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# Risk-averse optimal operation of Multiple-Energy Carrier systems considering network constraints

Mohammad H. Shams[a], Majid Shahabi[a,*], Mohammad E. Khodayar[b]

[a] Department of Electrical and Computer Engineering, Babol Noshirvani University of Technology, Babol, Iran
[b] Department of Electrical and Computer Engineering, Southern Methodist University, Texas, USA

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ABSTRACT

Integrated Multiple-Energy Carrier (MEC) systems with electricity and natural gas infrastructure systems offer distinctive opportunities to enhance the efficiency and the flexibility of energy supply. Efficient operation of these interdependent infrastructure systems faces several challenges corresponding to the risk associated with the uncertainty in the environmental parameters. In this paper, a risk-based framework for energy management of interconnected energy hubs in MEC systems is proposed to minimize the expected system operation cost. The conditional value at risk (CVaR) method is used to quantify the risk associated with uncertainties in the electrical and thermal loads, and the real-time price of electricity. The probability distribution function of the uncertain parameters and auto regressive integrated moving average (ARIMA) models are used to generate scenarios to represent the uncertainty in the system parameters. The proposed model is formulated as a mixed integer linear programming (MILP) problem and solved using CPLEX solver. The developed case studies show the risk-averse and risk-taker operator strategies to demonstrate the merits of the proposed risk-based scheduling over the risk-neutral operation scheme. It is further investigated that how the expected operation cost depends on the risk measures in the risk-averse operation. Also, sensitivity analyses are conducted to assess the energy procurement scheduling based on the proposed approach. Furthermore, the effect of risk parameter on managing the congestion in electricity and natural gas networks is examined.

## 1. Introduction

Multiple-Energy Carrier (MEC) systems capture the interactions among multiple energy infrastructure systems including electricity and natural gas, to supply heat and electricity to the consumers. These integrated systems improve the flexibility, economics, and environmental benefits compared to individual energy networks.

The past decade has seen the rapid advances in MEC network operation. Early investigations focused on the vision of future energy networks in which the key elements of MEC systems are referred to as energy hubs [1,2]. An energy hub is introduced as an interface between the energy carriers and loads that converts or stores energy to serve the desired demand [2].

Recently, considerable research efforts have been focused on the configuration design and performance of energy hubs. In Ref. [3] a method is developed to model the MEC systems with energy hubs to determine the economic dispatch between the energy converters, and the optimal power flow in the system. The general model proposed in Ref. [3] is modified in Ref. [4] to integrate the renewable energy resources. The optimal design of energy hubs considering the reliability constraints is addressed in Ref. [5]. In Ref. [6] the operability and economic feasibility of Power-to-Gas technology are evaluated in the context of energy hubs. A simulation model for an energy hub comprising natural gas-fired turbines, wind turbines, and photovoltaic solar cells is introduced in Ref. [7] to evaluate the cost of energy, as well as the amount of produced emissions.

Recent developments in energy hub-based systems have intensified the need for introducing efficient approaches for expansion planning and operation scheduling of these systems. A model for optimal expansion planning of an energy hub in MEC system is introduced in Ref. [8], where optimal investment choices in the system such as transmission lines, natural gas pipelines and elements of energy hubs were determined. The presented model in Ref. [8] is further extended in Ref. [9] to consider the reliability constraints. Optimal expansion planning of electric distribution system using the notion of energy hub is proposed in Ref. [10]. The objective is to minimize the investment and

* Corresponding author.
*E-mail addresses:* Shams@stu.nit.ac.ir (M.H. Shams), Shahabi.m@nit.ac.ir, shahabi.m@ieee.org (M. Shahabi), mkhodayar@mail.smu.edu (M.E. Khodayar).
*URL:* http://mailto:Shahabi.m@nit.ac.ir (M. Shahabi).

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**Nomenclature**

*Indices*

| | |
|---|---|
| $b$ | Batteries, $b = 1, 2, \ldots, B$ |
| | Boilers, $bo = 1, 2, \ldots, BO$ |
| $Bo_i$, $HP_i$, $HS_i$ | Set of boilers/heat pumps/heat storages connected to energy node $i$ |
| $hp$ | Heat pumps, $hp = 1, 2, \ldots, HP$ |
| $hs$ | Heat storages, $hs = 1, 2, \ldots, HS$ |
| $i, j$ | Energy carriers nodes, $i = 1, 2, \ldots, I$ |
| $J_i$ | Set of nodes directly connected to node $i$ |
| $m$ | Diesel generators, $m = 1, 2, \ldots, M$ |
| $n$ | Combined heat and power (CHPs), $n = 1, 2, \ldots, N$ |
| $N_i$, $M_i$, $B_i$ | Set of CHPs/diesel generators/batteries connected to energy node $i$ |
| $s$ | Scenarios, $s = 1, 2, \ldots, NS$ |
| $t$ | Time periods, $t = 1, 2, \ldots, T$ |
| $\omega$ | Set of units ($m$, $n$, $bo$, $hp$) |

*Constants and parameters*

| | |
|---|---|
| $COP_{hp}$ | Coefficient of performance for heat pump $hp$ |
| $ES_{hs}^{\min}$, $ES_{hs}^{\max}$ | Min/max capacity of stored energy in heat storage $hs$ [kWh] |
| $f_{ij}^{\max}$ | Capacity of the pipeline between node $i$ and node $j$ [$m^3$/h] |
| $G_{ij}$, $B_{ij}$ | Real/imaginary part of network admittance matrix [p.u.] |
| $GHV$ | Gross heating value |
| $k_{ij}$ | Coefficient of natural gas and pipelines specification |
| $KU_{\omega}$, $KD_{\omega}$ | Coefficients for startup/shutdown costs of unit $\omega$ |
| $PL_{i,s}^{t}$ | Real power of load of node $i$ at hour $t$ and scenario $s$ [kW] |
| $P_{\omega}^{\min}$, $P_{\omega}^{\max}$ | Min/max generation capacity of unit $\omega$ [kW] |
| $P_{hs}^{st,\max}$, $P_{hs}^{wd,\max}$ | Max storing/withdrawing capacity of heat storage $hs$ [kWh] |
| $P_{b}^{ch,\max}$, $P_{b}^{dis,\max}$ | Max charging/discharging capacity of battery $b$ [kWh] |
| $Pr_{i}^{\min}$, $Pr_{i}^{\max}$ | Min/max limits of natural gas pressure at node $i$ [Psig] |
| $Pr_i'$ | Natural gas initial pressure of node $i$ [Psig] |
| $P_{g,net}^{\max}$ | Capacity of main natural gas network [kW] |
| $QL_{i,s}^{t}$ | Reactive power of load of node $i$ at hour $t$ and scenario $s$ [kVar] |
| $S_{grid}^{\max}$ | Capacity of main utility transformer [MVA] |
| $S_{ij}^{\max}$ | Capacity of the line between node $i$ and node $j$ [kVA] |
| $SOC_{b}^{\min}$, $SOC_{b}^{\max}$ | Min/max capacity of stored energy in battery $b$ [kWh] |
| $TL_{i,s}^{t}$ | Thermal load of node $i$ at hour $t$ and scenario $s$ [kW] |
| $V_{i}^{\min}$, $V_{i}^{\max}$ | Min/max limits of voltage magnitude at node $i$ [p.u.] |
| $VoLL_e$, $VoLL_h$ | Value of loss of electrical/thermal loads [$] |
| $\alpha$, $\beta$ | Confidence level, risk parameter |
| $\eta_{\omega}$ | Efficiency of unit $\omega$ |
| $\eta_{b}^{ch}$, $\eta_{b}^{dis}$ | Charge/discharge cycle efficiency of battery $b$ |
| $\eta_{hs}^{st}$, $\eta_{hs,s}^{wd}$ | Store/withdraw cycle efficiency of heat storage $hs$ |
| $\pi_{DA}^{t}$ | Electricity price in day-ahead market at hour $t$ [$/kWh] |
| $\pi_{RT,s}^{t}$ | Electricity price in real-time market at hour $t$ and scenario $s$ [$/kWh] |
| $\pi_g$ | Natural gas price [$/kWh] |
| $\rho_s$ | Probability of scenario $s$ |

*Variables*

| | |
|---|---|
| $C_s$ | Operation cost of scenario $s$ [$] |
| | Conditional value at risk/value at risk [$] |
| $ES_{hs,s}^{t}$ | Stored energy in heat storage $hs$ at hour $t$ and scenario $s$ [kWh] |
| $ELC_{i,s}^{t}$, $TLC_{i,s}^{t}$ | Involuntary electrical/thermal load curtailment at hour $t$ and scenario $s$ [kWh] |
| $f_{ij,s}^{t}$ | Natural gas flow rate through pipeline between nodes $i$ and $j$ at hour $t$ and scenario $s$ [$m^3$/h] |
| $f_{i,s}^{t}$ | Injected natural gas into node $i$ at hour $t$ and scenario $s$ [$m^3$/h] |
| $P_{RT,s}^{t}$ | Purchased power in real-time electricity market at hour $t$ and scenario $s$ [kW] |
| $P_{DA}^{t}$ | Purchased power in day-ahead electricity market at hour $t$ [kW] |
| $P_{g,net,s}^{t}$ | Purchased natural gas at hour $t$ and scenario $s$ [kW] |
| $P_{\omega,s}^{t}$ | Output power of unit $\omega$ at hour $t$ and scenario $s$ [kW] |
| $P_{m,s}^{t}$ | Output power of diesel generator $m$ at hour $t$ and scenario $s$ [kW] |
| $P_{n,e,s}^{t}$, $P_{n,h,s}^{t}$ | Output electrical/thermal power of CHP $n$ at hour $t$ and scenario $s$ [kW] |
| $P_{hp,s}^{t}$ | Injected power to heat pump $hp$ at hour $t$ and scenario $s$ [kW] |
| $P_{bo,s}^{t}$ | Output thermal power of boiler $bo$ at hour $t$ and scenario $s$ [kW] |
| $P_{hs,s}^{t,st}$, $P_{hs,s}^{t,wd}$ | Store/withdraw power of battery $b$ at hour $t$ and scenario $s$ [kW] |
| $P_{b,s}^{t,ch}$, $P_{b,s}^{t,dis}$ | Charge/discharge power of battery $b$ at hour $t$ and scenario $s$ [kW] |
| $P_{ij,s}^{t}$ | Real power flow of line between nodes $i$ and $j$ at hour $t$ and scenario $s$ [kW] |
| $Pr_{i,s}^{t}$ | Natural gas pressure of node $i$ at hour $t$ and scenario $s$ [Psig] |
| $Q_{ij,s}^{t}$ | Reactive power flow of line between nodes $i$ and $j$ at hour $t$ and scenario $s$ [kVar] |
| $Q_{DA}^{t}$, $Q_{RT,s}^{t}$ | Imported reactive power to the system in day-ahead/real-time market at hour $t$ [kVar] |
| $Q_{n,e,s}^{t}$ | Generated reactive power by CHP $n$ at hour $t$ and scenario $s$ [kVar] |
| $Q_{m,s}^{t}$ | Generated reactive power by diesel generator $m$ at hour $t$ and scenario $s$ [kVar] |
| $Q_{hp,s}^{t}$ | Injected reactive power to heat pump $hp$ at hour $t$ and scenario $s$ [kVar] |
| $SUC_{\omega}^{t}$, $SDC_{\omega}^{t}$ | Startup/shutdown cost of unit $\omega$ at hour $t$ [$] |
| $SOC_{b,s}^{t}$ | State of charge in battery $b$ at hour $t$ and scenario $s$ [kWh] |
| $S_{ij,s}^{t}$ | Apparent power flow of line between nodes $i$ and $j$ at hour $t$ and scenario $s$ [kVA] |
| $u_{\omega}^{t}$ | Indicates on/off status (1/0) of unit $\omega$ at hour $t$ |
| $u_{hs,s}^{t,st}$, $u_{hs,s}^{t,wd}$ | Indicates store/withdraw status (1/0) of heat storage $hs$ at hour $t$ and scenario $s$ |
| $u_{b,s}^{t,ch}$, $u_{b,s}^{t,dis}$ | Indicates charge/discharge status (1/0) of battery $b$ at hour $t$ and scenario $s$ |
| $V_{i,s}^{t}$ | Magnitude of voltage of node $i$ at hour $t$ and scenario $s$ [p.u.] |
| $\delta_{i,s}^{t}$ | Voltage angel of node $i$ at hour $t$ and scenario $s$ [rad] |
| $\pi_{m}^{nl}$, $\pi_m$ | No-load and marginal cost of diesel generator $m$ at hour $t$ [$,$/kWh] |
| $\psi_s$ | Auxiliary variable of risk constraint |

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