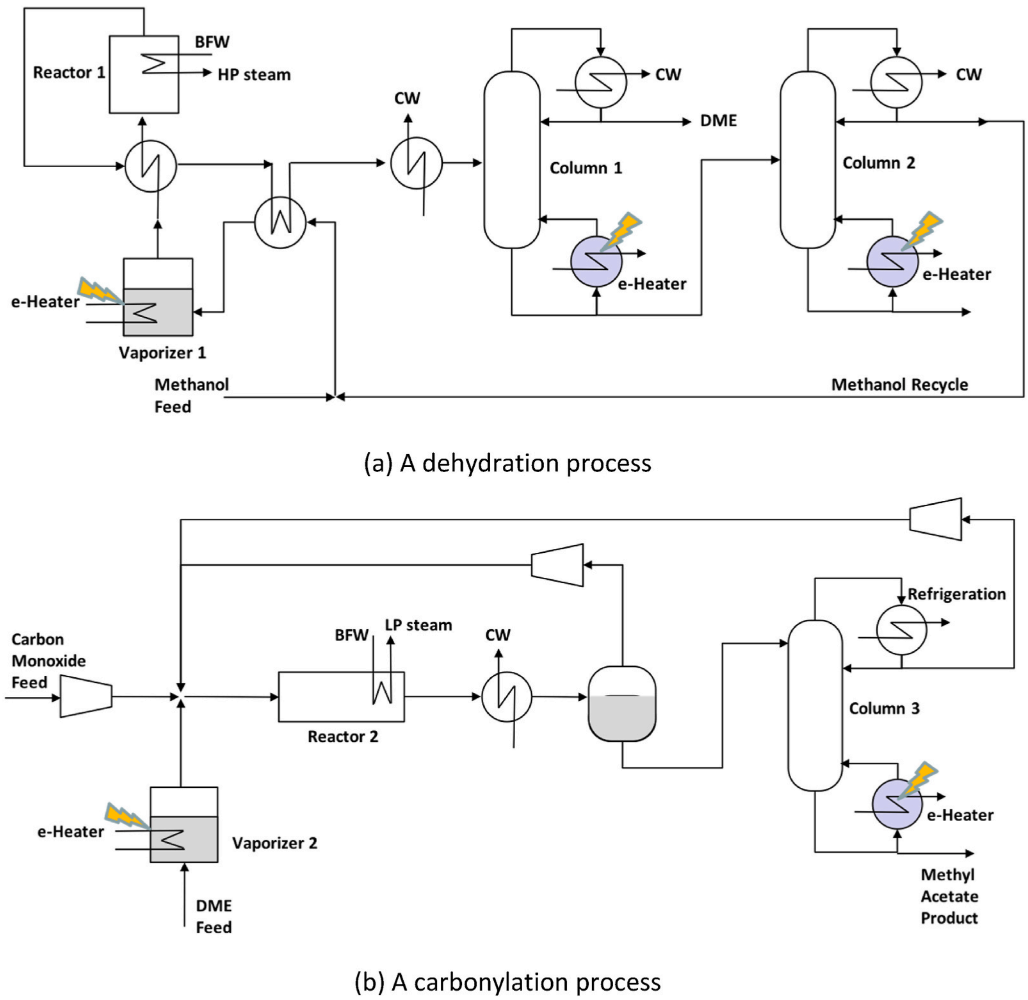


Fig. 4. A semi-electrified a methyl acetate process.

by-step procedure for the process design of utility systems with and without electrification can be found in Ref. [27], whereas the targeting procedure for utility systems, subject to steam recovery and cogeneration, can be found in Ref. [37].

It should be noted that such a transition to electrified energy management provides not only sustainable benefits for reducing CO_2 emissions but also offers configurational simplicity in the design of utility systems. One of the drawbacks of steam-based utility systems is that a large number of auxiliary units must be introduced; hence, the system configuration is highly integrated and complex. The energy infrastructure under electrification in process industries can be more simplified than that in a steam-based system.

The techno-economic impact of electrification on utility systems is presented in Table 3, in which changes in capital investment and energy costs are compared across the three cases considered in this case study. The parameters and basis for economic cost are listed in Table 2. The economic cost presented in Table 3 only considers the capital cost of the main units and the operating cost related to energy consumption and CO_2 tax, which clearly illustrates how the economics of energy systems are influenced by the degree of electrification. It should be noted that the capital cost presented in Table 3 is the result of the purchasing cost of equipment multiplied by the Lang factor used to account for the direct cost of capital investment. Indirect project costs for the evaluation of capital and operating costs were not added because of the uncertainty in process designs and economic analyses. The estimation of the capital cost for heat exchangers was only considered for exchangers that are relevant to electrification. The information required to evaluate the heat exchanger areas are provided in Appendix A. The estimation of the heat exchanger cost was made using the correlation in Table 2, which is provided in Ref. [34]. For the design of the ORC systems, butylbenzene was selected as the working fluid for reactor 1. Butylbenzene has a relatively high critical temperature and is the most energy-efficient fluid among various alkanes, aromatics, and linear siloxanes studied in Ref. [40] when integrated with an internal heat exchanger and operated at high temperatures. Toluene was selected as the working fluid of the ORC for Reactor 2 because the critical temperature of toluene is significantly higher than that of the waste heat available [39].

The cost for grid integration and load balancing is 10 $/MWhr, which is only applied for the cases of renewable power import.

As the cost of renewable electricity is highly technology-specific, the cost range is considered to be 0.039 USD/khW (observed in onshore wind power as the minimum cost) to 0.108 USD/kWh (observed in concentrated solar power) [16]. The capital cost of the fully-electrified scenario was 160% higher than that of the conventional scenario and 10% of the semi-electrified scenario was 10% cheaper. The fuel cost for the base scenario was 4.49 MM$/y, but the cost required for the purchase of renewable electricity can range from 3.57 to 11.34 MM$/y. The annual costs for the semi- and fully-electrified scenarios were 76.3% and 74.4% higher, respectively, than that of the fossil fuel scenario, while the semi- and fully-electrified scenarios had cheaper annual costs (by 22.0% and 11.4%, respectively) than did the fossil fuel scenario. When renewable electricity is integrated, further expenditure is required for grid integration and load balancing at 5–13 Euros/MWh for wind and solar power [41]. The annual cost, including this integration cost, was

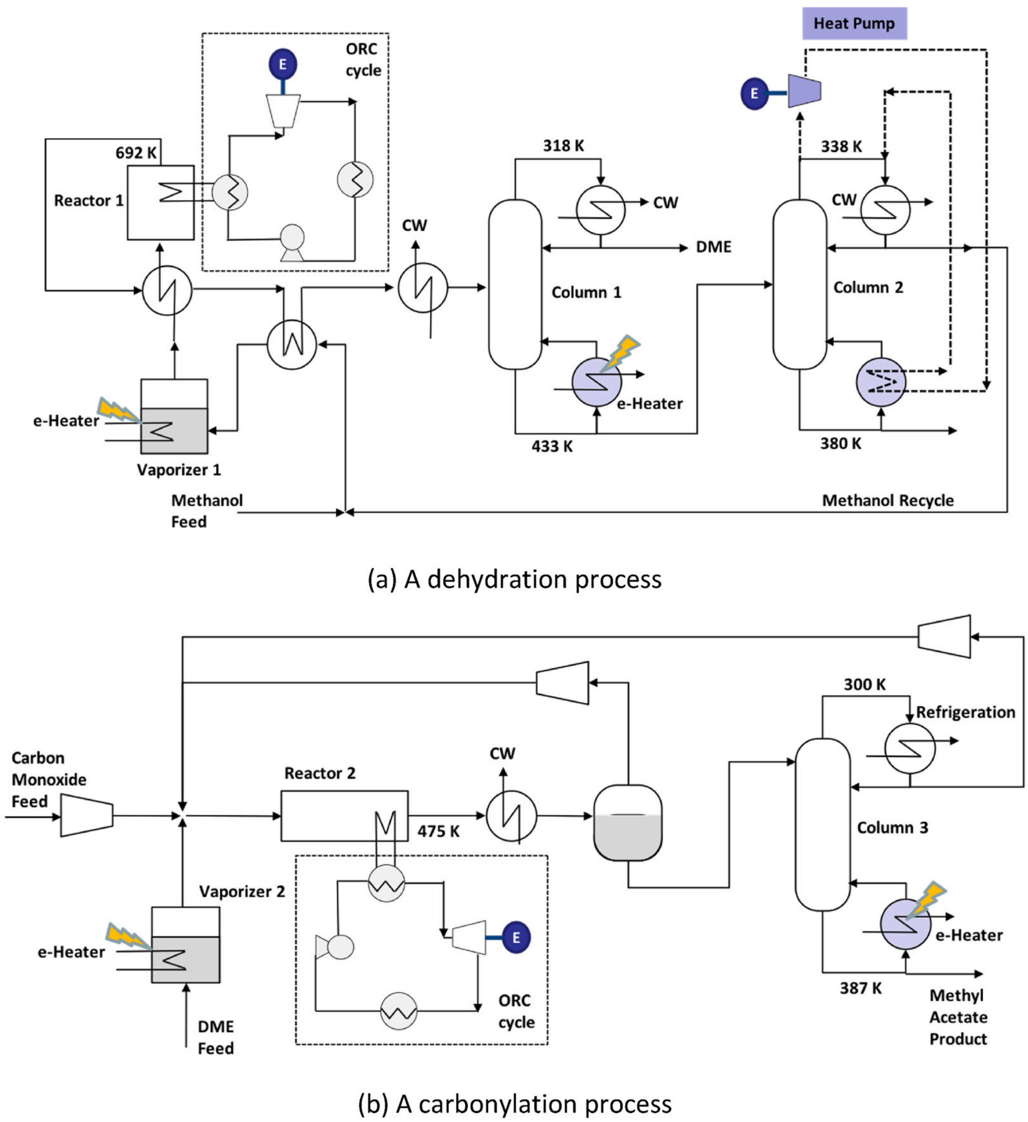


Fig. 5. A fully electrified case for a methyl acetate process.

calculated by assuming that 10 US$/MWh was required as an additional cost related to system integration and is also presented in Table 3.

This implied that electrified energy systems can be economically viable, under favorable conditions having low renewable electricity costs and cheaper investment costs associated with electrified heating. In addition, the introduction of the ORC with heat recovery may be justified for reducing the amount of electricity imported as long as the capital investment for the ORCs is not excessively large. A rapid decrease in power generation costs based on renewable sources has been observed, and this declining trend is expected to be continued [16]. The economic advantage of using power-to-heat technologies in process industries will increase further.

The CO_2 emissions presented in Table 2 are not based on the total life-cycle CO_2 emissions, but on the generation of CO_2 related to process heating only. CO_2 is emitted from the upstream and downstream processing of renewable power generation. For example, 13 gCO_2/kWh was reported as the median value for wind power generation [42], although t life-cycle CO_2 emissions were not explicitly addressed in this study. It should be noted that the life-cycle CO_2 emissions of renewable electricity are considerably smaller than the 256.05 gCO_2/kWh used for fossil fuel combustion in this study, and there are additional CO_2 emissions beyond the plant boundary related to the supply and discharge of fossil fuels.

4. Case study 2

This case study is based on the conceptual design of the ethylbenzene process presented by Turton et al. [38]. A schematic of the process is shown in Fig. 7(a). Benzene and toluene were preheated in a furnace, which was then reacted through three stages in the inter-cooled reactors. An additional reactor was employed to facilitate the reaction of a recycled benzene-rich stream from the C1 column, with the recycled 1, 4-Dimethylbenzene stream being obtained from the C2 column. Two distillation columns, C1 and C2, were used to recover the ethylbenzene product and recycle the unconverted feed materials. Although the furnace shown in Fig. 7 is represented by two separate units, it is a single integrated unit.

The electrified heating considered in Case Study 1 was based on the flowsheet given in the referenced study, and no process-to-process heat recovery was considered. No flowsheet modifications related to process heating and heat recovery were considered in Case Study 1, although there exists considerable potential for energy saving through heat integration. Two sub-scenarios are considered for Case Study 2: one considers electrification for a process as provided without heat integration within the plant, while the other implements electrified heating for a plant that is designed to achieve maximum energy recovery.

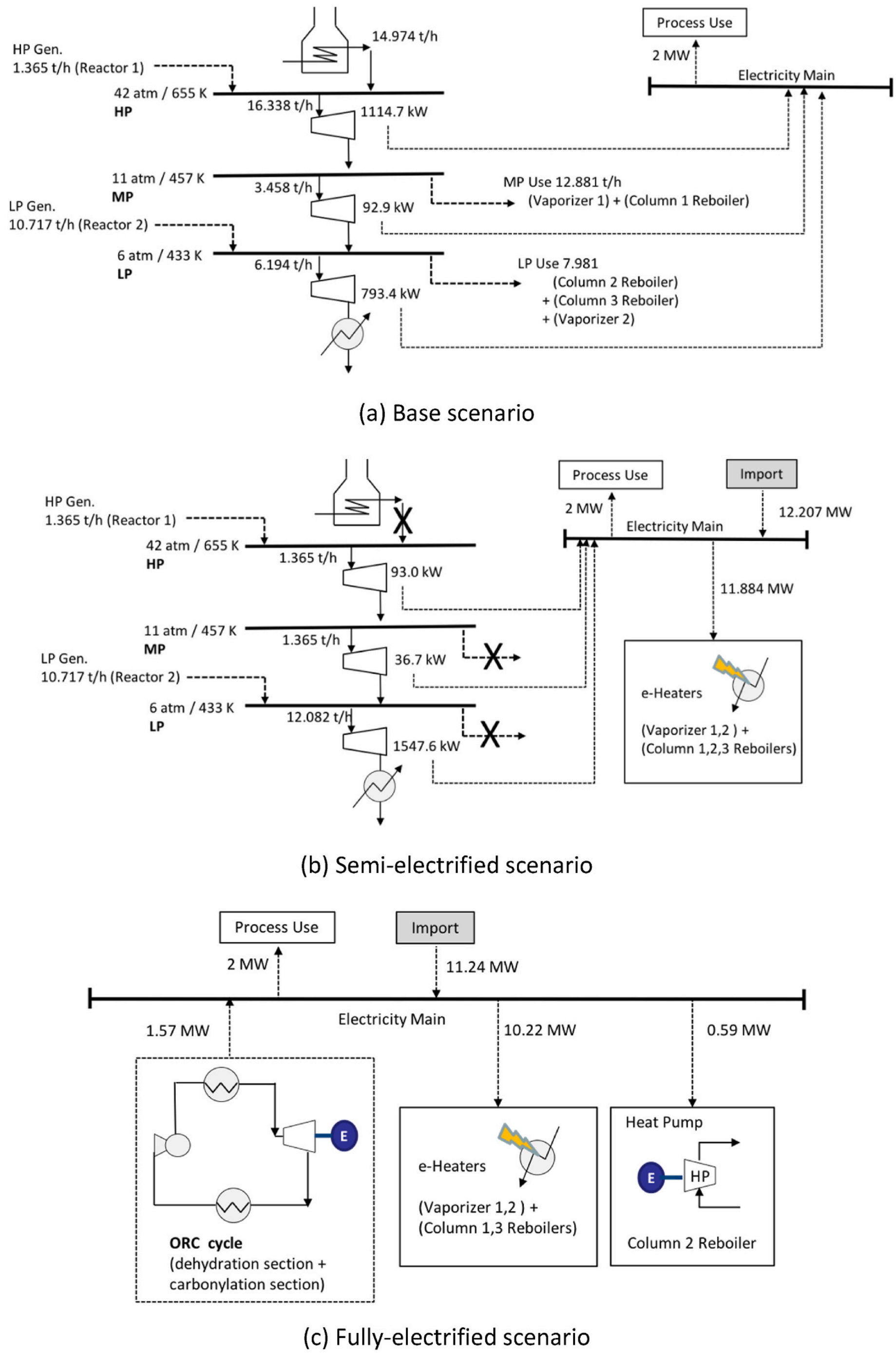


Fig. 6. Utility systems for a methyl acetate process.

4.1. *Electrification without heat integration*

The options for electrification in this scenario include an electric furnace for the conventional furnace, an electric heater for the column reboiler, an ORC system with waste heat recovery for Reactors 1, 2, and 3, and heat pumping between Columns 1 and 2. Two electrification scenarios were considered, which are the electrification processes without (Fig. 7(b)) and with (Fig. 7(c)) heat pumping, respectively. The matching of heat pumping depicted in Fig. 7(c) was selected between the condenser of Column 2 and the reboiler of Column 1 and results from the screening of all the possible heat sinks and sources, as well as from the rule employed in Case Study 1.

Under the same design basis and philosophies adopted in Case Study 1, the utility systems for three scenarios were designed. The conventional utility system for the base scenario consisted of two back-pressure turbines and one condensing turbine. The steam balances are shown in Fig. 8(a) were determined without considering additional power generation than is required to utilize the additional HP steam available. As approximately 5.2 t/h of HP and LP steam is generated from the waste heat recovery of the reactor exit streams, a boiler was not required, as illustrated in Fig. 8(a). The electricity generated from the three turbines was 726.2 kW, of which the surplus was exported.

The overall power consumed by the pumps and drivers used in the process is given as 21.1 kW [38], although these units are not explicitly shown in Fig. 7. For Case Study 2, 50 kW was assumed as the overall process demand to account for additional domestic power consumption.

Table 2
Design basis and costing information for Case Study 1.

Basis for the design of utility systems with electrification	
Conditions of steam mains	HP (42 atm, 655 K); MP (11 atm, 457 K) LP (6 atm, 433 K); Condensate (0.12 atm, 323 K)
Energy efficiency for utility systems	Boiler = 85%; Turbine = 70%; Furnace = 75%
Energy efficiency for electrified units	Electric furnace = 93.5% [21] Electric heater = 99% [19]
Boiler feed water temperature	100 °C
ORC system performance	$W/Q = 0.025\ T_{CR} + 10.947$ where, T_{CR} = critical temp. of the working fluid [°C] W = electricity generation [kW] Q = heat utilized for ORC [kW] [27]
Costing parameters and correlations for economic analysis	
Project life	15 years
Interest rate	5%
Lang factor	4.74 for fluids processing plant [36]
Exchange rates	1 GBP = 1.35 USD; 1 EURO = 1.1 USD
CEPCI for costing basis	761.4 (Oct. 2021)
Steam boiler equipment cost [$]	Cost = $3.28 \times 10^5 (P_s/20{,}000)^{0.81}$, where P_s = steam flowrate in $kg{\bullet}hr^{-1}$ and CEPCI = 391.1 [37]
Steam turbine equipment cost (C_{ST}) [$]	$\log_{10}(C_{ST}) = 2.6259 + 1.4398 \log_{10}(P_p) - 0.1776 [\log_{10}(P_p)]^2$ where P_p = power in kW and CEPCI = 397 [38]
Condensing turbine equipment cost (C_{CT}) [$]	$C_{CT} = -14{,}000 + 1900\ (P_p)^{0.75}$, where P_p = power in kW and CEPCI = 532.9 [36]
Electric heaters [GBP]	50 GPB/kW [19]
Compressor equipment cost [$]	Cost = $9.84 \times 10^4 (P_p/250)^{0.46}$ where P = power in kW and CEPCI = 391.1 [37]
Heat exchangers equipment cost [$]	Cost = $7295(A)^{0.65}$ where, A = area in m^2 and CEPCI = 585.7 [34]
ORC system costs based on waste-heat recovery systems[a]	Cost [GBP/kW] = $-1016.7 + 5216.7(P_p)$ where, P_p = power in kW and CEPCI = 556.8
Operating hours	8600 h/yr
Electricity import unit cost[b]	0.039 USD/kWh (Min cost for onshore wind-based power); 0.108 USD/kWh (Max cost for concentrated solar power) [16]
Fuel (fuel oil) cost	10.797 $/GJ
Fuel (fuel oil) CO_2 emission factor	71.124 $kgCO_2$/GJ
CO_2 tax	35 USD/tCO_2

[a] This specific cost correlation is obtained from the regression of cost data provided by van Kleef et al. [39].
[b] The export cost is assumed to be the same with import cost.

Table 3
Economics of the energy systems designed for Case Study 1.

Cases		Base case	Semi-electrified case	Fully-electrified case
Capital Cost [MM$]		19.15	17.15	30.72
Electricity Import[a] Cost [MM $/y]	Max	–	11.34	9.89
	Min	–	4.10	3.57
Fuel Cost [MM$/y]		4.49	–	–
CO_2 Tax [MM$/y][a]		1.04[b]	–	–
Annualized Cost [MM$/y] (w/o renewable integration cost)	Max	7.37	12.99	12.85
	Min	7.37	5.75	6.53
Annualized Cost [MM$/y] (with renewable integration cost)	Max	7.37	14.04	13.76
	Min	7.37	6.80	7.45

[a] Assume that renewable electricity is imported for electrified cases.
[b] CO_2 emission rate = 29.57 $ktCO_2$/yr.

For the electrified scenarios, power imports of 8.88 MW and 6.91 MW, as shown in Fig. 8(b) and (c), respectively, were necessary to support electrified heating of 10.32 MW and 7.76 MW, respectively, although power was generated from the waste heat recovery and ORCs. As assumed and discussed earlier, additional cogeneration via further steam generation has not been exploited. The power required to operate the heat pump was calculated using a 3.5 of COP value under a heat pumping temperature of 46.5 °C, which is based on performance data obtained from the literature [35].

4.2. Electrification with heat integration

The flowsheet presented in Fig. 7(a) includes a certain degree of heat recovery by generating steam from the heat available within the plant, although the additional use of heat within the plant has not been fully exploited. Systematic matchings between heat sources and sinks were identified using a well-established heat integration method. Energy Composite Curves can be used for identifying the maximum energy recovered from the process, and the most economic placement of utilities for process heating can be judged with the aid of GCCs [37]. The first step in the heat integration study was to extract stream data from process information. Five hot streams and four cold streams were identified, as shown in Table 4, and the temperature and heat flow values were based on the energy balances reported in the literature [38].

The minimum temperature approach (ΔT_{min}) for energy recovery was assumed to be 20 °C in this study. Without heat integration, the hot utility consumed for the base case in Fig. 7 (a) was 22,376 MJ/h, assuming that the HP and LP steam produced from the reactor outlets are used for the reboilers of Columns 1 and 2. With the application of the heat integration method, the minimum hot and cold utility requirements are targeted to be 6285.2 MJ/h and 14006.2 MJ/h, respectively, as shown in the GCCs of Fig. 9, which is significantly lower than that of the base scenario. This implies a very different process-wide configuration when the process is fully heat-integrated. In addition, it can be stated that the implementation of electrification and its techno-economic impact are highly dependent on heat integration.

GCC, based on the maximum energy recovery achieved for the base case, offers different approaches for the implementation of hot utilities. A furnace can be solely used for providing 6285.2 MJ/h of heating for the process, as shown in Fig. 9(a), while steam with 5300 MJ/h is coupled with the furnace with 985.4 MJ/h for cogeneration, as shown in Fig. 9(b). The cogeneration target between the HP and LP steam was determined by the shape of the composite curves and the heating profile of the furnace. It was assumed that heating from the furnace is available from 2000 °C, and the lower limit as an acid dew point is 180 °C. It should be noted that the pocket between the HP and LP steam mains in GCC can be utilized for additional power generation. This feature was not considered in this study because of the increase in the design complexity of the heat recovery systems.

The design options for electrified heating to be applied in the heat-integrated process were determined using the GCC, and the results are schematically presented in Fig. 9(c) and (d). Heating of 985.4 MJ/h at a very high temperature was made by an electric furnace, and heating of 5300 MJ/h at a low temperature was considered either by an electric heater (Fig. 9 (c)) or a heat pump (Fig. 9 (d)). Based on the four potential heating strategies, a heat exchanger network was designed to achieve the minimum utility target, as shown in Fig. 10. The design of the heat recovery network for using LP steam in Fig. 9(b) or electrified heating shown in Fig. 9(c) was the same, as long as the heating with LP steam for stream C1 in Fig. 10(b) was replaced with an electric heater. The electrification of a single furnace with an electric furnace can be considered, although this was not compared in this study. This is because there is no difference in the configuration of the heat exchanger network between an electrified furnace and fossil-fuel-based furnace.

The network design presented in Fig. 10 follows the rules of the maximum energy recovery (MER) design method, which is well established and widely practiced in process industries. It should be noted that the design from the application of the MER method does not guarantee minimum-costs, as the rules of the design were constructed to minimize the use of external heating and cooling utilities. As a combinatorial nature exists for the network considered in the scenarios, flowrate ratios

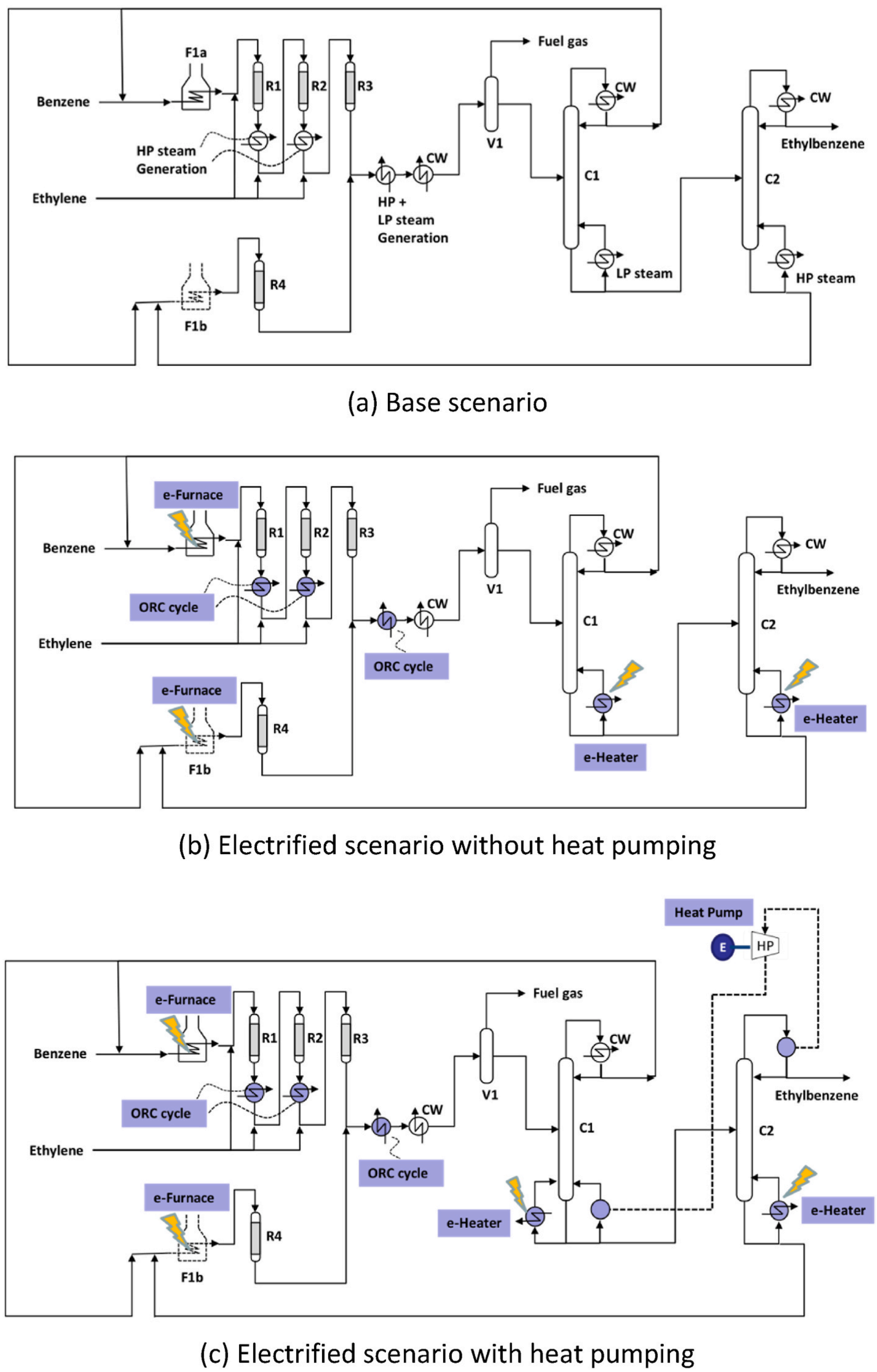


Fig. 7. Flow diagrams for an ethylbenzene process.

for stream to be multiply split can be varied, and different configurations for matching between hot and cold stream can also be designed.

The network designs in Fig. 10 (b) and (c) are slightly more complex than those in Fig. 10 (a). This is related to the lower temperature of the hot utilities used in the electrified scenarios, which results in more stream splitting for streams C1 and H3; therefore, an additional heat exchanger is required for the electrified scenarios. The optimality of the heat recovery networks was highly influenced by decision parameters, mainly the decision on the choice of ΔT_{min} and the relative cost between exchangers and energy. The focus of this study was to understand the impact on process-level and site-wide energy management under electrification; hence, improving the economics or simplifying the network complexities has not been investigated. These topics have been well-documented in various studies [43, 44].

As illustrated in Fig. 10, the network configurations for the three scenarios were rather complicated, mainly because of the multiple stream splitting. The introduction of electrification provided an opportunity to reduce the number of heat exchangers and to simplify the network configuration, compared with heat recovery networks using traditional fossil-fuel energy management [28]. Under the conventional steam supply from fossil fuel utility systems, high-grade steam is first expanded through a steam turbine for cogeneration, and then the degraded low-temperature steam is used for process heating. The use of steam at low temperatures often results in additional pinch point(s) or a

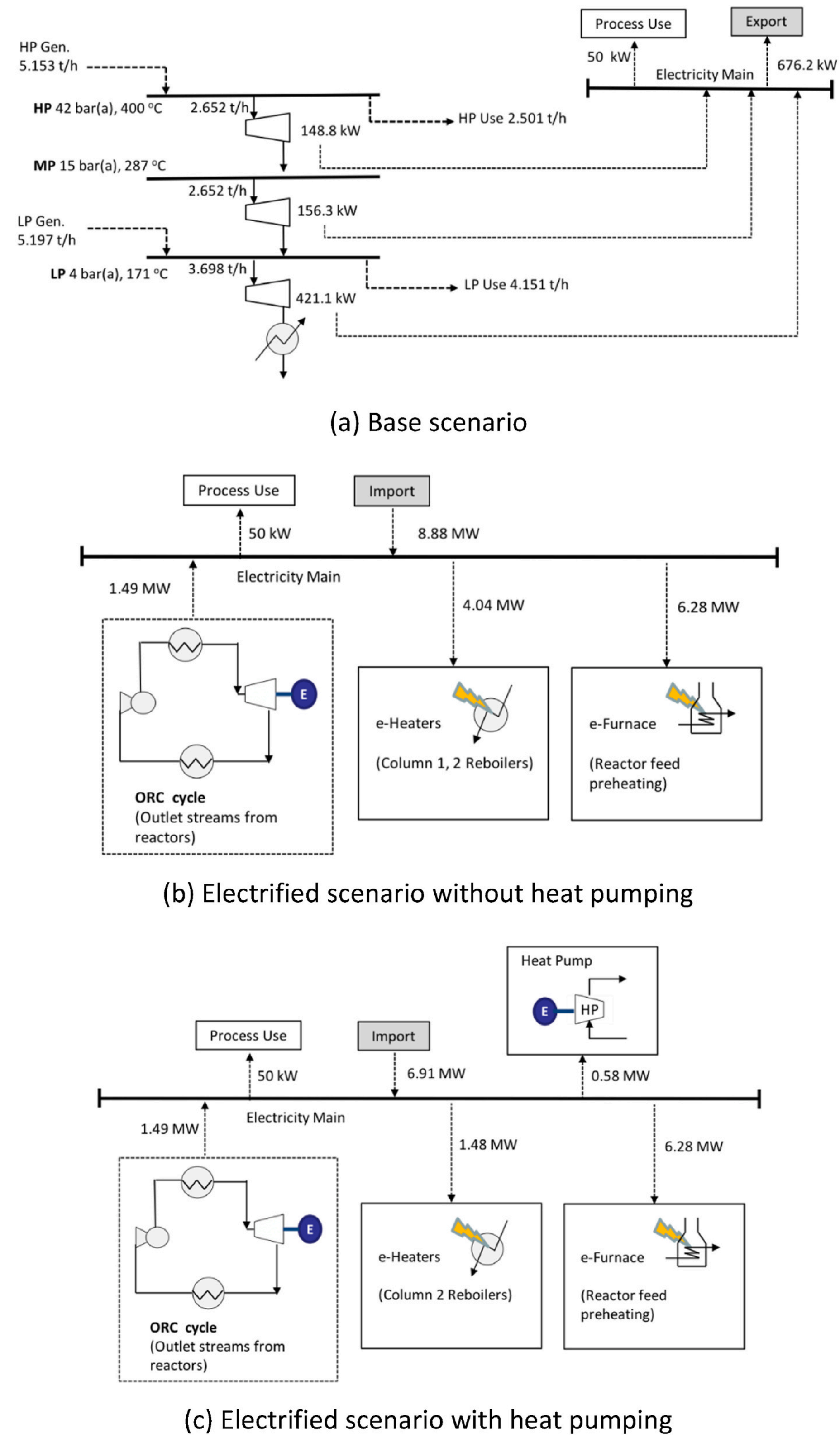


Fig. 8. Utility systems for an ethylbenzene process.

small temperature gap in the design of the heat exchanger networks, which, in turn, leads to complex heat exchanger networks with additional exchangers. As electricity generation is not required in an electrified heating environment, the supply temperature of heating can be chosen away from the pinch points, and the heat exchanger networks can be designed with a large temperature driving force [28]. However, in this particular case study, no considerable benefit from electrified heating was observed in terms of simplifying the network. This is mainly related to a large pocket existing between the HP and LP steam levels, for which several matchings between heat sources and sinks are to be introduced.

With the design of heat recovery systems and targeting of minimum

Table 4
Steam data for an ethylbenzene process.

Stream Name	Stream Description	Supply Temp. [°C]	Target Temp. [°C]	Heat Flow [MJ/h]
H1	Stream from R1 to R2	396.5	380	1967.0
H2	Stream from R2 to R3	398.2	380	2592.0
H3	Stream R3 to V1	458.1	80	27390.0
H4	Column 1 condensation	81.4	81.3	7276.0
H5	Column 2 condensation	139.1	139	5262.0
C1	Column 1 re-boiling	145.4	145.5	9109.0
C2	Column 2 re-boiling	191.1	191.2	5281.0
C3	Feed preheating for R1	58.5	400	17270.0
C4	Feed preheating for R4	121.4	500	5106.0

utility requirements from heat integration studies, utility systems can be constructed. The resulting utility systems for the four scenarios considered are schematically compared in Fig. 11, which is relatively simplified compared to the utility systems of the non-heat-integrated scenarios presented in Fig. 8.

The economics of all the scenarios presented in this section were evaluated, and the results of the capital investment required for electrification and their associated energy costs were calculated, as listed in Table 5. Except for the cost correlation for shell-and-tube heat exchangers, the same costing parameters and assumptions applied for Case Study 1 were used, as follows [36]:

$$C_{HX} = 32{,}000 + 70(A)^{1.2} \qquad \text{Eq. (1)}$$

where A is the heat exchanger area in m^2 and the cost was based on 532.9 CEPCI. This correlation was used to account for the differences in the number of exchangers when calculating the capital costs. Because the heat transfer coefficients were not reported in the study [38], the heat exchanger areas for the exchangers shown in Fig. 10 were determined by estimating the overall heat transfer coefficients, as explained

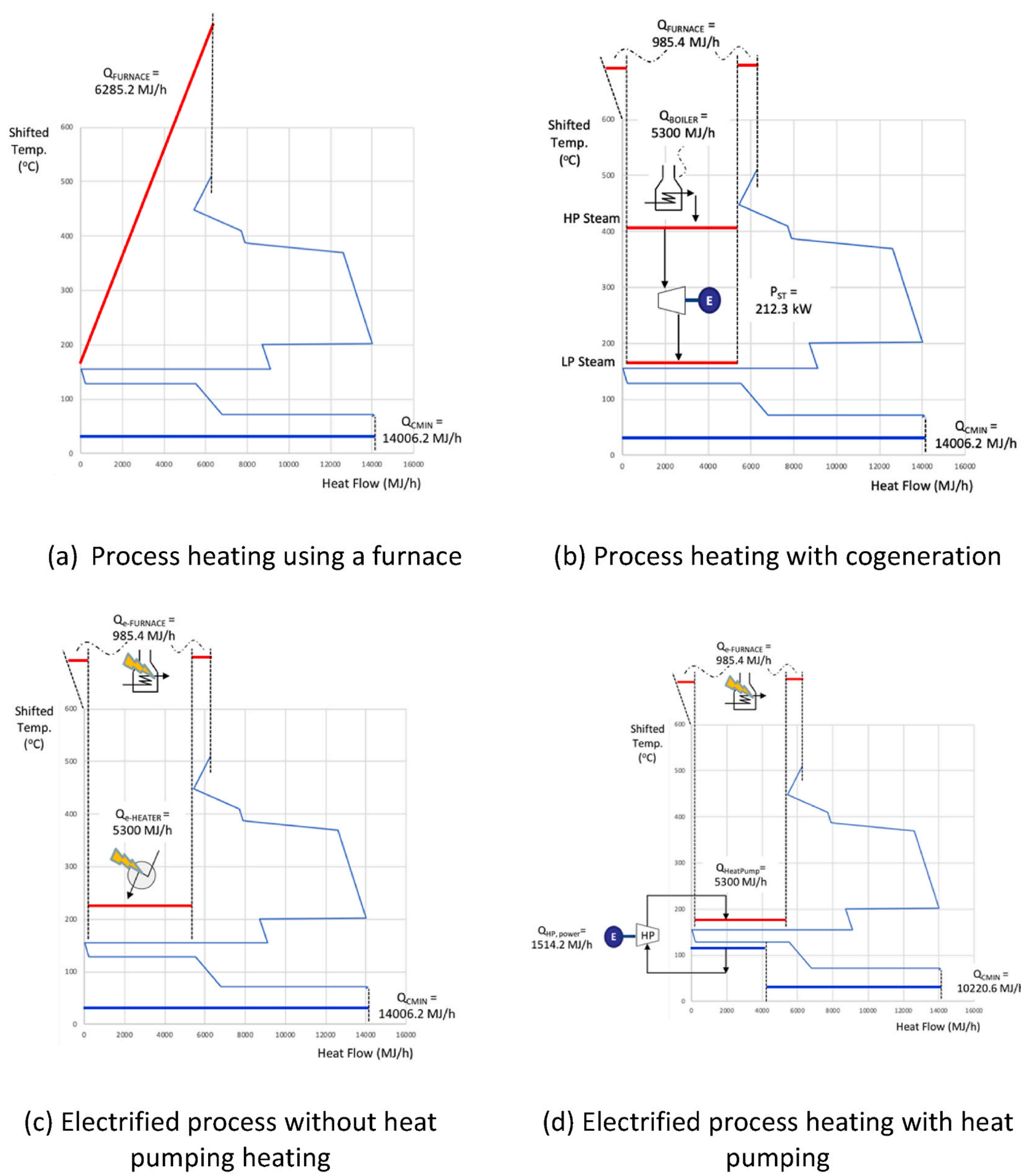


Fig. 9. Approaches of process heating and cogeneration for heat-integrated processes.

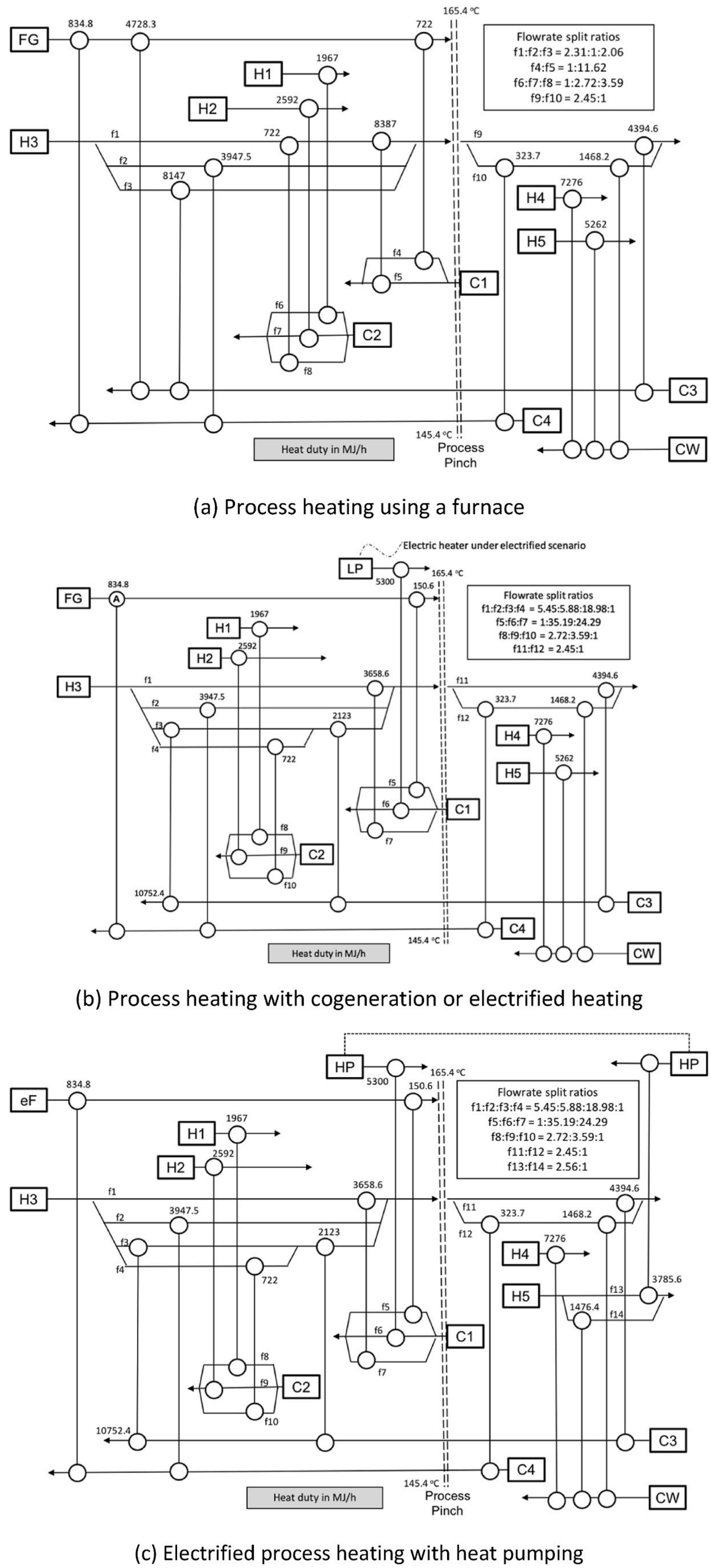


Fig. 10. Design of heat exchanger networks for an ethylbenzene process.

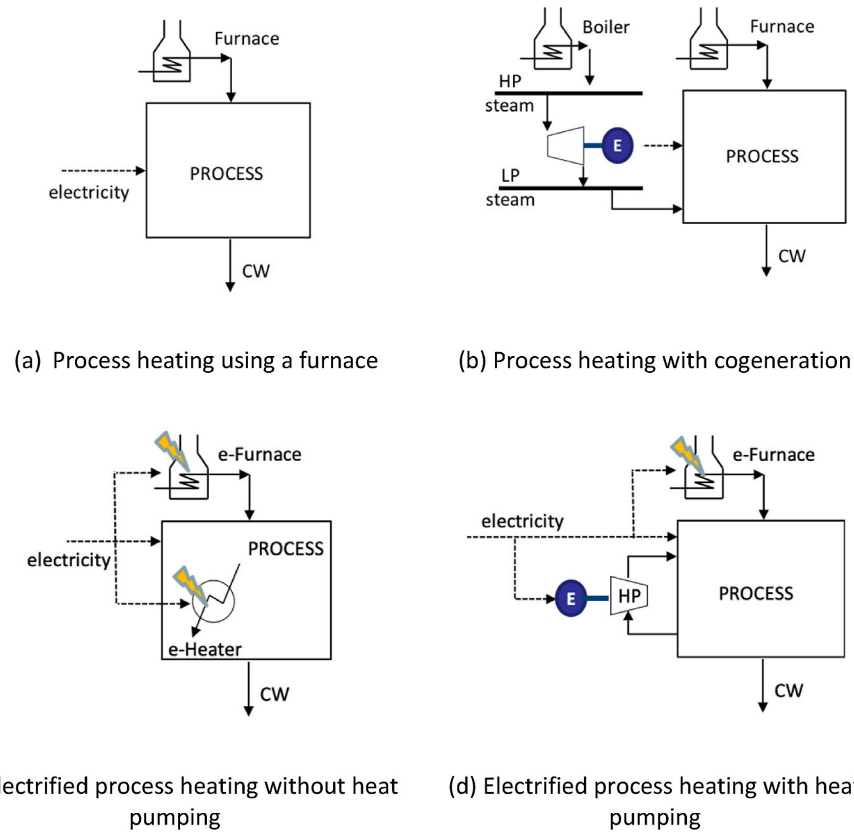


Fig. 11. Simplified diagrams of utility systems used during heat-integrated processes.

Table 5
The economics of energy systems designed for Case Study 2.

Cases			No Heat Integration			Heat Integration			
			Base case	Electrified case without heat pumping	Electrified case with heat pumping	Furnace Only	Furnace + Boiler + Turbine	e-Furnace + e-Heater	e-Furnace + Heat pump
Capital Cost[a] [MM$]			12.86	66.21	66.72	7.16	7.98	11.46	12.70
Electricity import[b] cost [MM$/y]		Max	−0.63	8.59	7.21	0.05	−0.15	1.70	0.71
		Min	−0.23	3.10	2.60	0.02	−0.05	0.61	0.26
Fuel Cost [MM$/y]			2.44	–	–	0.92	0.82	–	–
CO_2 Tax [MM$/y][c]			0.56[d]	–	–	0.21[e]	0.19[(f)]	–	–
Annualized cost [MM$/y]	w/o renewable integration cost	Max	3.62	14.97	13.64	1.86	1.63	2.80	1.93
		Min	4.02	9.48	9.03	1.83	1.73	1.72	1.48
	with renewable integration cost[g]	Max	3.62	15.76	14.31	1.87	1.63	2.96	2.00
		Min	4.02	10.28	9.70	1.84	1.73	1.88	1.55

[a] The capital cost includes heat exchangers.
[b] The export unit cost is assumed to be same as the import one.
[c] Assume that renewable electricity is imported for electrified cases.
[d] CO_2 emission rate = 16.10 ktCO_2/yr.
[e] CO_2 emission rate = 6.03 ktCO_2/yr.
[f] CO_2 emission rate = 5.43 ktCO_2/yr.
[g] The cost for grid integration and load balancing is 10 $/MWhr, which is only applied for the cases of renewable power import.

in Appendix B. The investment cost of electric furnaces 3.5–5 MM Euros/MW_{th} was quoted in 2018 as the requirement for an electric furnace with a capacity of 10 MW, which was later used to estimate the 919 MW of the electric furnace at SABIC with a scaling factor of 0.7 [21]. This information was used to estimate the overall capital expenditure of electric furnaces introduced in this study by taking the average value of 4.25 MM Euros/MW_{th}. As this estimation includes other direct costing elements related to installation, cabling adjustment, and project handling [21], multiplication with the Lang factor was not considered in the current economic analysis.

In the scenario without heat integration, a considerable increase in capital investment was required for both electrified cases because of the heavy investment required for the introduction of electric furnaces. For example, the heating requirement to be met by the furnace shown in Fig. 10(a) is 22,376 MJ/h, which requires 0.96 MM$ of the purchased equipment cost for the conventional furnace, but 9.86 MM$ of that for the electrified unit. This can be explained by the relatively low technology readiness level (TRL) of the electric furnace compared with other electrified heating units. The difference in the overall capital cost between the electrified and non-electrified cases was relatively smaller for the heat-integrated case than for the non-heat-integrated case. This was related to the small contribution of the furnace to the heating process.

From the heat-integrated scenarios, there were economic incentives to introduce steam turbines for the generation of additional power at the expense of capital investment, as shown in Table 5. In this case study, it was also observed that better economics can be achieved when process-level heat recovery is increased. This implies that the design and operation of industrial energy systems under electrified heating should be performed in a holistic and integrated manner. As illustrated in Table 3 on Case Study 1, two sets of annual costs are given in Table 5 to compare the cost with and without the cost related to grid integration and load balancing.

The sensitivity of the cost of renewable electricity to economics in industrial energy systems is clearly illustrated in this case study. The overall annual cost of electrification was significantly reduced when the unit cost of renewable electricity generation decreased. For heat-integrated scenarios, electrified energy systems were better than fossil fuel-based energy systems. These results may not be generalized enough to be applicable to industrial cases in general because there are many uncertainties in economic cost calculations and process design parameters. However, the results presented in Table 5 strongly suggest that the implementation of electrified heating in process industries can be technically feasible and economically viable and can be regarded as a realistic and practical approach to achieving carbon neutrality.

5. Conclusions and future work

Two case studies were conducted to understand the techno-economic impact of electrified heating on energy systems at the process level and utility systems at the site level. In addition, the transition from conventional fossil fuel heating to decarbonized electric heating influenced the configuration of industrial energy systems. Process-wide design interactions between the implementation of electrified heating and the process design of energy systems were systematically examined using heat integration methodology.

Both case studies are typical processes for producing chemicals, in which the mixed-use and consumption of different utilities are required for production. Energy systems under electrification were first considered at the process level, at which the design of utility systems was made. The effect of the energy recovery at the process level on the electrified supply for heating was also investigated. The heat-integrated scenario was compared with a non-heat-integrated process flowsheet in terms of their abilities to achieve maximum energy recovery for their respective plants. This provided economic incentives not only to reduce the inherent heating requirements for a process itself but also for improving the economics of electrified energy systems.

Although two case studies may not be sufficient to represent all the characteristics of energy management in process industries, conceptual insights and design guidelines related to the implementation of electrified heating were obtained, which helps to gain our understanding of future carbon-neutral and net-zero energy systems in practice. As observed in the results of both case studies, changes from fossil-fuel-based heating to electrified heating may not be justified in the current economic scenario. However, the application of a systematic design methodology for achieving cost-effective electrification is important to minimize any potential economic burden imposed by electrification.

The work conducted in this study still needs to further accommodate for other design issues, although valuable knowledge has been obtained regarding the development of heat integration subject to electrification. The process diagram and associated mass and energy balances were fixed for the current study, and it would be useful to discuss how changes in the operating conditions or flowsheet configuration can additionally contribute to the cost-effectiveness of electrified heating. In addition, the results obtained from the application of heat integration considering electrified heating could be more practical for considering more detailed operational or performance characteristics of electrification technologies.

As the heat-integrated process design and its economic evaluation for case studies are based on the assumption of a steady-state operation without fully considering the fluctuating behavior in utility management, further studies should include this non-steady operational issue, such as capacity firming and energy storage management related to the integration of renewable electricity and its impact on CO_2 emissions.

Credit author statement

Jin-Kuk Kim is the sole author for the work presented.

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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Appendix

A. Data of heat exchangers for Case Study 1

Table A1
Data and assumptions for heat exchangers [34].

Unit[a]	Duty [kW]	Overall heat transfer coefficient [kW/Km^2]	Hot stream		Cold stream	
			Tin [K]	Tout [K]	Tin [K]	Tout [K]
Vaporizer 1	5149	0.85	457	457	400	423
Reactor 1	1040	0.28	692	628	373.15	655
C1 reboiler	1996	0.568	457	457	433	433
C2 reboiler	1650	0.568	433	433	380	380
C1 condenser	1646	0.852	318	318	310	310
C2 condenser	2315	0.852	338	338	310	310
Vaporizer 2	1280	0.85	433	433	298.15	372
Reactor 2	7165	0.28	475	389	373.15	460
C3 reboiler	1690	0.568	433	433	387	387
C3 condenser	653	0.852	300	300	253	253

[a] Only heat exchangers related electrified modification are considered.

B. The estimation of the overall heat transfer coefficients for Case Study 2

The overall heat transfer coefficient was estimated using the film transfer and fouling coefficients in Table A2, which was then used for calculating the heat exchanger areas. The ratio of the outside to inside diameter of the tube was assumed to be 1. The tube wall coefficient was assumed to be 10,000 W/m^2K, and the contribution to the overall coefficient was very small.

Table A2
Assumptions for coefficients related to heat exchange [37].

Stream	Film transfer coefficient		Fouling coefficient	
	Type[a]	Value[b] [W/m^2K]	Type[a]	Value[b] [W/m^2K]
Furnace flue gas	Gases (No change of state)	255	Flue gas	3500
Steam	Steam (Condensation)	10,000	Steam (Condensation)	7000
H1, H2, H3	Gases (No change of state)	255	Organic (Vapor)	7500
H4, H5	Organic (Condensation)	1750	Organic (Condensation)	12,500
C1, C2	Organic (Evaporation)	1250	Organic (Boiling)	6250
C3, C4	Organic (No change of state)	2000	Organic (Liquid)	7000
Cooling water	Water (No change of state)	4000	Cooling water (Good quality)	4500

[a] The definition for stream types is based on reference [37].
[b] The average value is selected from the range given from reference [37].

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