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Efficient planning of energy production and maintenance of large-scale combined heat and power plants

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ABSTRACT

In this study, an efficient optimization framework is presented for the simultaneous planning of energy production and maintenance in combined heat and power plants, and applied in the largest coal-fired cogeneration plant of Kazakhstan. In brief, the proposed optimization model considers: (i) unit commitment constraints for boilers and turbines; (ii) minimum and maximum runtimes as well as minimum idle times for boilers and turbines; (iii) bounds on the operating levels for boilers and turbines within desired operating regions; (iv) extreme operating regions for turbines; (v) energy balances for turbines; (vi) total electricity and heat balances for satisfying the corresponding demands for electricity and heat (for each heat network); and (vii) maintenance tasks for units that must occur within given flexible time-windows. The minimization of the annual total cost of the cogeneration plant constitutes the optimization goal here, and consists of startup and shutdown costs, fixed operating and fuel costs, maintenance costs, and penalties for deviation from heat and electricity demands, and penalties for turbines for operating outside the desired operating regions. An extensive data analysis of historical data has been performed to extract the necessary input data. In comparison to the implemented industrial solution that follows a predefined maintenance policy, the solutions derived by the proposed approach achieve reductions in annual total cost more than 21% and completely avoid turbines operation outside their desired operating regions. Our solutions report substantial reductions in startup/shutdown, fuel and fixed operating costs (about 85%, 15%, and 13%, respectively). The comparative case study clearly demonstrates that the proposed approach is an effective means for generating optimal energy production and maintenance plans, enhancing significantly the resource and energy efficiency of the plant. Importantly, the proposed optimization framework could be readily applied to other cogeneration plants that have a similar plant structure.

1. Introduction

Kazakhstan is a low-populated vast country that is the major financial player in Central Asia due to its huge reserves in major natural and mineral resources, such as coal, oil and gas, uranium, lead, chromium, zinc, copper, manganese, iron and gold. From 2000 to present, the country has experienced a remarkable economic growth and an increase in population from 15 to 18 million [24,19], resulting in a significant increase in energy demand. The electricity demand in Kazakhstan has increased from 55 billion kWh in 2000 to 90.8 billion kWh in 2015, and it is estimated to reach 104.1 billion kWh in 2022 [14,13]. Heat demand is also large in Kazakhstan due to its sharply continental climate with extremely cold large winter periods. In addition, the energy intensity of Kazakhstan's economy is twice as high as the average level of OECD countries, and 12% higher than that of Russia. Kazakhstan adopted the “Energy Efficiency 2020” programme with the aim to reduce its energy intensity by 50% in 2050 (reference year is 2008).

Kazakhstan was ranked first in the world from the standpoint of intensity of carbon dioxide emissions per unit of GDP [10], and has set an ambitious target of 15–25% economy wide reduction in greenhouse gas emissions by 2030 (reference year is 1990) within the framework of the Intended Nationally Determined Contribution under United Nations Climate Change Conference, COP21 [7]. The international commitment is primarily reinforced by the “Concept for Transition of the Republic of Kazakhstan to Green Economy” addressing the efficient management of

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Nomenclature

Indexes/sets

$i \in I$	units (boilers and turbines)
$j \in J$	heat networks (note: a reduction cooling unit is associated to each heat network)
$t,t' \in T$	time periods
$i \in I^B$	set of boiler units
$i \in I^T$	set of turbine units
$i \in I_j^T$	set of turbine units $i \in I^T$ that are connected to heat network j

Binary variables

$X_{(i,t)}$	= 1, if unit i operates during time period t
$Y_{(i,t)}$	= 1, if turbine unit $i \in I^T$ operates during time period t within the desired operating region
$Y^+_{(i,t)}$	= 1, if turbine unit $i \in I^T$ operates during time period t within the upper extreme operating region
$Y^-_{(i,t)}$	= 1, if turbine unit $i \in I^T$ operates during time period t within the lower extreme operating region
$S_{(i,t)}$	= 1, if unit i starts operating at the beginning of time period t
$F_{(i,t)}$	= 1, if unit i stops operating at the beginning of time period t
$W_{(i,t)}$	= 1, if the maintenance task of unit i starts at the beginning of time period t

Continuous variables (non-negative)

$E^T_{(i,t)}$	electricity generation level of turbine unit $i \in I^T$ in time period t
E^{buy}_t	electricity purchases in time period t (or unsatisfied electricity demand)
E^{ex}_t	excessive electricity generation in time period t
$H^{buy}_{(j,t)}$	heat purchases for heat network j in time period t (or unsatisfied heat demand)
$H^{ex}_{(j,t)}$	excessive heat generation for heat network j in time period t
$H^{RCU}_{(j,t)}$	direct heat flow to heat network j (via its associated reduction cooling unit) in time period t
$Q^B_{(i,t)}$	heat generation level of boiler unit $i \in I^B$ in time period t
$Q^{Tin}_{(i,t)}$	inlet heat flow to turbine $i \in I^T$ in time period t
$Q^{Tout}_{(i,t)}$	outlet heat flow from turbine $i \in I^T$ in time period t

Parameters

$\alpha_{(i,t)}$	startup cost for unit i in time period t
β^E_t	factor for internal electricity requirements of the plant in time period t
β^H_t	factor for internal heat requirements of the plant in time period t
γ_i	number of time periods before the beginning of the current time horizon that unit i has been continuously operating since its last startup
δ_i	maximum runtime for unit i (continuous operation from its startup)
$\Delta\varepsilon^+_{(i,t)}$	maximum operating level for the upper extreme operating region of turbine unit $i \in I^T$ in time period t
$\Delta\varepsilon^-_{(i,t)}$	minimum operating level for the lower extreme operating region of turbine unit $i \in I^T$ in time period t
$\varepsilon^{max}_{(i,t)}$	maximum operating level for the desired operating region of turbine unit $i \in I^T$ in time period t
$\varepsilon^{min}_{(i,t)}$	minimum operating level for the desired operating region of turbine unit $i \in I^T$ in time period t
ζ^{el}_t	electricity demand in time period t
$\zeta^{heat}_{(j,t)}$	heat demand for heat network j in time period t
$\eta_{(i,t)}$	efficiency for turbine unit $i \in I^T$ and boiler units $i \in I^B$ in time period t
η^{RCU}_j	heat efficiency factor for reduction cooling unit associated to heat network j
$\theta^{max}_{(i,t)}$	maximum heat generation level for boiler unit $i \in I^B$ in time period t
$\theta^{min}_{(i,t)}$	minimum heat generation level for boiler unit $i \in I^B$ in time period t
$\theta^{Tmax}_{(i,t)}$	maximum outlet heat flow from turbine $i \in I^T$ in time period t
λ^{buy}_t	cost for acquiring electricity from externals sources in time period t
λ^{ex}_t	cost for excessive electricity generation in time period t
$\kappa_{(i,t)}$	maintenance cost for unit i if maintenance starts in time period t
$\mu^{buy}_{(j,t)}$	cost for acquiring heat from externals sources for heat network j in time period t
$\mu^{ex}_{(j,t)}$	cost for excessive heat sent (i.e., disposed heat) to heat network j in time period t
M	a large number
ν_i	duration of maintenance task for unit i
$\pi_{(i,t)}$	fixed operating cost for unit i in time period t fuel cost for boiler unit i in time period t
$\rho^+_{(i,t)}$	penalty for turbine $i \in I^T$ for operating in the upper extreme operating region
$\rho^-_{(i,t)}$	penalty for turbine $i \in I^T$ for operating in the lower extreme operating region
τ^{max}_i	latest starting time for the maintenance task of unit i (i.e., upper bound of time-window)
τ^{min}_i	earliest starting time for the maintenance task of unit i (i.e., lower bound of time-window)
$\varphi_{(i,t)}$	shutdown cost for unit i in time period t
ψ_i	minimum idle time for unit i (from its last shutdown)
ω_i	minimum runtime for unit i (from its last the startup)
Cq_t	fuel calorific value in time period t
$loss_i$	heat losses coefficient due to combustion loss/unburned fuel for all boiler units $i \in I^B$

the resources, developing a new national infrastructure and renovating the existing infrastructure. Kazakhstan Strategy 2050 aims at emissions reduction to 40% by 2050 through higher penetration of renewables and improvements in resource and energy efficiency [8]. However, the current fossil fuel-friendly regulatory framework, and huge availability of conventional resources result in low-cost energy for both residential and industrial uses, making low-carbon solutions unattractive economically [11,12]. There is a clear need for strategic energy system planning incorporating environmental and economic trade-offs [26]. This should involve improvements in resource and energy efficiency in energy consuming and generation sectors, while acquiring economic benefits [22]. Efficient management strategies both in the investment-strategic and operational level in the power sector are also essential [17].

In Kazakhstan in 2015, coal-fired Combined Heat and Power (CHP) plants account for 81.6% of the total installed capacity for energy generation, followed by 10.2% of hydro, and 8.0% of gas [14]. There are 111 CHP plants with total installed capacity of 21.3 GW and available power of 17.5 GW [18]. Most CHP plants are located in Pavlodar, Karaganda and East Kazakhstan due to a well-developed industrial infrastructure and associated steady electricity demand and high heat demand. The wide deployment of CHP plants in the power