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Optimal Operation of a Smart Multi-Energy System Considering Demand Response

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***Abstract*—With the rising uncontrolled growth of energy demand, smart multi-energy systems (MESs) have emerged as a promising energy-efficient concept that provides the opportunity of supplying multiple energy services (electricity, heating, and cooling) to end-users simultaneously. To this end, a smart multi-energy system consisting of renewable energy sources (RESs), combined heat and power units (CHPs), heat pumps (HPs), community energy storage (CES), electric vehicles (EVs) and multi-energy demands are considered in this study, with the objective of maximizing the total system efficiency and minimizing the total operating costs, while meeting the required demands. The optimal operation of the smart MES is also evaluated by considering demand response (DR) based on the time-of-use (TOU) tariff for electricity, and the associated constraints throughout the whole operational horizons with the interconnected relationship between heating, cooling and power are taken into account.**

Index Terms—Cost optimization, demand response, energy storage, electric vehicles, multi-energy system.

NOMENCLATURE

The following is a list of the sets of indices, parameters, and variables used in the study.

TABLE I. SETS AND INDICES

e	Set of EVs
m	Set of CHP units
n	Set of HP units
t	Set of time intervals
v	Set of PV production scenario
w	Set of wind production scenario

TABLE II. PARAMETERS

CE^{CES}	Charging efficiency of the CES
CE_e^{ev}	Charging efficiency of *eth* EV
chp_hp_m	Integration multiplier for *mth* CHP unit
COP_n	Performance coefficient of *nth* HP unit
DE^{CES}	Discharging efficiency of the CES
EER_n	Energy efficiency ratio of *nth* HP unit
N	Sufficient big number
$P_{m,t}^{CHP,elec,max}$	Max. supply power of *mth* CHP unit in time interval *t*
$P_{m,t}^{CHP,heat,max}$	Max. heat supply power of *mth* CHP unit in interval *t*
$P_{v,w,t}^{end-user,cool}$	End-user cooling demand in interval *t* for *v* and *w* scenarios
$P_{v,w,t}^{end-user,elec}$	End-user electricity demand in interval *t* for *v* and *w* scenarios
$P_{v,w,t}^{end-user,heat}$	End-user heating demand in interval *t* for *v* and *w* scenarios
$P_{n,t}^{HP,cool,max}$	Max. cooling supply power of *nth* HP unit in time interval *t*
$P_{n,t}^{HP,heat,max}$	Max. heat supply power of *nth* HP unit in time interval *t*
$P_{v,t}^{pv}$	PV power production in interval *t* for *v* and *w* scenarios
$P_{w,t}^{wind}$	Wind power production in interval *t* for *v* and *w* scenarios
$R^{CES,ch}$	Max. charging power of CES
$R_{e,t}^{ev,ch}$	Max. charging power of *eth* EV in interval *t*
$SOE^{CES,ini}$	Initial energy level of CES
$SOE^{CES,min}$	Minimum energy level of CES
$SOE^{CES,max}$	Maximum energy level of CES
$SOE_e^{ev,ini}$	Initial SOE of *eth* EV
$SOE_e^{ev,min}$	Minimum SOE of *eth* EV
$SOE_e^{ev,max}$	Max. SOE of *eth* EV
T_e^a	Arrival time of *eth* EV
T_e^d	Departure time of *eth* EV
λ_t^{elec}	Price of electricity in time intervals
λ_t^{gas}	Marginal cost of the natural gas supplied from gas source in time interval *t*
η_m^{elec}	Efficiency of energy conversions from gas to electricity at *mth* CHP unit
η_m^{heat}	Efficiency of energy conversions from gas to heat at *mth* CHP unit

TABLE III. DECISION VARIABLES

$P_{v,w,t}^{CES,ch}$	CES charging power in interval *t* for *v* and *w* scenarios
$P_{v,w,t}^{CES,dis}$	CES discharging power in in interval *t* for *v* and *w* scenarios
$P_{m,v,w,t}^{CHP,elec}$	Electricity production of *mth* CHP unit in interval *t* for *v* and *w* scenarios
$P_{m,v,w,t}^{CHP,heat}$	Heat production of *mth* CHP in interval *t* for *v* and *w* scenarios
$P_{m,v,w,t}^{CHP,input}$	Power of *mth* CHP in interval *t* for *v* and *w* scenarios
$P_{m,v,w,t}^{CHPel,end-user}$	Power injected from *mth* CHP to end-user in period t for scenario *v* and *w*
$P_{m,v,w,t}^{CHPel,HP}$	Power injected from *mth* CHP to HP unit in interval *t* for *v* and *w* scenarios
$P_{v,w,t}^{direct-user}$	Power injected from grid to end-user in interval *t* for *v* and *w* scenarios
$P_{v,w,t}^{elec}$	Grid power supply in interval *t* for *v* and *w* scenarios
$P_{v,w,t}^{elec,HP}$	Grid electricity for all the HP in interval *t* for *v* and *w* scenarios
$P_{e,v,w,t}^{ev,ch}$	Charging power of *eth* EV for *v* and *w* scenarios
$P_{v,w,t}^{gas}$	District gas input from fuel distribution system in interval *t* for *v* and *w* scenarios
$P_{n,v,w,t}^{HP,cool}$	Cooling power of *nth* HP unit in interval *t* for *v* and *w* scenarios
$P_{n,v,w,t}^{HP,heat}$	Heating power of *nth* HP unit in interval *t* for *v* and *w* scenarios
$P_{n,v,w,t}^{HP,input}$	Power of *nth* HP unit in interval *t* for *v* and *w* scenarios
$SOE_{v,w,t}^{CES}$	State-of-energy level of CES in time interval *t* for *v* and *w* scenarios
$SOE_{e,v,w,t}^{ev}$	State-of-energy level of *eth* EV in time interval *t* for *v* and *w* scenarios
$u_{n,v,w,t}^{HP}$	Binary variable
Δt	Time granularity

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I. INTRODUCTION

A. Motivation and Background

Energy has always been one of the basic human essential resources for survival and development. Nowadays, this need becomes more evident with the increasing environmental concerns, depletion of fossil fuel sources, increasing dependence of human lifestyle on energy, and rising uncontrolled growth of demand. Therefore, providing a clean, reliable, cost-effective, and sustainable energy system is one of the main challenging tasks of today and the coming decades. Sustainable integrated energy systems will be the type of energy systems used in the future and a smooth transition will benefit greatly from multi-energy systems (MESs), which play a vital role in addressing the concerns mentioned above [1].

In this context, with the widespread use of renewable energy sources (RESs) and with a strong tendency to transfer energy systems efficiently and economically, the concept of smart MESs has been introduced and attracted increasing attention in the recent years [2, 3]. A smart MES, in which electricity, heating, cooling, transportation, etc. interact optimally at various levels, represents a considerable opportunity to boost economic, technical, and environmental performances compared to the conventional energy systems operated separately and independently.

MESs are considered as an effective model leading to higher energy efficiency, lower operating costs and higher robustness [4, 5]. In addition, smart MESs can achieve energy cascade utilization and can promote the penetration of RESs, which offers significant opportunities in system operation. Furthermore, EVs have gained market share as a greener type of transportation and are projected as a potential solution in the recent years [6]. Besides, demand response (DR) can provide valuable solutions to several challenges the current energy market has been facing. It plays an important role in mitigating supply-demand imbalances, promotes energy utilization efficiently, manages load demands, especially in peak periods, and further improves the system flexibility, reliability and economy.

B. Relevant Literature

Any mismatch between production and demand at the operational level may lead to system instability. Hence, with the rapidly increasing share of RESs, and in order to ensure the long-term goal of RES-based systems operate in a secure, reliable, and economical manner, synergies between different energy vectors and system components should be considered precisely. Thus, optimizing the operation of smart MESs is a challenging task due to their structural complexity, highly interconnected nature of multiple energy carriers, as well as the uncertainty associated with RESs [7]. Various research efforts have been made in the literature to address those concerns by taking MESs and DR into account.

In order to coordinate various renewable uncertainties and flexible DR, a bi-level optimal dispatching model for the community-integrated energy system with an electric vehicle (EV) charging station was developed in multi-stakeholder scenarios in [8]. An optimal integrated energy system planning method under high penetration of RESs was proposed in [9], in which the coordinated operations of renewable energy production, energy aggregation equipment, multi-energy load, and automatic electric taxi were considered.

To clarify the effect of DR on the optimal operating mode of the multi-energy cooperative system (MECS), the authors of [10] presented a MECS-optimized operational approach that considers the market's elastic price-type DR. By considering the energy storage and a mix of renewable energy generation, a two-dimensional price-based DR model (vertical load transfer and horizontal energy conversion) was applied in [11]. The authors of [12] developed a two-step approach to enable the residential DR programs in the MESs including renewable generation, CHP unit, boiler, and an energy storage system.

Access to photovoltaic (PV) power can reduce the integrated energy system carbon emissions and improve the energy supply economics; however, the output uncertainty of PV also poses further challenges to the optimal system performance. By taking these challenges and DR into account, the authors of [13] focused on the coordinated optimization for the MESs. A concept of integrated demand response (IDR) and integrated energy system framework for multi-energy coordination was developed in [14]. Besides, an incentive-based IDR model for multiple energy carriers considering the effect of consumer behavioral coupling was proposed in [15].

C. Contributions and Organization

When dealing with the optimized operation of MESs, it is essential to consider the operational constraints and linkages on both the source and load sides in order to reduce system failures and achieve improved energy efficiency.

The major contribution of the proposed approach is to optimally manage a wide variety of multi-energy technologies, including CHPs, heat pumps (HPs), renewable-based generation units, community energy storage (CES), EVs and multi-energy demands, by considering the associated constraints throughout the whole operational horizons with the objective of maximizing efficiency and minimizing the total operating costs while meeting the required demands. It takes into account a schedule optimization strategy where the cost function serves as the optimization target, and the optimal topology is determined by considering all of the system's components.

The organization of this research paper is presented as follows. Section II provides the proposed scheme of the smart MES and the mixed integer linear programming (MILP) based optimization problem. Section III presents the simulation results and a thorough comparison of the results conducted for different cases. Finally, Section IV summarizes the conclusions.

II. METHODOLOGY

A. Overview of the Structure

A smart MES at the community level is proposed in this study as shown in Fig. 1. The input ports of the MES are connected to the electricity and natural gas networks. The output ports can simultaneously provide electricity, heating, and cooling services.

B. Mathematical Formulation

A MILP-based problem is presented by considering different energy input and output forms as well as multi-level energy conversion processes. It considers a scheduling optimization approach that defines cost as the optimization target. Therefore, all the system components need to be taken into account for the optimal topology.

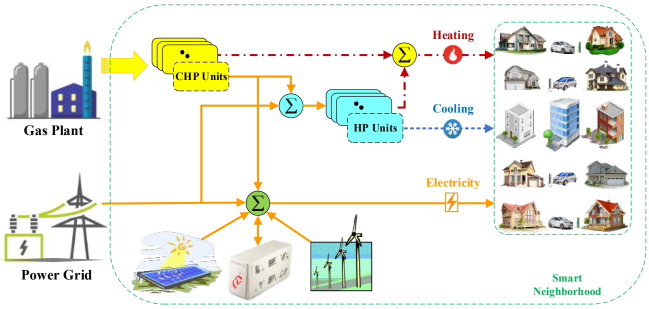

Fig. 1. Proposed smart multi-energy system.

The constraints and equations of the system consist of the input and output balance constraints, the cooling and heating energy balance limitations, the operational constraints of each unit, and the conditional limitations for the safe and reliable system operation. In addition, each unit is modeled with its own operational limits and uncertainties for optimum operation of the MES. Equations (1)-(27) that take into account the related constraints for each component are listed in the following subheadings.

1) Objective function

The objective function of the optimization problem to minimize the total operational cost is formulated as (1). The total cost of the smart MES depends on the total power injected from the main grid and the gas as well as the electricity and gas prices purchased from the outer energy networks during the time *t* for PV and wind production scenarios.

$$Total\ Cost = \sum_t \sum_v \sum_w \left(P_{v,w,t}^{elec} \cdot \lambda_t^{elec} + P_{v,w,t}^{gas} \cdot \lambda_t^{gas}\right), \quad \forall v, \forall w, \forall t \tag{1}$$

2) Modelling of CHPs

The input of the CHP units is supplied from the gas network, the CHP units then convert the input gas to heat and power. The equations including the conversion processes and related terms are denoted in (2-7).

$$P_{v,w,t}^{gas} = \sum_m P_{m,v,w,t}^{CHP,input}, \quad \forall m, \forall v, \forall w, \forall t \tag{2}$$

$$P_{m,v,w,t}^{CHP,input} \le \frac{P_{m,t}^{CHP,elec,max}}{\eta_m^{elec}} + \frac{P_{m,t}^{CHP,heat,max}}{\eta_m^{heat}}, \quad \forall m, \forall v, \forall w, \forall \tag{3}$$

$$P_{m,v,w,t}^{CHP,input} = \frac{P_{m,v,w,t}^{CHP,elec}}{\eta_m^{elec}} + \frac{P_{m,v,w,t}^{CHP,heat}}{\eta_m^{heat}}, \quad \forall m, \forall v, \forall w, \forall t \tag{4}$$

$$P_{m,v,w,t}^{CHP,elec} = P_{m,v,w,t}^{CHPel,end-user} + P_{m,v,w,t}^{CHPel,HP}, \quad \forall m, \forall v, \forall w, \forall t \tag{5}$$

$$P_{m,v,w,t}^{CHP,heat} \le P_{m,t}^{CHP,heat,max} \quad \forall m, \forall t \tag{6}$$

$$P_{m,v,w,t}^{CHP,elec} \le P_{m,t}^{CHP,elec,max} \quad \forall m, \forall t \tag{7}$$

3) Modelling of HPs

The HP units are supplied from the main power grid and the power from the CHP units. They change the input power to heating and cooling to meet the end-user heating and cooling demands. All CHP units are integrated into HP units and the (chp_hp_m) is considered as 1. The HP unit equations in the conversion conditions are given in (8)-(15).

$$P_{v,w,t}^{elec} = P_{v,w,t}^{elec,HP} + P_{v,w,t}^{direct-user}, \quad \forall v, \forall w, \forall t \tag{8}$$

$$\sum_n P_{n,v,w,t}^{HP,input} = \sum_m P_{m,v,w,t}^{CHPel,HP} \cdot chp\_hp_m + P_{v,w,t}^{elec,HP}, \quad \forall m, \forall n, \forall v, \forall w, \forall t \tag{9}$$

$$P_{n,v,w,t}^{HP,input} = \frac{P_{n,v,w,t}^{HP,heat}}{COP_n} + \frac{P_{n,v,w,t}^{HP,cool}}{EER_n}, \quad \forall n, \forall v, \forall w, \forall t \tag{10}$$

$$P_{n,v,w,t}^{HP,input} \le \frac{P_{n,t}^{HP,heat,max}}{COP_n} + \frac{P_{n,t}^{HP,cool,max}}{EER_n}, \quad \forall n, \forall v, \forall w, \forall t \tag{11}$$

$$P_{n,v,w,t}^{HP,heat} \le N \cdot u_{n,v,w,t}^{HP}, \quad \forall n, \forall v, \forall w, \forall t \tag{12}$$

$$P_{n,v,w,t}^{HP,cool} \le N \cdot \left(1 - u_{n,v,w,t}^{HP}\right), \quad \forall n, \forall v, \forall w, \forall t \tag{13}$$

$$P_{n,v,w,t}^{HP,heat} \le P_{n,t}^{HP,heat,max}, \quad \forall n, \forall v, \forall w, \forall t \tag{14}$$

$$P_{n,,v,w,t}^{HP,cool} \le P_{n,t}^{HP,cool,max}, \quad \forall n, \forall v, \forall w, \forall t \tag{15}$$

4) Modelling of CES

The CES is used to supply end-user electricity demand when it is more economic and beneficial to the system. It can be charged from the power grid, the output power of CHPs, and RES. The equations of the state of charge (SoC), charging and discharging power of the CES are presented in (16)-(19).

$$0 \le P_{v,w,t}^{CES,ch} \le R^{CES,ch}, \quad \forall v, \forall w, \forall t \tag{16}$$

$$SOE_{v,w,t}^{CES} = SOE^{CES,ini} + CE^{CES} \cdot P_{v,w,t}^{CES,ch} \cdot \Delta t, \quad \forall v, \forall w, \forall t \tag{17}$$

$$SOE_{v,w,t}^{CES} = SOE_{v,w,(t-1)}^{CES} + CE^{CES} \cdot P_{v,w,t}^{CES,ch} \cdot \Delta t - \left(\frac{P_{v,w,t}^{CES,dis}}{DE^{CES}}\right) \cdot \Delta t, \quad \forall v, \forall w, \forall t \tag{18}$$

$$SOE^{CES,min} \le SOE_{v,w,t}^{CES} \le SOE^{CES,max}, \quad \forall v, \forall w, \forall t \tag{19}$$

5) Modelling of EVs

EVs are a more environmentally friendly means of transportation that has a dynamic character and a variety of modeling constraints. The equations (20)-(24) indicate the charging constraints and limitations of EVs.

$$0 \le P_{e,v,w,t}^{ev,ch} \le R_e^{ev,ch}, \quad \forall t \in [T_e^a, T_e^d] \tag{20}$$

$$SOE_{e,v,w,t}^{ev} = SOE_e^{ev,ini} + CE_e^{ev} \cdot P_{e,v,w,t}^{ev,ch} \cdot \Delta t, \quad if\ t = T_e^a \tag{21}$$

$$SOE_{e,v,w,t}^{ev} = SOE_{e,v,w,(t-1)}^{ev} + CE_e^{ev} \cdot P_{e,v,w,t}^{ev,ch} \cdot \Delta t, \quad \forall t \in (T_e^a, T_e^d] \tag{22}$$

$$SOE_e^{ev,min} \le SOE_{e,v,w,t}^{ev} \le SOE_e^{ev,max}, \quad \forall t \in [T_e^a, T_e^d] \tag{23}$$

$$SOE_{e,v,w,t}^{ev} = SOE_e^{ev,max}, \quad t = T_e^d \tag{24}$$

6) Modelling of end-users

By indicating all generating and consuming units including RES, CES and EVs, the equations of end-users' electricity, heating, cooling demands, and supply balances are given in (25), (26), and (27) respectively.

$$P_t^{end-user,elec} = P_{v,w,t}^{direct-user} + P_{v,t}^{pv} + P_{w,t}^{wind} + \sum_m P_{m,v,w,t}^{CHPel,end-user} + P_t^{CES,dis} - P_t^{CES,ch} - \sum_e P_{e,v,w,t}^{ev}, \quad \forall m, \forall e, \forall v, \forall w, \forall t \tag{25}$$

$$P_t^{end-user,heat} = \sum_m P_{m,v,w,t}^{CHP,heat} + \sum_n P_{n,v,w,t}^{HP,heat}, \quad \forall m, \forall n, \forall v, \forall w, \forall t \tag{26}$$

$$P_t^{end-user,cool} = \sum_n P_{n,v,w,t}^{HP,cool}, \quad \forall n, \forall v, \forall w, \forall t \tag{27}$$

III. TEST AND RESULTS

The proposed smart MES management model is tested in GAMS 28.2.0 environment with a CPLEX solver. In the next subsections, the input data and the results for various scenarios are explained. The list and description of conducted cases are given in Table IV.

A. Input Data

The real electricity and gas prices are shown in Fig. 2. The constant gas price (0.045 \$/kWh) is taken from [16], the varying prices of electricity based on a TOU tariff (0.071 \$/kWh, 0.135 \$/kWh, and 0.213 \$/kWh) and the real constant electricity price non-TOU tariff (0.133 \$/kWh) are extracted from [17].

The energy purchase prices within the time of hours can be seen in Fig. 2, the time-varying prices affect the usage of HPs, CHPs and the gas and electricity inputs of the smart MES.

The electricity, heating, and cooling energy demands of the smart neighborhood, which is derived from [18], are shown in Fig. 3. Technical specifications of CHPs and HPs are taken from [19] and [20], respectively, and these values are shown in Table V and Table VI. In the designed smart MES model, a total of five CHPs with five different features and a total of ten HPs with five different features are used.

The PV and wind energy generation profile and the technical specifications of EVs data (generated from [6]) are presented in Fig. 4 and Table VII, respectively. Generally, the PV has production values between 6 a.m. and 7 p.m. There are three types of EVs with a total number of six EVs: three vehicles are used for residential purposes, and the next three EVs are used for commercial purposes.

Lastly, Table VIII contains the technical specifications of CES, which are taken from [21].

TABLE IV. DESCRIPTION OF THE EVALUATED CASES

Case #	**Descriptions**
Case-1	Only grid
Case-2	Only gas
Case-3	Grid and gas (Base Case)
Case-4	Grid, gas, and PV production
Case-5	Grid, gas, PV & wind productions
Case-6	Grid, gas, PV & wind productions, CES
Case-7	Grid, gas, PV & wind productions, CES, EV (Desired Case)
Case-8	Same as Case 7; gas prices increased by +50%
Case-9	Same as Case 7; gas prices increased by +200%
Case-10	Same as Case 7; electricity price (Non-TOU tariff)

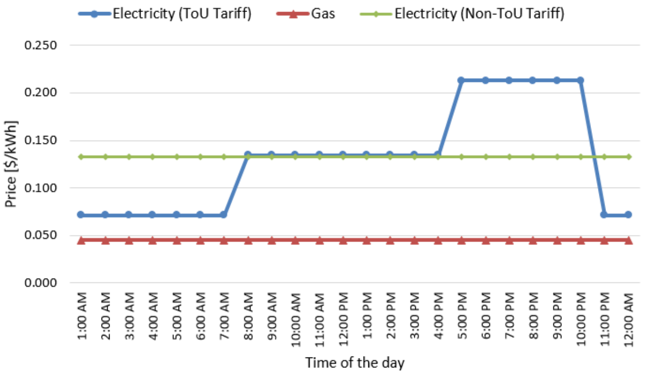

Fig. 2. Energy purchase prices.

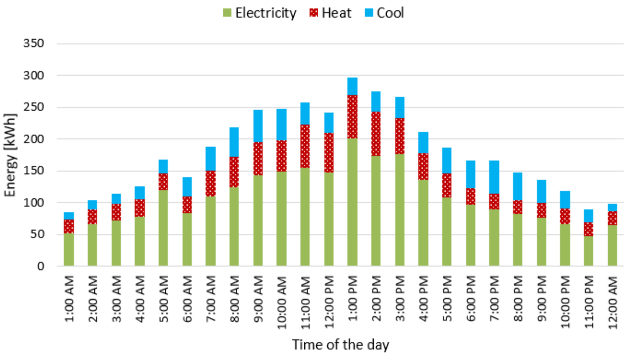

Fig. 3. Electricity, heating and cooling energy demands.

TABLE V. CHP UNITS' TECHNICAL DATA

	Electrical		**Heat**	
CHP Unit Type	**Output (kW)**	**Efficiency (%)**	**Output (kW)**	**Efficiency (%)**
CHP 1	20	30.7	41.8	64.1
CHP 2	30	32.4	58.1	62.8
CHP 3	50	34.2	88.5	60.6
CHP 4	81	35.1	120	52.2
CHP 5	85	33.7	141	56.1

TABLE VI. HP UNITS' TECHNICAL DATA

	Heat		**Cool**	
HP Unit Type	**Output (kW)**	**COP**	**Output (kW)**	**EER**
HP 1	3.2	4.78	2.5	5
HP 2	3.7	4.57	3.5	4.02
HP 3	8	3.83	7.1	3.53
HP 4	6.8	4.07	6	3.77
HP 5	10.3	3.5	9	3.24

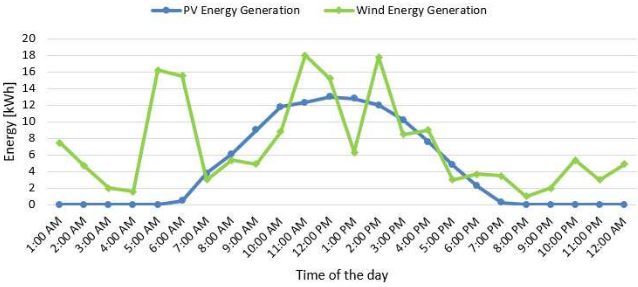

Fig. 4. PV and wind productions.

TABLE VII. TECHNICAL CHARACTERISTICS OF EVS

Type of EV	$R_{e,t}^{ev,ch}$	CE_{e}^{ev}	$SOE_{e}^{ev,ini}$	$SOE_{e}^{ev,min}$	$SOE_{e}^{ev,max}$
EV 1	3.3	0.95	6.4	3.2	16
EV 2	7.2	0.95	9.6	4.8	24
EV 3	6.6	0.95	8.8	4.4	22

TABLE VIII. TECHNICAL CHARACTERISTICS OF THE CES SYSTEM

CES Unit Characteristics	**Value**	**Unit**
Min. Capacity	60	kWh
Max. Capacity	300	kWh
Charge Rate	60	kW
Discharge Rate	60	kW
Initial Energy State	150	kWh
Charge Efficiency	95	%
Discharge Efficiency	95	%

B. *Simulation Results*

The energy consumption from the grid is shown in Fig. 5 before and after the RES integration. As expected, the consumption after the integration of RES is decreased. The electricity demand of the system only changes when EVs are charging and it is fixed for the rest of time intervals.

The MES electricity balance is depicted in Fig. 6. The net demand for electricity varying between 47.17 kW and 200.71 kW. The smart MES manages the all inputs and constraints, and based on the objective function the algorithm determines when the best moment is to utilize electricity or gas. The obtained results show that the proposed model can effectively reduce the total operational costs.

The equilibrium balance of the produced and consumed heating and cooling energy for Case-7 and Case-10 are shown in Fig. 7 and Fig. 8, respectively. For Case-7, both the heating and cooling demands are supplied by HP units; however, in Case-10, the heating is supplied by CHP units while the cooling is produced by HP units.

Figure 9 shows the SoC, charging and discharging power of the CES, and the charging power of EVs. The commercial EVs are charged during the daytime, while the residential EVs are charged after the arrival time.

The gas inputs and power inputs of the smart MES from outer energy networks for Cases 7-10 are shown in Fig. 10. and Fig. 11.

Therefore, Case-8, Case-9, and Case-10 are conducted to examine the sensitivity of the process to fuel prices. The MES gas inputs are decreased and electricity inputs are increased when the gas price is increased.

For Case-10, while the non-TOU tariff is used, the gas inputs increase and power inputs decrease. The algorithm decides which input is cheaper to use and reduces the usage of the other one.

Finally, the total operational costs ($) and cost changes (%) for all ten cases are shown in Fig. 12. The costing results are acceptable, showing the effectiveness of the proposed approach.

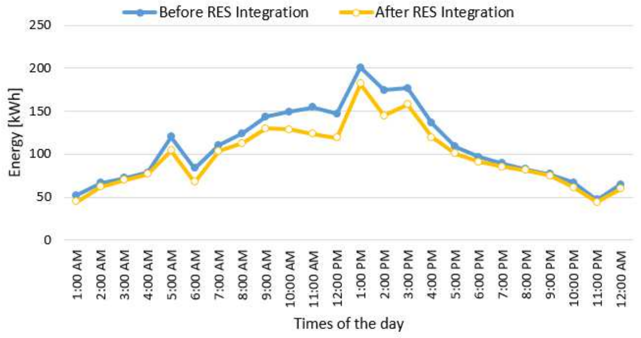

Fig. 5. Electricity consumption from the main grid.

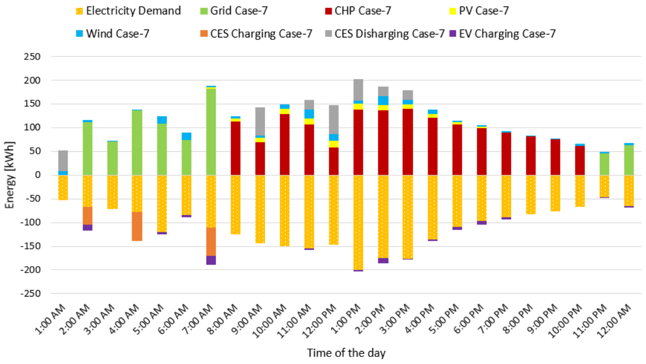

Fig. 6. Electricity demand and supply balance for Case-7.

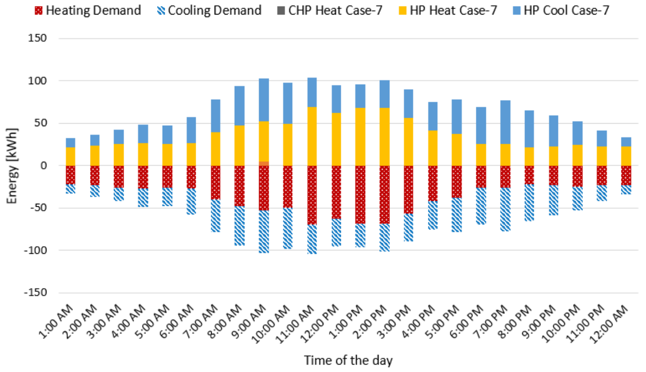

Fig. 7. Heating and cooling demand & supply balances for Case-7.

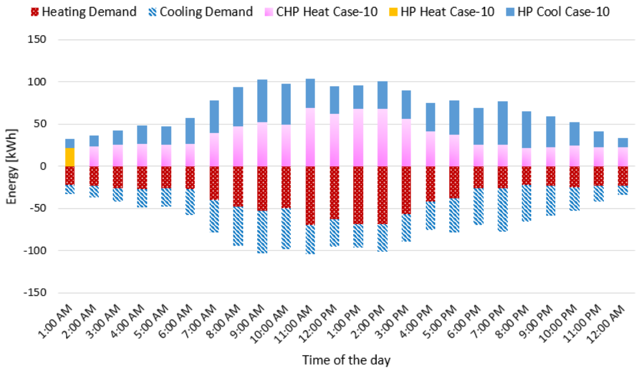

Fig. 8. Heating and cooling demand and supply balances for Case-10.

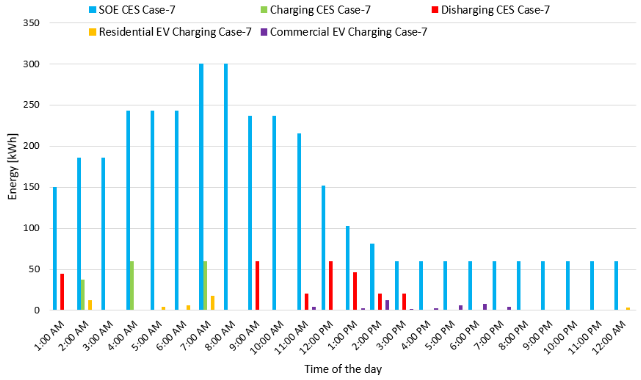

Fig. 9. SoC of the CES system and charging power of EVs.

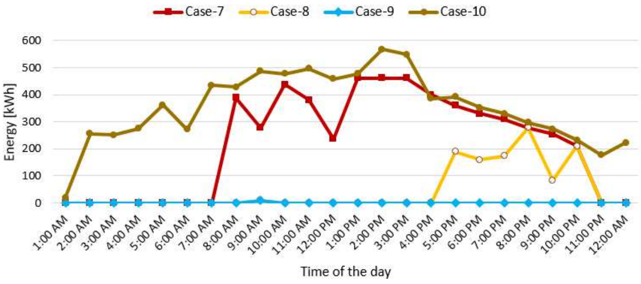

Fig. 10. Gas inputs of the smart-MES for Cases 7-10.

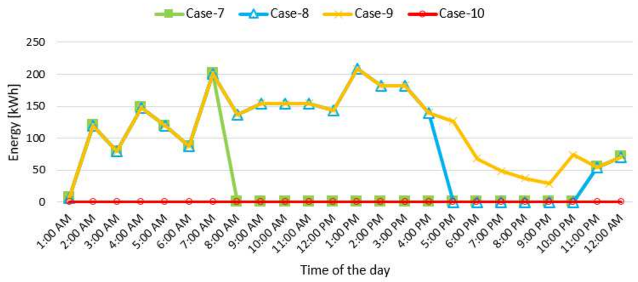

Fig. 11. Electricity inputs of the smart-MES for Cases 7-10

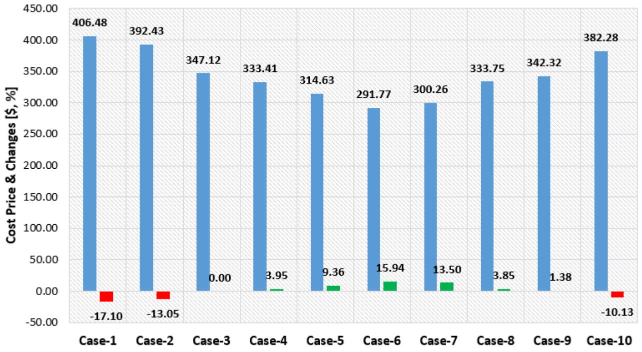

Fig. 12. Total operation costs of the considered cases.

As a result, it is clear that the operational cost of the Case-3 (Base Case) is lower with respect to Case-1 and Case-2 in which only the power grid and gas network supply the MES, respectively. Also, the Base Case has a lower cost than Case-10 where the non-TOU tariff is used for electricity prices. However, when PV and wind productions are introduced in Case-4 and Case-5, respectively, the cost decreases compared to Case-3. When CES is introduced to the system in Case-6, the operational cost is decreased to the lowest cost of 291.77 $, which is 15.94% less than the Base Case. Case-7, which is the desired case and has added EV consumption, is still 13.15% less than the Base Case.

IV. CONCLUSIONS

The optimal operation of a smart MES aiming to minimize the total cost on the premise of meeting different energy demands of end-users was designed in this paper. The optimal topology is determined by considering the whole system together with the relevant components, energy demands and energy prices. A smart MES considering DR-based on TOU electricity tariff and real gas price as MILP problem was employed and formulated. Various case studies conducted show the effectiveness of the proposed optimization algorithm on maximizing the efficiency and minimizing the operational costs while meeting the demands. Further research will be undertaken on the system and component uncertainty.

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