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A multi-agent based optimization of residential and industrial demand response aggregators

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ABSTRACT

Today's power systems are subject to the high penetration of renewable power. Volatility and intermittency of the renewable power need to be compensated through alternative forms of flexibility. This paper proposes a novel agent-based structure to integrate the flexibility potential of industrial and residential demands. In this approach, a central demand response provider (DRP) is suggested to coordinate the responsive plans of industrial and residential demand response aggregators (IDRA, RDRA). The suggested IDRA integrates the flexibility potential of whole production lines for two energy-intensive heavy industries, i.e. cement manufacture and metal smelting. Besides, the RDRA uses the thermal and electrical storage capabilities of thermostatically-controlled appliances (TCAs) and electrical storage systems linked with roof-top photovoltaic (ESS-RPV) sites through home energy management systems (HEMS). The integrated flexibility is traded in the electricity market to maximize the profit of the market participants in a competitive environment, instead of subsidizing the responsive consumers by supportive regulations. Finally, the suggested structure is tested on the Danish sector of the Nordic Electricity Market to show applicability and proficiency of the proposed approach. The results show that the integrated flexibility can safeguard the future of power systems against the intermittent power.

0. Nomenclature

In this section, the main nomenclatures are described. However, brief discussions are provided in the text where a mathematical formulation is presented.

A. Indices and sets

t	index of time, $t = \tau,\ldots, \tau_T$
ω	index of scenarios, $\omega = 1,\ldots,N_\omega$
D, A, B	indices of day-ahead, adjustment and balancing markets, $M = \{D, A, B\}$.
S	index of sold power to market
P	index of purchased power from market
ρ	index of cement plants, $\rho = 1,\ldots, \Theta$
κ	index of sub-processes in cement plant, $\kappa = 1,\ldots,K$
α	index of metal industries, $\alpha = 1,\ldots,N_\alpha$
β	index of potlines in metal industries, $\beta = 1,\ldots,N_\beta$
sm	index of smart milling in cement plants
ns	index of non-smart sub-processes in cement plants
sp	index of smart potlines in metal industries
i	index of IDRAs, $i = 1,\ldots,I$
r	index of RDRAs, $r = 1,\ldots,R$
h	index of household consumers, $h = 1,\ldots, H$

B. Constants

L	length of mill (m)
K_l	loading factor of mill (%)
D_m	effective diameter of mill (m)
J	fractional slurry hold up in the grinding media (%)
γ	grate design parameter of mill
A_m	total discharge grate open area (m^2)
η_c	current efficiency of the cells in potlines
R_w	thermal resistance of electric water heater (^{0}C/kW)
C_w	thermal capacitance of electric water heater (kWh/^{0}C)
M_w	capacity of electric water heater (kg)
$C_{p,r}$	heat capacity of room air (kJ/^{0}C)
$C_{p,w}$	heat capacity of water in floor heating pipe (kJ/^{0}C)
$C_{p,f}$	heat capacity of room floor (kJ/^{0}C)
$U_{f,r}$	heat transfer coefficients between floor and room (kJ/^{0}Ch)
$U_{r,a}$	heat transfer coefficients between room and ambient (kJ/^{0}Ch)
$U_{w,f}$	heat transfer coefficients between water and floor (kJ/^{0}Ch)

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η^{HPS}	coefficient of performance of heat pump
ρ	fraction of solar irradiation emitted on the floor
θ_{ε}	tolerance value for TCAs' temperature
Π_{max}^{RPV}	installed capacity of RPV (kW)
$\Pi_{max}^{battery}$	upper capacity of electrical batteries
δ^{Ch}	charging efficiency of the batteries
δ^{Dch}	discharging efficiency of the batteries
γ^{Ch}	rate of charging for batteries
γ^{Dch}	rate of discharging for batteries
$\Pi_{IDRA}^{min/max}$	lower/upper capacity of contracted consumers for IDRA (kW)
$\Pi_{RDRA}^{min/max}$	lower/upper capacity of contracted consumers for RDRA
$\widetilde{\Pi}_{ns}$	rated power consumption of non-smart sub-processes (kWh/ton)

C. Variables

λ^X	electricity price of market X∈{D, A, B}($/MWh)
Π^X	bid to market X∈{D, A, B}(MW)
Π^{TCA}	power consumption of TCAs (kW)
Π^{EWH}	power consumption of electric water heater (kW)
Π^{HPS}	power consumption of heat pump (kW)
Π^{Dch}	power injected from ESS to grid (kW)
Π^{Ch}	power charged from RPV to ESS (kW)
$\overline{\phi}$	production level of sub-process (ton/h)
ϕ	rate of output production of sub-process (ton/h)
η	ratio of output weight to input weight
ϑ	rotational speed of smart mills (rpm)
SoS	state of storage for cement siloes
SOC	state of charge for electrical batteries
Ψ	function of electricity consumption
Γ	function of production level
ϕ_o	ordered value of customers for heavy industries (ton)
ν	input voltage for potline (v)
θ_{hw}	temperature of hot water (°C)
θ_a	ambient temperature (°C)
m	hot water usage of households (kg/hour)
θ_r, θ_f, θ_w	temperature of room, floor and water in heat pump (°C)
Π^S	power of solar irradiation

D. Abbreviations

DR	demand response
DRA	demand response aggregator
IDRA	industrial demand response aggregator
RDRA	residential demand response aggregator
DRP	demand response provider
ESS	energy storage system
RPV	roof-top photovoltaic
TCA	thermostatically controlled appliance
ARIMA	auto regressive integrated moving average
HEMS	home energy management system
MAS	multi-agent system

In this section, the main nomenclatures are described. However, brief discussions are provided in the text where a mathematical formulation is presented.

1. Introduction

1.1. Motivation and problem description

The penetration of renewable energies is increasing in the power systems all over the world. In the Danish sector of the Nordic Electricity Market, the share of renewable power is scheduled to be increased from 5.5 GW (44% of total installed capacity) at 2015 to 6.4 (55%) and 8.1 GW (60%) at 2020 and 2025, respectively. On the other hand, Denmark has decided to decrease the thermal power plant capacity until 2030. In this way, the capacity of central combined heat and power (CHP) is expected to drop from 3800 MW to 1900 MW in 2030, a 50% reduction [1]. Increasing the penetration of renewable energies, the main concern is that how to hedge against the volatility and intermittency of the renewable power [2]. Although recent studies have proposed to coordinate the operation of the renewable resources with battery storage system [3] and pumped storage hydro [4], more flexible resources are needed to facilitate the integration of the renewable energies to the power systems. In this way, if enough strategic reserve is not prepared, the future power systems may be at risk. In order to overcome the problem, there are some kinds of heavy industries whose consumption behaviors have structural flexibility inherently. Moreover, in the residential sector, some appliances can provide operational flexibility to the power system. As a result, regarding different kinds of demands, i.e. residential, commercial and industrial consumers, if the flexibility potential is adequately integrated and coordinated, demand-side flexibility can ensure the secure operation of the power system when a renewable power shortage occurs in the supply-side. Demand response aggregator (DRA) is a practical suggestion to integrate the power flexibility, from residential to industrial consumers, into a power system. Consequently, the main challenge is that how to propose an applicable structure for the DRAs to overcome the intermittency of renewable power.

1.2. Literature review

Demand Response Programs are defined as opportunities for consumers to play a significant role in the operation of the electric grid by reducing or shifting their electricity usage during peak periods in response to time-based rates or other forms of financial incentives [5]. Residential and industrial consumers are the most energy-intensive sectors of power systems. According to the report of U.S. Energy Information Administration, residential and industrial sectors consume 22% and 36% of the total world electricity use in 2018, respectively [6].

In the residential sector, the home energy management system (HEMS) is defined as the optimal system providing energy management services in order to efficiently manage and monitor electricity consumption, generation, and storage in the smart houses [7]. The main controllable household appliances can be classified into three categories as (1) Thermostatically-controlled appliances (TCAs) (2) Non-thermostatically-controlled appliances (Non-TCAs) (3) Electrical storage systems (ESS).

Traditionally, TCAs are subject to DR programs. The TCAs have thermal storage capacity and therefore, are good candidates for household-level DR programs. In this way, electric water heaters [8], heat pumps [9], air conditioning systems [10] and heat ventilation [11] attracted many attentions in recent studies. In contrast, the Non-TCAs, e.g. washing machines or tumble dryers, have lower compatibility with the DR programs [12]. Regarding emerging residential-level battery market, the household preferences for battery attributes and functionality are increasing. As a result, studying the role of ESSs on power system property [13], household cost saving [14] and electricity price [15] are the subjects of newly suggested HEMS. Minimization of energy cost is the main objective of the HEMS studies. Besides, maximizing the occupants' comfort level [16], minimizing the peak to average ratio (PAR) [17] and minimizing the emission [18] are multiple objectives with a higher prominence in the literature of the HEMS.

In the industrial sector, the heavy industries, e.g. cement plants [19], steel milling [20] and paper/wood pulp [21] can provide operational flexibility to the power system through DR programs. The key feature of demand-side management for heavy industries is that if the DR programs are not well-coordinated, an interruption of a production line may lead to a violation of daily production constraints. In addition, some sub-processes of heavy industries, e.g. the kiln system in cement plants, must run continuously without regular shutting down. Implementing DR programs on these sub-processes, a heavy financial loss may be imposed on the industries due to serious damages to the equipment.

Industrial consumers have traditionally participated in classic DR programs, e.g. the energy market, for load curtailment during infrequent peak periods [22]. In contrast, by increasing the penetration of intermittent power, the ancillary services are more needed as the DR programs for the industrial sector. In this way, replacement reserve, regulation, and spinning/non-spinning reserve are the most prominent types of DR programs for ancillary services [23]. The major differences between the classical and current applications of DR programs for heavy industries are as follows: (1) the reduction of notification time and (2) the increase of smartness level and technical requirements to immediately respond to the systems' signal [23]. The reaction speed for the ancillary services is from a few seconds to lower than 30 min. Consequently, in order to propose a DR program for heavy industries, detailed information about the operational characteristics of different sub-processes is needed.

Recently, a fuzzy-based self-scheduling study is done to maximize the profit of a cement industry in the electricity market [24]. In [25] low-carbon strategies of ancillary services for cement plants and aluminum smelting industry are analyzed. A coordination method based on model predictive control is proposed in [26] for cement crushing to provide regulation and ancillary services for the power system. In [27] three alternative process models for the energy-intensive melt shop of a steel plant are proposed with considering the energy constraints. In another study [28], an energy management optimization is proposed for a steel mill industry. The key feature of the problem is that the improvement is based on not only the optimization of power consumption but also the optimization of material usage and the quantity of the final product.

1.3. Paper contributions and organization

In the residential sector, the common feature of the studies in the literature is that the role of DR programs is not evaluated comprehensively in the competitive structure of electricity markets. In the same way, to the best of our knowledge, no research study is carried out to integrate the flexibility potential of different heavy industries. In addition, most research studies tend to subsidize the demand-side flexibility through incentive-based DR programs. Against the background, this paper suggests a novel structure to integrate the flexibility potential of residential consumers and different kinds of heavy industries through a multi-agent system (MAS). In this paper, a practical structure for the demand response aggregators (DRAs), including industrial demand response aggregator (IDRA) and residential demand response aggregator (RDRA), is proposed to integrate the power flexibility of the contracted consumers. The DRAs are able to make decisions according to their own demand bids, instead of subsidizing by supportive regulations. In this paper, power flexibility from smart industrial mills with variable speed and smelting pots with variable voltage is suggested for the first time. The proposed optimization approach maximizes the profit of the market participants in the energy and ancillary services markets. All in all, the contributions of the paper can be stated as follows:

(1) Developing process-based electricity load models for cement manufacturing and aluminum smelting plants to economically and efficiently incorporate industrial demand flexibility in a DR application.
(2) Scheduling the industrial operation of variable speed mills and variable voltage pots to respond to the DR programs by optimizing the electricity consumption.
(3) Developing a market-based method to coordinate profit-based entities such as IDRA and RDRA through bidding strategy in a MAS framework.

In order to achieve the aims, the complex problem is split into different simpler agents. The proposed agents are located in three layers according to their characteristics. The DR values are aggregated from layer to layer to be traded in the electricity market.

The rest of paper is organized as follows. Section 2 illustrates the general framework of the MAS. The structure of the first layer is described in Section 3. Besides, the agents of second and third layers are illustrated in Sections 4 and 5, respectively. In Section 6, the coordination mechanism of the multi-layer structure is addressed. Simulation results and discussions are presented in Section 7. Finally, the approach is concluded in Section 8.

2. Multi-agent system

Increasing the size of problems, modeling and computation tasks are becoming much more complex. In the today's restructured electricity markets, the market operators have to hedge against the increasing complex structure to provide the market participants with adequate tools to adapt themselves to the new market structure. To overcome the problem, the multi-agent system (MAS) is a solution to split the complex problem into simpler ones. In this way, the market model can be easily simulated by different agents and may be enlarged by the new emerged entities. In this study, the proposed approach optimizes the market strategies for different entities, i.e. DRP, IDRA and RDRA. In addition, two kinds of consumers, including industrial and residential consumers, are simulated. For this reason, in order to simulate the complex problem, the problem framework is suggested as a MAS structure. In this way, the major advantages of the MAS structure include: (1) mutual interactions between market-based entities can be modeled and investigated easily (2) difficulties in modeling of different entities are organized as different agents located in sublayers.

The key components of the MAS include a number of market-based agents and a simulation platform with a graphical user interface. The agents represent market players, including demand response provider (DRP), industrial demand response aggregators (IDRA), residential demand response aggregator (RDRA) and large/small consumers, i.e. heavy industrial plants and household consumers. The simulation platform is implemented in GMAS and MATLAB. Moreover, GAMS Java API is currently developing to provide a Java programming interface to the GAMS.

In order to simulate the MAS, the market participants are split into different agents organized in three layers. The agents with the same specifications are located in the same layer. Fig. 1 depicts framework of the proposed multi-layer agent-based structure.

In order to demonstrate the main measures of the proposed agents, a description is provided for the agents in three layers as follows.

In the first layer, the demand response provider (DRP) participates in three successive trading floors, i.e. day-ahead, adjustment and balancing markets, on behalf of the second layer agents (IDRA and RDRA),

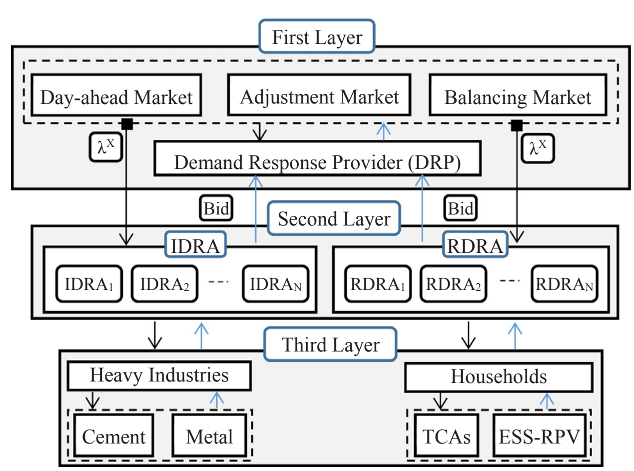

Fig. 1. Framework of the multi-agent system.

to procure energy for the contracted responsive consumers. The DRP coordinates three kinds of DR programs for DRAs: (1) long notice-based DR programs like time of use (TOU) or critical peak pricing (CPP) through participating in the day-ahead market (2) mid notice-based DR programs through taking part in the adjustment market and (3) short notice-based DR programs, i.e. contingency programs like spinning reserve and power regulation, through participation in the balancing market.

In the second layer, the IDRA and RDRA play an intermediary role between DRP and responsive consumers. The DRAs construct demand bids to be sent to the DRP on one side and optimize the operation of the contracted consumers on the other side. The DRAs are profit-based entities which participate in DR programs based on their own demand bids, instead of subsidizing the responsive consumers. In fact, no supportive regulations are considered to reward the flexible consumers with incentive prices for participating in DR programs.

Finally, in the third layer, two kinds of responsive consumers, i.e. residential and industrial consumers, are considered. Regarding the heavy industries, two energy-intensive consumers, including cement plants and aluminum smelting, are addressed. In this way, the whole production lines of the factories are formulated mathematically to investigate the DR opportunities compatible with DR programs on long, mid and short notices. On the other hand, the household consumers having HEMS are considered. The HEMS uses the thermal and electrical storage capabilities of TCAs and ESS-RPV to respond to the DR programs.

In order to show the interaction between different agents, e.g. sending data, Fig. 2 describes the transfer of information from an agent to another one. Based on the figure, the DRP is located in the supply-side and the responsive consumers, i.e. heavy industries and household consumers, stand on the demand-side. The DRAs, including IDRAs and RDRAs, play an intermediary role between the supply and demand sides. Firstly, in the demand-side, the DRAs receive energy consumption data of the contracted consumers. Regarding the heavy industries, the main data include electricity consumption of the whole production lines and the ordered value of cement/aluminum by the customers. In the residential sector, consumption data of household appliances and the residents' convenience constraints are the most important data. The main duty of the DRAs is to optimize the operation of the consumers to achieve two main aims: (1) provide power flexibility to the power system through DR programs (2) optimize the energy consumption of the consumers. Therefore, in the supply-side, the DRAs receive the data of electricity price and DR programs from the DRP. Aggregating the data from the electricity market with the received consumption data from consumers, the DRAs construct demand bids. The DRAs send the demand bids to the DRP; therefore, the DRP participates in the electricity market on behalf of the DRAs. Clearing the electricity market, the DRAs determines the final operation schedule for the contracted consumers during the next 24 h. Note that the DRP is considered to prevent the participation of a large number of DRAs in the electricity market individually. In fact, the DRP aggregates the demand bids of the DRAs to participate in the electricity market on behalf of them. However, if the number of DRAs is low or the participation of the DRAs is not limited by the market regulations, the DRP can be omitted from the approach.

After giving a general overview of the suggested approach, mathematical models of the agents are described in the next sections.

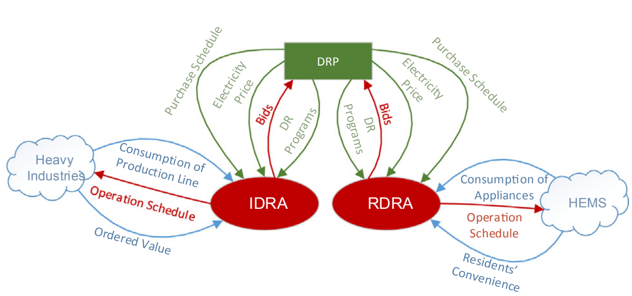

Fig. 2. Information flow diagram between market agents.

3. Agent in the first layer

In the first layer, the DRP is a market-based agent which collects the demand bids of IDRA and RDRA to participate in the electricity market on behalf of them. In the big enough power systems, there are many DRAs whose coordination should be provided by a market-based entity. Moreover, the DRAs cannot participate in the electricity market individually. For this reason, the DRP is suggested to play an intermediary role between the DRAs and wholesale electricity market. The DRP has two main duties. First of all, the DRP integrates all the demand bids from the DRAs located in the second layer. Afterward, the DRP participates in the electricity market, on behalf of the contracted DRAs, to procure their required energy. The major reason for locating the DRP in the first layer is to prevent the participation of many small-scale DRAs in the electricity market individually. However, the DRP may be omitted if the DRAs are enough large-scale or the number of market participants is reasonable.

Due to the responsive characteristics of the consumers, the aim of DRP is to maximize the profit of contracted DRAs. Therefore, market clearance in the first layer can be stated as follows:

$$\underset{(\Pi_{t,i}^{X}(\omega),\Pi_{t,r}^{X}(\omega))}{Min}\left[\sum_{t=\tau}^{\tau_T}\sum_{X\in M}\left[\sum_{i=1}^{I}\Pi_{t,i}^{X}(\omega)\times\lambda_t^{X}(\omega)+\sum_{r=1}^{R}\Pi_{t,r}^{X}(\omega)\times\lambda_t^{X}(\omega)\right]\right] \tag{1}$$

$$(\Pi_{\mathrm{IDRA}}^{\min}+\Pi_{\mathrm{RDRA}}^{\min})\leqslant\sum_{X\in M}\left[\sum_{i=1}^{I}\Pi_{t,i}^{X}(\omega)+\sum_{r=1}^{R}\Pi_{t,r}^{X}(\omega)\right]\leqslant(\Pi_{\mathrm{IDRA}}^{\max}+\Pi_{\mathrm{RDRA}}^{\max}) \tag{2}$$

Eq. (1) determines the best economic solution in the market clearance procedure. In this model, the DRP integrates the demand bids of IDRAs i = {1,…,I} and RDRAs r = {1,…,R} by participating in three successive trading floors of the electricity market X = {D, A, B}, i.e. day-ahead (D), adjustment (A) and balancing markets (B). The inequality (2) restricts the power traded in the three floors of the electricity market to min/max contracted power of IDRA and RDRA. The main reason is to prevent from speculating on the electricity market.

4. Agents in the second layer

In the second layer, two kinds of demand response aggregators, i.e. IDRA and RDRA, are addressed. The DRAs are profit-based agents who play an intermediary role between the first layer (supply-side) agent and the third layer (demand-side) agents. The DRAs have two main duties:

(1) Collecting the operational constraints of the contracted consumers to participate in DR programs.
(2) Constructing demand bids to be sent to the DRP located in the first layer.

In fact, the DRAs are entities who provide power flexibility to the power system on one side and optimize the operation cost of the contracted consumers on the other side. Due to the different characteristics of consumption pattern for industrial and residential consumers, the DRA for these two kinds of consumers is different inherently.

Regarding the heavy industries, the IDRA integrates the flexibility potential of the two energy-intensive industries, i.e. cement manufacture and metal smelting. The IDRA collects the operational constraints, e.g. daily production order, daily maintenance plans, and crew constraints. Afterward, the IDRA constructs demand bids to procure energy for the contracted responsive consumers. In this way, the whole production lines of the industries are investigated to maximize the profit from trading DR in the electricity market.

In the residential sector, the RDRA has a two-way communication with the HEMS. The HEMS is a technology platform comprised of both hardware and software that allows the household residents to monitor energy usage and production and to manually control and/or automate the use of energy within a household. The HEMS uses the thermal and electrical storage capabilities of TCAs and ESS-RPV, respectively. The RDRA collects the convenience constraints of the households through the HEMS. Afterward, the RDRA constructs demand bids to participate in the DR programs on behalf of the responsive households.

It is worth mentioning that the IDRA and RDRA participate in the DR programs to maximize their own profits. From the consumers' viewpoint, the profit maximization means energy cost minimization. In fact, the DRAs can purchase power from energy market with low price and sell it to the balancing market with a high price if the contracted consumers respond to the DR programs in near real-time condition. In this situation, the electricity bills of the consumers reduce noticeably. The difference between the energy costs is interpreted as the profit obtained from trading DR values in the electricity market. The DRAs take a predefined percentage commission on the profit they make. It is supposed that the DRAs's income is equal to a predefined percentage of the consumers' profit (income = k × profit, $0 \le k \le 1$). In this paper, the income factor k is 0.1 which is suggested in a recent study [29]. Therefore, both the DRAs and responsive consumers take the advantage of DR programs in terms of profit maximization and cost minimization, respectively.

In this way, they use the potential of electricity price containing important data about deficit/excess of renewable power in the electricity market. Therefore, they construct their own demand bids instead of subsidizing by governmental entities. In fact, no supportive regulations are considered to motivate the responsive consumers to participate in the DR programs. In the proposed approach, the competitive structure of the electricity market makes it possible to maximize the participation of the consumers in the DR programs without needing to allocate incentive costs. All in all, the objective of the IDRA and RDRA can be formulated as the following three-stage stochastic programming:

$$\begin{aligned}\underset{(\Pi_t^D(\omega),\Pi_t^A(\omega),\Pi_t^B(\omega))}{\text{Minimize}[\text{Expected Cost}]}=Min\Bigg[\sum_{\omega=1}^{N_\omega}\sum_{t=\tau}^{\tau_T}[\mathrm{E}_{\omega_1}[\lambda_t^D(\omega_1)\times\Pi_t^D(\omega_1)\\ +\mathrm{E}_{\omega_2|\omega_1}[\lambda_t^A(\omega_2)\times\Pi_t^A(\omega_2)+\mathrm{E}_{\omega_3|\omega_1,\omega_2}[(\lambda_t^B(\omega_3)\times\Pi_t^B(\omega_3))]]]]\Bigg]\end{aligned} \tag{3}$$

The three terms in the objective function (3) describe the costs result from purchasing energy from day-ahead, adjustment and balancing markets, respectively. The structure of objective function for both IDRA and RDRA is the same as Eq. (3). However, because of major differences between the consumption behavior of the contracted consumers, the DRAs are subject to the different constraints which are described in the following subsections.

In the stochastic programming Eq. (3), the electricity price is considered as a stochastic variable with imperfect data. To model the uncertainties associated with the electricity price, Normal PDF (probability density function) is used with mean price μ and standard deviation σ. Moreover, in order to cover the range of prices that a consumer may pay in the market, the time-series-based seasonal ARIMA is used to generate price scenarios.

4.1. Industrial demand response aggregator

The IDRA integrates the flexibility potential of two heavy industries, i.e. cement and metal, into the three trading floors of the electricity market. The objective function (3), for the IDRA, is subject to the following constraints:

$$\forall\, X \in \mathrm{M}:\;\; \Pi_t^X(\omega) = \Pi_{t,P}^X(\omega) - \Pi_{t,S}^X(\omega) \tag{4}$$

$$0 \leqslant \Pi_t^D(\omega_1) \leqslant \left(\sum_{\rho=1}^{\Theta}\sum_{\kappa=1}^{\mathrm{K}}\Pi_t^{\rho,\kappa} + \sum_{\alpha=1}^{N_\alpha}\sum_{\beta=1}^{N_\beta}\Pi_t^{\alpha,\beta}\right) \tag{5}$$

$$|\Pi_t^A(\omega_2)| \leqslant \left(\sum_{\rho=1}^{\Theta}\sum_{\kappa=1(\kappa\neq CP)}^{\mathrm{K}}\Pi_t^{\rho,\kappa} + \sum_{\alpha=1}^{N_\alpha}\sum_{\beta=1}^{N_\beta}\Pi_t^{\alpha,\beta}\right) \tag{6}$$

$$|\Pi_t^B(\omega_3)| \leqslant \left(\sum_{\rho=1}^{\Theta}\sum_{\kappa\in\{KFP,FG\}}\Pi_{t,sm}^{\rho,\kappa} + \sum_{\alpha=1}^{N_\alpha}\sum_{\beta=\mathrm{B}_1}^{N_\beta}\Pi_{t,sp}^{\alpha,\beta}\right) \tag{7}$$

$$\Pi_t^D(\omega_1) + \Pi_t^A(\omega_2) + \Pi_t^B(\omega_3) = \sum_{\rho=1}^{\Theta}\Pi_t^\rho + \sum_{\alpha=1}^{N_\alpha}\Pi_t^\alpha \tag{8}$$

Eq. (4) describes the net power traded in the day-ahead, adjustment and balancing markets. The inequalities (5)–(7) bound the power traded in the day-ahead, adjustment and balancing markets, respectively. In this way, the power purchased from the day-ahead market is restricted to the sum of energy consumption in sub-processes of the two factories which can be scheduled 24 h prior to the energy delivery time (long notice-based DR programs). The power traded (purchased/sold) in the adjustment market is restricted to the electricity consumption of sub-processes which can be switched off/on 60–10 min prior to the energy delivery time (mid notice-based DR programs). The power traded (purchased/sold) in the balancing market is limited to the energy consumption of the smart sub-processes with the ability to change power within a few minutes (short notice-based DR programs). Finally, Eq. (8) explains the power balance for the IDRA.

4.2. Residential demand response aggregator

The RDRA integrates the flexibility potential of residential consumers through the HEMS. The objective function of the RDRA, i.e. Eq. (3), is subject to the following constraints:

$$\forall\, X \in \mathrm{M}:\;\; \Pi_t^X(\omega) = \Pi_{t,P}^X(\omega) - \Pi_{t,S}^X(\omega) \tag{9}$$

$$0 \leqslant \Pi_t^D(\omega_1) \leqslant \sum_{h=1}^{\mathrm{H}}\Pi_{\mathrm{t,h}}^{\mathrm{TCA}} \tag{10}$$

$$|\Pi_t^A(\omega_2)| \leqslant \sum_{h=1}^{H}\Pi_{\mathrm{t,h}}^{\mathrm{TCA}} \tag{11}$$

$$|\Pi_t^B(\omega_3)| \leqslant \sum_{h=1}^{H}\Pi_{\mathrm{t,h}}^{\mathrm{Dch}} \tag{12}$$

$$\Pi_t^D(\omega_1) + \Pi_t^A(\omega_2) + \Pi_t^B(\omega_3) = \sum_{h=1}^{H}(\Pi_{\mathrm{t,h}}^{\mathrm{TCA}} + \Pi_{\mathrm{t,h}}^{\mathrm{Dch}}) \tag{13}$$

Eq. (9) describes the net power traded by the RDRA in the day-ahead, adjustment and balancing markets. Eqs. (10)–(12) determine the household appliances which are subject to DR in the time-oriented program. First of all, the electricity consumptions of the TCAs are scheduled in the day-ahead market through Eq. (10). Secondly, the TCAs with the ability to change power within 60–10 min notice are incorporated into the adjustment market through Eq. (11). The ESSs with the response capability on short notice (a few minutes) are integrated to regulate power in the balancing market through Eq. (12). Finally, the power balance is denoted by Eq. (13).

5. Agents in the third layer

The consumers of the power system cannot directly participate in the electricity market to procure their energy. Therefore, each group of consumers with the same consumption behavior is connected to an associated DRA. The DRA has a direct connection to the contracted consumers to procure their energy on one side and provide operational flexibility to the power system on the other side. In the following subsections, the consumption behavior of the understudied industrial and residential consumers is formulated mathematically.

5.1. Responsive cement manufacturing plants

In order to investigate the role of cement industries in providing power flexibility, the whole production line of a smart cement factory is formulated mathematically. The production line of the modern cement plant can be modeled through four sub-processes as (1) Crushing (C) (2) Kiln Feed Preparation (KFP) (3) Clinker Production (CP) and (4) Finish Grinding (FG). There is a storage between every two sub-processes to store the output production. It can provide flexibility to the power system by shutting down the process when a power shortage occurs in the electricity network. In addition, two Smart-Variable Speed (S-VS) milling systems are considered in the raw mill and cement mills in KFP and FG, respectively. Against the studies in the cement industries, this paper proposes a mathematical formulation for the whole production line of a modern cement manufacturing plant. In this way, the electric energy consumptions and production levels are formulated for four abovementioned sub-processes individually. Moreover, the storage capacity of siloes, variable energy consumption and variable output production of smart S-VS mills are formulated. The proposed structure provides a comprehensive overview of electricity consumption in cement plants in which is barely seen in the literature. The suggested model is validated by the actual operation of the cement manufacturing industries.

In this paper, the cement plant can provide power flexibility in two ways as follows:

(1) Adjusting the rotational speed of S-VS raw and cement mills
(2) Turning the sub-process off and using the stored materials in the siloes.

The mathematical structure of the production line is suggested as the following matrix space:

$$\Pi_t^{\rho} = \sum_{\kappa=1}^{K} \Pi_t^{\rho,\kappa} \tag{14}$$

$$\Pi_t^{\rho,\kappa} = \sum_{s=1}^{S} \Pi_{t,sm}^{\rho,\kappa} + \sum_{n=1}^{N} \Pi_{t,ns}^{\rho,\kappa} \tag{15}$$

$$[\Pi_{t,ns}^{\rho,\kappa}] = [\widetilde{\Pi}_{t,ns}^{\rho,\kappa}] \times [\overline{\phi}_{t,ns}^{\rho,\kappa}] \tag{16}$$

$$[\Pi_{t,sm}^{\rho,\kappa}] = [\Psi(\vartheta_{t,sm}^{\rho,\kappa})] \times [\overline{\phi}_{t,sm}^{\rho,\kappa}] \tag{17}$$

$$[\overline{\phi}_{t,ns}^{\rho,\kappa}] = [\eta_{t,ns}^{\rho,\kappa}] \times [\underline{\phi}_{t,ns}^{\rho,(\kappa-1)}] \tag{18}$$

$$[\overline{\phi}_{t,sm}^{\rho,\kappa}] = [\eta_{t,sm}^{\rho,\kappa}] \times [\underline{\phi}_{t,ns}^{\rho,(\kappa-1)}] \times [\Gamma(\vartheta_{t,sm}^{\rho,\kappa})] \tag{19}$$

$$[SoS_t^{\rho,\kappa}] = [SoS_{t-1}^{\rho,\kappa}] + [\overline{\phi}_t^{\rho,\kappa}] - [\underline{\phi}_t^{\rho,\kappa}] \tag{20}$$

The model comprises a set of cement industries $\rho = \{1,2,\ldots,\Theta\}$. The production line of each factory contains $K \in N_+$ sub-processes. Eq. (14) describes the total electric energy consumption of the cement plants Π_t^{ρ} (MW) as a summation of $K \in N_+$ sub-processes, i.e. $\kappa = 1,\ldots,K$ including C, KFP, CP and FG. Eq. (15) divides the consumption of a sub-process $\Pi_t^{\rho,\kappa}$ (MW) into smart $\Pi_{t,sm}^{\rho,\kappa}$ (MW) (if any) and non-smart $\Pi_{t,ns}^{\rho,\kappa}$ (MW) sections. The smart sections include the raw mill and cement mills in KFP and FG, respectively. The other sections are considered non-smart ones. Eq. (16) illustrates the electric energy consumption of the non-smart sub-process κ as a function of rated electricity consumption $\widetilde{\Pi}_{t,ns}^{\rho,\kappa}$(MWh/t) and production level $\overline{\phi}_{t,ns}^{\rho,\kappa}$(t/h). Eq. (17) describes the electric energy consumption of the smart sub-processes, i.e. KFP and FG, as a function of S-VS electricity consumption Ψ (MWh/t) and production level $\overline{\phi}_{t,sm}^{\rho,\kappa}$(t/h). The S-VS electricity consumption Ψ shows the energy consumption of raw and cement mills in the KFP and FG as a function of variable rotational speed $\vartheta_{t,sm}^{\rho,\kappa}$ (rpm). Eq. (18) illustrates the relation between the rate of output $\underline{\phi}_t^{\rho,\kappa-1}$ and input $\overline{\phi}_t^{\rho,\kappa}$ weight for each non-smart sub-process κ. Note that, in the cement manufacturing process, weight losing/gaining in sub-process κ occurs due to some chemical/physical changes, e.g. water vaporizing or gypsum added to cement clinker. In this way, η describes the ratio of output weight to input weight. In the smart sub-processes, due to variable speed of raw and cement mills, the production level cannot be a fixed rate. In fact, in the S-VS sections, the production level depends on the rotational speed $\vartheta_{t,sm}^{\rho,\kappa}$ (rpm) of the mills. For this reason, Eq. (19) illustrates the production level of the smart sub-process κ as a function of variable production level Γ. The variable production level Γ itself describes the production level as a function of rotational speed. Eq. (20) illustrates the State of Storage for siloes as a function of previous SoS $SoS_{t-1}^{\rho,\kappa}$, input and output production.

The proposed model is bounded by the following equalities and inequalities:

$$\sum_{t=\tau}^{\tau+\tau_N} \underline{\phi}_t^{\rho,(\kappa=K)} = \phi_o^{\rho} \tag{21}$$

$$\overline{\phi}_{\min}^{\rho,\kappa} \leqslant \overline{\phi}_t^{\rho,\kappa} \leqslant \overline{\phi}_{\max}^{\rho,\kappa} \tag{22}$$

$$\underline{\phi}_{\min}^{\rho,\kappa} \leqslant \underline{\phi}_t^{\rho,\kappa} \leqslant \underline{\phi}_{\max}^{\rho,\kappa} \tag{23}$$

$$SoS_{\min}^{\rho,\kappa} \leqslant SoS_t^{\rho,\kappa} \leqslant SoS_{\max}^{\rho,\kappa} \tag{24}$$

$$\vartheta_{sm,\min}^{\rho,\kappa} \leqslant \vartheta_{t,sm}^{\rho,\kappa} \leqslant \vartheta_{sm,C}^{\rho,\kappa} \tag{25}$$

$$\Psi(\vartheta_{t,sm}^{\rho,\kappa}) = \left(\frac{\vartheta_{t,sm}^{\rho,\kappa}}{\vartheta_{sm,C}^{\rho,\kappa}}\right) \times D_m^{2.5} \times L \times K_l \tag{26}$$

$$\Gamma(\vartheta_{t,sm}^{\rho,\kappa}) = 6100 \times J^2 \times \gamma^{2.5} \times A_m \times \left(\frac{\vartheta_{t,sm}^{\rho,\kappa}}{\vartheta_{sm,C}^{\rho,\kappa}}\right)^{-1.38} \times D_m^{0.5} \tag{27}$$

Eq. (21) guarantees that the production level satisfies the customer ordered value $\varnothing_o^{\rho}$ (ton). Inequality (22) restricts the production level of each sub-process to a lower $\overline{\phi}_{min}^{\rho,\kappa}$ and upper $\overline{\phi}_{max}^{\rho,\kappa}$ bounds. Inequality (23) limits the flow of output from the previous storage to the next sub-process. The capacity of storage is bounded to lower $SoS_{min}^{\rho,\kappa}$ and upper $SoS_{max}^{\rho,\kappa}$ capacities through inequality (24). The rotational speed of S-VS milling systems, including raw and cement mills, is bounded by the inequality (25). In addition, Eq. (26) describes the electricity consumption of smart mills as a function of rotational speed $\vartheta_{t,sm}^{\rho,\kappa}$ (rpm) [30]. Note that $\vartheta_{sm,C}^{\rho,\kappa}$ is the critical speed and defined as the speed at which steel balls remain at the shell of the mill without falling when the centrifugal force equals its weight. Finally, Eq. (27) illustrates the production level of smart sub-process as a function of rotational speed [30]. It is worth mentioning that the Eqs. (26) and (27) are implemented only to the smart sub-processes, i.e. cement and raw mills in the KFP and FG, respectively.

Fig. 3 depicts a schematic diagram to show how the IDRA participates in the three trading floors of the electricity market. In order to take part in the time-oriented DR program, first of all, the IDRA participates in the day-ahead market based on the forecasted price of day-ahead, adjustment and balancing markets (first stage). In the first stage, the electricity prices of the three markets are unknown and are considered as uncertain variables. Although the IDRA participates in the day-ahead market, it forecast its operation in the adjustment and balancing markets based on the generated scenarios of electricity price. In this way, long notice-based DRPs, e.g. CPP and ED-CPP, are incorporated into the decision-making procedure. Due to enough

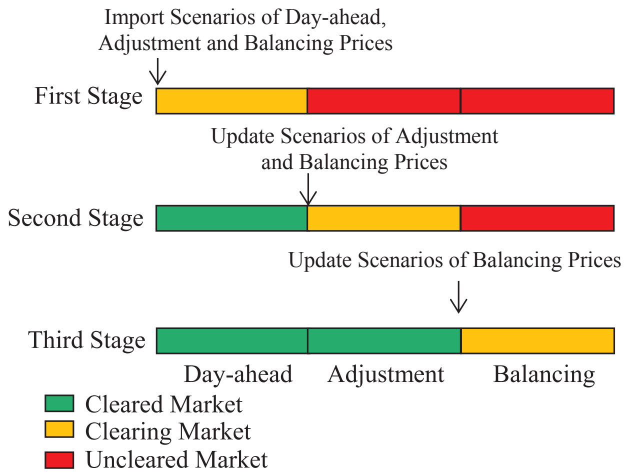

Fig. 3. Market clearance procedure in three-stage stochastic programming.

flexibility of cement industries, the most sub-processes, e.g. CR, KFP, and FG can be subject to the DR programs in this stage.

Approaching the energy delivery time, the uncertainty level associated with intermittent power decreases noticeably. Therefore, in order to incorporate the certainty gained on production availability of renewable power into the consumption schedule, the IDRA participates in the adjustment market to provide spinning reserve (second stage). In the second stage, the day-ahead market was cleared before; as a result, the day-ahead price is realized. The electricity price of adjustment and balancing markets are considered as an uncertain variable. Although the IDRA participates in the adjustment market, it forecasts its operation in the balancing market based on the electricity price scenarios. Due to approaching the market clearance, the electricity price of adjustment and balancing market can be updated with lower uncertainty. In this way, on mid notice, the sub-processes like KFP and FG can be switched off/on to provide a spinning reserve to the power system 10–60 min prior to the energy delivery time.

Finally, the IDRA participates in the balancing market to use the capacity of S-VS milling system to provide up/down regulation to the power system (third stage). In this stage, the day-ahead and adjustment markets were cleared before; therefore, the electricity price of them are realized. In this stage, the rotational speed of smart raw and cement mills is controlled to receive/inject energy from/to the power system when an excess/deficit of renewable energy occurs. All in all, different sub-processes of the cement plant participate in a time-oriented DR program from a long notice (24 h ahead) to short notice (near real-time).

To sum up, Fig. 4 describes the potential levels of the cement factory to participate in the DR programs.

5.2. Responsive aluminum smelting industries

The aluminum smelter is an energy-intensive industry which uses

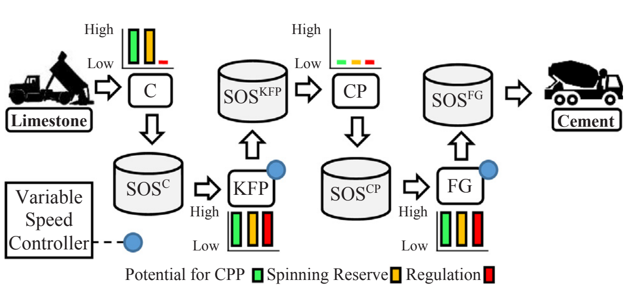

Fig. 4. Potential levels of the modern cement plant to participate in DR programs.

DC electric current in the smelting pot to separate the aluminum from the oxygen. The aluminum smelting pot is the heart of these industries which consumes the most electrical energy. Investigating the DR opportunities in the operation of pots, two kinds of responsive plans can be outlined as follows:

(1) Adjusting potline input voltage
(2) Turning the entire potline off

In the first plan, the input voltage of the potline is changed to manage the electricity consumption of the pot. In this case, the production line is turned down, instead of turned off. The reaction speed is very fast, within a few seconds. However, due to limited voltage variation, only a small reduction in the electricity consumption is expected. This responsive plan is compatible with the short notice-based DR programs to be implemented in the adjustment and balancing markets. Regarding the second plan, the entire potline is turned off; therefore, a large amount of consumption reduction is obtained. The duration of an interruption is more critical and can be sustained from minutes to about two hours [31]. The characteristics of the second plan are compatible with the structure of long and mid notice-based DR programs to be incorporated in the day-ahead and adjustment markets.

In this paper, a mathematical formulation is proposed for the potlines of an aluminum smelting industry. Against the literature, this paper suggests a mathematical formulation to investigate the flexibility potential of the aluminum smelting industries. Therefore, the electricity consumption of the potlines is formulated for the first time to be implemented in the DR programs. The suggested model is validated by the actual operation of the aluminum smelting industries.

The mathematical formulation for an aluminum smelting industry with multiple potlines can be stated as follows:

$$\Pi_t^{\alpha} = \sum_{\beta=1}^{B_1} \Pi_{t,ns}^{\alpha,\beta} + \sum_{\beta=B_1}^{N_\beta} \Pi_{t,sp}^{\alpha,\beta} \tag{28}$$

$$[\Pi_{t,ns}^{\alpha,\beta}] = [\widetilde{\Pi}_{t,ns}^{\alpha,\beta}] \times [\phi_t^{\alpha,\beta}] \tag{29}$$

$$[\Pi_{t,sp}^{\alpha,\beta}] = [\Psi(\nu_t^{\alpha,\beta})] \times [\phi_t^{\alpha,\beta}] \tag{30}$$

The model comprises a set of aluminum smelting plants $\alpha = \{1,\ldots,N_\alpha\}$. The production line of each plant contains $\beta = \{1,\ldots,N_\beta\}$ smelting pots. Eq. (28) describes the total electricity consumption of the aluminum industry Π_t^{α}(MW) as the electrical demand of the smart $\Pi_{t,sp}^{\alpha}$(MW) and non-smart $\Pi_{t,ns}^{\alpha}$(MW) pots. The smart pots $\beta = \{\beta_l,\ldots,N_\beta\}$ refer to the pots with variable voltage controller. Adversely, the input voltage of the non-smart pots $\beta = \{1,\ldots,\beta_l\}$ is fixed. Eq. (29) illustrates the electricity consumption of the non-smart pots as a function of rated electricity consumption $\widetilde{\Pi}_{t,ns}^{\alpha,\beta}$ (MWh/t) and production level $\phi_t^{\alpha,\beta}$ (t/h). Eq. (30) shows the electricity consumption of the smart pots as a function of electricity consumption at variable voltage pots Ψ (MWh/t) and production level $\phi_t^{\alpha,\beta}$ (t/h). The electricity consumption of smart pots Ψ describes the energy consumption as a function of variable voltage $\nu_t^{\alpha,\beta}$ (V).

The simplified model of the potlines is bounded by the following equalities and inequalities:

$$\sum_{t=\tau}^{\tau+\tau_N} \sum_{\beta=1}^{N_\beta} \phi_t^{\alpha,\beta} = \phi_o^{\alpha} \tag{31}$$

$$\phi_{\min}^{\alpha,\beta} \leqslant \phi_t^{\alpha,\beta} \leqslant \phi_{\max}^{\alpha,\beta} \tag{32}$$

$$\nu_{t,\min}^{\alpha,\beta} \leqslant \nu_t^{\alpha,\beta} \leqslant \nu_{t,\max}^{\alpha,\beta} \tag{33}$$

$$\Psi(\nu_t^{\alpha,\beta}) = 2.98 \times \nu_t^{\alpha,\beta} \times \eta_C^{-1} \tag{34}$$

Eq. (31) ensures that the daily production level of the smelting industry, for the whole potlines $\beta = \{1,\ldots,N_\beta\}$, during the understudied

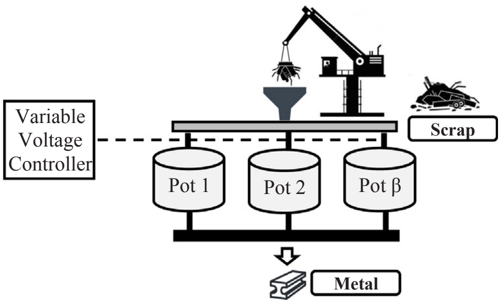

Fig. 5. Structure of multiple potlies in a metal smelting industry.

duration $t = [\tau\ \tau + \tau_N]$, satisfies the ordered value of the customers $\varnothing_o^\alpha$ (ton). Eq. (32) restricts the production level of each pot $\phi_t^{\alpha,\beta}$ to lower $\phi_{min}^{\alpha,\beta}$ and upper $\phi_{max}^{\alpha,\beta}$ bounds. Eq. (33) denotes the upper $v_{t,max}^{\alpha,\beta}$ and lower $v_{t,min}^{\alpha,\beta}$ bounds of the input voltage for smart pots. Finally, Eq. (34) describes the electricity consumption of the smart pots as the function of input voltage. The voltage function (34) is extracted from Hall-Heroult Cells Data [32]. Note that η_c refers to current efficiency of the cells and is considered 0.93 in this study. To sum up, Fig. 5 depicts a schematic diagram of the multiple potlines in a metal smelting industry.

5.3. Responsive residential consumers

In the residential sector, the HEMS plays an intermediary role between RDRA and households. The HEMS collects the households' consumption data and residents' convenience conditions and sends them to the RDRA through a two-way communication. The HEMS manages two kinds of household appliances as follows:

(1) TCAs including heat pump and electric water heater
(2) ESS linked with RPV.

Against the heavy industries proposed in the previous sections, the mathematical formulations of TCAs are extracted from the recent studies. In this way, although the consumption behavior is based on the current framework, a novel algorithm is suggested to optimize the operation of TCAs.

In order to illustrate the mathematical formulation of the household appliances, first of all, the consumption behavior of the TCAs is presented. Afterward, the model of the ESS linked with RPV is illustrated.

The consumption behavior of the TCAs can be stated as follows:

$$\Pi_{t,h}^{TCA} = \Pi_{t,h}^{EWH} + \Pi_{t,h}^{HPS} \tag{35}$$

$$\theta_{hw}^{t} = \theta_{a}^{t} + (R_w \times \Pi_t^{EWH}) - \left(\frac{M_w - m^t}{M_w}\right)(\theta_a^t - \theta_{hw}^{t-1})\exp\left(\frac{-\tau}{R_w \times C_w}\right) \tag{36}$$

$$\begin{cases} \frac{d\theta_r}{dt} = \frac{U_{fr}}{C_{p,r}}(\theta_f - \theta_r) - \frac{U_{ra}}{C_{p,r}}(\theta_r - \theta_a) + \frac{1-\rho}{C_{p,r}}(\Pi_t^S) \\ \frac{d\theta_f}{dt} = \frac{U_{wf}}{C_{p,f}}(\theta_w - \theta_f) - \frac{U_{fr}}{C_{p,f}}(\theta_f - \theta_r) + \frac{\rho}{C_{p,r}}(\Pi_t^S) \\ \frac{d\theta_w}{dt} = \frac{\eta^{HPS} \times \Pi_t^{HPS}}{C_{p,w}} - \frac{U_{wf}}{C_{p,w}}(\theta_w - \theta_f) \end{cases} \tag{37}$$

$$(\theta_{min} \pm \theta_\varepsilon) \leqslant \theta^t \leqslant (\theta_{max} \pm \theta_\varepsilon) \tag{38}$$

The model of TCAs includes electric water heater (EWH) and heat pump system (HPS). Eq. (35) denotes that the electric energy consumption of TCAs $\Pi_{t,h}^{TCA}$ includes the electricity consumption of the electric water heater $\Pi_{t,h}^{EWH}$ and heat pump system $\Pi_{t,h}^{HPS}$. Eq. (36) illustrates the thermal dynamic behavior of an electric water heater considering the heat exchange with the environment and with cold water inflows. In this way, θ_{hw} and θ_a are temperatures of hot water and environment, respectively. R_w and C_w are thermal resistance and capacitance of the EWH. M_w and m^t are capacity and hot water usage of households in time slot t in Kg [33]. Note that the parameter τ refers to time interval duration (hour). The set of Eq. (37) uses a third order linear model to describe the thermal behavior of the HPS [34]. In this model, θ_r, θ_f and θ_w are the room air temperature, floor temperature and water temperature in the floor heating pipes, respectively. Moreover, $C_{p,r}$, $C_{p,f}$ and $C_{p,w}$ denote the heat capacity of the room air, of the floor and of the water in the floor heating pipes, respectively. U_{fr}, U_{ra} and U_{wf} describe the heat transfer coefficients between floor and room, room air and ambient, water and floor, respectively. Π^S is energy extracted from the solar irradiation. η^{HPS} is the coefficient of performance of heat pump and ρ is the fraction of solar irradiation emitted on the floor. Finally, Eq. (38) enforces the comfort band of the TCAs' temperature. The comfort band is defined by the residents. Note that θ_ε is a temperature tolerance to prevent oscillation behavior of the TCAs near the upper/lower temperature bound.

The mathematical formulation of the ESS linked with RPV is described as follows:

$$SOC_t = SOC_{t-1} + (\delta^{ch} \times \Pi_t^{Ch}) - (\Pi_t^{Dch} \times (\delta^{Dch})^{-1}) \tag{39}$$

$$0 \leqslant \Pi_t^{Ch} \leqslant \Pi_{max}^{RPV} \tag{40}$$

$$0 \leqslant \Pi_t^{Dch} \leqslant \Pi_{max}^{battery} \tag{41}$$

$$\gamma_t^{Ch} = (SOC_t - SOC_{t-1}) \times (\delta^{ch})^{-1} \leqslant \overline{\gamma_t^{Ch}} \tag{42}$$

$$\gamma_t^{Dch} = (SOC_{t-1} - SOC_t) \times \delta^{Dch} \leqslant \overline{\gamma_t^{Dch}} \tag{43}$$

$$\underline{SOC_t} \leqslant SOC_t \leqslant \overline{SOC_t} \tag{44}$$

Eq. (39) denotes a state-transition equation to describe the battery's state of charge (SOC). In this model, Π^{Ch} and Π^{Dch} are charging and discharging power, respectively, and δ^{Ch} and δ^{Dch} are charging and discharging efficiency, respectively. Eq. (40) and (41) bound the charging and discharging power to the capacity of RPV Π_{max}^{RPV} and battery $\Pi_{max}^{battery}$, respectively. Charging and discharging rates (γ^{Ch}, γ^{Dch}) of the batteries are presented through Eq. (42) and (43). Finally, the SOC of the batteries is bounded to lower $\underline{SOC}$ and upper $\overline{SOC}$ levels through Eq. (44).

In the residential sector, the TCAs, including electric water heaters and heat pump system, are capable of participating in day-ahead and adjustment markets. In this way, the HEMS determines the 24-hour schedule based on forecasted electricity price. Optimizing the energy consumption, first of all, the operation of TCAs is scheduled in the low-cost hours through the energy market. i.e. day-ahead market. Afterward, the capability of TCAs to provide DR is traded in the adjustment market on 60–10 min notice. Finally, the ESS participates in the balancing market to inject power on short notice when a power shortage occurs in the electricity network. Note that although the TCAs can participate in the balancing market to be turned down/off on short notice, the residents' convenience may be affected; therefore, it is avoided in this paper.

Due to the performance of successive market floors, the proposed approach should respond to the DR programs with appropriate response time, especially for short notice programs. The thermal dynamics of the TCAs have non-linear behavior because of exponential time-dependent terms in Newton's Laws of Cooling. This feature increases the computational time burden of the problem. Therefore, the optimization may be failed especially when the response time is crucial. To reduce the computational burden of the problem, a heuristic Forward-Backward Algorithm (F-BA) is suggested in this paper. The F-BA minimizes the energy cost of the TCAs satisfying the residents' convenience. Moreover, due to a fast-convergence characteristic of the algorithm, it can be used to respond to the mid/short notice DR programs like ancillary services. The detailed description of the F-BA is illustrated in Algorithm 1 step-by-step.

Algorithm 1 (*Forward-backward for households' TCAs*).

I: Sort the electricity price of market X in ascending order:

$$\Lambda = \left\{ \forall\, i = \tau, \cdots, \tau + \tau_T \colon \hat{\lambda}_t^X(i) \le \hat{\lambda}_t^X(i+1) \right\}$$

II: Based on the predicted consumption pattern of TCAs, calculate the electrical energy needed to meet the demand: $\Pi_{t,h}^{TCA} = \{\Pi_{t,h}^{EWH}, \Pi_{t,h}^{HPS}\}$.

III: Turn on the TCA for the hour associated with the lowest electricity price: $(t_{i=1}, \hat{\lambda}_t^X(i))$

IV: Check the temperature of all time spots on the horizon. If all the temperature values are within the comfort band, stop the problem, otherwise, go to the next step.

V: Turn on the TCA for the next hour ($i \to i+1$) associated with lowest electricity price

$(t_{i+1}, \hat{\lambda}_t^X(i+1))$

VI: Check the temperature of all time spots on the horizon. There are three states:

State 1: If all the temperature values are within the comfort band, stop the problem.

State 2: If there is at least one temperature between t_i and t_{i+1} exceeding the comfort band, use the backward operator in step VII.

State 3: If all the temperatures within $[t_i\ t_{i+1}]$ are within the comfort band and there is at least one temperature between t_{i+1} and $t_{i=NT}$ exceeding the comfort band, use the forward operator in step VIII.

VII: Remove t_{i+1} (turn TCA off at t_{i+1}) and go back to step V to resolve the problem for interval $[t_i\ t_{i+1}]$.

VIII: Preserve t_{i+1} (keep TCA on at t_{i+1}) and go back to step V to solve the problem for interval $[t_{i+1}\ \tau_T]$.

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6. Coordination mechanism of the agents

The main aim of multi-agent systems is to split a complex problem into simple ones. Therefore, the problem can be solved with lower computational time burden. However, the tractability of the problem may be affected if the complex problem cannot be modeled through a multi-agent structure.

In this paper, the market agents are located in three layers as follows:

(1) First Layer: supply-side including DRP.
(2) Second Layer: intermediary-side including DRAs.
(3) Third Layer: demand-side including responsive consumers.

In order to provide market coordination between the agents, first of all, the DRAs, i.e. IDRA and RDRA, provide demand bids based on received data from their contracted consumers. In this way, information such as convenience constraints and historical consumption behavior is used for the residential sector (RDRA). In the industrial sector, the IDRA negotiates with the heavy industries, i.e. cement and metal smelting, to incorporate their preferences into the demand bids. Minor maintenance schedule (in the form of hourly/daily), daily/weekly ordered value and specific limitations of the production lines are the most important data received by the IDRA. Besides, the DRAs receive the historical data of electricity price from the wholesale market. Therefore, the demand bids, based on Eq. (3), are provided and submitted to the DRP. Secondly, the DRP participates in the wholesale market, on behalf of the DRAs, to maximize the profit of the market participants (Eq. (1)). In this way, three market floors are cleared. In each trading market, the demands compatible with time-based notices, i.e. long, mid and short notices, participate in the program. The general procedure of the coordination mechanism between different agents is described in Algorithm 2.

Fig. 6 illustrates how different flexible resources can be dispatched in the time-oriented DR programs to provide demand flexibility to the power system. The flexible resources comprise two heavy industries, i.e. cement and metal, and household appliances. Each flexible resource can be employed in time-oriented notices, from long notice to short notice, to meet the requirement of system flexibility.

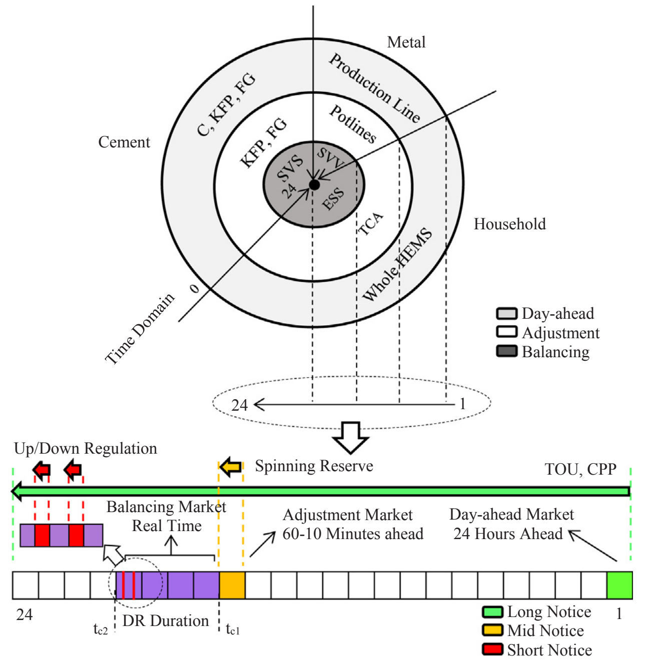

Fig. 6. Dispatching of flexible resources in three successive trading floors of electricity market.

First of all, the flexible resources participate in the day-ahead market. In this stage, long notice-based DR programs, e.g. TOU and CPP, are incorporated into the decision-making procedure. Due to enough time flexibility of the day-ahead market, the most industrial subprocesses, e.g. C, KFP, and FG in the cement industries and whole potlines in the metal industries can participate in this stage. In addition, in the residential sector, the whole household appliances can be scheduled to provide power flexibility to the electricity market.

Approaching the energy delivery time, the time flexibility of the resources decreases noticeably. Therefore, in the adjustment market, which is cleared 60–10 min before the power delivery, those flexible resources can participate that respond to the request of load change within less than 60 min. In the industrial sector, the KFP and FG from cement plants and smelting pots from metal factories can be switched off/on to provide spinning reserve. In the residential sector, the thermal capacity of TCAs can provide power flexibility to this stage.

In near real-time condition, the balancing market is cleared. In this stage, fast-response flexible resources participate in the market to provide up/down regulation during deficit/excess of generation. In the industrial sector, smart variable speed mills from cement plants and smart variable voltage pots from metal factories provide power regulation to the electricity market. Regarding the residential consumers, the electrical storage capacity of ESS provides power flexibility to balancing market.

Although the flexible capacities of this paper are limited to two heavy industries and households, there are some other heavy industries and electrical consumers which can provide power flexibility to the network when a power shortage occurs or system reliability is jeopardized. Considering all the capacities, the tractability of the problem may be affected.

To sum up the problem, the operation flowchart of the suggested approach is depicted in Fig. 7.

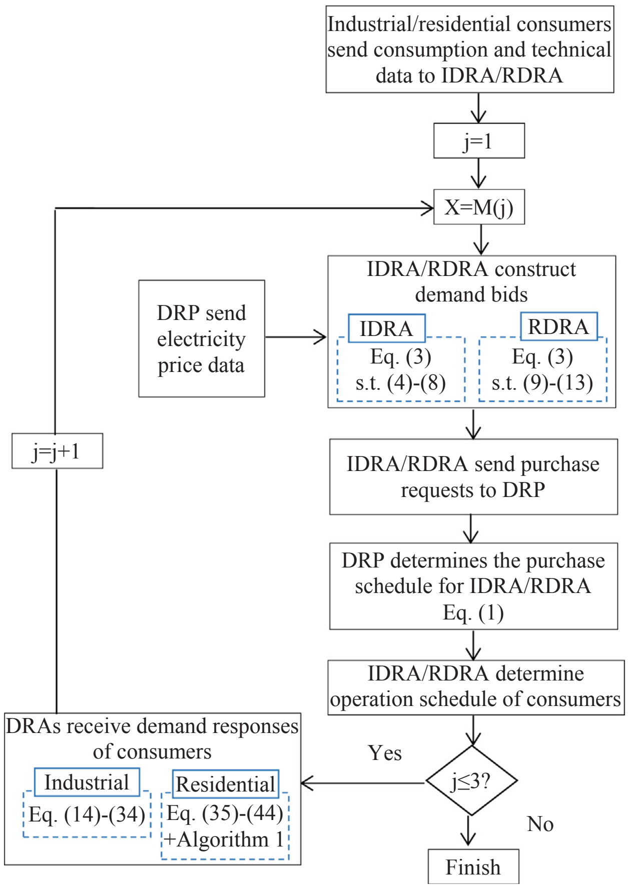

Fig. 7. Operation flowchart of the proposed approach.

7. Numerical results

7.1. Input data and test system

In this paper, the study horizon is a single day (24 h). The suggested approach is implemented on the horizon to supply the responsive consumers on one side and provide power flexibility to the power system on the other side. In the industrial sector, 8 cement factories and 2 aluminum smelting industries are considered with total demand of 184 and 43 MW, respectively [35]. In the residential sector, the RDRA procures the energy of 10 MW residential consumers for the TCAs. In this way, four classes of households are considered with different patterns of active occupants in the 24 h.

In order to show how the suggested approach can be implemented in an electricity market with high penetration of intermittent power, the electricity market for Danish sector of Nordic Electricity Market is addressed [36]. For this reason, the target day is considered 28 February 2018. To forecast the price behavior of the Nordic Electricity Market, a time series-based seasonal auto-regressive integrated moving average approach (S-ARIMA) is used. The historical data used for fitting the process of electricity price correspond to the days between September 2017 and February 2018. The number of scenarios generated by the ARIMA model is 50, 50 and 50 for the day-ahead, adjustment, and balancing markets, respectively. Therefore, a total number of scenarios equals 125000, which is tractable. As an example, Fig. 8 depicts the generated scenarios associated with uncertain electricity price of day-ahead market.

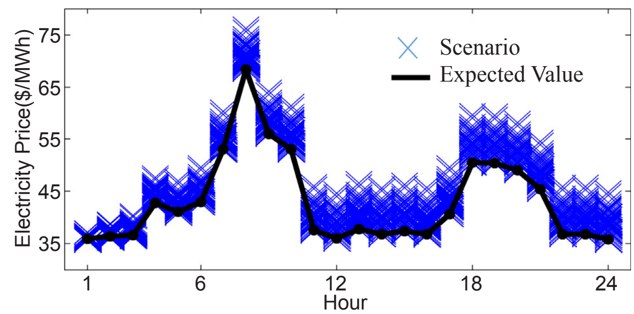

Fig. 8. Electricity price scenarios for day-ahead markets, ARIMA model (p,d,q) × (P,D,Q)s = (1,0,1) × $(1,1,1)_{24}$.

Algorithm 2 (*Multi-layer coordination mechanism***).**

I: The DRAs, i.e. IDRA and RDRA, receive the consumption priorities of contracted consumers, e.g. consumption data, convenience constraints, daily/hourly interruption of production line etc.

II: The DRAs forecast the electricity price for the day-ahead, adjustment and balancing markets, based on the received data from the history of the electricity market.

III: The DRAs provide demand bids, based on Eq. (3), for three time-oriented trading markets. Afterward, the DRP participates in the wholesale market, on behalf of the contracted DRAs, based on Eq. (1). The procedure is done in three steps as follows:

Step1
- **State 1:** The DRAs provide demand bids to the energy market, i.e. day-ahead market, based on forecasted day-ahead, adjustment and balancing market prices.
- **Stage 1:** The DRP participates in a day-ahead market based on received demand bids from state 1, then go to →**DR 1.**

Step2
- **State 2:** The DRAs provide demand bids to the ancillary service market, i.e. adjustment market, based on realized day-ahead price and forecasted price of adjustment and balancing markets.
- **Stage 2:** The DRP participates in adjustment market based on received demand bids from state 2, then go to → **DR 2.**

Step3
- **State 3:** The DRAs provide demand bids to the ancillary service market, i.e. balancing market, based on realized day-ahead and adjustment prices and forecasted price of balancing market.
- **Stage 3:** The DRP participates in balancing market-based on received demand bids from state 3, then go to→ **DR 3.**

IV: The consumption schedules of the responsive consumers are determined based on the time-oriented notices for participation in DR programs:

DR 1: The consumption schedules compatible with long notice DR programs are determined $\left[\left(\Pi_{t,h}^{TCA}\right),\left(\Pi_{t}^{\rho,\kappa},\Pi_{t}^{\alpha,\beta}\right)\right]$.

DR 2: The consumption schedules compatible with mid notice DR programs are determined $\left[\left(\Pi_{t,h}^{TCA}\right),\left(\Pi_{t}^{\rho,\kappa}|_{\kappa\neq CP},\Pi_{t}^{\alpha,\beta}\right)\right]$.

DR 3: The consumption schedules compatible with short notice DR programs are determined $\left[\left(\Pi_{t,h}^{Dch}\right),\left(\Pi_{t,sm}^{\rho,\kappa}|_{\kappa=KFP,FG},\Pi_{t,sp}^{\alpha,\beta}\right)\right]$.

It is worth mentioning that the electricity price/tariff for industrial, commercial and residential consumers is substantially different. For this reason, investigation of the role of electricity pricing on providing power flexibility can be an attractive issue for this regard. In the next sub-section, the simulation results and discussions are described.

7.2. Simulations and discussions

This section presents the simulation results of the proposed approach. The problem is coded in two software, including GAMS 24.1.2 and MATLAB 2014R. The stochastic programming approach is coded in GAMS and solved using the CONOPT solver. The results of the electricity market are imported to the MATLAB to optimize the operational strategies of household appliances by HEMS. The software is linked through GDX (GAMS Data eXchange) interface files.

In order to investigate the flexibility potential of heavy industries in the Danish sector of the Nordic Electricity Market, the responses of a sample cement factory and a metal industry to the prices of the three market floors are depicted in Figs. 9 and 10, respectively.

Regarding the cement plant, Fig. 9(a) shows the total demand for a cement plant in response to the electricity price of three market floors. In Fig. 9(b) the expected values of electricity price for three floors of the electricity market are illustrated. Note that the electricity price in Fig. 9(b) is the expected value of the electricity price scenarios generated using ARIMA. In Fig. 9(a), the electricity consumption of the cement plant is described in three stages of the stochastic programming. In the first stage, only the day-ahead market is considered, in the second stage day-ahead and adjustment markets are addressed. Finally, in the

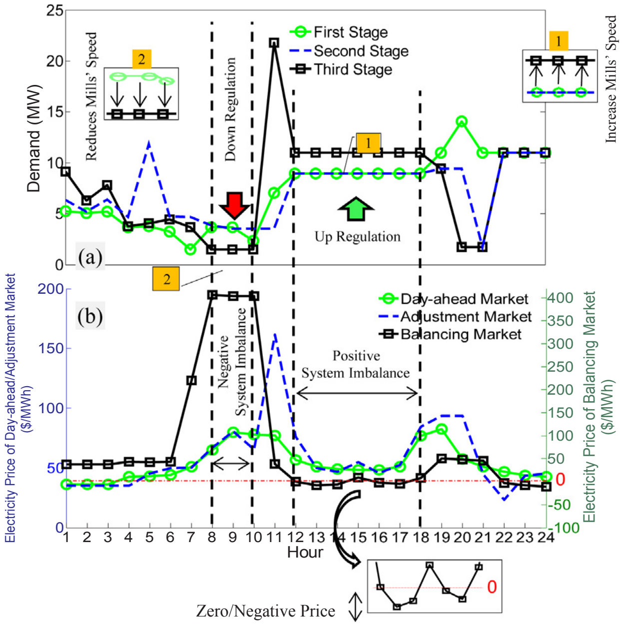

Fig. 9. (a) Demand response of a cement plant to three trading floors of Nordic Electricity Market (b) The price of Nordic Electricity Market on 28 Feb. 2018.

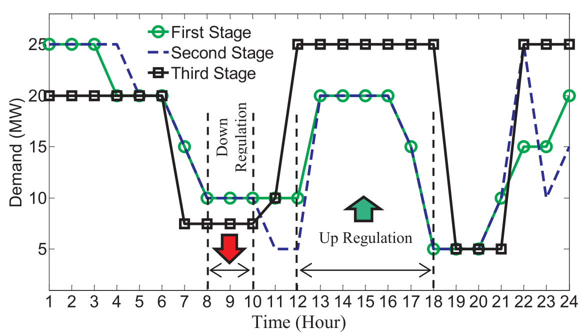

Fig. 10. Response of a metal smelting plant to the electricity price of Nordic Electricity Market on 28 Feb. 2018.

third stage, the day-ahead, adjustment and balancing markets are discussed.

Based on the first stage (day-ahead market as an energy market), the IDRA schedules operation of the cement plant mostly in the hours when the day-ahead price is relatively low. In the second and third stages (adjustment and balancing markets as ancillary service markets), the IDRA changes the energy consumption of the cement plant in response to the price variations in the adjustment and balancing markets. Approaching the energy delivery time, the uncertainty of renewable power decreases noticeably. In the target day, the Nordic Electricity Market experienced a severe deficit of energy in hours between 8 and 10 when a huge jump in the balancing electricity price is seen, an eightfold increase. In contrast, an excess of energy production is seen during hours 12–18 when the price of balancing market reaches zero or negative values. In the former state, the cement industries use the capacity of S-VS milling system to provide down-regulation for the power system. Adversely, in the latter state, the S-VS milling system provide up-regulation for the power system by increasing the mills' speed or switching on the sub-processes on short notice. As the graph reveals, if the near real-time market floors, i.e. adjustment and balancing markets, are not considered in the problem, the DRAs are not able to respond to the variations of the renewable energy. The reason is that the day-ahead market is cleared 24 h prior to the renewable power realization; therefore, it could not forecast the availability of renewable power accurately. In contrast, addressing the adjustment and balancing markets, the cement plant can respond to the variations of the renewable power 60–10 min before energy delivery when the renewable power forecast is updated more accurately. In this paper, it is supposed that the price signal contains important data about the availability of renewable power.

In the metal smelting industry, by approaching the energy delivery time from the first stage to the third stage, the smelting pots respond to the signal of electricity price more accurately. As a result, in the first stage (day-ahead market), most pots are scheduled in the hours with low electricity price. In the second and third stages, the input voltage of pots reaches the lower value to provide down-regulation for the power system, between hours 8–10. In contrast, the IDRA uses the upper capacity of potlines to provide up-regulation during hours 12–18.

Note that the smelter industry has multiple potlines. Therefore, the industry can rotate the voluntary interruption from line to line. Based on Fig. 9(b), a huge jump occurs in the price of adjustment market at hour 11. Consequently, according to Fig. 10, the smelting industry provides down-regulation at hour 11 through interrupting some pots without needing to switch off the whole potlines. Therefore, the smelting industry with smart potlines can respond to the variations of renewable power when a down-/up-regulation is needed.

In Fig. 11, the operation schedule of the sample cement plant for each sub-process of the production line is illustrated individually. As the graph reveals, the most energy-intensive sub-processes are scheduled in the hours when the electricity price is relatively low. During the negative system imbalance, i.e. hours 8–10, the KFP and FG are turned off to provide down-regulation to the power system. In this way, the cement plant uses the stored materials in the siloes to prevent interruption of production line. Adversely, these sub-processes are turned on during the positive system imbalance, i.e. hours 12–18, to provide up-regulation. The result clearly shows that what kinds of sub-processes can provide flexibility for the power system on short notice without disturbing the daily order value of the factory. It is worth mentioning that the capacity of storages (silos) plays an important role in providing flexibility for the power system. In fact, if the capacity of storages is designed appropriately, the flexibility of the cement plant for participation in the DR programs increases and vice versa.

Fig. 12 describes the role of the S-VS milling system and variable input voltage of smelting pots in providing regulation for the power system. In this figure, the average values of rotational speed and input voltage are depicted. Based on the graph, the rotational speed and input voltage reach the lower values during hours 8–10 when a deficit of renewable energy occurs in the market. Adversely, the rotational speed and input voltage maintained the upper level during hours 12–18 when an up-regulation is needed for the power system.

There is a similar pattern for the household appliances where the TCAs, including electric water heaters and heat pump systems, participate in the day-ahead and adjustment markets. Fig. 13(a) and (b) describes the consumption behavior of a sample heat pump system and electric water heater towards the day-ahead and adjustment market

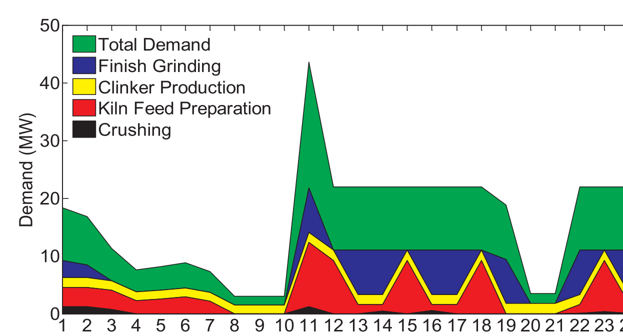

Fig. 11. Operation plan for whole production line of the cement plant.

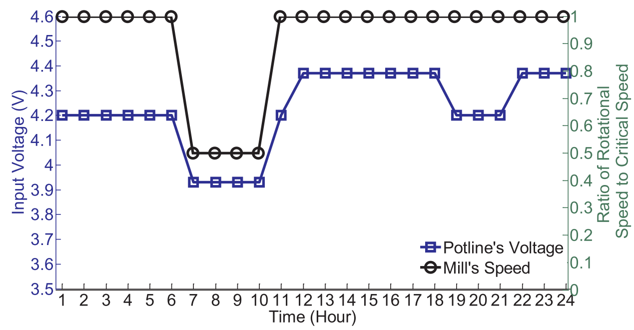

Fig. 12. Profile of rotational speed and input voltage for cement's mills and smelting pots, respectively.

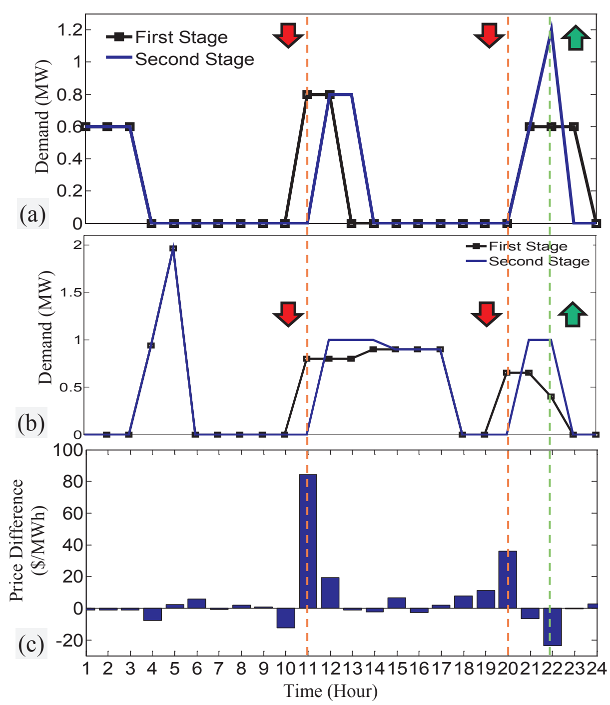

Fig. 13. Profile of energy consumption for (a) a heat pump (b) an electric water heater and (c) profile of difference values between market prices.

prices, respectively. Besides, Fig. 13(c) depicts the difference between the electricity prices of day-ahead and adjustment markets. As the graphs reveal, for hours 11 and 20 when the price difference is relatively high, the TCAs are turned down temporarily to provide down-regulation for the power system.

In addition, to ensure the residents' convenience, the dynamic temperature of the TCAs are illustrated in Fig. 14(a) and (b) for the electric water heater and the heat pump, respectively. The figures explain clearly how the F-BA converges to an optimum point through different iterations. As can be seen, for hours 11 and 20 when the TCAs participate in DR program, the temperature reaches the lower bound to provide the down-regulation for the power system.

In the residential sector, the ESS is charged from the RPV and discharged to the power grid. The ESS participates in the balancing markets to provide down-regulation for the power system. Fig. 15 presents the charge/discharge strategies of a sample ESS linked with RPV. The subfigure 15(a) depicts the charging power extracted from the RPV. The sub-Fig. 15(b) illustrates the optimized operation of the ESS to participate in the balancing market. As the bar graph reveals, the ESS injects power to the grid between hours 8 and 11 when a power shortage occurs in the electricity market. The value of injected power in the duration of down-regulation is relatively low in comparison with the

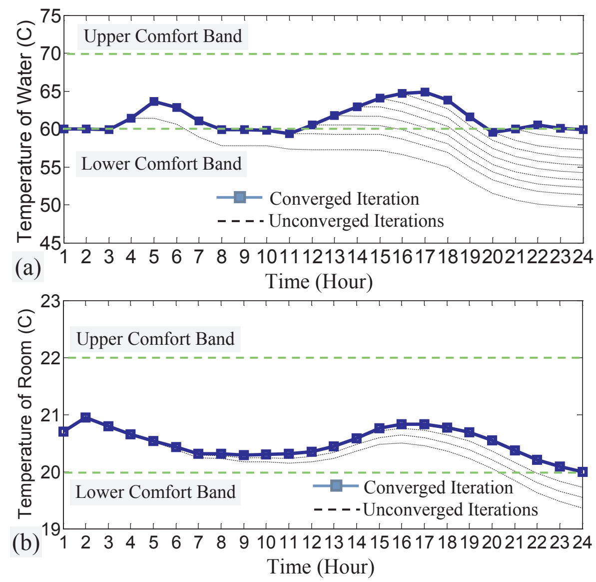

Fig. 14. Thermal dynamics of (a) the electric water heater and (b) the heat pump system during participation in DR programs.

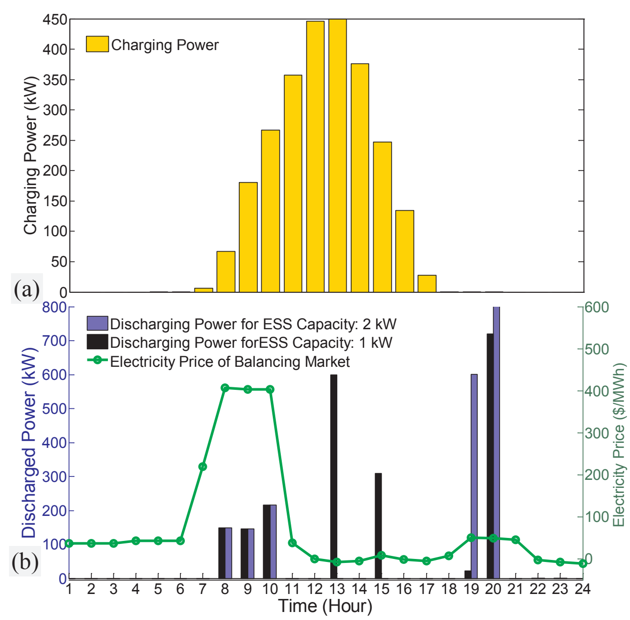

Fig. 15. Profile of (a) charging power from RPV (b) discharging power to the grid "The 1 kW solar panel located in Copenhagen (55.72,12,38)x,y [37]"

other time durations. The reason is that the power shortage occurs in the early morning when the solar irradiation is weak. The other challenge is that if the ESS capacity is not designed properly, the ESS has to inject power to the grid when the balancing price may be low, e.g. injection of power at hours 13 and 15. In order to overcome the problem, the ESS capacity increases from 1 kW to 2 kW; consequently, the ESS is able to store more energy and injects the power when a down-regulation is needed. In such condition, the ESS has higher flexibility to sell energy at higher prices and provides down-regulation for the power system.

Fig. 16 describes the demand bids of the IDRA. As the bar graph reveals, the ability of the IDRA to provide DR opportunities increases from the first stage to the third stage. During the negative system imbalance, i.e. hours 8–10, the value of demand bids decreases from the first stage to the third stage. In contrast, during the positive system imbalance, i.e. hours 12–18, the demand bids of the IDRA increases

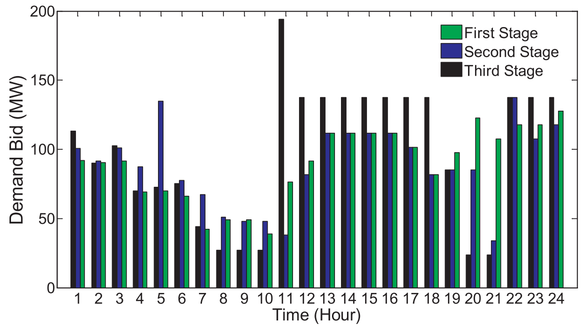

Fig. 16. Demand bidding by the IDRA.

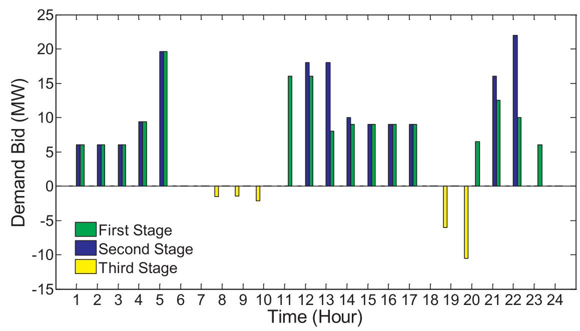

Fig. 17. Demand bidding by the RDRA.

from the first stage to the third stage. It means that by addressing the ancillary service market in the second and third stages, the IDRA can provide up/down regulation when an excess/deficit of power occurs in the electricity market. In this way, if the ancillary service market is neglected, the S-VS milling system and variable voltage pots could not provide power regulation in near real-time condition.

Fig. 17 illustrates the demand bids of the RDRA. By using the thermal capacity of the TCAs, the HEMS is able to turn off the appliances during the negative system imbalance, i.e. hours 8–10. Adversely, the demand bids of the TCAs increases during positive system imbalance, i.e. 12–18. Therefore, the RDRA can provide down (up) regulation through turning down/off (up/on) the TCAs when a deficit (excess) of generation occurs in the electricity market. Besides, it is clear that the RDRA uses the highest capacity of ESS to inject energy to the market when a deficit of energy occurs, e.g. hours 8–10 and 19–21.

Fig. 18 describes the integrated values of DR traded in the three floors of the electricity market. In the first stage where the only day-ahead market is addressed, the DRAs prefer to bid more demands in the duration of negative imbalance, i.e. 8–10, and lower demands in the duration of positive system imbalance, i.e. 12–18, in comparison to the other stages. The reason is that the data of renewable power availability could not be updated accurately 24 h prior to the power delivery.

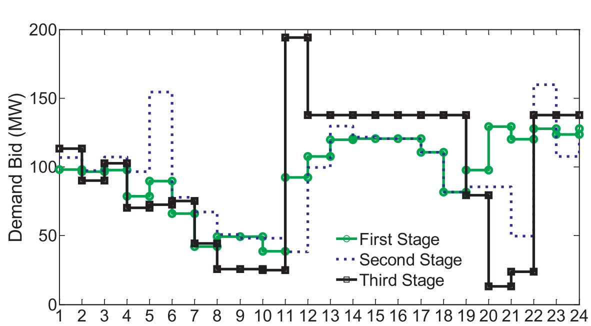

Fig. 18. Integrated values of DR traded in three trading floors of the electricity market.

Table 1
Average values of energy cost reduction for different consumers.

No.	Responsive demand	Reduction of energy cost (%)
1	Household	12
2	Aluminum smelting	18
3	Cement manufacture	34

Implementing the ancillary service markets, i.e. adjustment and balancing markets, the DRAs provide down and up regulations during negative and positive system imbalances, respectively. The reason is that the ancillary service markets clear in near real time; therefore, they take the advantage of updated data of renewable power availability. Consequently, in the third stage, the value of demand bids decreases during hours 8–10 and increases during hours 12–18. It means that the consumers can respond to the short notice DR programs in the adjustment and balancing markets to provide power flexibility when deficit/excess of renewable energy occurs in the electricity market. The integrated DR programs can safeguard the future of power systems which are subject to the increasing renewable energies.

Table 1 illustrates the percentage of cost reduction for different consumers due to participation in the three-stage DR programs. Based on the table, the cement industry has upper flexibility than the other consumers. The reason is that a cement plant consists of different sub-processes with a storage between them. Therefore, one sub-process can be turned down/off without disturbing the daily production value. In the metal smelters, the multiple potlines make it possible to rotate the interruption from line to line. This feature plays an important role in providing the opportunity for the smelter industries to participate in the DR programs. In the residential sector, due to severe convenience constraints, the expectation of energy cost is relatively low.

It is worth mentioning that the cost reduction is the result of optimization in an energy market (day-ahead market) and ancillary service markets (adjustment and balancing). Making a comparison between the share of each trading floor in the cost reduction, the main energy consumption is scheduled in the energy market with moderate price. In the ancillary service markets, the electricity price is high during the negative imbalance and is low during the positive imbalance. For this reason, participating in the ancillary service markets, a substantial profit can be earned. The key limiting factor in the ancillary service markets is that the capacity of consumers to respond to the short notice DR programs is limited. Therefore, the value of profit depends heavily on the ability of responsive consumers to participate in the short notice DR programs.

Fig. 19 illustrates the statistical variations of energy cost reduction with respect to three electricity price PDFs, including Normal, Weibull and Log-normal distributions. To provide a detailed analysis, the electricity price is divided into three levels: low, median and high price

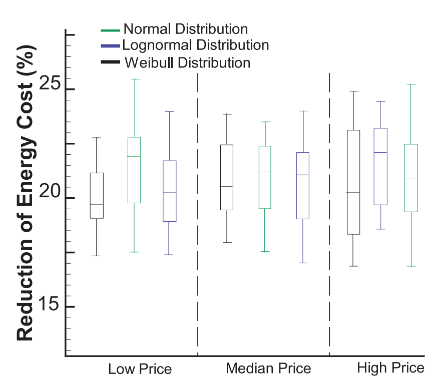

Fig. 19. Sensitivity of energy cost reduction with respect to price PDFs (the average energy cost reduction for three consumers is investigated).

levels. The high price data are the prices higher than μ + σ, in which μ is the mean price and σ is the standard deviation of the price. The low price data are the prices lower than μ − σ. Other price data are considered as the median price data. Based on the boxplot, Normal PDF causes the most reduction of energy cost in low price data, while it results in a lower cost saving in the high price data. In contrast, Lognormal PDF shows higher cost reduction in high price data. In fact, the electricity price does not follow the normal distribution in high price data, and it should be considered as logarithmic normal distribution if there were some price spikes. The reason is that the price spikes influence the statistical properties of electricity price. Furthermore, Weibull PDF results in moderate cost reduction in contrast to the Normal and Lognormal PDFs.

8. Conclusion

This paper suggested a novel market-based approach to integrating the flexibility potential of different responsive consumers, i.e. residential and industrial sectors, into a power system with high penetration of intermittent power. The ultimate aim was to provide up/down regulation for the power system when a deficit or excess of generation occurs. To achieve the aim, the complex problem was split into the multi-agent structure. Therefore, three kinds of agents, including DRP, IDRA and RDRA, were addressed. The IDRA investigates the flexibility potential among the whole production lines of two energy-intensive industries, i.e. cement factories and metal smelting plants. Besides, the RDRA integrates the DR opportunities of household appliances, including electric water heaters and heat pumps. Moreover, the electrical capacity of ESS-RPV is used to provide down-regulation to power system on short notice.

In order to ensure the power system flexibility, the time-oriented DR program was proposed to optimize the total cost of energy, and regulation by allowing the DRP to trade DR opportunities in three successive floors of the electricity market, i.e. day-ahead, adjustment and balancing markets. In this way, the DRAs could trade DR values in a competitive structure based on the demand bids, instead of subsidizing the demand-side flexibility.

In the industrial sector, the key feature of the proposed framework was that the sub-processes with the ability to change consumption on long, mid and short notices were determined. The results showed that the S-VS milling systems and variable voltage potlines play a crucial role in providing immediate regulation to the power system.

All in all, the simulation results showed that the suggested framework can safeguard the future of power systems against the increasing penetration of renewable power on one side and decrease the energy cost of consumers on the other side. However, the former is more important for Nordic Electricity Market which is subject to large variation of renewable power. Therefore, it can be interpreted as a win-win game for all market participants.

However, the paper suggested a comprehensive approach to provide flexibility to the power system, some problems remained for future researches. The following ideas can be the subject of new researches:

(1) Integrating the operational strategies urban transportation, e.g. plug-in hybrid electric vehicles, into the suggested flexible resources.
(2) Optimization of the problem regarding power network constraints.

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