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Industrial multi-energy and production management scheme in cyber-physical environments: a case study in a battery manufacturing plant

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Abstract: Among the various electricity consumer sectors, the consumption level of the industrial sector is often considered as the largest portion of electricity consumption, highlighting the urgent need to implement demand response (DR) energy management. However, implementation of DR for the industrial sector requires a more sophisticated and different scheme compared to the residential and commercial sector. This study explores all the elastic segments of plant multi-energy production, conversion, and consumption. We then construct a real-time industrial facilities management problem as an optimal dispatch model to enclose these elastic segments and production constraints in cyber-physical environments. Moreover, a model predictive-based centralised dispatch scheme is proposed to address the uncertainties of real-time price and renewable energy forecasting while considering the sequence of the production process. Numerical results demonstrate that the proposed scheme can enhance energy efficiency and economics of lithium battery manufacturing plant through responding to the real-time price whilst ensuring the completion of production tasks.

1 Introduction

With the development of smart power grid, demand response (DR) is playing an increasingly important role, which will help power system operators enhance operational flexibility, improve economic efficiency, set energy prices, and increase reliability. With respect to consumers, the electricity bill reduction can be achieved by adjusting electricity demand in response to time-varying electricity prices or incentive-based programs [1, 2]. Among various electricity consumer sectors, the industrial sector represents the largest portion of electricity consumption. According to statistics from the International Energy Agency, the industrial sector accounted for 42.3% of the world's electricity consumption in 2015 [3], and the proportion has even reached 72% in China. Thus, the industrial sector has the greatest potential for providing significant amounts of DR services.

Nevertheless, the implementation of successful DR schemes in the industrial sector is challenging and difficult because many industrial processes are sequential, interdependent and correlated [4–6]. In addition, the industrial process is a real-time domain which must satisfy the real-time production and inventory constraints. Furthermore, interruption of service for DR may lead to interruption of production or violating the daily operational constraints of a plant. So many factors have to be taken into consideration before one or more industrial loads can be temporarily shut down or shifted.

On the other hand, industrial loads also have many advantages for DR. First, most industrial loads have already been equipped with sensors, meters, controller and communications for factory energy management system which are necessary for DR implementing; second, there are many kinds of energy consumption, include electricity, heating, cooling, and compressed air and so on [7, 8] in industrial plants. At the same time, the energy consumption is large, if we can make full use of the conversion and storage between different energies, the DR potential will be greater than that of the residential and commercial sector [9]; third, the factory often has enough space to install renewable energy and cogeneration units, so it can participate in

DR with greater flexibility and economy. In summary, implementation of DR for the industrial sector has a huge potential but requires a more sophisticated and different scheme compared to the residential and commercial sector.

Addressing above-mentioned issues requires handling both physical (e.g. energy flows) and cyber aspects (information and communication) of the factory, thus the cyber-physical systems (CPS) approach is necessary. Industrial multi-energy and production for intelligent factory regards the CPS as its kernel and takes the deep fusion of ICT and different segments of the manufacturing process, to realise highly efficient production [10]. A CPS for implementing receding horizon control-based alternating current optimal power flow (ACOPF) in smart grids was given in [11], and the common information model was provided for standardised information exchange for implementing multi-period ACOPF including renewable energy sources and energy storage devices. A demand side management strategy for a cyber-physical smart distribution system considering price-based and reward-based scheduling programs was given in [12]. A cyber-physical energy system consisting of renewable energy, gradable vehicles, and conventional thermal units was presented in [13], and particle swarm optimisation was applied to generate intelligent scheduling of multi-energy.

In general, the previous studies mostly refer to DR in residential or commercial sectors and only a few works focus on DR in the industrial sector. Some research efforts have been devoted to the new pricing framework and market mechanism enables industrial consumers to transfer their power consumption [14, 15]. In respect of scheduling algorithms, the authors of [16, 17] proposed a DR modelling scheme for an industrial sector using a resource task network scheduling process and stochastic dynamic programming. A DR energy management scheme for industrial facilities based on the state task network was given in [18]. This scheme divided the industrial processing tasks into non-schedulable tasks and schedulable tasks. Using day-ahead hourly electricity prices, the scheme determines the scheduling of state tasks and distributed energy in order to shift the demand from peak periods to off peak periods. In [19], a model predictive control (MPC) of industrial
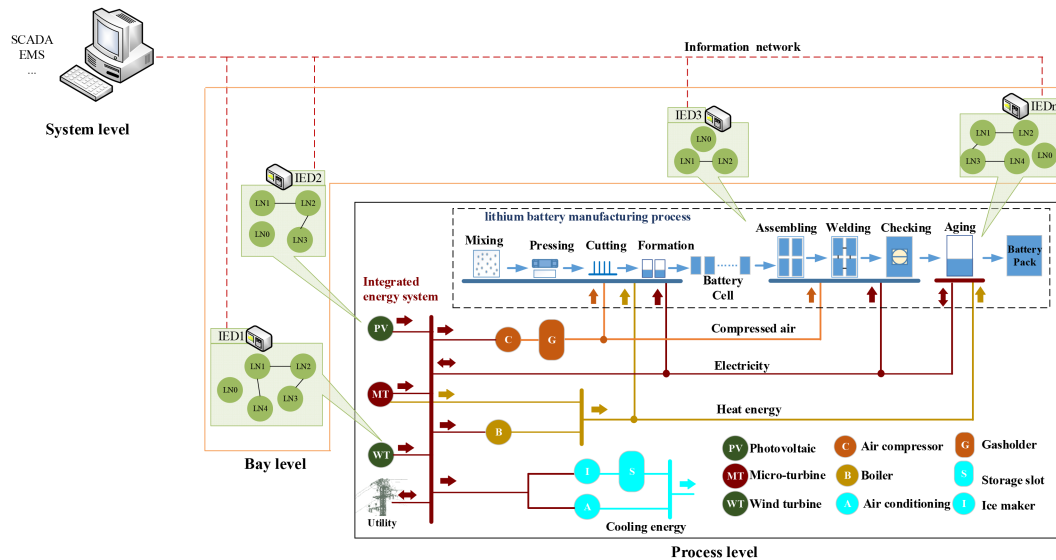
Fig. 1 *Energy demand and supply of lithium battery manufacturing plant in cyber-physical environments*

loads and energy storage was put forward for DR. In summary, these studies focused only on specific schedulable tasks, which was unable to take full advantage of elastic segments of plant multi-energy production, conversion, and consumption, more importantly, various uncertainties in the scheduling process are not considered.

The energy consumption of industrial users is much higher than others, thus there is great potential for energy saving in DR programs. However, the application of DR programs must build on their different production process, energy consumption characteristics, and equipment. For example, in the non-ferrous metal industry, most equipment continuously produces throughout the day with a stable annual load, thus its potential is mainly to fine tune production support department projects slightly. However, the main loads for the machinery manufacturing industry change greatly, and the production capacity is higher than the market demand. With no need for continuous production, it has a strong ability to transfer loads. In building materials industry, continuous production and high reliability requirement of power supply are shown, part of production lines are able to adjust following some damage. Relative to the above industries, the lithium battery plant has representative characteristics. Fully automatic production lines are driven by power and compressed air. Power driven facilities include manipulators, welders etc. Compressed air driven facilities include conveyor belts, cutting machines etc. At the same time, the production line has both heat and cooling energy requirements. The thermal energy requirements include drying, heating, and other equipment. The cooling requirements are mainly the air conditioner loads, which are used to ensure constant temperature during production.

From the above, few research studies take the factory production plan and production process sequence into account in energy supply optimisation. Therefore, to coordinate the operation of a variety of energy in the process of industrial production and periodic production tasks, this study proposes a comprehensive optimisation scheduling model for battery energy supply coupling dynamically with the industrial production process. The novelty of this work is multiple compared to previous studies: firstly, we explored all the elastic segments of multi-energy production, conversion, and consumption in the lithium battery manufacturing plant, which consist of a compressed air gasholder, ice storage tank, battery aging interval process, different production operation and so on. Secondly, to ensure the completion of production tasks, a multi-stage real-time dynamic production mathematical model is established to meet the characteristics of elastic segments and production process constraints, which could be easily modified and adapted to other industrial facilities at any scale. Thirdly, to avoid forecast uncertainties of real-time price (RTP) and renewable energy, a model predictive-based centralised dispatch scheme is formulated to optimise the controllable segments of multi-energy

supply and production lines by factory energy management system (EMS) in a rolling horizon. Finally, the result in analysis shows that the proposed optimisation model not only can ensure the completion of production tasks, global energy balance and operation economy in the meanwhile under all possible scenario realisations but also ensure the stability and anti-interference ability of the system operation by reducing the impact of uncertain factors effectively.

The paper is organised as follows. Section 2 briefly describes energy demand and supply of lithium battery manufacturing plant and its potential of DR. The optimal dispatch mathematical model of a lithium battery manufacturing plant is presented in Section 3. Section 4 proposes the centralised MPC scheme of the factory EMS system, followed by the detailed steps to solve and complete. Section 5 shows the simulation results of the proposed multi-energy and production management scheme. Conclusions are drawn in Section 6 eventually.

2 Energy demand/supply of lithium battery manufacturing plant and its potential of DR

Due to the requirements of industrial production, the lithium battery manufacturing plant must follow the established process from one section to the next section at the fully automated production line, and final aging. During the production, the energy demand in each section is different, so multi-energy supply should be configured correspondingly in cyber-physical environments, as shown in Fig. 1.

The CPS shown in Fig. 1 includes the process level, bay level, and system level. IEC 61850 is the international information standard and provides the basic communication structure for typical energy equipment, covering the principles, the abstract communication service interface, the common data classes (CDC), and the compatible logical node (LN), which can be used for object-oriented modelling of CPS.

The IEC 61850-7-420 standard provides the IEC 61850 information model to be used in the information exchange with distributed energy resources, which comprise dispersed generation devices and dispersed storage devices such as reciprocating engines, fuel cells, combined heat and power (CHP), and photovoltaic (PV) system. IEC 61850-6 also presents the system configuration language and work procedures of intelligent electronic devices (IED) and configuration tool, and provides the overall framework for industrial multi-energy and production management in cyber-physical environments, including devices of electricity, heating, cooling, and compressed air in the process level, IED in the bay level, and communication system for EMS in the system level.

IEC 61850 7-4 has provided the fundamental LNs for controlling, monitoring, protecting, and scheduling of multi-energy

and production. LN is the smallest unit of data exchange function and is defined by its data and method, such as ZBAT is used for battery pack, ZBTC for charge/discharge of battery aging, MMXU for measured values, which are the typical LN for industrial multi-energy in cyber-physical environments. LN consists of multiple data object (DO) that represents different types of specific function, represented by the CDC. CDC defines the data structure consisting of one or more data attributes. IED can build the CPS model of electricity, heating, cooling, and compressed air, according to the requirements of devices applications, based on IEC 61850.

2.1 Production process and energy requirements of lithium battery manufacturing plant

Each product of lithium battery will be finished through the fully automated production line and aging. The production process of the fully automated production line consists of three stages:

(i) *The first stage:* the lithium battery cell production line. This stage produces the lithium battery cell, through the process of mixing, pressing, cutting, formation and so on.
(ii) *The second stage:* the lithium battery pack line. This stage produces the lithium battery, mainly including the process of assembling, welding, and checking of semi-finished products.
(iii) *The third stage:* The battery aging line

Battery aging is used to saturate the electrolyte sufficiently and inactivate some active components in the positive and negative by certain reactions to make the overall performance of battery more stable. In the aging room, the batteries are transferred into battery aging equipment, and then the process of discharging and charging is completed at a given capacity rate within a specified time. The aging process must follow the order from discharging to charging. Meanwhile, thermal energy is required in the aging line due to the fact that the temperature in the aging room needs to be kept at 38°–40°.

For the production line to participate in the DR programs, the lithium battery cell and pack production line must strictly follow the process in order. Most process order cannot be adjusted and some section cannot be interrupted such as formation. The lithium battery cell and pack production line have an advanced automation control system, IED can be configured based on this system to gather operational data and status information of the production process for CPS. IED mainly comprises a data sampling module, a field communication module, a central processing unit, a digital/analogue output module, and an IEC 61850 process module. IED obtains the status information and the operation data of the production line through the data sampling module and the field communication module. Then, IED dynamically updates the corresponding status information DOs and the measured values DOs and sends them to EMS through the IEC 61850 process module.

However, the production line of the lithium battery cell and the pack still has the ability to participate in the DR programs through the production line turn on/off while meeting the turn on/off constraints. Therefore, careful scheduling is required to participate in the DR through the production line turn on/off. As for the aging line of the lithium battery pack, it is more flexibly responding to electricity prices. Although the power and duration of charging and discharging cannot be continuously regulated, it is noteworthy that the beginning time of charge or discharge process for each pack can be flexible arranged based on the electricity price, which can provide a certain capability of DR without interval time constraint from the discharging process to the charging process. IED can be configured mainly for the battery aging equipment with gathering operational data and status information of battery aging line, and scheduling and controlling the process of discharging and charging in cyber-physical environments.

Owing to the fact that the three stages of the battery production process interact with each other, each production line must be processed coupling to the others.

2.2 Integrated energy system of lithium battery plant

During the production process of the fully automated production line, pneumatic conveyor belts which are driven by compressed air, transfer material from one section to the next section. Besides, in order to ensure the work environment with a constant temperature, the air conditioner is always required for workspace indoors. Based on the energy consumption characteristics mentioned above, energy demand for the fully automated production line includes electricity, compressed air, thermal energy, and cooling energy.

According to the energy requirements of the battery manufacturing facilities, the plant must provide these energies through an integrated energy system to ensure that all facilities can continuously operate. The typical integrated energy system of a battery manufacturing plant is shown in Fig. 1, the production and supply of energy is described as follows:

Electricity: Electricity supply includes micro-turbine, wind power, PV and utility power. Renewable energy sources are difficult to control, while micro turbine can be flexibly dispatched. The LNs for the reciprocating engine model, the fuel cell model, the electrical storage systems, and the PV panel model have been provided based on IEC 61850, and the model of electricity can be formed in cyber-physical environments.
Compressed air: The compressed air system is comprised of an air compressor machine, gasholder, and filter. Mechanic energy is transformed from the electric energy by the motor and transmitted to an air compressor, which compresses the air into the gasholder. The compressed air with high pressure is used to drive the air-driven facilities in the production line. According to compressed air demand of the production line and electricity price, the power of air compressor, turn on/off time and the state of charge (SOC) of the compressed air storage can be flexibly scheduled.
Thermal energy: Considering the thermal energy requirements such as drying, heating, and other equipment, CHP-based micro-turbine is used to supply heat mainly, and the remaining heat is compensated by a gas boiler or electrothermal boiler consuming electricity. Changes in thermal energy and temperature have inertia, so thermal energy supply can be adjusted with certain range guaranteeing the temperature is within the allowable limits.
Cooling energy: Cooling energy is mainly supplied by the air conditioner and ice storage system, which transform electricity to cooling energy. The ice storage system which mainly includes ice-making machine, ice storage tank and ice-melting pump. The ice-making machine consumes electricity to produce ice in the ice storage tank to storage cooling energy or releases it through the ice-melting pump to respond to RTP program.

In addition to electricity, IED can build the CPS model of compressed air, thermal energy, and cooling energy, according to the requirements of IEC 61850 based on the application function of the equipment. Under certain conditions, if the controller of the energy system itself has a CPS model, it can be unified with the CPS model in the corresponding IED, and the IED is used to complete the CPS tasks. Above all, compressed air, cooling energy, and partial heat depend on the conversion from electricity in the integrated energy system. Moreover, energy storage equipment such as a gas storage tank, ice storage tank and heat storage are generally equipped to ensure the stable supply of energy. In this way, the integrated energy system can adjust the purchasing power of the plant from utility to respond to RTP through the conversion.

3 Optimal dispatch mathematical model of lithium battery manufacturing plant

3.1 Objective function

To ensure the industrial users participate in the DR program effectively and optimise economic operation, the operation plan of the production loads and schedulable generators should be reasonably arranged according to the forecast information for electricity price and renewable energy power while meeting the basic production tasks. Thereby, in this study, the comprehensive cost of the industrial system consists of the purchasing energy cost,

the energy supply cost, and the maintenance cost of production equipment, as described in (1) is selected as the optimisation objective function

$$\min p = \sum_{t=1}^{N_t} (C_{g,\mathrm{sum}} + C_{e,\mathrm{sum}} + C_{\mathrm{om,sum}}), \qquad (1)$$

$$C_{g,\mathrm{sum}} = \lambda_t^{\mathrm{RT}} P_{\mathrm{grid},t}, \qquad (2)$$

$$\begin{aligned}
C_{e,\mathrm{sum}} = & \sum_{\mathrm{MT}=1}^{N_{\mathrm{MT}}} (C_{\mathrm{gas}} P_{\mathrm{MT},t} + C_{\mathrm{MT},su} su_{\mathrm{MT},t}) \\
& + \sum_{b=1}^{N_b} C_{\mathrm{gas}} P_{b,t} + \sum_{ca=1}^{N_{ca}} C_{ca} P_{ca,t} \\
& + \sum_{is=1}^{N_{is}} C_{is} P_{is,t} + \sum_{pl=1}^{N_{pl}} C_{pl,su} su_{pl,t} \\
& + \sum_{cl=1}^{N_{cl}} C_{cl,su} su_{cl,t},
\end{aligned} \qquad (3)$$

$$C_{\mathrm{om,sum}} = \sum_{cl=1}^{N_{cl}} C_{cl,\mathrm{on}} u_{cl,t} + \sum_{pl=1}^{N_{pl}} C_{pl,\mathrm{on}} u_{pl,t} + \sum_{am=1}^{N_{am}} C_{am} u_{am,t}, \qquad (4)$$

where p is the total plant comprehensive operation cost, N_t is the optimisation cycle, $C_{g,\mathrm{sum}}$ is the total maintenance cost, $C_{e,\mathrm{sum}}$ is the total energy supply cost, and $C_{om,\mathrm{sum}}$ is the total maintenance cost.

The purchase energy cost as shown in (2), mainly refers to the electric charge when the factory is short of electricity, where λ_t^{RT} is the spot price at hour t, $P_{\mathrm{grid},t}$ represents the purchasing power from the external network at the hour t. Among them, $P_{\mathrm{grid},t}$ is the optimisation variable.

The energy supply cost: as shown in (3), mainly refers to the energy cost of production equipment during the start-up and operation. The production loads and integrated energy supply systems usually require technicians to operate them, especially when they start up, so the energy supply cost includes the start-up costs and gas fuel of the micro-gas turbine, the fuel cost of gas boiler, the operation cost of the compressed air system and ice storage system, where C_{gas} represents the fuel price, C_{ca} and C_{is} are the operating cost coefficients of air compressors and ice storage systems, respectively, $C_{\mathrm{MT,su}}$, $C_{cl,\mathrm{su}}$ and $C_{pl,\mathrm{su}}$ are the start-up cost coefficients of the micro-gas turbine, the cell line, and the pack line, respectively. N_b, N_{MT}, N_{ca}, N_{is}, N_{pl}, and N_{cl} are the amount of gas boiler, micro-gas turbine, compressed air system, ice storage system, pack lines, and cell lines, respectively, $P_{b,t}$, $P_{\mathrm{MT},t}$, $P_{is,t}$, and $P_{ca,t}$ represent the output power of the gas boiler, the micro-gas turbine, the ice storage system, and the compressed air system respectively, $su_{\mathrm{MT},t}$, $su_{pl,t}$ and $su_{cl,t}$ mean the starting variable of the micro gas turbine, the pack line, and the cell line at time t. Among them, $u_{\mathrm{MT},t}$, $u_{ca,t}$, $P_{b,t}$, $P_{\mathrm{MT},t}$, $P_{is,t}$, $su_{pl,t}$ and $su_{cl,t}$ are optimisation variables, and the rest are the fixed parameters.

The maintenance cost of production equipment: mainly refers to the maintenance cost of the aging machines and the production lines, as shown in (4), where N_{am} is the number of aging machines, C_{am}, $C_{pl,\mathrm{on}}$ and $C_{cl,\mathrm{on}}$ are the maintenance cost coefficients of the aging machines, pack lines and cell lines, respectively, $u_{pl,t}$, $u_{cl,t}$ and $u_{am,t}$ are the operation variables of the pack lines, the cell lines and the aging machines at time t. Among them, $u_{pl,t}$, $u_{cl,t}$ and $u_{am,t}$ are optimisation variables, and the rest are the fixed parameters.

3.2 Constraint function

3.2.1 Production line operation constraints: The start-stop time constraints, production task constraints and so on are both inclusive in the operation constraints of the cell and pack production lines. Thus, take the pack production line as an example. Equation (5) defines the relationship between the start-stop variables and operation variables. Equation (6) means the pack production line is unable to start up and shut down at the same time. The minimum and maximum start-up time constraint are defined in (7) and (8). Equation (9) indicates the minimum shut-down time constraint. Equation (10) refers to the minimum pack production task limit

$$su_{pl,t} - sd_{pl,t} = u_{pl,t} - u_{pl,t-1}, \qquad (5)$$

$$su_{pl,t} + sd_{pl,t} \leq 1, \qquad (6)$$

$$\sum_{t=h}^{h+T_{pl,\mathrm{on}}^{\min}-1} u_{pl,t} \geq T_{pl,\mathrm{on}}^{\min} \cdot su_{pl,h}, \quad \forall h \in [1, N_t], \qquad (7)$$

$$\sum_{t=h}^{h+T_{pl,\mathrm{on}}^{\max}-1} sd_{pl,t} \geq su_{pl,h}, \quad \forall h \in [1, N_t], \qquad (8)$$

$$\sum_{t=h}^{h+T_{pl,\mathrm{off}}^{\min}-1} (1 - u_{pl,t}) \geq T_{pl,\mathrm{off}}^{\min} \cdot sd_{pl,h}, \quad \forall h \in [1, N_t], \qquad (9)$$

$$\sum_{t=1}^{N_t} \sum_{pl=1}^{N_{pl}} u_{pl,t} \cdot K_{pl} = K_{\mathrm{sum}}, \qquad (10)$$

where $sd_{pl,t}$ is the shut-down variable of the pack production lines, $T_{pl,\mathrm{on}}^{\max}/T_{pl,\mathrm{on}}^{\min}$ is the maximum/minimum running period for the pack production line. $T_{pl,\mathrm{off}}^{\min}$ is the minimum shutdown time of the pack production line. K_{pl} is the number of battery packs produced of each pack production line per hour. K_{sum} is the total number of battery packs that need to be completed. Among them, $u_{pl,t}$, $su_{pl,t}$ and $sd_{pl,t}$ are optimisation variables, and the rest are fixed parameters.

3.2.2 Aging machine operation constraints: To ensure the specified capacity of battery packs final products, each battery pack requires to experience a discharging process and a charging process in the aging machine after packaged on the pack production line. Therefore, the battery pack in the aging machine needs to meet the following constraints: (11) defines the actual charging and discharging power of the aging machine. (12) and (13) refers to the charging and discharging task demand

$$u_{am,t}^c \cdot P_{am}^c + u_{am,t}^c \cdot P_{am}^d = P_{am,t}, \qquad (11)$$

$$\sum_{t=1}^{N_t} \sum_{am=1}^{N_{am}} u_{am,t}^c \cdot K_{am}^c = K_{\mathrm{sum}}, \qquad (12)$$

$$\sum_{t=1}^{N_t} \sum_{am=1}^{N_{am}} u_{am,t}^d \cdot K_{am}^d = K_{\mathrm{sum}}, \qquad (13)$$

where $u_{am,t}^c$, $u_{am,t}^d$ and $P_{am,t}$ are the charging status variable, discharging status variable and output power of the aging machine at time t, respectively, P_{am}^c and P_{am} are the charging and discharging power of the aging machines, respectively, K_{am}^c and K_{am}^d the amount of the completed charging and discharging battery packs of each aging machine per hour. Among them, $u_{am,t}^c$ and $u_{am,t}^d$ are optimisation variables.

3.2.3 Compressed air system operation constraints: The main constraints in the operation of the compressed air system include

SOC constraints of air storage tank, energy balance constraints of air storage tank, tank pressure constraints etc. Equation (14) defines the relationship between the current SOC and the previous SOC for the air storage tank. Equation (15) represents that the difference between the end SOC and the initial SOC must be within the allowable error range for the air storage tank. Equation (16) shows the upper and lower limits of the air storage tank. Equations (17) and (18) indicate that the start–stop status of air compressors is determined by the pressure in the gas tank. When the pressure of the air storage tank reaches the upper limit, the air compressor must shut down to prevent compressed air from entering the tank as shown in (17). In contrast, when the pressure of the air storage tank reaches the lower limit, the air compressor must start up to compress more air to the tank as defined in (18)

$$E_{ca,t} = E_{ca,t-1} - D_{ca,t} \cdot \Delta t + \eta_{ca} \cdot P_{ca,t} \cdot \Delta t, \qquad (14)$$

$$E_{ca,0} \cdot 0.8 \le E_{ca,N_t} \le E_{ca,0} \cdot 1.2, \qquad (15)$$

$$V_{ca} \cdot p_{ca,min} \le E_{ca,t} \le V_{ca} \cdot p_{ca,max}, \qquad (16)$$

$$E_{ca,t} + u_{ca,t} V_{ca} p_{ca,max} \le 1.1 V_{ca} p_{ca,max}, \qquad (17)$$

$$1.1 V_{ca} p_{ca,min} \le E_{ca,t} + u_{ca,t} V_{ca} p_{ca,min}, \qquad (18)$$

where $E_{ca,t}$ is the SOC of the air storage tank at time t, $u_{ca,t}$ and $P_{ca,t}$ represent the operation status variable and the output power of air compressor at time t, $D_{ca,t}$ is the released compressed-air volume of the compressed-air system at time t. $p_{ca,max}/p_{ca,min}$ is the allowable maximum/minimum pressure of the air storage tank. Among them, $u_{ca,t}$ is the optimisation variable, and $E_{ca,t}$ and $D_{ca,t}$ are state variables.

3.2.4 Ice storage system operation constraints: In this study, it is assumed that ice making and melting can be done during the operation of an ice storage system. Equation (19) defines the iterative relationship between the current cool energy and previous cool energy in the ice storage tank. Equations (20) and (21) refer to the upper and lower limits of the ice melting power and ice making power. Equation (22) refers to the upper and lower limits of the ice storage tank

$$E_{is,t} = E_{is,t-1} - M_{is,t} \cdot \Delta t + \eta_{is}^c \cdot P_{is,t} \cdot \Delta t, \qquad (19)$$

$$M_{is}^{min} \le M_{is,t} \le M_{is}^{max}, \qquad (20)$$

$$P_{is}^{min} \le P_{is,t} \le P_{is}^{max}, \qquad (21)$$

$$E_{is}^{min} \le E_{is,t} \le E_{is}^{max}, \qquad (22)$$

where $E_{is,t}$ is the SOC of the ice storage tank at time t, $M_{is,t}$ and $P_{is,t}$ are the ice melting amount and ice making power at time t, η_{is}^c is the ice making efficiency, $M_{is}^{min}/M_{is}^{max}$ is the allowable maximum/minimum ice melting amount, $P_{is}^{min}/P_{is}^{max}$ is the allowable maximum/minimum ice making power, $E_{is}^{min}/E_{is}^{max}$ is the lower/upper limit of the ice tank.

3.2.5 Energy balance constraints: Owing to the integration of the cold, heat, electric, and air energy in the factory system, the energy balance constraints will include air energy balance, cold energy balance, thermal balance, and electricity power balance.

i. *Air energy balance:* The air energy is mainly applied to maintain the aerodynamic load, such as pneumatic manipulator and pneumatic conveyor, which are necessary during the operation of the production line. The equilibrium relationship between the aerodynamic load of the production line and the air supply volume of the air compression system is defined in (23), where $D_{ca,t}$ represents the air supply of compressed air at time t, D_{pl} and D_{cl} are the volumes of compressed air used in each pack production line and cell production line in the unit time

$$D_{ca,t} = D_{pl} \cdot \sum_{pl=1}^{N_{pl}} u_{pl,t} + D_{cl} \cdot \sum_{cl=1}^{N_{cl}} u_{cl,t}. \qquad (23)$$

ii. *Cold energy balance:* Cold energy is mainly used for keeping the factory constant temperature, which is mainly related to the outdoor temperature. Even when the production line is in the stopped status, it still ought to maintain the temperature of finished products and semi-finished products of the battery packs. Equation (24) gives the cold energy balance constraint, where M_t represents the cold load at time t, η_{dis} and η_{ae} are the cooling efficiency of ice storage system and industrial air condition, $P_{ae,t}$ is the output of the industrial air conditioner. In particular, $M_{is,t}$ and $P_{ae,t}$ are optimised variables and the rest are fixed parameters

$$\eta_{is}^d M_{is,t} + \eta_{ae} P_{ae,t} = M_t. \qquad (24)$$

iii. *Thermal energy balance:* The thermal energy in the factory is used for the basic heat load, and drying the battery products. The totally thermal energy balance is shown in (25), where R_{MT} represents the thermoelectric ratio of micro gas turbine, $H_{base,t}$ represents the totally basic heat load, H_{pl}, H_{cl}, and H_{am} are the thermal energy consumption coefficients for each pack production line, cell production line and each aging machine, respectively, η_{MT}^h and η_b^h represent the thermal efficiency of micro-gas turbine and boiler, respectively

$$\eta_{MT}^h \frac{P_{MT,t}}{R_{MT}} + \eta_b^h P_{b,t} \ge H_{base,t} + H_{cl} \cdot \sum_{cl=1}^{N_{cl}} u_{cl,t}$$
$$+ H_{pl} \cdot \sum_{pl=1}^{N_{pl}} u_{pl,t} + H_{am} \cdot \sum_{am=1}^{N_{am}} u_{am,t}. \qquad (25)$$

iv. *Electricity power balance:* Electricity power balance mainly refers to the electric power balance between power supply and power consumption as shown in (26), where $P_{WT,t}$, $P_{PV,t}$, and $P_{es,t}$ refer to the output power of wind turbine, PV and battery, $P_{cl,t}$ and $P_{pl,t}$ are the electricity consumption of each cell production line and pack production line in time t, $P_{ae,t}$ is the output power of industrial air condition, $P_{EL,t}$ is the basic electricity load (see (26)) .

3.2.6 Factory production sequence constraints: Since each battery pack must be produced in strict accordance with the production sequence. Only if the amount of the battery cells produced reaches the critical amount at the beginning, the pack production line is allowed to start up as shown in (27). Apart from that, the production sequence of the aging lines must follow by the pack production lines as shown in (28). As for the total aging period, the battery pack is going to experience an hour of recharge after an hour of discharge in the aging machines as shown in (29), where K_{cl} represents the number of battery cells produced in each cell production line per hour, A_{cp} is the amount of battery cell

$$\sum_{MT=1}^{N_{MT}} P_{MT,t} + P_{WT,t} + P_{PV,t} + P_{es,t} + P_{grid,t}$$

$$= \sum_{am=1}^{N_{am}} P_{am,t} + \sum_{pl=1}^{N_{pl}} P_{pl,t} + \sum_{cl=1}^{N_{cl}} P_{cl,t} + P_{ca,t} + P_{is,t} + P_{ae,t} + P_{EL,t}. \qquad (26)$$
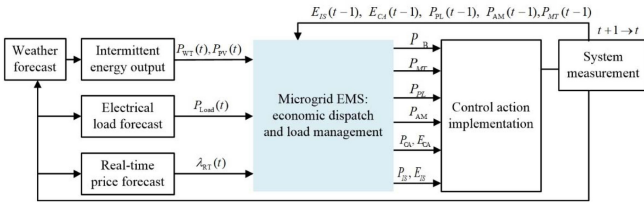
Fig. 2 *Control framework of factory EMS*

integrated into a battery pack, m is the minimum sum of the cell production time and cell warehouse waiting time, n is the minimum sum of the pack production time and pack warehouse waiting time

$$\sum_{t=1}^{h+m}\sum_{pl=1}^{N_{pl}} u_{pl,t}\cdot K_{pl}A_{cp} \leq \sum_{t=1}^{h}\sum_{cl=1}^{N_{cl}} u_{cl,t}\cdot K_{cl}, \quad \forall h\in[1,N_t], \quad (27)$$

$$\sum_{t=1}^{h+n}\sum_{am=1}^{N_{am}} u_{am,t}^{d}\cdot K_{am}^{d} \leq \sum_{t=1}^{h}\sum_{pl=1}^{N_{pl}} u_{pl,t}\cdot K_{pl}, \quad \forall h\in[1,N_t], \quad (28)$$

$$\sum_{t=1}^{h+1}\sum_{am=1}^{N_{am}} u_{am,t}^{c}\cdot K_{am}^{c} \leq \sum_{t=1}^{h}\sum_{am=1}^{N_{am}} u_{am,t}^{d}\cdot K_{am}^{d}, \quad \forall h\in[1,N_t]. \quad (29)$$

3.2.7 Factory warehouse constraints: Due to the fact that the battery pack must go through three stages from the material to the battery pack, the battery packs ought to enter into the warehouse between every two stages to wait for the next stage. Equations (30) and (31) show the continuity constraint and upper/lower limit of the cell warehouse. Equations (32) and (33) show the continuity constraint and upper/lower limit of the pack warehouse, where $S_{cp,t}$ is the capacity of the cell warehouse between the cell line and pack line, and $S_{cp}^{max}/S_{cp}^{min}$ is its maximum/minimum capacity. In addition, $S_{pa,t}$ is the capacity of the pack warehouse between the pack line and aging machines, and $S_{pa}^{max}/S_{pa}^{min}$ is its maximum/minimum capacity

$$S_{cp,t} = S_{cp,t-1} + \sum_{cl=1}^{N_{cl}} u_{cl,t}\cdot K_{cl} - \sum_{pl=1}^{N_{pl}} u_{pl,t}\cdot K_{pl}\cdot A_{cp}, \quad (30)$$

$$S_{cp}^{min} \leq S_{cp,t} \leq S_{cp}^{max}, \quad (31)$$

$$S_{pa,t} = S_{pa,t-1} + \sum_{pl=1}^{N_{pl}} u_{pl,t}\cdot K_{pl} - \sum_{am=1}^{N_{am}} u_{am,t}^{d}\cdot K_{am}^{d}, \quad (32)$$

$$S_{pa}^{min} \leq S_{pa,t} \leq S_{pa}^{max}. \quad (33)$$

4 MPC-based operation scheme

The optimal dispatch model of the lithium battery manufacturing plant in Section 3 is an open-loop day-ahead model based on the prediction of weather conditions, energy demand, and electricity price. Nevertheless, the schedule produced through this static method may not remain optimal in real-time scenarios with unexpected factors fluctuations. In this study, we handle this problem with an MPC strategy. In the MPC approach, a finite time horizon optimisation problem determining the series of optimal dispatch is solved before each step, but only the first action is implemented. MPC is considered as the closed-loop method due to its on-going adjustment of dispatch actions to compensate for prediction errors.

The whole centralised MPC scheme of the industrial integrated energy system and production dispatch is presented in Fig. 2. In the context of economic dispatch, factory EMS generates suitable set points for all controllable segments of production lines and the integrated energy system responding to the RTP from the electricity market, with the aim of minimising the total operation cost. Wind speed, load variations, and electricity prices belong to

uncertain disturbances, and their predictions are continuously updated by the factory EMS.

The unified modeling language (UML) model of the typical equipment for the factory EMS is presented in Fig. 3. The main types of DO in the CPS model contain the status information of DO (which show either the status of the process or of the function allocated to the LN class, such as the position of a breaker), measured values of DO (which is measured from the specific process or calculated in the functions such as currents, voltages, and power), controls DO (which are changed by commands such as MT control mode), and settings of DO (which are needed for the function to operate, such as energy power output).

Applying the above MPC approach, the energy cost minimisation problem with forecasted RTP and renewable energies can be implemented as shown in Fig. 4.

5 Case study and optimisation results

In this section, we use the proposed MPC-based operation scheme on a practical lithium battery manufacturing plant, and the selected lithium battery production lines are shown in Fig. 5.

The production lines and integrated energy system of this plant are the same as the system shown in Fig. 1. The plant has a 600 kW CHP-based micro-turbine, a 300 kW wind power generator, a 100 kW PV system, a 300 kW gas boiler, a 600 kW air conditioner, a 300 kW compressed air system, and a 700 kW ice storage system. The parameters of the production lines are shown in Table 1. The parameters of the compressed air system and ice storage system are listed in Tables 2 and 3.

5.1 Scheduling result analysis

Fig. 6 shows the comparison electricity demand of the lithium battery manufacturing plant in response to the RTP program scenario and non-response to the RTP program scenario.

When not responding to the RTP, the plant completes the production tasks according to the normal schedule and production rules. The production lines run from 8:00 to 18:00 every day. The battery packs need be aged immediately after production, and the aging process must follow the rule of charging immediately after the discharge is completed. Thus, from the beginning of the operation of the production line, the purchase of electricity gradually increased. Furthermore, due to the aging battery packs have discharge time, the purchasing electric power has also declined in the day.

When responding to RTP, the purchasing electric power was transferred to the lower price period by scheduling the energy production, energy storage, and consumption. During the peak price period, the discharging of the battery aging is processed, which even result in the plant selling electricity to the utility.

Detailed scheduling results for the production lines and integrated energy system are as follows:

5.1.1 Scheduling result of the production lines: Fig. 7 displays the scheduling result of the production lines. By tracking real-time prices, the MPC-based schedule transfers not only the production lines of cell and pack but also the charging process of the aging lines in the price valley period (2:00–10:00). In the price peak period, the discharge process of the aging lines is carried out to reduce the electricity consumption of the plant, and even to sell electricity to the utility.

5.1.2 Scheduling result of the cooling energy supply: Figs. 8 and 9 show scheduling results of the cooling energy supply and electricity consumption. The demand for cooling energy is mainly related to outdoor temperature changes. Although the production line loads shift to night, it still needs more cooling energy during the daylight. With the higher energy conversion efficiency, the industrial air conditioner maintains the full-load running state in the majority of the other periods. When the price is higher than a critical value, the industrial air conditioner stopped working, and mainly uses ice storage at peak price instead. Compared to the previous scenario which was only cooling by the air conditioner,
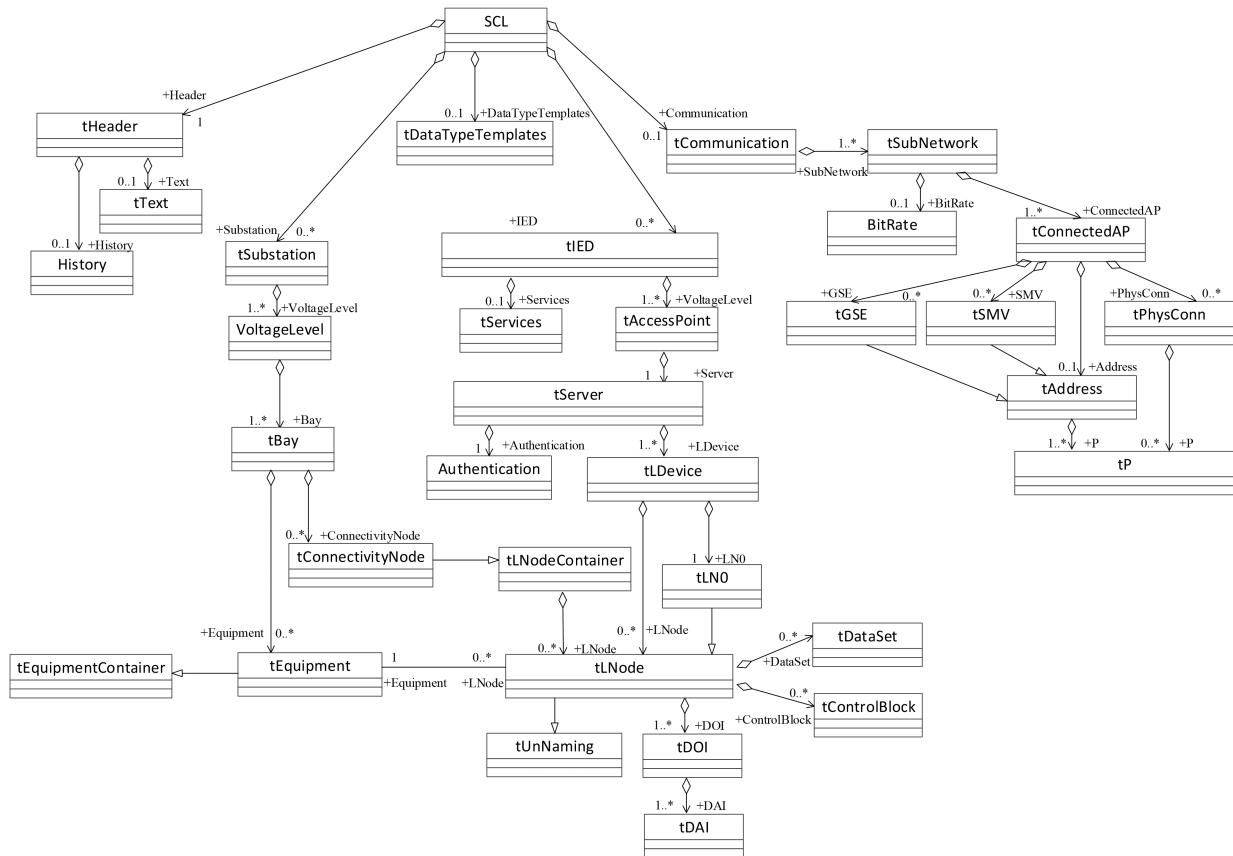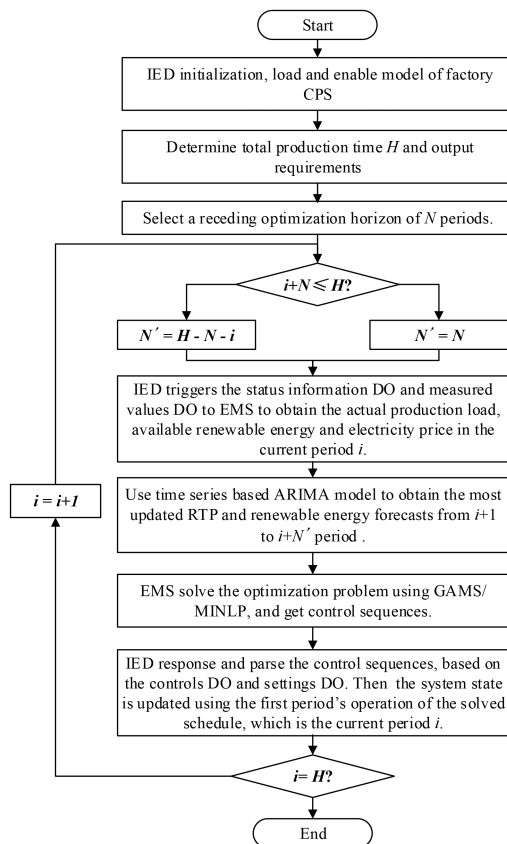
Fig. 3 *UML model for factory EMS*

Fig. 4 *Solution process of MPC-based scheme*

the ice storage reduces 22.50% cooling cost through the reasonable use of the electricity and cooling energy conversion during the peak-valley periods.

Fig. 5 *Photograph of the selected battery production lines*

Table 1 Parameters of the production line

	No.	Electricity demand, kWh	Heat demand, kWh	Compressed air demand, m^3/h
cell line	2	1000	200	100
pack line	2	800	120	80
aging machine	4	300/−200	40	0

Table 2 Parameters of compressed air system

Parameter	value
rated power, kW	300
conversion efficiency from electricity to compressed air	1
gasholder volume, m^3	40
maximum/ minimum pressure, Pa	7.5/3.5

5.1.3 Scheduling result of the thermal energy supply: Fig. 10 shows the scheduling result of the thermal supply. Apart from the basic thermal demand for industrial hot water, the demand for
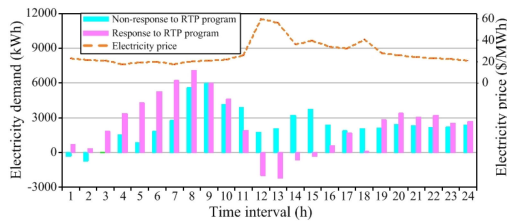
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Fig. 6 *Electricity demand of lithium battery manufacturing plant during each time interval*
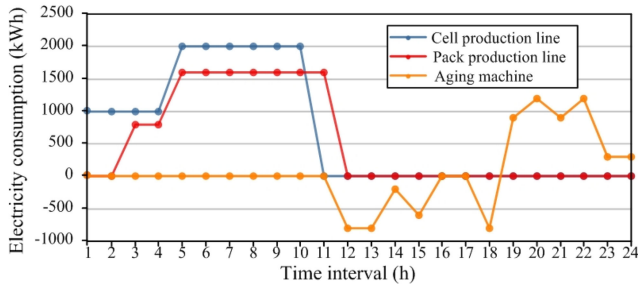

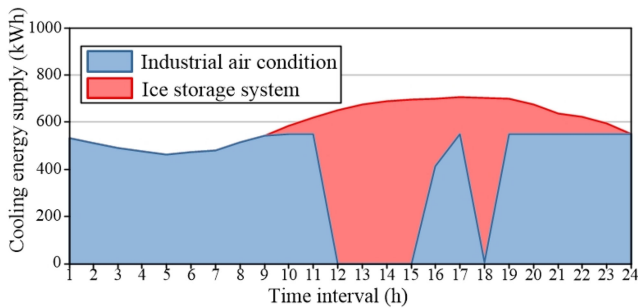**Fig. 7** *Scheduling result of the production line and aging equipment*

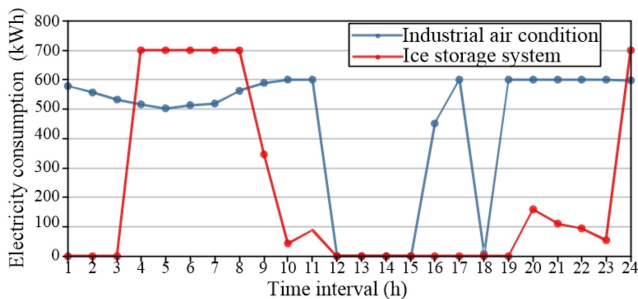**Fig. 8** *Scheduling result of cooling energy supply*

Fig. 9 *Electricity consumption of the cooling system*

thermal energy is mainly related to the production lines. When the production loads shift to the early in the morning, the heat consumption also shifts.

During the peak production period, the demands for electricity and thermal energy have both reached peak levels, and then micro-turbine provides both electric and heat energy with high efficiency for energy utilisation. Insufficient thermal energy is supplied by the gas boiler. In the thermal load demand valley period, the CHP micro-turbine shuts down because of the low economy in providing electricity, so the gas boiler bears all the thermal load.

5.1.4 Scheduling result of the compressed air supply: Fig. 11 shows the output power and storage change of the compressed air system. During the operation of the battery cell and pack production line, the amount of air released is basically consistent with the operation of production lines. In addition, the air compressor is driven to compress the air into the gasholder during the valley price period. To meet production demand in the next day, the air compressor is still running to keep the gas storage back to the specified pressure before the cycle ends.

Table 3 Parameters of ice storage system

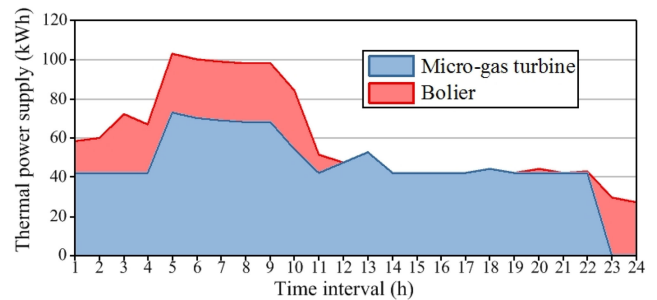| Parameter	value
conversion efficiency from electricity to cooling power	0.78
maximum/ minimum ice making power, kW	700/0
maximum/ minimum ice melting power, kW	700/0

Fig. 10 *Scheduling result of thermal energy supply*
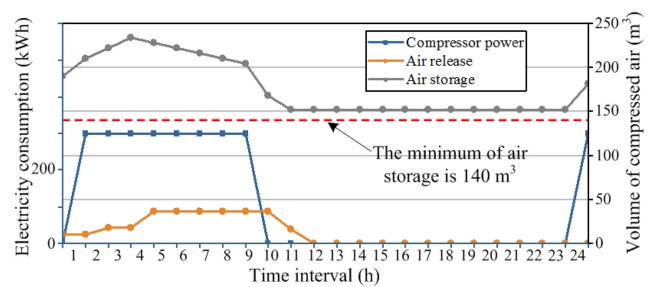

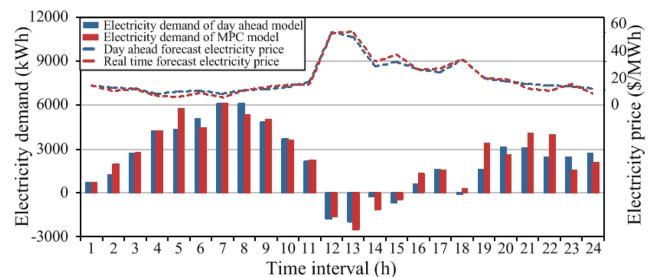**Fig. 11** *Scheduling result of compressed air supply*

Fig. 12 *Electricity demand of lithium battery manufacturing plant with the MPC-based schedule and day-ahead schedule*

5.2 Verification and economic analysis of the MPC-based scheme

To verify the effect of the proposed algorithm, we simulate two scenarios. Scenario one is use the proposed MPC-based scheme with the whole production lines and integrated energy system. Scenario two is use the day-ahead scheme with the whole production lines and integrated energy system. We assume that the day-ahead forecast error of the PV, wind power, and RTP follows a normal distribution with zero mean and the standard deviation of 10%, and the standard deviation is reduced to 3% in the real-time forecast. Fig. 12 compares electricity demand for lithium battery manufacturing plant in two scenarios. Relative to the day-ahead model, the MPC model can update the scheduling plan in time based on actual scheduling results and fluctuating predict information, which reduces the effect of uncertain factors on scheduling results.

For more comprehensive analysis of the key factors that influence the cost savings, we add three scenarios based on scenarios one and two for producing 10 MWh batteries. Scenarios three and four, respectively, use the proposed MPC-based and the day-ahead scheme with the integrated energy system and the production lines exclude the cell and pack lines. Scenario four is use the proposed MPC-based scheme only with the integrated

Table 4 Economical comparison of different scenarios

	Scenario one	Scenario two	Scenario three	Scenario four	Scenario five
total cost, $	245.99	297.21	321.67	326.87	330.39
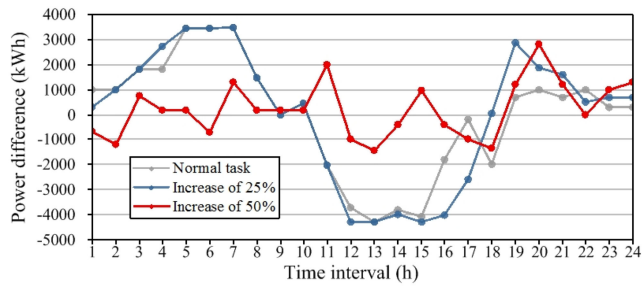
Fig. 13 *Effect of production line output requirement on the response capability to RTP*

energy system. Scenario five is non-response to RTP. Table 4 compares the economics of five scenarios.

As can be seen from Table 1, firstly, forecast error of RTP leads to less economic in the day-ahead schedule; secondly, the decrease of the amount of the production lines participating in the demand side response results in the economy cost rising and the relative optimisation effect of MPC model reducing gradually; thirdly, owing to the large share of the cell and pack production line in total DR, the full response economic difference between the day MPC model and ahead model reaches the largest compared to the part response economic difference.

5.3 Effect of production line output requirement on the response capability to RTP

DR capability is mainly reflected in the sensitivity of the response to the RTP, i.e. whether there are enough time slots to adjust the production schedule. We define the response capability as the difference between the electricity purchase with response to RTP and without response to RTP. Fig. 13 shows the effect of the production line output requirement on the capability response to RTP in three scenarios. The scenario one is normal production in a day, and scenarios two and three increase 25 and 50% of production line output per day on the basis of the scenario one, respectively.

The more production tasks to be completed within a given period, the longer the production line and integrated energy system will work, which result in decline in the response capability to RTP. Especially when the output requirement of production lines is increased by 50%, the system still has a certain response capability under the proposed MPC-based scheme, but it is close to the result of non-response to RTP.

6 Conclusion

Under the background of CPS and Industry 4.0, intelligent manufacturing has become an orientation. The CPS view of industrial multi-energy and production and use of RTP, instead of direct load control, to guide factory electricity consumption has become a trend. In this study, a cyber-physical energy system of a battery manufacturing plant consisting of electricity, heating, cooling, and compressed air is presented. We explored real-time industrial multi-energy and facilities management optimal dispatch model in the battery manufacturing plant for participating RTP DR Program. Then we probed the use of the MPC strategy in optimising the dispatch problem to counteract the unfavourable influences of uncertain factors. The proposed scheme was tested on a battery manufacturing plant and compared with the general day-ahead schedule. Results show that the proposed scheme was able to shift electricity demand from peak periods to valley periods, which reduced the energy costs. The proposed MPC-based scheme

outshines the day-ahead scheme in both economy and robustness, thus it is of high feasibility in practical applications. Through the analysis of different production scenarios, it shows that the production line is the most critical factor affecting the DR capability, and the energy consumption and production varies with its change. Also, the DR capability decreases with the increase of the production task due to the short time slot to adjust the schedule. In the near future, research should be carried out to apply the scheme to different industrial facilities.

8 References

[1] Ma, O., Alkadi, N., Cappers, P.*, et al.*: 'Demand response for ancillary services', *IEEE Trans. Smart Grid*, 2013, **4**, (4), pp. 1988–1995

[2] Aghaei, J., Alizadeh, M.-I.: 'Demand response in smart electricity grids equipped with renewable energy sources: a review', *Renew. Sustain. Energy Rev.*, 2013, **18**, pp. 64–72

[3] International Energy Agency: '*Key world energy statistics 2016*' (International Energy Agency, Paris, France, 2016). Available at http://www.iea.org/publications/freepublications/publication/key-world-energy-statistics.html

[4] Mohagheghi, S., Raji, N.: 'Dynamic demand response: a solution for improved energy efficiency for industrial customers', *IEEE Ind. Appl. Mag.*, 2015, **21**, (2), pp. 54–62

[5] Shoreh, M.H., Siano, P., Shafie-Khah, M.*, et al.*: 'A survey of industrial applications of demand response', *Electr. Power Syst. Res.*, 2016, **141**, pp. 31–49

[6] Mohagheghi, S., Raji, N.: 'Managing industrial energy intelligently: demand response scheme', *IEEE Ind. Appl. Mag.*, 2014, **20**, (2), pp. 53–62

[7] Diekerhof, M., Hecker, S., Monti, A.: 'Modeling and optimization of industrial compressed-air energy systems for demand response'. 2016 IEEE Int. Energy Conf. (ENERGYCON), Leuven, Belgium, 2016, pp. 1–6

[8] Zhang, X., Hug, G., Kolter, Z.*, et al.*: 'Demand response of ancillary service from industrial loads coordinated with energy storage', *IEEE Trans. Power Syst.*, 2017, **PP**, (99), pp. 1–1

[9] Mathaba, T., Xia, X., Zhang, J.: 'Analysing the economic benefit of electricity price forecast in industrial load scheduling', *Electr. Power Syst. Res.*, 2014, **116**, pp. 158–165

[10] Xu, X.Y., Hua, Q.: 'Industrial big data analysis in smart factory: current Status and research strategies', *IEEE. Access*, 2017, **5**, pp. 17543–17551

[11] Maffei, A., Srinivasan, S., Meola, D.*, et al.*: 'A cyber-physical systems approach for implementing the receding horizon optimal power flow in smart grids', *IEEE Trans. Sustain. Comput.*, 2018, **3**, (2), pp. 98–111

[12] Srikanth Reddy, K., Panwar, L., Panigrahi, B.K.*, et al.*: 'Demand side management with consumer clusters in cyber-physical smart distribution system considering price-based and reward-based scheduling programs', *IET Cyber-Phys. Syst. Theor. Appl.*, 2017, **2**, (2), pp. 75–83

[13] Saber, A.Y., Venayagamoorthy, G.K.: 'Efficient utilization of renewable energy sources by gridable vehicles in cyber-physical energy systems', *IEEE Syst. J.*, 2010, **4**, (3), pp. 285–294

[14] Xu, F.Y., Lai, L.L.: 'Novel active time-based demand response for industrial consumers in smart grid', *IEEE Trans. Ind. Inf.*, 2015, **11**, (6), pp. 1564–1573

[15] Ma, K., Hu, G., Spanos, C.J.: 'A cooperative demand response scheme using punishment mechanism and application to industrial refrigerated warehouses', *IEEE Trans. Ind. Inf.*, 2015, **11**, (6), pp. 1520–1531

[16] Reka, S.S., Ramesh, V.: 'Industrial demand side response modelling in smart grid using stochastic optimisation considering refinery process', *Energy Build.*, 2016, **127**, pp. 84–94

[17] Zhang, X., Hug, G., Kolter, Z.*, et al.*: 'Industrial demand response by steel plants with spinning reserve provision'. 2015 North American Power Symp. (NAPS), Charlotte, NC, USA, 2015, pp. 1–6

[18] Ding, Y.M., Hong, S.H., Li, X.H.: 'A demand response energy management scheme for industrial facilities in smart grid', *IEEE Trans. Ind. Inf.*, 2014, **10**, (4), pp. 2257–2269

[19] Zhang, X., Hug, G., Kolter, J.Z.*, et al.*: 'Model predictive control of industrial loads and energy storage for demand response'. 2016 IEEE Power and Energy Society General Meeting (PESGM), Boston, MA, USA, 2016, pp. 1–5